

# The introduction of advanced biofuels

A consequential assessment of environmental and climate aspects in the context of European legislation



**Benedikt Buchspies**

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assessment of environmental and climate aspects in the  
context of European legislation

**De invoering van geavanceerde biobrandstoffen - Een consequentiële  
beoordeling van de milieu- en klimaataspecten in het kader van de  
Europese wetgeving  
(met een samenvatting in het Nederlands)**

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# Samenvatting

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## Samenvatting

In het licht van de waargenomen en voorspelde negatieve effecten van een veranderend klimaat worden momenteel maatregelen genomen om de (antropogene) uitstoot van broeikasgassen (BKG) te verminderen. Hiertoe is wereldwijd wetgeving geïmplementeerd die gericht is op het terugdringen van het gebruik van fossiele energie in de transport- en energiesector. Binnen de EU is in 2008 de Richtlijn Hernieuwbare Energie (RED) geïmplementeerd om de introductie van alternatieve brandstoffen te vergemakkelijken. Ondersteund door de richtlijn zijn biobrandstoffen, voornamelijk gemaakt van voedsel- en voedergewassen, zogenaamde eerste generatie (1G) biobrandstoffen, op de markt gekomen. De introductie van deze brandstoffen ging gepaard met kritiek op de concurrentie van de productie van biobrandstoffen met de voedsel- en voedervoorziening en de potentiële uitbreiding van landbouwgrond. Daarom is met de wijziging van de RED, de RED II, die in 2018 is ingevoerd, de bijdrage van 1G-biobrandstoffen aan de algemene Europese doelstellingen voor hernieuwbare energie gemaximeerd. In plaats daarvan bevordert de RED II de invoering van biobrandstoffen uit landbouwresiduen en -afval, de zogenaamde geavanceerde of tweede generatie (2G) biobrandstoffen. Ongeacht de grondstof moeten alternatieve brandstoffen voldoen aan vastgestelde duurzaamheidscriteria. Een belangrijke duurzaamheidsindicator die door de beleidsmakers is gekozen, is de uitstoot van broeikasgassen. De RED en RED II bieden methoden om de broeikasgassen (BKG)-emissies van concepten voor de productie van alternatieve brandstoffen te schatten, uitgedrukt in *GHG savings*. Deze *GHG savings* omvatten de BKG-emissies van de totale brandstoflevenscyclus, vanaf de levering van de grondstoffen tot aan het gebruik van de brandstof. De methodologie richt zich uitsluitend op de BKG-emissies die binnen de levenscyclus plaatsvinden en veronachtzaamt de effecten die daarbuiten ontstaan.

Het doel van het gepresenteerde proefschrift was een dieper inzicht te verschaffen in de veranderingen in broeikasgasemissies als gevolg van de introductie van nieuwe bioraffinageconcepten en de implicaties van de methodologische keuzes die zijn gemaakt om deze veranderingen te evalueren. Daartoe werden de volgende onderzoeksvragen behandeld:

1. Wat zijn de milieueffecten en broeikasgasemissies van biobrandstofconcepten binnen de productieketen en welke zijn de belangrijkste parameters die de resultaten beïnvloeden?
2. Welke veranderingen in broeikasgasemissies worden veroorzaakt door de introductie van nieuwe biobrandstofconcepten?
3. Wat is de invloed van een verandering in de tijd van de emissies op de BKG-balansen van biobrandstoffen?

Om een antwoord te geven op deze vragen werden verschillende benaderingen op basis van attributieve en consequentiële LCA, de RED (II)-methodologie en methoden die verder gaan dan de traditionele LCA-methodologie, toegepast op de selectie van bestaande en potentiële

toekomstige bioraffinageconcepten. De evaluatie van de onderzoeksvragen wordt gepresenteerd in de hoofdstukken 2 tot en met 7:

## **Hoofdstuk 2: Sustainability aspects of biokerosene**

De introductie van biokerosine als alternatief voor conventionele fossiele kerosine wordt gedreven door de intentie om de uitstoot van BKG te verminderen, de afhankelijkheid van fossiele energiedragers te verminderen en door het potentieel om economische voordelen te creëren, vooral in landelijke gebieden. In dit hoofdstuk worden duurzaamheidsaspecten van biokerosine besproken voor een brede scala aan grondstoffen en omzettingroutes met betrekking tot de milieu- en sociaal-economische gevolgen.

Vanuit een milieuperspectief laten de resultaten zien dat het gebruik van biokerosine de uitstoot van broeikasgassen kan verminderen in vergelijking met het gebruik van conventionele vliegtuigbrandstof. Dit is echter sterk afhankelijk van de directe en indirecte effecten van veranderingen in landgebruik (LUC), die zelfs tot een aanzienlijke toename van de emissies kunnen leiden. De emissievoordelen zouden tot op zekere hoogte kunnen worden verminderd door niet-CO<sub>2</sub>-emissies van verbranding. De teelt van grondstoffen beïnvloedt de bodem- en waterkwaliteit door koolstofverlies in de bodem, bodemerosie en uitspoeling van voedingsstoffen en landbouwchemicaliën, enz. Passende beheerspraktijken kunnen de negatieve gevolgen verminderen. De gevolgen zijn bovendien afhankelijk van de geschiedenis van het landgebruik en het type gewas: bepaalde gewassen kunnen bijvoorbeeld de bodemkwaliteit verbeteren. Uit de beoordeling van de behoefte aan land blijkt dat algen, schakelgras, miscanthus, suikerriet en oliepalmen de grootste hoeveelheid brandstoffen per hectare opleveren. In de wetenschappelijke literatuur wordt melding gemaakt van overwegend negatieve effecten van biobrandstoffen op de biodiversiteit. Deze negatieve gevolgen kunnen worden verzacht door het gebruik van afval en lignocellulose-residuen.

Wat de sociaal-economische aspecten betreft, blijkt uit de beoordeling dat geen van de beoordeelde brandstoftrajecten financieel concurrerend is met conventionele kerosine, zelfs als men uitgaat van een volwassen productietechnologie. De levering van waardevolle nevenproducten of de belastingheffing op fossiele brandstoffen zijn manieren om de invoering van biokerosine te vergemakkelijken. Bovendien wordt het effect van biobrandstoffen op de voedselprijzen en de volatiliteit van de voedselprijzen besproken. In de meeste wetenschappelijke literatuur wordt melding gemaakt van stijgende voedselprijzen als gevolg van het bestaande biobrandstofbeleid. Ingebed in een flexibele regelgevende context kunnen biobrandstoffen echter de prijsvolatiliteit verminderen. Uit de analyse blijkt bovendien dat biobrandstoffen investeringen stimuleren en werkgelegenheid en inkomsten in plattelandgebieden creëren.

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De meeste milieu- en sociaaleconomische gevolgen zijn afhankelijk van de grondstof, het omzettingsspad, de lokale milieu- en sociaaleconomische omstandigheden, de marktstructuren en de politieke context. Het overzicht van verschillende belangrijke aspecten van duurzaamheid dat in deze studie wordt gegeven, onderstreept het belang van een individuele duurzaamheidsbeoordeling om de voordelen te optimaliseren en de negatieve gevolgen van de levering en het gebruik van biokerosine tot een minimum te beperken. Het wordt bovendien duidelijk dat veel negatieve effecten inherent zijn aan de landbouwproductie in het algemeen en dat deze aspecten moeten worden besproken in een bredere context dan die van biobrandstoffen alleen. Dit zou de synergiën van de voedsel-, vezel- en brandstofproductie kunnen bevorderen en een duurzaam gebruik van de hulpbronnen kunnen vergemakkelijken.

### **Hoofdstuk 3: Life cycle assessment of bioethanol from wheat and sugar beet discussing environmental impacts of multiple concepts of co-product processing in the context of the European Renewable Energy**

De milieuprestaties van biobrandstoffen worden vaak beoordeeld door meerdere grondstoffen te vergelijken, terwijl de implicaties van verschillende opties voor de verwerking van nevenproducten worden verwaarloosd. Deze studie presenteert een levenscyclusanalyse (LCA) van verschillende concepten voor de verwerking van nevenproducten van de productie van ethanol uit tarwe en suikerbieten in Duitsland. Inventarisatiegegevens zijn gegevens uit de eerste hand van de industrie die de meest moderne installaties presenteren. De methodologie die is gedefinieerd door de RED wordt toegepast.

Het cradle-to-gate onderzoek toont aan dat de coproductie van voedergewassen de laagste impact heeft op ethanol: 37 g CO<sub>2</sub>-eq. per MJ ethanol uit suikerbieten. De totale effecten zijn lager in het geval van ethanol op basis van suikerbieten in impactcategorieën, die worden gedomineerd door emissies van de teelt, zoals eutrofiëring en verzuring. De coproductie van biogas leidt weliswaar tot de laagste totale emissies, maar tot hogere emissies die aan ethanol worden toegeschreven. Een gevoeligheidsanalyse laat zien hoe bepaalde aannames, zoals het gebruik van een andere energiedrager, het drogen van graan, etc., deze resultaten beïnvloeden.

De resultaten geven aan dat de milieueffecten van verschillende concepten voor de verwerking van nevenproducten verschillen. Daarom moet bij de vergelijking van de milieueffecten van biobrandstoffen speciale aandacht aan dit aspect worden besteed. Verder wordt geadviseerd om bij de toewijzing van emissies een methode toe te passen die rekening houdt met het nut en de voordelen van bijproducten, in tegenstelling tot de RED-methode.

#### **Hoofdstuk 4: The Influence of Co-product Handling Methodology on Greenhouse Gas Savings of Biofuels in the European Context**

Het hanteren van multi-output systemen vormt een cruciaal aspect van de berekening van de uitstoot van BKG en de certificering van biobrandstoffen, en het is een uitdaging om een robuuste en toepasbare methode te vinden die rekening houdt met de onderscheidende kenmerken en voordelen van alle producten. In dit hoofdstuk worden de broeikasgasemissiereducties van elf concepten voor de productie van biobrandstoffen beoordeeld. De implicaties van methodologische aannames worden besproken door toepassing van de methodologie die is gedefinieerd in de RED, allocatie op basis van fysieke parameters, twee hybride benaderingen en zes substitutievarianten. De broeikasgasemissiereducties volgens de RED-methodologie variëren van 35% tot 57%. Ethanol op basis van suikerbieten levert de grootste besparing op. Uit de resultaten blijkt dat de BKG-besparingen volgens de RED-methodologie samengevat een relatief goede benadering vormen van de emissiereducties als gevolg van substitutie-effecten onder bepaalde aannames. De invoering van credits voor producten waarmee de RED-methodologie nauwelijks of niet rekening houdt als gevolg van de toewijzing op basis van de lagere verwarmingswaarde, d.w.z. meststoffen en nevenproducten van vochtrijk veevoer, vermindert het verschil tussen de RED-resultaten en de resultaten op basis van substitutie. Als met substitutiemechanismen rekening wordt gehouden, leveren ethanol op basis van suikerbieten, de productie van ethanol door natmalen van tarwe en zonnebloem-biodiesel de grootste emissiebesparing op in het licht van de gegeven veronderstellingen, indien de olie die moet worden geleverd als gevolg van de voorkomende verdringingsmechanismen afkomstig is van koolzaad. De toepassing van een methode die concepten met een hoog emissiereductiepotentieel ondersteunt, bijvoorbeeld toewijzing op basis van de lagere verbrandingswaarde van droog materiaal, zou de emissiereductie van de levering van biobrandstoffen kunnen bevorderen.

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#### **Hoofdstuk 5: A consequential assessment of changes in greenhouse gas emissions due to the introduction of wheat straw ethanol in the context of European legislation**

Tot op heden domineren 1G biobrandstoffen de markt voor alternatieve brandstoffen. De Europese Commissie heeft besloten een maximum te stellen aan 1G-biobrandstoffen en 2G biobrandstoffen te bevorderen met de bedoeling de uitstoot van BKG te verminderen, de concurrentie op het gebied van levensmiddelen, diervoeders en biobrandstoffen te beperken en de maatschappelijke goedkeuring te verbeteren. De beoordeling van de gevolgen die een verschuiving van 1G naar 2G biobrandstoffen met zich meebrengt, is nodig om te beoordelen of een dergelijke verschuiving al dan niet raadzaam is. Volgens de RED moet voor alle biobrandstoffen een *GHG savings* worden vastgesteld. Tegen eind 2020 moeten de brandstofmengsels een BKG-besparing van 6% opleveren. De *GHG savings* zal dus bepalend zijn voor de hoeveelheid biobrandstof die met fossiele brandstoffen moet worden gemengd en daarmee uiteindelijk de vraag naar biobrandstoffen

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bepalen. In dit hoofdstuk worden de gevolgen van een verschuiving van een 1G naar een 2G biobrandstof beoordeeld aan de hand van het voorbeeld van bio-ethanol uit tarwekorrels en stro. In totaal worden drie concepten van 2G-ethanolproductie uit tarwestro bekeken: vergisting van C6-suikers met (1) coproductie van veevoer, (2) gekoppeld aan biogasproductie en (3) co-vergisting van C5- en C6-suikers met coproductie van voer. Om het effect van de invoering van 2G-ethanol te bepalen, worden eerst de *GHG savings* volgens RED berekend en worden in een tweede stap de gevolgen van de verschuiving van 1G naar 2G-ethanol beoordeeld door rekening te houden met substitutiemechanismen en emissies door directe en indirecte LUC. De *GHG savings* van deze 2G-concepten volgens de RED-methode varieert van 103 tot 105%. De verschuiving van 1G ethanol naar deze 2G-concepten wordt beoordeeld aan de hand van twee scenario's: 1) extra productie van 2G-ethanol en 2) vervanging van 1G-ethanol door 2G-ethanol. De resultaten geven aan dat de broeikasgasemissies in scenario 1 afnemen als alle additionele ethanol fossiele brandstoffen vervangt. Onder de gegeven aannames varieert de emissiereductie van 9.0 tot 12.1 kg CO<sub>2</sub>-eq./GJ ethanol-gasolinemengsel. Als 1G ethanol wordt vervangen door 2G ethanol, neemt de BKG-emissie toe in een bereik van 7.5 tot 16.5 kg CO<sub>2</sub>-eq./GJ brandstofmengsel. Dit is voornamelijk het gevolg van de aanvoer van veevoer dat moet worden geleverd als gevolg van de verschuiving in de productie: De productie van 1G ethanol levert veevoer met een hoog eiwitgehalte op dat op een andere manier moet worden geleverd. De belangrijkste drijfveer voor een toename van de emissies is dan ook de levering van sojameel en de daarmee gepaard gaande emissies van LUC. Uit een gevoeligheidsanalyse blijkt dat deze resultaten robuust zijn wat betreft de inputparameters en de LUC-veronderstellingen. Deze bevindingen wijzen erop dat het van het grootste belang is om de door de invoering van nieuwe brandstoffen teweeggebrachte veranderingen te beoordelen in plaats van deze los van de marktomstandigheden te beoordelen. Op basis van deze bevindingen kan worden geconcludeerd dat de huidige en voorgestelde wetgeving effecten kan hebben die tegengesteld zijn aan de beoogde effecten.

## **Hoofdstuk 6: Potential changes in GHG emissions arising from the introduction of biorefineries combining biofuel and electrofuel production within the European Union – A location specific assessment**

In het komende decennium zullen biobrandstoffen uit landbouwresiduen, -afval en -bijproducten hoogstwaarschijnlijk een integraal onderdeel vormen van de biobrandstofvoorziening om broeikasgasreductiedoelstellingen te halen. Maar nieuwe bioraffinaderijen die gebruik maken van lignocellulosehoudende biomassa kunnen naast brandstof ook andere producten leveren. Om te bepalen welke concepten het meest kunnen bijdragen aan de vermindering van de antropogene broeikasgasemissies, is het belangrijk om potentiële veranderingen in de broeikasgasemissies als gevolg van de invoering van alternatieve brandstofconcepten te evalueren. Daartoe worden potentiële veranderingen in broeikasgasemissies als gevolg van de invoering van 36 bio-ethanolconcepten die een combinatie zijn van bioraffinaderijen

en elektrobrandstofproductie en die een breed spectrum van producten (bv. brandstoffen, chemicaliën, voeder- en levensmiddelenadditieven) opleveren, beoordeeld. Een gedetailleerde analyse omvat de grondstoffen- en energievoorziening en de marginale verplaatsingseffecten voor 26 Europese lidstaten. De potentiële veranderingen in broeikasgasemissies als gevolg van de invoering van deze concepten variëren van -206 tot 135 en van -221 tot -17 g CO<sub>2</sub> per MJ bio-ethanol uit respectievelijk tarwekorrels en tarwestro. Uit de analyse blijkt dat de BKG-intensiteit in verband met de marginale grondstoffen- en energievoorziening en de verdringingseffecten tussen de landen sterk uiteenloopt. Deze grote verschillen wijzen erop dat bij de ontwikkeling van beleidsdoelstellingen voor alternatieve brandstoffen op lange termijn rekening moet worden gehouden met de plaatselijke omstandigheden. Uit de analyse blijkt voorts dat de methode die binnen de Europese Unie wordt gebruikt om de broeikasgasemissies te evalueren en die in de RED (II) is opgenomen, vele concepten en productiemodaliteiten uitsluit die het potentieel hebben om de broeikasgasemissies te verminderen.

### **Hoofdstuk 7: Straw utilization for biofuel production: A consequential GHG assessment of bioethanol and biomethane provision with a focus on the time-dependency of emissions**

De verschuiving van de integratie van stro naar de productie van biobrandstoffen leidt tot veranderingen in de uitstoot van BKG door de productie, veranderingen in de organische koolstof in de bodem (SOC) en door de levering van (mede-)producten en de daarmee gepaard gaande verdringingseffecten. Dit document analyseert de veranderingen in broeikasgasemissies als gevolg van de verschuiving van de verwerking van stro naar de productie van biomethaan en bio-ethanol. Het biomethaanconcept omvat versnipperen, anaërobe vergisting en aminewassen. Het levert bovendien een organische meststof op. De productie van bio-ethanol bestaat uit het energetisch gebruik van lignine, stoomexplosie, enzymatische hydrolyse en co-fermentatie. Daarnaast wordt er veevoer verstrekt. Er wordt een gedetailleerde BKG-balans uitgevoerd met een diepgaande focus op de tijdsafhankelijkheid van de emissies: a) de verandering in de atmosferische belasting van de emissies als gevolg van de verandering in de tijd van de emissies, waarbij twee stationaire staten met elkaar worden vergeleken (vóór de verschuiving en zodra een nieuwe stationaire staat is vastgesteld) en b) de jaarlijkse verandering in de totale emissies in de loop van de tijd vanaf de verschuiving worden beoordeeld. De verschuiving van de integratie van stro naar de productie van biomethaan leidt tot netto veranderingen in de broeikasgasemissies van (a) -979 (-436 tot -1654) en (b) -955 (-220 tot -1623) kg CO<sub>2</sub>-eq. per t<sub>DM</sub>-stro dat in biomethaan is omgezet (minimum en maximum). De verschuiving naar de productie van bio-ethanol leidt tot netto veranderingen van (a) -409 (-107 tot -610) en (b) -361 (57 tot -603) kg CO<sub>2</sub>-eq. per in bio-ethanol omgezette t<sub>DM</sub>-stro. Indien de atmosferische belasting van de emissies als gevolg van een verschillende timing van de emissies wordt verwaarloosd in geval van (a), verschilt de verandering in de BKG-emissies tot 54%. In geval b) worden koolstofterugverdientijden van 0 (0 tot 58) en 19 (0 tot 100) jaar in

## Samenvatting

het geval van respectievelijk de productie van biomethaan en bio-ethanol. Deze resultaten tonen aan dat de gedetailleerde opname van temporele aspecten in de BKG-balansen nodig is om een volledig inzicht te krijgen in de veranderingen in de BKG-emissies als gevolg van de invoering van 2G-biobrandstoffen uit landbouwresiduen.

Op basis van deze bevindingen kunnen de volgende belangrijke conclusies worden getrokken:

- **De introductie van geavanceerde biobrandstofconcepten heeft het potentieel om de uitstoot van broeikasgassen te verminderen.**

Momenteel worden vloeibare biobrandstoffen bijna uitsluitend geproduceerd uit suiker, zetmeel en oliegewassen. De invoering van deze brandstoffen heeft geleid tot een toename van de vraag naar deze gewassen. Een dergelijke toename van de vraag brengt het risico met zich mee dat LUC worden veroorzaakt die mogelijk leiden tot broeikasgasemissies, biodiversiteitsverlies en andere negatieve gevolgen. Vanwege deze potentiële negatieve effecten is een verhoging van de productie van 1G-biobrandstoffen niet raadzaam. Daarentegen kan de invoering van geavanceerde biobrandstoffen uit landbouwresiduen leiden tot een aanzienlijke netto vermindering van de BKG-emissies, indien dit op passende wijze wordt gerealiseerd: als er überhaupt een netto vermindering wordt bereikt en de omvang van de potentiële netto vermindering hangt af van de modaliteiten van de invoering. Uit de evaluatie van de potentiële verdringingseffecten als gevolg van de invoering van geavanceerde biobrandstoffen is gebleken dat een verdringingseffect van bepaalde concepten van 1G-biobrandstoffen niet raadzaam is zonder aanvullende maatregelen die ervoor zorgen dat er geen ongewenste substitutie-effecten optreden. De meeste 1G-bio-ethanolconcepten die momenteel in gebruik zijn, leveren bijvoorbeeld eiwitvoer op. Een verdringing van deze brandstofconcepten door andere (bio-)brandstofconcepten kan leiden tot het betrekken van voer van elders, met mogelijk negatieve gevolgen die opwegen tegen de positieve effecten. Dergelijke maatregelen moeten dus worden ondersteund door andere maatregelen (die buiten het toepassingsgebied van de RED (II) vallen) om een netto vermindering van de BKG-uitstoot te bereiken.

- **Locatie is een belangrijke parameter die van invloed is op potentiële netto veranderingen in broeikasgasemissies.**

De potentiële netto vermindering van de BKG-emissies is afhankelijk van de plaats van herkomst van de grondstoffen en de lokaal heersende marktomstandigheden. De landbouwopbrengsten en andere teeltparameters verschillen aanzienlijk afhankelijk van de locatie, wat resulteert in een brede scala aan BKG-emissies als gevolg van de levering van grondstoffen. Ook de lokale omstandigheden zijn van invloed op het koolstofgehalte in de bodem en de afbraak van

landbouwresiduen. Bovendien verschillen de lokale marktomstandigheden en dus de marginale veranderingen in de vraag (bv. het energieaanbod voor de productie van brandstoffen) en de mogelijk daaruit voortvloeiende substitutie-effecten binnen de EU. De invoering van nieuwe brandstofconcepten kan dus leiden tot verschillende veranderingen in de emissies, afhankelijk van waar de grondstof vandaan komt, waar de faciliteit is gevestigd en aan welke markten producten worden geleverd. In concepten en wetgeving moet dus rekening worden gehouden met lokale milieuaspecten en marktomstandigheden.

- **De door de RED II verstrekte methode voor het bepalen van de *GHG savings* vertoont verschillende tekortkomingen om de indirecte effecten van de RED II te begrijpen en de diversificatie van de bioraffinaderijen te stimuleren**

Potentiële verdringingseffecten als gevolg van de invoering van biobrandstofconcepten kunnen oplopen tot 90% van de totale broeikasgasemissies als gevolg van de productie en het gebruik van de biobrandstof en alle belangrijke markteffecten die worden veroorzaakt. Deze emissies komen voor in sectoren die niet door de RED (II) (of enige andere regelgeving) worden gereguleerd. De mechanismen die in de RED (II) zijn opgenomen om de invoering van bepaalde concepten voor alternatieve brandstoffen te bevorderen, veroorzaken dus effecten die buiten het toepassingsgebied van de RED (II) vallen. De RED (II)-methodologie voor de raming van de *GHG savings*, een metriek voor de evaluatie van de broeikasgasemissies in de productieketen, houdt geen rekening met deze effecten. Dit brengt het risico met zich mee dat er ongewenste gevolgen en verschuivingen in de lasten ontstaan. Bovendien kunnen bepaalde mechanismen, d.w.z. bijmenging op basis van *GHG savings* of het negeren van emissies in verband met de voorziening van grondstoffen bij gebruik van landbouwresiduen, de potentiële vermindering van de BKG-emissies verminderen of zelfs de negatieve effecten verergeren. Uit de evaluatie van de potentiële effecten van veranderingen in de organische koolstof in de bodem als gevolg van een verschuiving van de verwerking van stro in de bodem is gebleken dat deze veranderingen in de BKG-balansen moeten worden opgenomen. Bovendien moeten de temporele aspecten van veranderingen in de organische koolstof in de bodem in de BKG-balansen worden opgenomen. De verschuiving naar de productie van bio-energie kan leiden tot een verandering in de tijd van de emissies. Uit de resultaten blijkt dat deze effecten in de BKG-balansen moeten worden opgenomen.

Bovendien wordt in de methodologie een duidelijke focus gelegd op concepten die energie en brandstoffen leveren. De focus op emissies die binnen de productieketen plaatsvinden en een relatieve vergelijking van de daarop gebaseerde concepten bevordert mogelijk concepten met lage emissies die binnen de productieketen plaatsvinden (die mogelijk slechts een klein deel van de totale veranderingen in de emissies uitmaken) of concepten die producten met een hoge energie-inhoud opleveren. Complexe processen die grotere inspanningen vergen en leiden tot

## Samenvatting

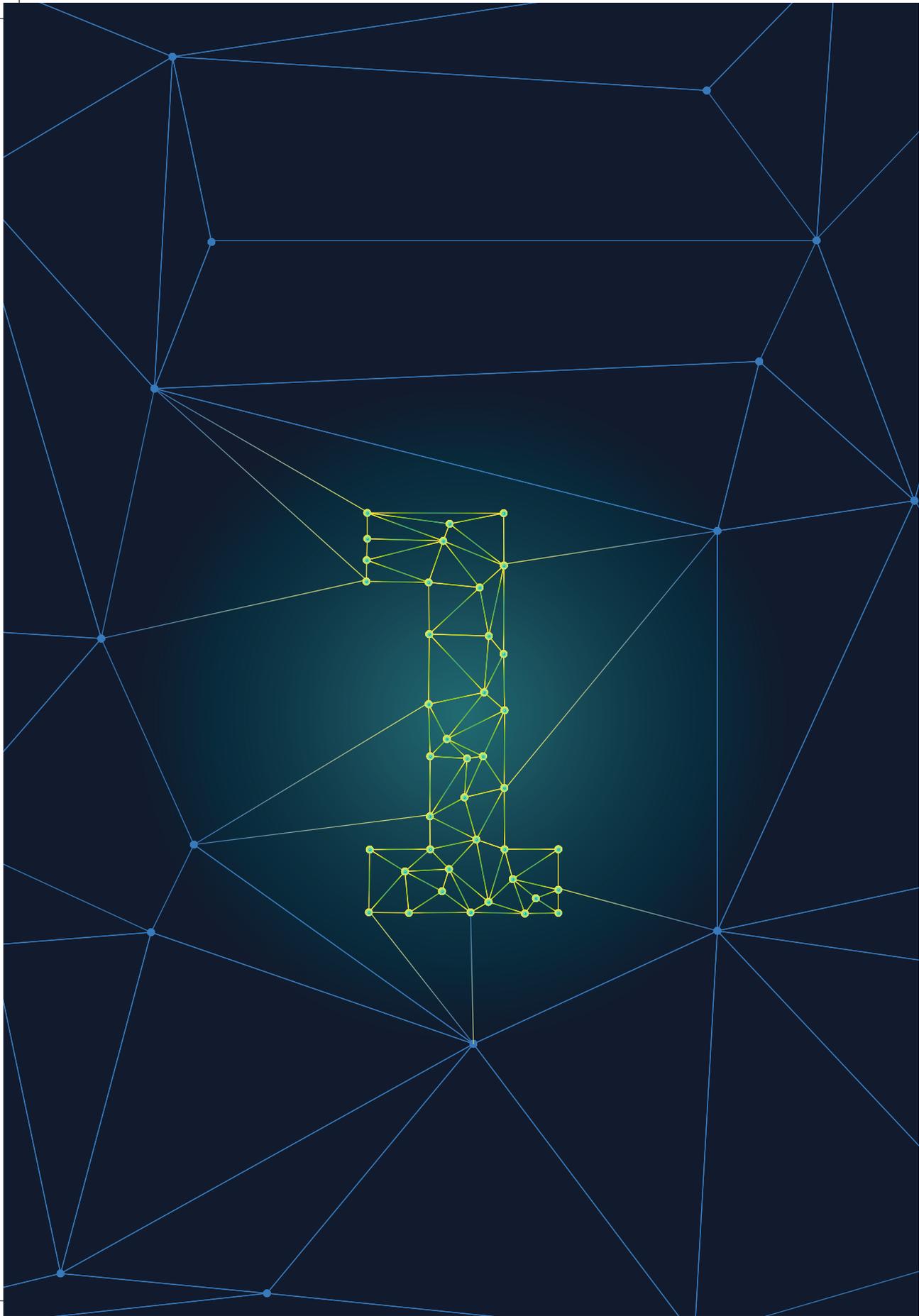
hogere BKG-emissies, presteren slechter volgens de gedefinieerde methodologie, ook al kunnen ze leiden tot een groter potentieel om de totale BKG-emissies te verminderen (of bij te dragen tot andere gunstige effecten). Dit zou kunnen voorkomen dat bepaalde innovatieve concepten op de markt komen die een hoger potentieel hebben om de BKG-uitstoot te verminderen en een duurzamere voorziening van een verscheidenheid aan producten te bieden. Het risico bestaat dat door de beperkte focus een lock-in situatie ontstaat, waardoor de introductie van bepaalde concepten die een duurzamere voorziening in de behoeften van de samenleving mogelijk maken, kan worden belemmerd.

- **De regelgeving moet worden uitgebreid**

Op basis van deze bevindingen kan worden geconcludeerd dat de RED II, moet worden uitgebreid. Nieuwe bioraffinageconcepten hebben de potentie om naast brandstoffen een brede scala aan producten te leveren. De wetgeving moet daarom alle sectoren die mogelijk worden beïnvloed, van de toewijzing van grondstoffen (en uiteindelijk land) tot alle sectoren die worden beïnvloed door producten die door bioraffinaderijen worden geleverd, uitgebreid behandelen. Bovendien moeten de duurzaamheidscriteria verder gaan dan de uitstoot van broeikasgassen en ook andere relevante aspecten omvatten (naast de duurzaamheidseisen die in de RED zijn opgenomen). Deze criteria moeten worden toegepast op alle soorten landgebruik en biomassagebruik, ongeacht de sector.

Deze belangrijke bevindingen wijzen erop dat beslissingen die binnen de brandstof- en energiesector worden genomen, kunnen leiden tot veranderingen (in de BKG-emissies) in andere sectoren die minder of helemaal niet gereguleerd zijn met betrekking tot de BKG-emissies. Bovendien kunnen er effecten ontstaan in regio's die niet onder controle staan van de politieke instellingen die de aanzet hebben gegeven tot deze beslissingen. De omvang van deze effecten kan veel groter zijn dan de broeikasgasemissies die binnen het gereguleerde systeem worden uitgestoten. Bovendien kan de beperkte focus van de huidige wetgeving de doeltreffendheid van de politieke maatregelen verminderen en het risico van lastenverplaatsing met zich meebrengen. De interconnectiviteit tussen sectoren en de noodzaak om met duurzamere middelen in alle behoeften van de samenleving te voorzien, vereisen wetgeving, concepten, mechanismen en structuren die verder gaan dan afzonderlijke sectoren. Geconcludeerd kan worden dat de beperkte focus van de RED (II) op het gebruik van biomassa voor uitsluitend energie onvoldoende is met betrekking tot het voornemen om de algemene afhankelijkheid van fossiele hulpbronnen te verminderen (voor de voorziening van alle behoeften van de samenleving, niet alleen van energie en energiedragers) en om de klimaatverandering te verzachten. De vereiste transformatie van de totale economie vereist wetgeving die de totale (bio-)economie in haar geheel omvat en die aanvullende overwegingen van duurzaamheid omvat die verder gaan dan klimaatverandering. Deze duurzaamheidseisen moeten worden toegepast op alle vormen van landgebruik en biomassageproductie, ongeacht het

uiteindelijke gebruik van de biomassa. Anders wordt biomassa die aan de duurzaamheidseisen voldoet, geleverd aan gereguleerde markten, terwijl andere, niet-duurzame productie wordt geleverd aan minder gereguleerde markten.



# Introduction

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## Chapter 1

The introduction provided below includes a brief overview of the role of biofuels and the context of the current legislative frameworks governing the introduction of biofuels within the European Union (EU). Additionally, knowledge gaps are discussed and research questions are derived. These research questions are addressed in the subsequent chapters.

### 1.1. The role of biofuels in the ongoing transition of the transport sector

The following chapter highlights the role and importance of biofuels in the past and today.

#### 1.1.1. Biofuels at the dawn of the automotive area

Even in the early days of the automotive era in the 19<sup>th</sup> century, biofuels played an important role. The first prototype of an internal combustion engine, developed by Samuel Morey in 1826 was fueled by ethanol. Half a century later, Nicolaus Otto started experimenting with ethanol as a fuel for his prototypes of the (later called) Otto engine. In 1861, Nicolaus Otto and his brother Wilhelm applied for a patent on an engine running on *Spiritus* (or “Kartoffelsprit” – ethanol made from potatoes) [1]. Royal Prussian authorities rejected the application. Likewise, the inventor of the diesel engine, Rudolf Diesel, used vegetal oil, such as peanut oil and castor oil, as well as oils derived from animal fats [2]. These trials were propelled by the French government in hope of being able to use oils that can be easily obtained from areas being French colonies at these times.

In the beginning of the 20<sup>th</sup> century, the promotion of biofuels was driven by various governments with the intention to support domestic farmers and, for example in case of France and Germany, to overcome the limited availability of fossil oil resources [3]. The French government heavily pushed the development of engines that could use alcohol by offering prizes and arranging fairs. A mandatory blending quota of 10% was introduced in 1923. Likewise, the German government of the Weimar Republic introduced a mandatory quota for “Kartoffelsprit” in order to support domestic potato farmers also in 1923 [4]. In many European countries, the ethanol fuel consumption peaked in the 1930s [5]. At that time, political support and mandatory quotas were also introduced in other countries: In the beginning of the 1930s, 30 countries had implemented blending quotas or other incentives to support the use of bioethanol as a transportation fuel [3]. In addition to bioethanol research, numerous experiments were conducted at these days to test different renewable feedstock that can either be directly used in diesel engines or for the production of biodiesel [6].

In the decades following World War II, the use of renewable fuels from biogenic feedstock became less popular due to the low oil price. It was not until the 1970s that the use of non-fossil fuels gained momentum: the oil crises 1973 and 1979 again raised concerns regarding the limitation of fossil energy carriers and the dependency on very few exporting countries forming a monopoly or at least an oligopoly. This stimulated the search for alternatives to fossil oil [7, 8]. Brazil was the first country to implement mechanisms to substitute fossil fuels on a large scale by sugarcane

ethanol after World War II. This happened decades before other countries started to substantially introduce biofuels within the transportation sector. It was initiated by the aim to reduce the dependency on oil, to improve the trade balance, to create labor in rural areas, and to provide a market for domestic sugar mills [9–11].

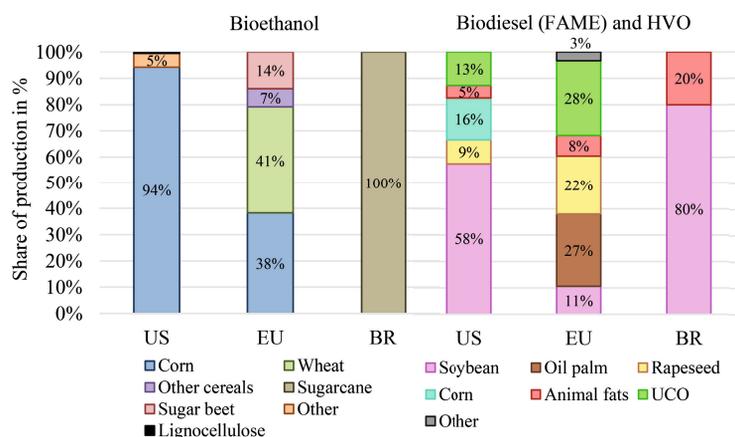
In all these exemplary cases, the use of biofuels was mainly driven by concerns over the limitation of fossil energy carriers, the strategic goal to reduce the import dependency on oil-exporting countries (i.e. to achieve an increase in energy security), and for economic reasons such as the reduction of the trade deficit and the support the domestic agricultural industries.

### **1.1.2. The game changer: climate change**

It took until the end of the 1980s before another aspect gained importance and received public and political attention: climate change. Before that, scientists were already discussing the implications of increasing concentrations of greenhouse gases (GHG) in the atmosphere [12]. However, only starting from the late 1980s, the topic aroused great interest in the public and among policy makers. Because of this strongly increasing interest in climate change on a global scale, the Intergovernmental Panel on Climate Change (IPCC) was founded in 1988. In the following years, the topic continued to gain importance and policies were implemented with the intention to reduce anthropogenic GHG emissions. The international conventions on climate change mitigation agreed upon in 1992 (“Rio Convention” [13]) and 1998 (“Kyoto Protocol” [14]) present clear evidence that the scientific debate on climate change and anthropogenic GHG emissions entered the political debate and ultimately resulted in binding multilateral political agreements.

For example, the Kyoto Protocol established binding emission reduction targets. This stimulated the implementation measures to reduce GHG emissions. Hence, many governments enacted laws to support the introduction of renewable fuels in the years following these international conventions. In the United States (US), for example, the Energy Policy Act of 1992 set a framework for the introduction of biofuels [15]. As a consequence of an expected increase in demand and the resulting implications on GHG emissions, a mandatory biofuel blending target of 2% was established in 2003 within the EU [16, 17]. Apart from the reduction in GHG emissions, the creation of new market opportunities in the agricultural sector and the reduction of the dependency on oil-exporting countries were clearly stated additional reasons when setting and implementing these targets. This motivation was underpinned by the Stern Review on the Economics of Climate Change predicting high economic costs of global warming [18]. As a consequence biofuel mandates were enacted world-wide [19]. These mandates led to the production and use of biofuels predominantly derived from starch, sugar and oil crops; so called first generation (1G) biofuels (Figure 1-1). In the US, 37% of the overall corn consumed within the US is used for fuel ethanol production (incl. protein feed) [20].

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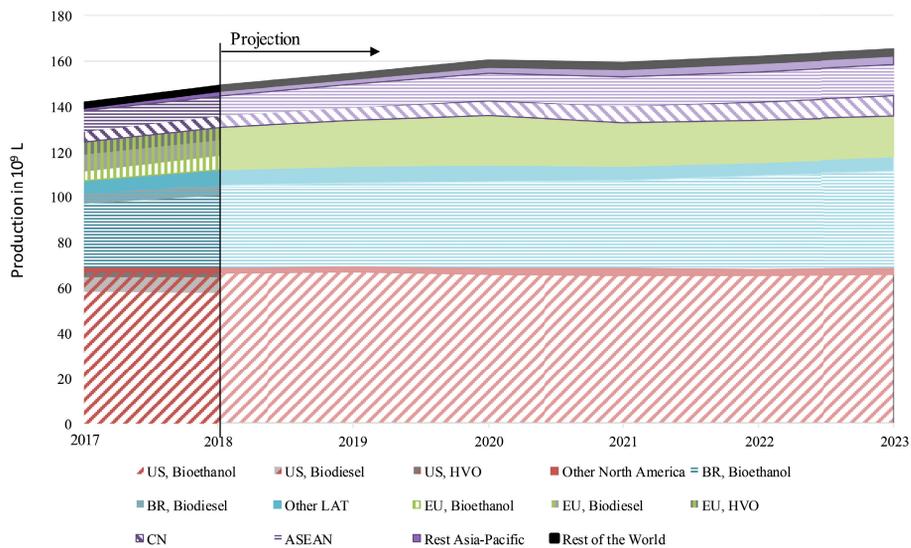
**Figure 1-1** Feedstock use for the production of bioethanol and biodiesel and hydrotreated vegetable oil (HVO) in the three most important biofuel markets in 2018 [21–24]. Abbr.: BR – Brazil; EU – European Union; FAME – fatty acid methyl ester; HVO – hydrotreated vegetable oil; UCO – unused cooking oil.

### 1.1.3. Emerging criticism of biofuels and the shift towards second generation biofuels

Numerous proven and supposed negative consequences accompanied the rise of 1G biofuels on a global scale. Among these, the expected competition of biofuel production with the needs for (affordable) food and feed is the most widely discussed topic within the scientific community as well as the concerned public [25–29]. There has been a lively and very controversial debate on the impact of biofuel mandates on food prices worldwide; especially as some scientific studies reported increasing staple food prices [30]. However, the magnitude of the effect varies considerably among studies, feedstock, regions and investigator / researcher. Additionally, even the question whether high staple food prices are beneficial (e.g. through increased income for farmers) or detrimental (e.g. high prices make staple food unaffordable for poor people) is a controversially discussed aspect in this context [31–35].

Another aspect that sparked concerns about 1G biofuels is the environmental implications of land-use change (LUC). A change in cultivated crops (e.g. motivated by the demand for biofuels) can trigger a direct change in the land-use (dLUC). Additionally, indirect changes in land-use (iLUC) can occur through a change in land-use elsewhere as a consequence of the demand for land (e.g. as a consequence of increasing demand for feedstock or all other activities that occupy land that displaces the previous use of land). The conversion of land affects environmental spheres by changing soil properties and quality, biodiversity, water availability and quality, etc. With regards to the intention to reduce anthropogenic GHG emissions through the use of biofuels, the GHG emissions arising from LUC has been paid special attention [36–38]. The work of Searchinger et al. [39] initiated an ongoing debate on LUC caused by US biofuel mandates [40–42]. In the wake of the extensive criticism of 1G biofuels and Searchinger et al.’s publication [39] mandates were revised or capped in important markets and the introduction of biofuels produced from residues and lignocellulosic material, so called second generation (2G) biofuels, was promoted [43–47].

At present, 2G biofuels and other drop-in (bio)fuels<sup>1</sup> only play a minor role (Figure 1-2). Drop-in biofuels only constitute a share of 2% of the global biofuel production [48]. Most of these however, are still made from 1G feedstock and waste fats and oils. In the past decade, 2G ethanol production facilities using lignocellulosic feedstock reached market maturity. In recent years, several commercial scale facilities have started operation or are currently constructed within the US (e.g. Abengoa Bioenergy Biomass of Kansas, Beta Renewables, DuPont/Verbio AG, POET-DSM Advanced Biofuels), the EU (e.g. Beta Renewables, Clariant, Enviral, Maabjerg Energy Concept Consortium), Brazil (GranBio) and China (e.g. Beta Renewables, Longlive Biotechnology Co. Ltd., DOFCO Zhaodong Co) [49]. However, many of these projects either are on hold or idle. The major challenge for these processes are high production costs in comparison to conventional 1G ethanol and technical difficulties. Efficient, low cost pre-treatment resulting in low inhibitor concentrations, efficient fermentation of pentose and hexose sugars as well as enzyme costs and loadings constitute challenges to be solved [50]. Due to these difficulties and resulting high production costs, 2G biofuel facilities still rely on policy support and their market share is still negligible.



**Figure 1-2** Biofuel production worldwide in 10<sup>9</sup> L [51]. Fuel-specific production volumes of bioethanol, biodiesel and hydrotreated vegetable oil are displayed for the most important markets [52, 53]. Numbers presented from 2018 onwards are projections. Projections are not fuel-specific and represent the total estimated renewable fuel production. Abbr.: ASEAN – Southeast Asian Nations; BR – Brazil; CN – China; EU – European Union; FAME – fatty acid methyl ester; HVO – hydrotreated vegetable oil; LAT – Latin America; UCO – unused cooking oil, US – United States.

<sup>1</sup> Drop-in fuels are alternative fuels that can fully substitute fossil fuels or crude oil in crude oil refining [48]. They are characterized by a low oxygen content and distinctive functional characteristics that allow their direct use in existing fuel infrastructure.

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### 1.1.4. The regulatory framework of EU biofuel policy and its implication on evolved and evolving biofuel concepts

The use of biofuels within the EU is regulated by the Renewable Energy Directive (RED) and its successor, the RED II. In 2008, the RED was enacted as the central framework to facilitate the introduction of renewable energy until 2020. It comprises mandatory renewable energy targets for 2020 of 20 and 10% of the overall energy demand and the energy used in the transportation sector, respectively [54]. It turned out that 1G biofuels were the most favored way to reach these envisaged targets within the transportation sector [55]. Apart from mandatory targets of renewable energy use, the RED defines sustainability criteria for biofuels to respond to the serious concerns of many different non-governmental organizations (NGO). These criteria comprise GHG emission thresholds that limit the overall life cycle GHG emissions of the respective biofuel and the exclusion of feedstock derived from pristine forests, highly biodiverse grassland or areas with high carbon stocks. In order to prove the compliance with the defined GHG thresholds, biofuel providers need to calculate GHG emissions (reported as *GHG savings*<sup>2</sup>) using a methodological approach provided by the RED and the Fuel Quality Directive (FQD) [56–58]. Based thereon, fuel suppliers are required to achieve a certain GHG emission reduction by blending biofuels and fossil fuels.

Therefore, the provided methodology to determine *GHG savings* is a crucial element for shaping the biofuel market as it grants access to certain types of feedstock and specific biofuel provision concepts while excluding those that exceed the legally defined threshold. Consequently, only a limited variety of biofuel provision concepts established in the market that have proven economic viability under present market structures, feedstock prices and sustainability requirements. For example, aside from bioethanol and biodiesel as the main product, concepts mainly provide dried distiller's grains with soluble (DDGS), wheat gluten, yeast concentrates (ethanol concepts) and seed meal (biodiesel concepts) as by-products [22]. DDGS and seed meal, the most important co-products considering produced quantities, are used as an animal feed. Apart from bioethanol and biodiesel, anaerobic digestion to produce biomethane – which is another biofuel substituting natural gas – only plays a minor role within the transportation sector.

In response to the criticism, the RED was amended in 2015 [43]. A cap on 1G feedstock and increased *GHG savings* thresholds was implemented. In addition, set targets for 2G biofuels (so-

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2 The terminology „*GHG savings*“, here and hereafter, exclusively refers to the value calculated by RED (II) methodology. The thesis addresses in detail the capability of the RED (II) methodology to express potentially occurring reductions or savings in emissions. In order to emphasize the difference between the values determined by the RED (II) methodology and potentially occurring reductions in emissions (determined by a consequential approach), *GHG savings* is written in *italic*.

called advanced biofuels<sup>3</sup>) and implemented stronger initiatives to use electricity in the transport sector. Furthermore, provisional iLUC factors were introduced.

At the end of 2018, the RED II was adopted to succeed the RED. This framework regulates the use of renewable energy within the EU from 2021 to 2030. Again overarching targets are defined for the use of renewable energy in the transportation sector of 30 and 14% of the overall energy demand and the energy used within the transportation sector, respectively, in 2030 [47]. The cap on 1G fuel is maintained and a trajectory for the introduction of 2G fuels is defined. The minimum share of 2G biofuels is set to 3.5% in 2030. In addition, a phase-out of biofuels with a high risk of causing iLUC was implemented. According to the European Commission only palm-oil derived fuels are affected by this regulation [59]. In addition to biofuels, the RED II specifically addresses alternative fuels of non-biological origin such as hydrogen and fuels made of hydrogen and captured carbon. Again, sustainability criteria are defined for biofuels comprised of tightening minimum *GHG savings* (the fossil fuel comparator that is used for the determination of the *GHG saving* is increased, though, resulting in increasing *GHG savings* by default), and stricter restrictions regarding protected and biodiverse areas were defined. However, the RED II excludes forest biomass from the latter's requirements and defines new, less strict requirements for forest biomass. Again, the *GHG savings* and the methodology to calculate these constitute central aspects of biofuel certification. The procedure to account for (co-)products of the respective alternative fuel concept is a crucial aspect of the defined methodology used for the determination of the *GHG savings*. According to the methodology defined by this regulative framework, overall GHG emissions are allocated to each product based on the energy content of the respective product. This is especially critical regarding the need to transform the overall economy towards a non-fossil based economy. In this regard, the European Commission considers the RED II as part of a wider strategy towards a bio-economy [60]. Recent development of biofuel production concepts using lignocellulosic feedstock point towards integrated biorefineries that yield multiple other products and thereby allow a cascade use of biomass [61]. Biofuel and bioenergy production concepts therefore bear the potential to yield numerous other products and could therefore constitute an integral part of a bio-economy [62, 63].

## 1.2. Research gaps and motivation

Driven by the objectives to reduce the dependency on fossil resources, to increase energy security, to provide economic opportunities to the agricultural sector and to decrease anthropogenic GHG emissions, a transition in the transportation sector has taken place in the past decades that will continue in decades to come. Within the EU, the RED has regulated and catalyzed this transition process. Mechanisms and targets implemented by the RED resulted in the overall use of 5.7%

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3 The terminology “advanced biofuels” refers to the definition provided by the RED II and comprises biofuels made from agricultural residues (listed in Part A of Annex IX of the RED II [47]).

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renewable energy within the transportation sector in 2019 in the EU [22]. The most important renewable fuels used in the EU transportation sector are bioethanol and biodiesel with blending rates of on average 5.9 and 7.7%, respectively. They are almost exclusively provided by 1G concepts using sugar crops, cereal grains and oil seeds as a feedstock, except for biodiesel. In the latter case, unused cooking oil (UCO) presents the second most important feedstock accounting for 22% of biodiesel production in 2018. The use of UCO was propelled by double-counting mechanisms towards the overall renewable energy target and by GHG reduction threshold to be achieved by fuel suppliers that were implemented in certain EU member states. However, the use of UCO is strongly limited due to the limited availability of UCO. In addition, caps were introduced to ensure the use of UCO (instead of virgin oil) and to avoid fraud with regard to the double-counting scheme.

The RED provoked a substitution of fossil fuels and the introduction of 1G biofuels. The establishment of these 1G concepts resulted in the provision of numerous co-products that are now integral part of their respective market (e.g. the feed market). Since its enactment, the RED II is the most important driver for the introduction of novel 2G biofuel concepts and other means of renewable energy provision within the EU. In response to the criticism of 1G biofuels, the focus has been set on 2G biofuels, other renewable fuels and electricity from renewables. The 2G concepts using wastes, residues and other lignocellulosic material are likely to be integrated biorefineries that potentially provide numerous other products such as base chemicals, fertilizers, high-value compounds, etc. The introduction of these concepts again entails consequences, such as changes in agricultural practice and displacement effects arising from the provision of products. Aside from absolute changes in emissions, the temporal occurrence of emissions change. Depending on blending mandates and the fuel that is substituted (i.e. either fossil fuels or 1G biofuels) further consequences arise. The RED II provides a methodology that can be used to determine life cycle GHG emissions of the respective biofuel. The methodology however does not account for effects arising from the introduction of the respective fuel and entailed displacement effects. These potential consequences of the introduction of a specific (bio)fuel provision concept need to be assessed in order to identify those concepts that can contribute the most to the reduction of GHG emissions and to avoid potential negative effects (and criticism arising thereof). The assessment can furthermore evaluate the RED II methodology's capability of identifying those concepts that yield the highest reduction in GHG emissions (including effects arising from the shift from the existing market structure to the new concept). Understanding the consequences of the introduction of (bio)fuels and the ability of present certification methodology to account for these may help to improve policy instruments that facilitate the introduction of novel (bio)fuel concepts and will eventually help to promote these concepts contributing the most to the efforts to reduce anthropogenic GHG emissions.

With regards to these considerations, three major aspects are addressed within this thesis: the environmental implications of the introduction of novel biofuel concepts considering GHG emissions within the life cycle of biofuels and changes in GHG emissions triggered by changes in the fuel provision system, the impact of methodological choices as well as the time-dependency of emissions. The following subchapters give a brief overview on existing knowledge regarding these issues. Based thereon, research gaps are identified.

### **1.2.1. Determination of environmental consequences of novel biofuel concepts: Methodological choices and their implication on the evaluation of GHG emissions**

The use of alternative fuels has been accompanied by the interest to evaluate their environmental impacts. The most commonly applied methodology to assess environmental impacts of product systems or services, to facilitate the identification of environmental hotspots or for certification purposes is life cycle assessment (LCA) [64, 65]. Depending on the question to be answered and the methodological choices arising thereof, several approaches can be applied [66]. Among available approaches, attributional LCA (aLCA) and consequential LCA (cLCA) are most often applied.

- The methodology of aLCA is the method of choice if a product system or provision of a service is to be assessed as it is (either in the past, present or future). An aLCA does not consider effects of changes within the product system e.g. as a consequence of a (political) decision, behavior etc. It allows the analysis of the environmental impacts of a specific product system or service arising from mechanisms within the system boundaries and to determine its share of the overall reference burden (e.g. the share of overall GHG emissions in a country [66, 67]). An aLCA study can provide an evaluation of environmental implications of different stages of the life cycle of a product. Hence, the analyzed system is limited to the assessed product system and therefore does not account for effects that are caused by aspects outside of the analyzed system. System boundaries of aLCA are in most cases drawn right around the product system itself; neglecting (complex) displacement effects and changes outside the production system. Most commonly, allocation of environmental burdens or benefits to all products is applied. The method is easy to understand. It also circumvents many uncertainties arising from the inclusion of changes outside the system boundaries. Therefore, certification schemes (including the RED and RED II<sup>4</sup>) are based on aLCA methodology. The application of allocation based on the energy content is one of the most critical aspects of the methodology. The method was chosen, as it is easily applicable, results provide constant outcomes (opposed to allocation on market value) and prevents

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4 The RED and RED II GHG accounting methodology is an inconsistent approach that is mainly an aLCA but contains elements that are usually part of a cLCA (i.e. credits for certain co-products).

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fraud (e.g. dilution of co-product streams if allocation based on mass is applied). However, the shortcoming of the chosen approach is that co-products lacking an energy content are not considered. In addition, the methodology thereby strongly benefits concepts providing energy and fuels.

- A cLCA study allows the evaluation of changes in environmental impacts as a consequence of a change in a product system, demand, behavior or as a result of a specific decision [67, 68]. One of the most critical aspects of cLCA is the estimation of substitution effects or other changes induced by the analyzed change. This requires a comprehensive understanding of the linkages between the changing system and the physical, economic and social environment surrounding it and of the changes within the system itself. This includes potential identification and quantification of marginal displacement effects, changes in emissions and service flows, change in behavior, price effects etc. The quantification of these effects remains one of the main challenges of cLCA because often complex systems need to be analyzed involving complex changes [69]. Marginal displacement effects are often linked to LUC. In recent years, a variety of conceptually differing methods have been developed [70]. There are advantages and drawbacks of all methods and there is no consensus on what method is to be preferred under which frame conditions. LUC is directly linked to changes in soil organic carbon (SOC) and, consequently, changes in GHG emissions arising thereof. There are many methods to estimate the extent of changes in SOC and for its inclusion into the LCA framework [71, 72]. Changes in SOC are a continuous process that change over time and the inclusion of temporal patterns of these changes into LCA studies constitutes another methodological challenge that is specifically addressed in this thesis (chapter 1.2.2).

The introduction of renewable energies has been accompanied by the interest in and need for sustainability assessments of the respective technologies. This is mirrored by the exponential increase in publications addressing LCA of energy systems since the 1990s [73]. In recent years, the focus has shifted from a sole assessment of environmental implications of alternative energy technologies towards the application of LCA to support informed (political) decision making [74]. Within the scientific community, a vital debate evolved on whether aLCA or cLCA is the most suitable method to support robust (political) decision-making. Due to its ability to reflect potential consequences of certain decisions, cLCA is considered by some to be a useful method to support policy making [75, 76]. However, the fact that cLCA cannot accurately account for all market effects, that its results and hypotheses cannot be confirmed or falsified, and that emission reductions predicted by cLCA do not result in emission reductions if not accompanied by appropriate political measures, has led to criticism [77, 78]. Even though this dichotomy (aLCA or cLCA) has been questioned [79], these two methods still present the most often applied methodological concepts. Numerous studies assess the environmental impacts of 2G biofuels by means of LCA. Reviews covering LCA in the period from 1999 to 2017 show that bioenergy

systems in most cases lead to a net reduction in GHG emissions [80–84]. The reviews emphasize the high variability of methodological choices that strongly influence the outcomes of studies. The variety of conceptual and methodological choices underlines the importance to discuss the implications of these choices on the outcomes.

### 1.2.2. Time-dependency of emissions

A change in demand for biofuels (e.g. as a consequence of a change in biofuel mandates) results in changes in environmental impacts (e.g. through direct emissions from feedstock cultivation, processing and transportation, emission changes as a consequence of displacement effects and changes in above ground biomass and SOC). If the demand for a certain feedstock increases, it can be fulfilled by expansion of the cultivated area, a change in cultivated crops, intensification or harvesting of residues (in case of 2G biofuels). These practices affect above ground biomass as well as SOC formation and decomposition [85–88]. One crucial parameter that determines SOC formation is the input quantity and quality of organic matter, climatic conditions, soil properties and agricultural practices.

In most certification methods, it is acknowledged that SOC changes happen over time but nevertheless resulting environmental impacts and emissions are usually equally distributed over an arbitrary chosen period [89–91]. Likewise, it is common practice in LCA studies to consider the occurrence of emissions and, if accounted for, changes in emissions to happen at once [92]. Commonly the change from a previous type of land-use to bioenergy production is considered as a delta between two steady-states based on which carbon payback times are determined (e.g. [36, 38, 93]). This approach disregards two important temporal aspects of bioenergy production: the timing of emissions and its consequences on atmospheric GHG concentrations as well as the change in emissions over time:

- The first aspect is relevant as far as the temporal removal, storage or release of carbon changes the radiative forcing of the respective quantity of GHG. This is especially critical with regards to climatic tipping points and the short time remaining until emissions need to be lowered by a substantial amount to limit global mean temperature increases [94–96].
- The second aspect is important because the change in a system can potentially involve a certain transition time during which emissions are different to those at steady states (before the shift and once a new steady state is reached). A shift in feedstock cultivation, for example can lead to the decomposition of SOC. The extent of decomposition changes over time is thus not constant over time.

With increasing awareness of the importance of these two aspects, methodologies were developed that account for the dynamic emission pattern and its impact on GHG emission balances [92].

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While forest biomass and 1G feedstock have received attention with regard to at least one of the above mentioned aspects of the time-dependency of emissions (mostly the change in emissions over time, e.g. [97–99]), studies that address other 2G feedstock or that include the effect of the timing of emissions on the atmospheric GHG concentration are scarce. Few studies were found that address this aspect for 2G feedstock other than forest biomass [100–102]. Even fewer studies are available addressing the use of residues (e.g. straw) for biofuel production with consideration of the time-dependency of emissions and the impact on the GHG balance [103]. This indicates that the understanding of these temporal aspects and their inclusion into evaluation methods (i.e. LCA or GHG emission certification) is so far limited. The present thesis therefore addresses the inclusion of temporal aspects into the evaluation of novel bio-refinery concepts.

### 1.3. Study objectives, research questions and thesis outline

In the following chapter, study objectives and research questions derived from presented research gaps are explained.

#### 1.3.1. Objectives and research questions

The introduction of novel (bio)fuels as initiated by legislative frameworks such as the RED (II) has promoted transitions within the transportation sector. Such shifts involve environmental consequences that go beyond the fuel and energy sector itself. It is therefore important to understand potential consequences of the envisaged shifts for all markets and systems affected. Apart from a few restrictions on land-use and biodiversity, policy makers selected GHG emissions as a key indicator of sustainability and climate protection. The legislative definition of sustainability was narrowed down to GHG emissions and a few other restrictions that seek to prevent biodiversity loss. Thereby other aspects of sustainability are neglected. The assessment of GHG emissions, from biofuel provision consequently became an important aspect of biofuel legislation and certification. Taking this into account, it is of paramount importance to improve the capability to evaluate potential consequences of envisaged shifts in the transportation sector. Furthermore, it is necessary to evaluate the implications of present legislation and the methodology defined in it to evaluate GHG emissions:

- The representation of complex systems and mechanisms involved in the envisaged shifts by models requires necessarily abstractions of reality. As presented in the research gaps, these abstractions inherently affect the capability to represent the assessed processes and mechanisms. Therefore, the implications of the methodological choices to abstract reality must be better understood.
- The certification methodology defined by the RED (II) presents such an abstraction of reality used to certify alternative fuel provision concepts. The methodology thus ultimately permits certain alternative fuels concepts, excludes others, and thereby shapes the biofuel

industry with all implications on other sectors connected to it. In addition, other aspects of the biofuel legislation such as blending regulations and overall targets substantially affect the transportation sector and all other sectors connected to it.

Providing new insights into these aspects will strengthen evaluation methods and increase the capability of methodologies designed to evaluate the consequences of the introduction of biofuels. The objectives of the present thesis are thus to evaluate the consequences of the introduction of a selection of biofuel concepts and to discuss the implications of methodological choices. To this end, the following research questions are formulated:

1. What are environmental impacts and GHG emissions of biofuel concepts arising from within the production chain and which key parameters influence results?
2. What changes in GHG emissions are caused by the introduction of novel biofuel concepts?
3. What is the influence of a change in the temporal occurrence of GHG emissions on the GHG balances of biofuels made from agricultural residues?

These research questions are addressed for a selection of biofuel concepts. The assessed concepts cover a variety of 1G and 2G concepts with a focus on biofuels derived from wheat grain and wheat straw. The assessed concepts comprise established 1G concepts as well as complex biorefineries that provide multiple products aside from fuel such as feed, fertilizers, food additives, electricity, energy carriers and base chemicals. Most concepts are based on alcoholic fermentation of wheat grain and wheat straw. The provision of these products trigger changes in other sectors that are included in the assessment. Aside from the detailed analysis of displacement effects, the shift from present straw use to biofuel production is assessed with a dedicated focus on temporal aspects and uncertainties. The defined geographical scope of the assessment is the EU with a strong focus on biofuel production in Germany, the biggest market for biofuels within the EU.

The thesis addresses the identified knowledge gaps by

- delivering a detailed assessment of the changes in GHG emissions and other environmental impacts arising from the introduction as well as from within the life cycle of biofuel concepts,
- improving the conceptual framework for the assessment of environmental consequences of the introduction of novel fuel concepts, and
- providing a deeper understanding of the implications of methodological choices.

In this thesis, cLCA and aLCA approaches are applied with detailed considerations of displacement effects, methodological choices, changes in SOC and temporal occurrence of emissions. On the

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one hand, this yields valuable information on the capability of different approaches. On the other hand, it provides insights into environmental hotspots of production chains and the environmental implications of the introduction of novel biofuel production concepts and biorefineries. Both is of paramount importance to the ongoing transition of the transport sector as it allows for better informed decision making with regards to the future transportation system.

The thesis aims to advance the fields of energy system analysis and LCA. It provides methodological concepts that help to improve the capability of existing methods to evaluate the implications of ongoing transitions in the (bio)fuel sector. Additionally, it aims to deliver insights into the capabilities and weaknesses of available methodologies. Based thereon, multiple biorefinery concepts are analyzed providing in-depth insights on the environmental implications of proposed and existing legal frameworks to the scientific community and policy makers.

### 1.3.2. Thesis outline

The thesis is comprised of six scientific publications and a synthesis chapter. These publications address the stated research questions as listed in Table 1-1. Thereafter a brief summary of all chapters is given.

**Table 1-1** Thesis structure and addressed research questions.

Chapter	Title	Q1	Q2	Q3
<b>Chapter 2</b>	Sustainability aspects of biokerosene	x		
<b>Chapter 3</b>	Life cycle assessment of bioethanol from wheat and sugar beet discussing environmental impacts of multiple concepts of co-product processing in the context of the European Renewable Energy	x		
<b>Chapter 4</b>	The Influence of Co-product Handling Methodology on Greenhouse Gas Savings of Biofuels in the European Context	x	x	
<b>Chapter 5</b>	A consequential assessment of changes in greenhouse gas emissions due to the introduction of wheat straw ethanol in the context of European legislation		x	
<b>Chapter 6</b>	Potential changes in GHG emissions arising from the introduction of biorefineries combining biofuel and electrofuel production within the European Union – A location specific assessment		x	x
<b>Chapter 7</b>	Straw utilization for biofuel production: A consequential GHG assessment of bioethanol and biomethane provision with a focus on the time-dependency of emissions	x	x	x
<b>Chapter 8</b>	Synthesis of results and conclusions	x	x	x

### Chapter 2 Sustainability aspects of biokerosene

The second chapter provides a review of important aspects regarding the sustainability of biokerosene provision and use. The review includes environmental and socio-economic aspects.

**Chapter 3** Life cycle assessment of bioethanol from wheat and sugar beet discussing environmental impacts of multiple concepts of co-product processing in the context of the European Renewable Energy Directive

In the third chapter, a selection of bioethanol production concepts is evaluated by means of aLCA. The analysis comprises 1G production concepts using wheat grain and sugar beet as feedstock. Several mid-point indicators are assessed.

**Chapter 4** The Influence of co-product handling methodology on greenhouse gas savings of biofuels in the European context

The fourth chapter comprises a GHG assessment of several 1G biofuel production concepts. These concepts provide bioethanol and biodiesel from various feedstock. The broad range of concepts is evaluated to discuss the implications of different methods to account for multi-functionality. A dedicated focus is thereby set on the RED.

**Chapter 5** A consequential assessment of changes in GHG emissions due to the introduction of wheat straw ethanol in the context of European legislation

The fifth chapter provides an evaluation of potential changes in GHG emissions arising from the introduction of selected 2G concepts using wheat straw as feedstock. The analysis sets the focus on potential effects arising from the displacement of 1G fuels by 2G fuels. Additionally, implications of fuel blending based in *GHG savings* are discussed.

**Chapter 6** Potential changes in GHG emissions arising from the introduction of biorefineries combining biofuel and electrofuel production within the European Union – A location specific assessment

In the sixth chapter, potential changes in GHG emissions entailed to the introduction of 36 biorefinery concepts in 26 EU Member states are evaluated. The concepts comprise a selection of 1G and 2G concepts using wheat grain and wheat straw, respectively. All concepts provide ethanol plus various other co-products ranging from feed, food additives, fertilizers, energy, fuels to base chemicals. The analysis includes an evaluation of local factors influencing the overall net change in GHG emissions. These factors include feedstock provision, process energy supply as well as marginal displacement effects.

**Chapter 7** Straw utilization for bioenergy production: A consequential GHG assessment of bioethanol and biomethane with dedicated focus on the time-dependency of emissions

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The seventh chapter comprises an evaluation of potential changes in GHG emissions arising from the shift from straw incorporation to biofuel production. A shift to biomethane and bioethanol production are assessed. The focus of the analysis is set on temporal changes in GHG emissions and how these can be accounted for in the context of a GHG assessment.

## **Chapter 8** Synthesis of results and conclusions

The eighth chapter provides a synthesis of results and summarizes key findings with regards to the formulated research questions.

## Introduction

1



# Sustainability aspects of biokerosene

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**Buchspies B, Kaltschmitt M (2018) Sustainability Aspects of Biokerosene. In: Kaltschmitt M, Neuling U (eds) Biokerosene: Status and Prospects. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 325–373. Minor corrections and modifications were made to align the format and the nomenclature.**

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### Abstract

The introduction of biokerosene as an alternative to conventional fossil kerosene is driven by the intention to reduce GHG emissions, to reduce dependency on fossil energy carriers and by the potential to create economic benefits especially in rural areas. In this paper, sustainability aspects of biokerosene are discussed for a wide range of feedstocks and conversion pathways with regards to environmental and socio-economic consequences.

From an environmental perspective, results show that the use of biokerosene can reduce GHG emissions compared to the use of conventional jet fuel. However, this is strongly dependent on direct and indirect LUC effects, which could even lead to a considerable increase in emissions. Emission benefits might be alleviated to some extent by non-CO<sub>2</sub> emissions from combustion. The cultivation of feedstock affects soil and water quality by soil carbon loss, soil erosion and leaching of nutrients and agrochemicals etc. Appropriate management practices can reduce negative consequences. Impacts are furthermore dependent on land-use history and crop type: certain crops, for example, can improve soil quality. The assessment of land requirements shows that algae, switchgrass, miscanthus, sugarcane and oil palm yield the highest quantity of fuels per hectare. Scientific literature reports predominantly negative impacts of biofuels on biodiversity. These negative consequences can be alleviated by the use of wastes and lignocellulosic residues.

Regarding socio-economic aspects, the assessment shows that none of the assessed fuel pathways is financially competitive with conventional kerosene, even assuming a mature provision technology. The provision of valuable co-products or the taxation of fossil fuels present ways to facilitate the introduction of biokerosene. Furthermore, the effect of biofuels on food prices and volatility of food prices is discussed. Most scientific literature reports increasing food prices due to existing biofuel policy. However, embedded in a flexible regulative context, biofuels could reduce price volatility. The analysis furthermore reveals that biofuels trigger investment and create employment and income in rural areas.

Most environmental and socio-economic consequences are dependent on the feedstock, conversion pathway, local environmental, socio-economic conditions, market structures and the political context. The overview of several key aspects of sustainability provided in this study underlines the importance of an individual sustainability assessment in order to optimize benefits and minimize negative consequences of biokerosene provision and use. It becomes furthermore evident that many negative impacts are inherent to agricultural production in general and that these aspects need to be discussed in a wider context than that of biofuels alone. Doing so could promote synergies of food, fiber and fuel production and facilitate a sustainable use of resources

## 2.1. Introduction

The first documented considerations of a sustainable management of agricultural resources was published in 1713 by Hans Carl von Carlowitz, a German tax accountant and mining administrator. In the face of dwindling forest resources due to the consumption of wood to provide a raw material for mine support as well as for energy provision, eventually resulting in a part closure of the mining industry itself, von Carlowitz recognized the need for forest management that balances wood extraction and the forest's capacity of reproduction [104]. Since its origin, the understanding of sustainability has been widened and adapted, but there is, yet, no universal and holistic definition of what sustainability means, implies and entails [105]. Nowadays, the most popular definition of sustainability, linking ecology or environment, economy and society, has been provided by the Brundtland Commission, which defined sustainable development as “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” [106]. The Brundtland Commission identified environmental, social and economic aspects of development that jointly constitute sustainable development. This commission brought environmental concerns and development as an interlinked entity to the political agenda. In 1992, the United Nations (UN) published the so called Rio Declaration on the Environment and Development which constitutes, for the first time in human history, a global commitment to strive for a sustainable development [107].

A decade later, the definition of sustainable development comprised three pillars: economic development, societal development and environmental protection - at the local, national, regional and global levels [108]. The UN Environment Programme emphasizes the importance of an interlinkage between these dimensions by stating that poverty reduction can only be achieved by stopping environmental degradation combined with social measures and economic development [109]. A sustainable management of finite resources and natural capital is identified as being crucial for economic development, which in turn supports social well-being. Personal and social well-being is as well dependent on a healthy ecosystem, which is characterized by being able to sustain life at full potential [110]. Often, a desired state of sustainability is characterized by multiple objectives and interests that are not (fully) compatible. This results in the conflict of which objective is to be prioritized over the others [111]. This aspect has been a matter of discussion among economists decades before the Brundtland Commission's definition of sustainability: there is a trade-off to be made between natural and human capital and the question to what extent the achievement of benefits in one dimension by constraining the other is acceptable has resulted in the two opposing concepts of *weak* and *strong* sustainability.

- The concept of *weak* sustainability is based on the assumption that capital of either dimension can be exchanged or one can be used to increase the other [112, 113]. A decrease in natural capital can be considered acceptable as long as overall capital stocks do not decrease.

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- In contrast, *strong* sustainability is based on the idea that natural capital presents a prerequisite of all other types of capital and is thus not exchangeable [114]. It is furthermore questionable if many qualities and characteristics of a dimension are exchangeable at all (e.g. the intrinsic value of nature). Another argument supporting the concept of *strong* sustainability refers to the uncertainty related to the benefits in one type of capital at the expense of natural capital. Due to the fact that it is often uncertain whether the consumption of natural capital results in a comparable increase in another type of capital or not [115]. To what extent different assets of natural capital or certain functions of ecosystems are allowed to be constrained or exploited is an ongoing debate among advocates of *strong* sustainability [114], as well as in public and the scientific community.

Many of these conflicts between economic activities and environmental concerns, which arise from the introduction of innovative technologies, are of multi-dimensional nature and need to be evaluated by an interdisciplinary approach, rather than by an isolated discipline [116]. Defining sustainability is inherently a matter of perspective, societal and spatial context that is shaped by specific local or regional conditions prevailing at a certain location [105, 117, 118]. These conditions define what is considered as sustainable as well as the characteristics of a transition towards a sustainable socio-economic system. A definition of sustainability is furthermore a matter of a temporal scale, which is especially important when defining sustainability, as short-term interests might be opposed to long-term targets.

The Brundtland Commission defined the time horizon for the present and “*in the future*” [106]. This vague definition results in difficulties when applied to sustainability assessment: a managed monoculture forest with removal of deadwood, for example, might on the one hand help to mitigate climate change by providing a renewable energy carrier, might lead to an increase in biomass yields compared to natural forests and might furthermore maximize financial revenue. On the other hand, deadwood removal and monocultures potentially result in negative long-term consequences, such as extinction of species and decrease in resilience against vermin and effects of climate change [119–121]. Whichever time frame is chosen, the definition of what is considered sustainable might result in different outcomes. Consequently, defining sustainability and deriving criteria for the assessment of sustainability is dependent on perspective, specific local conditions and the time frame of consideration.

In the ongoing debate on the use of biofuels and entailed consequences, all these aspects become visible: Biofuels were introduced to provide a cleaner form of energy while creating economic opportunities in face of climate change [122]. Society “chose” biofuels as a way to mitigate climate change. In recent years, technical progress, political intentions and economic interests introduced biokerosene into the current debate of combatting climate change by the use of biofuels [123].

The International Air Transport Association (IATA) claims to achieve carbon-neutral growth by 2020. A substantial contribution to this target is planned to be achieved by biokerosene. This decision implied other environmental, economic and social consequences resulting in trade-offs to be made between benefits and drawbacks and between different actors in society, as well as a weighting of importance: climate change was considered a major concern and potential drawbacks were accepted on the way to mitigate it. As a prerequisite for this decision and in order to reduce negative consequences of it, a comprehensive understanding of the consequences is required. This motivated the assessment of sustainability and, ultimately, the definition of sustainability criteria.

In this work, several key aspects of sustainability of biokerosene provision and use are discussed. In a first step, possible feedstocks and conversion routes are explained briefly. Afterwards, environmental and socio-economic aspects are discussed in detail.

## 2.2. The biokerosene provision chain

The full life cycle of biokerosene comprises feedstock production, harvest, feedstock handling and transport, biokerosene production, transport, storage, blending and final use as aviation fuel. The production of kerosene from biogenic material can be realized via multiple conversion routes (Figure 2-1) [124, 125]:

- Oils can either be co-refined with fossil crude oil or processed via the HEFA-process to yield hydroprocessed esters and fatty acids synthetic paraffin kerosene (HEFA-SPK) or HEFA synthetic paraffinic kerosene with aromatics (SKA).
- Sugar from sugarcane or from sugar beet can be fermented to yield ethanol, which is further converted to alcohol-to-jet fuels (AtJ-SPK and SKA) or hydrocarbons, which are further converted to direct-sugar-to-hydrocarbons synthetic iso-paraffin (DSHC-SIP). Additionally, sugars can be transformed to fatty acids, which can be further converted to HEFA jet fuel.
- Starch can be converted to sugars via liquefaction and saccharification to be further processed analogously to sugar.
- Lignocellulosic (LC) biomass can be converted to sugars via hydrolysis and yield kerosene analogous to starch and sugar or be treated via gasification, pyrolysis, hydrothermal liquefaction (HTL), hydrothermal gasification (HTG) to yield syngas, bio-crude oil and methane, respectively. These intermediate products can be transformed to Fischer-Tropsch (FT) SPK or SKA and to hydrotreated depolymerized cellulosic jet fuel (HDCJ).

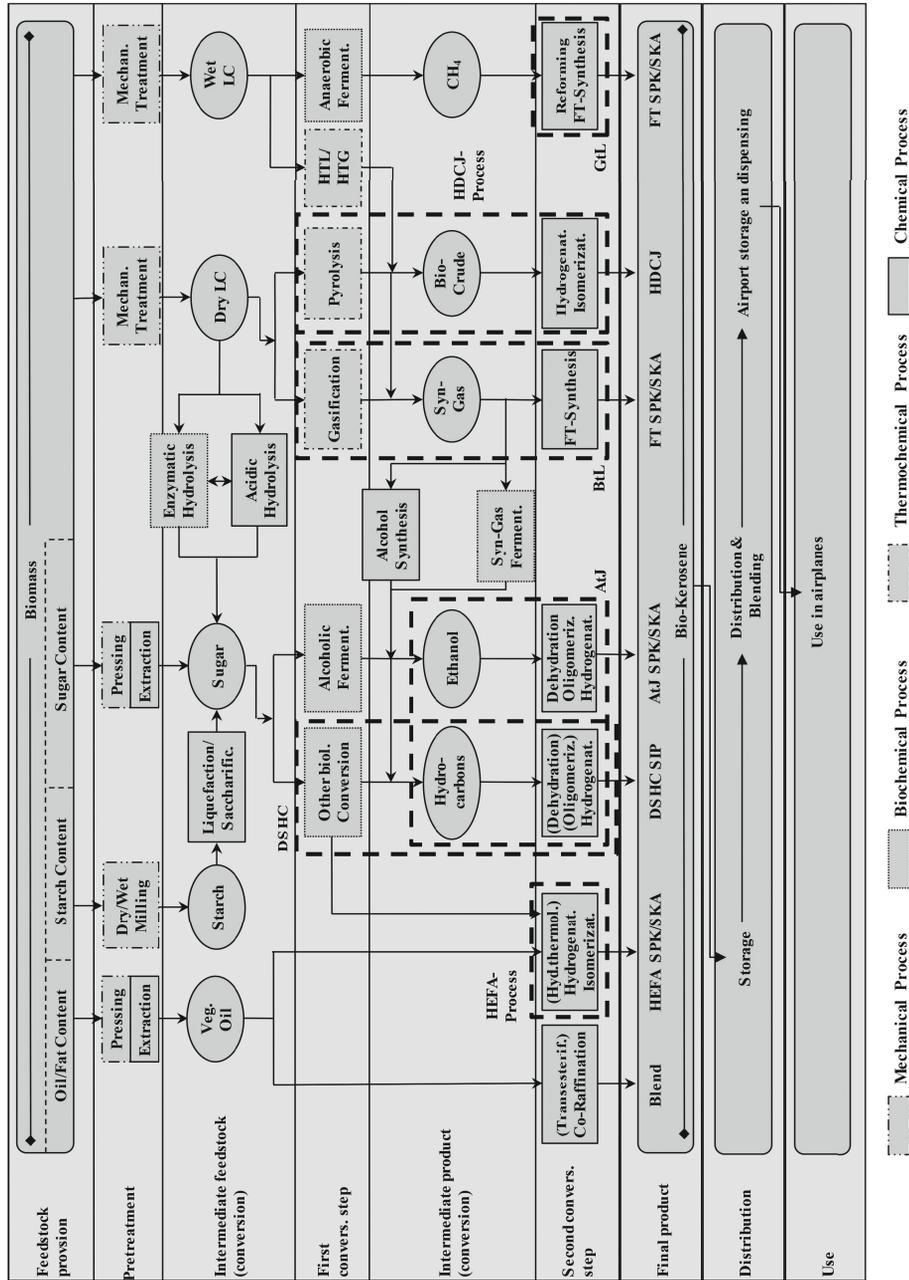


Figure 2-1 Biokerosene provision and use chain (adapted from [124]). Abbreviations are explained in the text.

These conversion routes allow the use of nearly all types of biogenic material (Table 2-1).

**Table 2-1** Selection of feedstock options for biofuel production

Feedstock type	Biokerosene option	Relevant crops/input material
Oils and fats	Co-refined jet fuel	• Oil crops (e.g. oil palm, rapeseed, soy, camelina)
	HEFA	• Algae
Starch crops	DSHC	• Used cooking oils and animal fats
	AtJ	• Cereals (e.g. maize, wheat, barley, rye, millet)
	HEFA	• Potato
Sugar crops	DSHC	• Cassava
	AtJ	• Sugar crops (sugarcane, sugar beet)
	HEFA	
Lignocellulosic material	DSHC	• Grasses (e.g. switch grass, miscanthus)
	AtJ	• Woody biomass from short rotation or forestry
	HEFA	• Residues (e.g. straw, corn stover, sugarcane bagasse, forestry and industrial wastes)
	FT SKP/SKA HDCJ	

Abbr.: AtJ – Alcohol to Jet, DSHC – Direct sugar to hydrocarbon, FT SPK/SKA – Fischer-Tropsch synthetic paraffin kerosene/synthetic paraffinic kerosene with aromatics, HDCJ – hydrotreated depolymerized cellulosic jet fuel, HEFA – hydroprocessed esters and fatty acids.

2

### 2.3. Sustainability aspects

In the following chapters, sustainability aspects of feedstock provision, biokerosene production, logistics and use are discussed. The demand for agricultural products for feed, food and fuel production, accompanied by the occurrence of negative consequences as results of their provisions, has drawn attention to sustainability aspects of agricultural production. As a result, governments, institutions and organizations have proposed or established laws, criteria and standards that define sustainability of agricultural and bioenergy systems. The Food and Agricultural Organization (FAO) of the United Nations (UN), for example, defines sustainable agriculture based on the Brundtland Commission's definition as *"the management and conservation of the natural resource base, and the orientation of technological change in such a manner as to ensure the attainment of continued satisfaction of human needs for present and future generations. Sustainable agriculture conserves land, water, and plant and animal genetic resources, and is environmentally non-degrading, technically appropriate, economically viable and socially acceptable"* [126]. Similarly, the European Commission considers sustainable agriculture as *"a management of natural resources in a way which ensures that the benefits are also available in the future"* [127]. Furthermore, a balance and value of natural capital stock needs to be preserved paying regard to socio-economic costs and benefits of consumption and conservation. In both definitions, the conflicts between conservation and the exploitation of natural resources as well between present-day and future fulfilment of needs play a key role. The definition used by the US Department of Agriculture (USDA) goes beyond a vague description and comprises criteria

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that define sustainable agriculture as an integrated system of plant and animal production that will over long-term

- *“satisfy human food and fiber needs;*
- *enhance environmental quality and the natural resource base upon which the agriculture economy depends;*
- *make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls;*
- *sustain the economic viability of farm operations; and*
- *enhance the quality of life for farmers and society as a whole” [128].*

Based on these, and other descriptions of sustainability of agricultural systems, legislative sustainability requirements, such as the RED [129, 130], as well as numerous voluntary schemes have been issued to guide and promote a sustainable provision of agricultural commodities, mostly in regard to biofuels. The remaining steps in the life cycle of biokerosene are also regulated by standards that affect sustainability, e.g. American Society for Testing and Materials (ASTM) fuel specifications. Sustainability aspects are covered in these standards by quality specifications and composition requirements, which ensure safe handling and use of fuel and limit the content of polluting compounds in fuel, e.g. sulfur.

### 2.3.1. Environmental dimension

The provision of biokerosene has significant implications on the environmental dimension of sustainability: feedstock provisions and airborne emissions are the most dominant factors affecting the environment. Agricultural production has experienced tremendous changes in the past 50 years to meet the demand of a growing world population and a change in consumption patterns: grain production doubled and yields increased [131]. These trends have been accompanied by environmental, economic and social changes. These improvements were achieved by the widespread application of mineral fertilizers and agrochemicals: nitrogen fertilizer use ten-folded and phosphorus fertilizer application tripled. Apart from fertilizers, the application of pesticides poses risks to the environment. Between 1990 and 2010, 82 countries for which data is available, applied 342000 t/a of insecticides on average [132]. 29% of these countries experienced an increase in insecticide use in that period, whereas a decrease or no clear trend was reported by 28% of these countries. Herbicides present the most applied pesticide: 75 countries reported an average annual consumption totaling 566000 t/a. In 40% of countries, herbicide application increased, while no clear trend was observed in 44% of countries. Application of herbicides decreased only in 9% of countries. In case of fungicides, 77 countries reported an average annual total consumption of 353,000 t/a. 34, 48 and 12% of countries reported an increase, no trend or decrease, respectively. Apart from the application of fertilizers and agrochemicals, irrigation, expansion of agricultural land, genetic improvements, and advances in plant and crop management helped to boost yields.

The large-scale provision of biokerosene presents one of many triggers for an intensification and expansion of agricultural production. The cultivation of feedstock affects the environmental compartments soil, water, air and biodiversity, whereas the use of biokerosene predominantly affects air quality. Furthermore, land requirements of different pathways are assessed. A selection of feedstock-specific effects is listed in Table 2-2<sup>5</sup>.

**Table 2-2** Selection of impacts on the environmental dimension of feedstock provision.

Feedstock	Selected impacts on environmental aspects of sustainability
Oil palm	<p><b>Soil</b></p> <p>Increase [133, 134] or decrease [133, 135, 136] in SOC observed subsequent to plantation establishment depending on previous vegetation: SOC might be higher than in natural forest, but lower in comparison to grassland. Best management practice can improve SOC and pH compared to conventional farming [137].</p> <p>Infiltrability is highly variable and lowest where heavy machinery is used [138].</p> <p>High erosion during and subsequent to plantation establishment [138, 139]. Higher erosion compared to native vegetation during plantation operation.</p> <p>Application of fronds and empty fruit bunches as mulch reduces mineral fertilizer demand, excessive nutrient enrichment in soil and fertilizer losses while increasing yields and improving soil structure [140].</p> <p><b>Water</b></p> <p>Per tonne of crude palm oil production, 2.5 to 3.5 t palm oil mill effluent (POME) are generated, which need to be treated due to its high biochemical oxygen demand [141].</p> <p><b>Air</b></p> <p>In Indonesia and Malaysia, peat land is drained to gain land for agricultural purposes, including oil palm cultivation [142]. By 2006, 47% of Indonesia's peatland has been drained and this trend is assumed to continue [143]. Peat drainage results in the decomposition of organic matter and, thus, in CO<sub>2</sub> emissions, which are estimated to range from 6 to 100 t CO<sub>2</sub>/(ha a). Furthermore, peat land drainage results in a significant increase in fire risk. Forest fires present another source of tremendous CO<sub>2</sub> emissions [144].</p> <p><b>Other ecological impacts</b></p> <p>Indonesia and Malaysia faced a substantial loss of native forests and peatland in the past 30 years, 30 and 20%, respectively, which can be partly attributed to the expansion of oil palm plantations [145, 146]. Agricultural expansion and native forest destruction take place in one of the most biologically diverse terrestrial ecosystems [147–149]. In oil palm plantations, species abundance is significantly lower compared to native or degraded forests and other land uses [147].</p>
Jatropha	<p><b>Soil</b></p> <p>Jatropha can be grown on degraded soils and has been shown to improve soil quality (reduction in erosion, increased infiltration) [150, 151].</p> <p>Jatropha possibly remediates soils contaminated by heavy metals and hydrocarbons by bioaccumulation and rhizodegradation [152–154].</p> <p><b>Water</b></p> <p>Rain-fed jatropha can result in lower water demands per unit output compared to irrigated cultivation despite lower yields [155].</p>

<sup>5</sup> Table 2-2 Selection of impacts on the environmental dimension of feedstock provision.2-2 presents a selection of impacts to give some insights into possible impacts on sustainability rather than giving a complete picture of environmental impacts.

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Table 2-2 Continued

Feedstock	Selected impacts on environmental aspects of sustainability
Salicornia	<p><b>Soil</b> Increase of SOC if plants are grown on very low SOC containing land [156]</p> <p><b>Water</b> Potential to remove excess nutrients from aquacultures [157]. Can be grown in saline environments.</p>
Short rotation coppice	<p><b>Soil</b> Meta-analysis reveals higher increase in infiltration capacity due to afforestation compared to agroforestry on former deforested land [158].</p> <p><b>Water</b> Field trials indicate that short rotation coppice plantations show very low nitrate leaching compared to arable crops, except for the first year after plantation establishment, and could be used in vulnerable zones, to improve ground water quality and to reduce eutrophication [159, 160] Due to deep roots and high interception of rainfall by foliage, water consumption and loss might be higher than in the case of arable plants: 11 to 31% loss due to interception in case of short rotation coppice plantations as opposed to circa 15% in case of food crops [161]. Not all intercepted water is a “loss” as it substitutes transpiration by some degree. Plant water demand is however site specific and water consumption is not always higher than that of arable plants [161, 162].</p>
Soybean	<p><b>Soil</b> Soybean fixes atmospheric nitrogen and requires, thus, only few or no artificial fertilizers [163].</p> <p><b>Other ecological impacts</b> Expansion of soy cultivation in Brazil between 2001 and 2005 took place in rainforests and in scrubland: 26 and 74%; respectively [164]. Efficiency of Brazilian soybean production increased considerably: increase in production by 103% between 1996 and 2006 while planted area increased by only 28% [165]</p>
Grasses	<p><b>Soil</b> Higher [134, 166] and lower [167] SOC compared to natural forest observed in tropics.</p>
Sugarcane	<p><b>Soil</b> Higher soil erosion than in pastures and natural vegetation due to bare soil exposure before planting and re-growth as well as after harvest [168]. Soil compaction due to harvesting operations.</p> <p><b>Water</b> Sediment loss and leaching of nutrients and contaminants, e.g. pesticides, worsen the state of waterbodies in proximity [168].</p> <p><b>Air</b> The pre-harvest burning of sugarcane to facilitate the harvest oxidizes organic matter and emits pollutants, such as carbon monoxide, methane, non-methane volatile organic compounds (NMVOC) and particles [169].</p>
Residues	<p><b>Soil</b> The impact of harvesting residues is site specific and depends on crop type, rotation and management practice [170]. The collection of residues, e.g. straw, is accompanied by soil compaction due to the use of heavy machinery. might decrease due to the removal of residues [171, 172] Incorporation of straw results in increase of nutrient levels. These nutrients need to be replaced when residues are removed [171, 172].</p>

### 2.3.1.1. Soil

The cultivation of feedstock (for biokerosene production) alters soil and changes its properties. The Soil Science Society of America defines soil quality (SQ) as “*the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health*” in order to characterize soil status and its changes [173]. SQ can be assessed via SQ indicators, which describe soil properties and processes that have the greatest sensitivity to changes in soil function [174]. The effect and magnitude of impact of agricultural activities on soil and SQ is not only dependent on the respective activity but on inherent soil properties, management history and locally prevailing environmental conditions and influences e.g. precipitation, climate [174, 175]. To assess SQ, indicators need to be selected that can serve as proxies for soil properties and soil functions. These indicators usually, but not exclusively, include SOC content, soil aggregation, pH value, electrical conductivity, microbial biomass carbon, bulk density, soil stability, salinity, available water capacity and nutrient content, such as plant available phosphorus and nitrate content. [174, 175]. Obviously, crop productivity is dependent on SQ. Crop production impacts SQ by management practices and the crop type that is cultivated.

According to their impact on SQ (and other environmental aspects), agricultural systems can be categorized as high intensity low diversity crops (HILD) and low intensity high diversity crops (LIHD) [176]. HILD crop systems are characterized by high inputs of fertilizers, pesticides, irrigation as well as intensive agricultural activity, e.g. tillage. Furthermore, only few or a single plant species are cultivated; monocultures are common. The intensive cultivation of plants requires the input of additional fertilizers that change the nutrient cycle in soils. In contrast to such HILD systems, LIHD crops are less intensive due to lower inputs and less disruptive activities. A LIHD crop system usually consists of multiple plant species. HILD systems might result in a decrease of SQ: ploughing and tillage result in a decrease of SQ, as opposed to no-tillage farming [175, 177]. Tillage and the removal of crop residues, e.g. straw, can result in a loss of SOC. The disintegration and increase in porosity result in an increase in biological activity, which results in a decomposition of soil organic matter due to biotic activity and exposure to environmental stress, such as freeze-thaw and wet-dry changes [178].

Regardless of the system that is established, the establishment of plantations results in a disruption of soil structure and a decrease in soil porosity and infiltration capacity due to compaction [136, 138]. The overall SOC changes resulting from land transformation can be positive or negative, depending on the previous vegetation [179]. Right after land is converted to plantations, soil is prone to erosion due to the lack of cover plants [180]. The establishment of new plantations is furthermore accompanied by the construction of infrastructure resulting in large quantities of sediments being eroded [181]. Once the plantation is established, a tree plantation might result in

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a stabilization of soil due to roots and reduce the risk of erosion due to cover plants and leaf litter cover as well as a protection of the soil from the erosive forces of wind and water. A reduction of surface cover plants might result from a closing of the canopy, which might increase soil loss [139]. In general, perennial crop systems tend to have less negative impacts on soil porosity compared to annual crop systems [170].

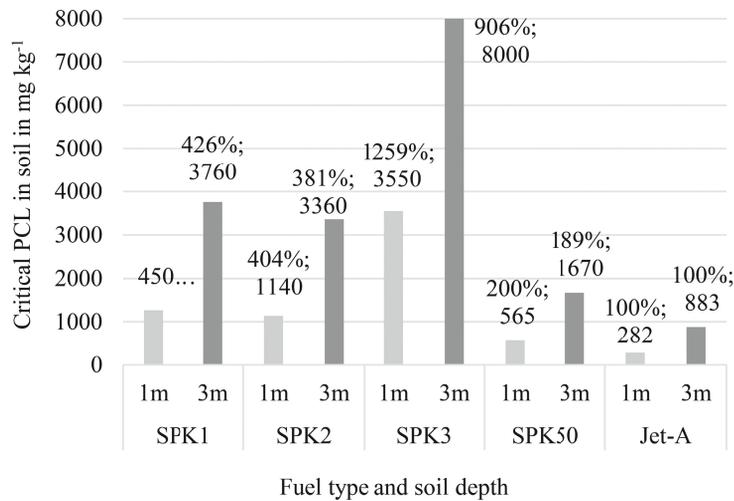
During the cultivation phase, mineral fertilizers and agrochemicals are applied. A positive correlation between fertilization and SOC was observed [182]. The effect on soil microbial biomass is dependent on the pH value of the soil: fertilization increases soil microbial biomass at pH values higher than 5. The opposing result can be observed at a pH level below 5. The input of fertilizers affects gaseous emissions and nutrient leaching. The application of pesticides severely affects microbial diversity in soil [183]. The effect is however strongly dependent on pesticide type, affected species and numerous environmental conditions, e.g. [184–186]. Table 2-2<sup>5</sup> lists a selection of crop-specific impacts.

Apart from feedstock provision, biokerosene logistics might affect soil quality in case of an accidental fuel spill. Based on the fuel composition, critical soil protective concentration levels (PCL) can be modelled for conventional jet fuel and for biokerosene. Mezher et al. [187] assessed fuel composition of three SPK-fuels from camelina and jatropha and modelled critical PCL assuming an accidental spill of fuel on soil near a residential area without public water utility. Critical PCL define the upper limit of substance that can be left in soil below which no environmental-risk is expected. The model comprises three exposure pathways: soil-groundwater-leaching, soil volatilization into air and soil dermal contact and applies conservative maximum contaminant levels in groundwater [187–189]. Results show significantly higher PCL for SPK50<sup>6</sup> and SPK100 than for conventional jet fuel (Figure 2-2). The critical PCL are controlled by benzene, which is not contained in any of the assessed SPK, and by the equivalent carbon number (ECN) >8 to 10 fraction<sup>7</sup>, for Jet A fuel and SPKs, respectively [187]. Benzene shows a higher mobility in the environment than the other compounds that are contained in the assessed fuels and, therefore, low regulatory limits are in place. Consequently, a spill of Jet A fuel is significantly more harmful compared to SPK50 and SPK100.

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6 SPK50 and SPK100 denote a mixture of conventional Jet-A fuel and SPK biokerosene of 50/50 and 0/100 (vol.-%/vol.-%), respectively.

7 The equivalent carbon number (ECN) is the difference between the total carbon number (CNo) and twice the number of double bonds (DB):  $ECN = CNo - 2DB$ .



**Figure 2-2** Critical soil-protective-concentration levels (PCL) of SPK50, SPK100 and conventional Jet A fuel. Data labels present absolute and critical PCL as percentage of PCL of JET-A kerosene. SPKs are derived from camelina (SPK1 and 2), and from jatropha (SPK3). The critical PCL of SPK3 at 3 m depth is set to 8,000 mg/kg, the mobility limit of middle distillates in fine to medium grained sands [187, 190]. Data obtained from [187].

### 2.3.1.2. Water

The biokerosene provision and use chain affects water most likely due to feedstock provision and to a minor extent by water demands for feedstock conversion. In a first step, general aspects of water contamination originating from agriculture are discussed. In a second step, an estimate of water requirements for different biokerosene production pathways is presented.

### 2.3.1.3. Water pollution

The application of fertilizers and agrochemicals might result in the eutrophication and contamination of waterbodies. Leached, washed and eroded nutrients lead to nutrient enrichment of waterbodies, which results in multiple negative consequences: shift in species composition [191], enhanced biomass production, bloom of toxic algae [192] and severe damage to (aquatic) ecosystems, e.g. marshes [193]. Freshwater ecosystems are usually limited in nitrogen, whereas oceans are limited in available phosphorus [194]. An influx of these nutrients will result in an increase in biomass production in the respective waterbody which might result in the formation of oxygen depleted zones: enhanced biomass production promotes microbial decomposition of dead organic matter, which increases oxygen demand [195]. A stratification of the water column eventually results in a transient depletion of oxygen triggering mass mortality of benthic animals. The increase in dead organic matter propels the former process and hypoxia occurs seasonally or periodically. If processes persist, hypoxic zones expand, which is accompanied by a microbial formation of toxic hydrogen sulfide (H<sub>2</sub>S). This is a globally occurring phenomenon and is not

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limited to any specific region or that occurs as a consequence of a specific plant that is cultivated. The use of fertilizer should hence be optimized and scheduled according to plant demand and climatic conditions. In specific cases, bioenergy crops can improve water quality and reduce negative impacts on water quality due to the capacity to remove nutrients or certain contaminants and to serve as a barrier that filters leachate and runoff from other agricultural lands [196].

Apart from nutrients originating from excessive fertilizer application, the intensive use of agrochemicals results in a contamination of the environment: in Europe, for example, 8% of groundwater measurement stations report excessive levels for one or more pesticides in 2010 [197]. In 1% of stations, quality standard levels were exceeded. River monitoring stations indicate a contamination by many pesticides of which Cyclodiene, Endosulfan and Chlorpyrifos are found to be the most present pollutants: 42.8, 35.4 and 4.8% of monitoring stations reported an exceedance of environmental quality standards as annual averages in 2009. In the US, 61% of agricultural streams, 90% of urban streams and 46% of mixed streams exceeded an aquatic-life benchmark for the period of 2002 to 2011 [198]. The presence of pesticides effects the aquatic environment in many ways: alteration of species composition, richness and food chain, changes in nutrient and oxygen dynamics and ultimately in the ecosystem function [199–201]. The production of feedstock for biokerosene, as any other agricultural production, possibly contributes to these trends. The extent of impact is depending feedstock and management practice; corn and soybean cultivation, for example, accounted for more than 60% of the pesticide use in the US [202].

### 2.3.1.4. Water demand of biokerosene production

An increase in feedstock cultivation for biofuel production will ultimately result in an increased demand for water, which might result in competition for water needed for conservation or food cultivation [203]. The use and consumption of water is commonly assessed by the water footprint (WF) methodology [204], which distinguishes *green*, *blue* and *grey* water consumption. *Green water* refers to precipitation that evapotranspires from plants; *blue water* refers to the consumption of surface water and ground water; *grey water* describes the volume of water needed to dilute pollutants contained in wastewater to a level below agreed quality standards. To assess the water demand of biokerosene a WF was conducted for HEFA, BtL-FT, DSHC and AtJ pathways for multiple feedstocks. Only few data on water and feedstock demand of these processes exist so far. Results presented here, are consequently just an overview and preliminary assessment of the water demand of biokerosene provision. In this analysis, the water demand was apportioned to all co-products based on average prices of products<sup>8</sup>. According to modelling data found in the

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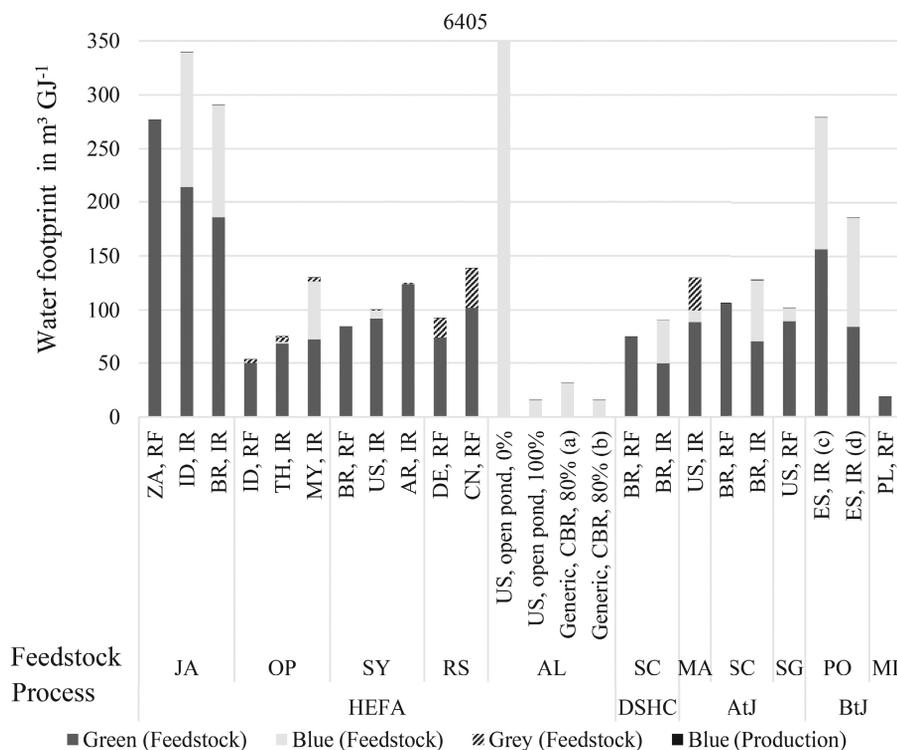
8 Prices for agricultural co-products and feed products are based on prices from August 2011 to July 2016 [205, 206], except for the following products: jatropha oil and seedcake [207], algae oil [208] and meal [209], as well as AtJ from corn and sugarcane [210]. In these cases, allocation is based on prices referred to in the respective study or based on reported monetary allocation factors.

literature, HEFA, BtL-FT and DSHC from sugarcane require 0.45, 0.11 and 0.34 L water per kg of feedstock input (no feedstock-specific data available), respectively [210, 211]. Feedstock inputs are: 6.37 kg biomass, 1.04 kg oil and 18.6 kg sugarcane per L of biokerosene for HEFA, BtL-FT and DSHC, respectively [210, 211]. AtJ from sugarcane, maize and switchgrass requires 0.58, 0.84 and 0.63 L water per kg of input material. Per L of biokerosene, 25.9 kg sugarcane, 6.8 kg maize and 11.4 kg switchgrass are needed, respectively [210]. The water demand for feedstock production is strongly dependent on location, prevailing climatic conditions and management practices<sup>9</sup>. Not all studies report grey water originating from leaching nutrients or agrochemicals. In those cases, grey water values were obtained elsewhere [215], if available. In this study, irrigated and rain-fed cultivation systems are assessed. It should be noted, though, that the WF can vary significantly within a country. For algae, *chlorella vulgaris* cultivation in open ponds and *neochloris oleoabundans* cultivation in closed bioreactor designs with varying recycling rates are assessed. Results show that the water consumption in the production phase is irrelevant in comparison to water requirements of the feedstock provision phase (Figure 2-3). Considering oil plants, oil palm appears to be more water efficient than jatropha or soybean. Interestingly, rain-fed jatropha cultivation is more water effective than irrigated jatropha, even taking lower yields into account. The WF is dominated by green water. An increase in productivity reduces the green WF. The blue WF, which represents irrigation, can be reduced by more efficient irrigation schemes and a synchronization of rainfall and crop scheduling, as well as by efforts in all other measures that influence evapotranspiration, e.g. plant alignment, canopy management, control of cover plants, etc. In case of algae, the recycling of water is crucial to reduce the WF. In case water is recycled, biokerosene from algae shows the lowest WF among all analyzed variants. Energy crops, i.e. miscanthus, rapeseed and poplar do not result in a more favorable WF than food crops. According to the feedstocks and origins assessed, there is no process that is preferable: The WF is feedstock dependent and thus only influenced by a minor extent of the water demand of the conversion process. However, the conversion efficiency is crucial. The decision what feedstock and what process is preferable in terms of water consumption should furthermore consider the water availability and demand in a specific region.

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<sup>9</sup> WFs were obtained from the following sources: jatropha [207, 212], oil palm [213, 214], soybean [165, 215], rapeseed [215], algae [216, 217], sugarcane [165], maize [218], switchgrass [210], poplar [219] and miscanthus [220].

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**Figure 2-3** Water footprint (WF) of biokerosene production from jatropha (JA), oil palm (OP), soybean (SY), rapeseed (RS), sugarcane (SC), maize (MA), switchgrass (SG), poplar (PO) and miscanthus (MI); irrigated (IR) and rain-fed (RF) systems are considered. Algae (AL) production is realized in open ponds or closed bioreactors (CBR). Percentages indicate water recycling rates. Other abbreviations present International organization for standardization's (ISO) 3166 county codes of the respective location of cultivation [221]. Case (a) and (b) refer to different biomass production rates of 0.5 and 1 g/L/d, respectively, In case of poplar, two different planting densities are assessed: 6666 (c) and 20000 (d) plants/ha.

### 2.3.1.5. Air

The reduction of GHG emissions is the core motivation of using biofuels in the aviation sector [222, 223]. In this chapter, a carbon footprint of biokerosene and the discussion of additional, non-CO<sub>2</sub>-related effects are provided.

### 2.3.1.6. Carbon footprint

A literature review reveals a high variability of GHG emissions of biokerosene production and use<sup>10</sup> (Figure 2-4). Only few studies assessing GHG emissions from the provision of biokerosene exist and results are often uncertain, as many technology options are not operating at industrial

10 The assessment does not consider non-CO<sub>2</sub> emissions from combustion and entailed effects, such as particle emissions, cloud formation, etc. These effects are considered separately below.

scale yet. Vertical bars reflect high and low emission scenarios based on yields and technical parameters. The inner data point represents the baseline scenario obtained from the respective literature source. A comparison of different studies is difficult due to differing assumptions, data sources, various and partly inconsistent methods to account for co-products<sup>11</sup>. The method to account for co-products is a crucial aspect of GHG emission estimation as results are profoundly affected by the chosen method. Results indicate, however, regardless of the fuel, that direct LUC (dLUC) plays a crucial role concerning GHG emissions. In case of HEFA from soy and palm oil, for example, the consideration of possible dLUC effects results in GHG emissions that are up to 8 times higher than those of conventional jet fuel. Jatropha results in lower GHG emissions than conventional jet fuel in all assessed cases, except for the case that scrubland is converted to plantations. HEFA-fuel from jatropha results in about the same GHG emissions, regardless of the use of jatropha seed cake, i.e. electricity generation from seeds [157], as feed (assuming detoxification) [226] or as fertilizer [225]. In case of HEFA-fuel from algae, dewatering accounts for 44% of emissions [227]. High algae concentrations and high lipid content of algae are consequently key parameters to reduce emissions of providing algae-based fuels. Salicornia can be grown on degraded soils and can be irrigated with saline water. The former aspect might increase SOC and thus sequester carbon. Results presented in Figure 2-4 refer to a cultivation on carbon depleted soils; in case soils contain a higher amount of carbon, carbon sequestration is expected to be lower [157]. The extent of N<sub>2</sub>O emissions from salicornia salt water farms or algae cultivation in open ponds is highly uncertain and has substantial impact on results [157, 229].

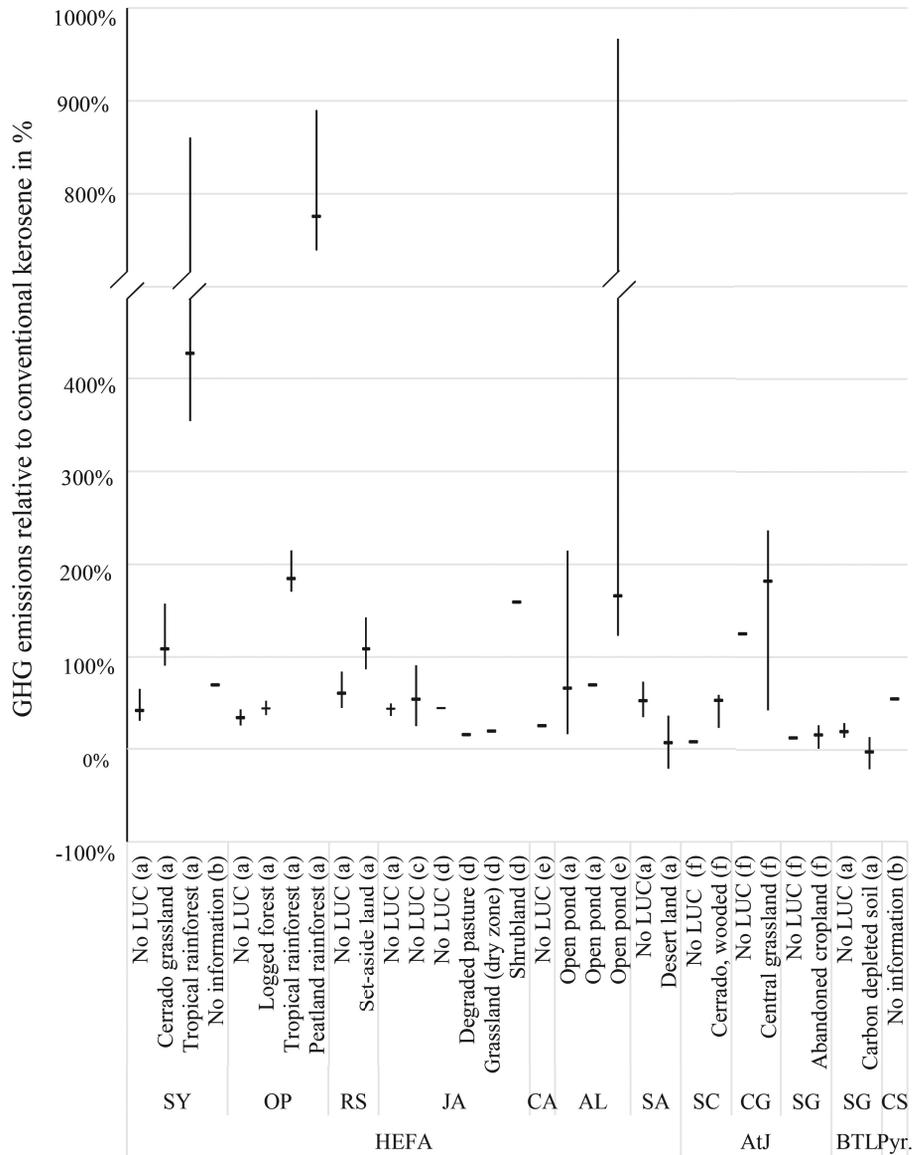
Emissions from AtJ-fuels [228] are as well based on low, high and baseline scenarios. For each feedstock, different platform molecules, which lead to other conversion routes than AtJ, e.g. via fatty acids or triglycerides, are assessed. Each feedstock reported in Figure 2-4 refers to AtJ-fuels, using an alcohol as a platform. The conversion pathways present low and high efficient concepts as defined by Staples et al. [228]: Sugarcane and switchgrass concepts use ethanol as a platform molecule and present low-emission scenarios, thus, highly efficient production routes. Corn grain is assumed to be converted to iso-butanol as a platform molecule. This route presents a high emission scenario according to Staples et al. [228]. These low and high emission scenarios of Staples et al. were taken as reference case and low and high dLUC emission estimations are added to obtain low and high estimates that are presented in Figure 2-4. Among AtJ-fuels assessed

<sup>11</sup> The analysed studies apply different approaches to account for co-products: Stratton et al. [157] use market value-based allocation at the oil mill stage and energy-based allocation at the fuel production stage and for energetic co-products, i.e. electricity; Egowainy et al. [224] assign credits for co-products other than fuels and apply energy-based allocation at the fuel processing stage; Meyer et al. [225] allocate emissions based on energy content and give credits for surplus heat; Bails et al. [226] apply energy-based allocation; Ou et al. [227] assign credits for co-products other than fuel, i.e. fertilizer, heat and electricity, and apply energy-based allocation for fuels; Staples et al. [228] allocate emissions based on market value.

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by Staples et al. [228], sugarcane results in lowest GHG emissions, followed by switchgrass. The conversion route of corn grains via iso-butanol is less efficient and entails higher LUC emissions.

A high degree of uncertainty exists in terms of fertilizer induced  $N_2O$  emissions, process parameters and the extent of direct and iLUC induced emissions. For some feedstocks,  $N_2O$  emissions constitute a considerable share of total emissions: More than 50 and 40% of emissions originate from  $N_2O$  volatilization at the cultivation stage in case of switchgrass and rapeseed, respectively [157]. The estimation of  $N_2O$  emissions is often based on the application of generic emission factors, which entail a high degree of uncertainty [230]. Emission estimations are furthermore often based on model assumptions due to the fact that the investigated concept does not operate at industrial scale yet. Still, analyzed studies reveal that biokerosene provision and use might even result in GHG emissions multiple-times larger than conventional kerosene, not even considering iLUC effects. iLUC is a change in land-use at another location triggered by change in utilization of the harvested crop or a change in crop type: The cultivation of biofuel crops (or for any other use) might displace food or fiber production, which will be provided from elsewhere, potentially triggering a conversion of land. The extent of dLUC and iLUC has been extensively discussed in the context of other biofuels and some studies indicate considerable emissions from dLUC and iLUC and a high uncertainty concerning iLUC [36, 39, 231–238]. There is a high variation among modelled iLUC factors, but the magnitude can be substantial and exceed emissions from fuel provision and combustion [236]. Even without being able to accurately quantify iLUC effects, it is obvious that mechanisms that help to avoid direct and indirect transformation of native vegetation into agricultural areas are needed to avoid the emission of substantial amounts of GHGs and to prevent various other negative effects, such as biodiversity loss.



**Figure 2-4** GHG emissions of biokerosene relative to conventional kerosene. The combustion and provision of conventional kerosene emits 90 gCO<sub>2</sub>eq/MJ [210]. Climatic effects due to non-CO<sub>2</sub> compounds emitted during combustion are not considered (see text). Several dLUC cases are considered. Biokerosene from salicornia includes HEFA and BtL-FT SPK from oil and biomass, respectively [157]. The vertical bar presents variations in results due to a change in yields, technical parameters and LUC effects, etc.: the lower and higher end present low- and high emission scenarios, respectively. The inner data points refer to baseline scenarios, as reported in the respective source. Feedstocks: algae (AL), camelina (CA), corn grain (CG), corn stover (CS), jatropha (JA), miscanthus (MI) oil palm (OP), rapeseed (RS), salicornia (SA), sugarcane (SC), switchgrass (SG), soybean (SY) and wheat (W). Data obtained from (a) [157], (b) [224], (c) [225], (d) [226], (e) [227], (f) [228].

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### 2.3.1.7. *Non-CO<sub>2</sub>-effects*

The combustion of biokerosene results in lower GHG emissions than conventional fuel due to a lower carbon content of fuel. The theoretical CO<sub>2</sub> emission reduction, assuming a complete conversion of educts, is 2.7 and 2.8%/MJ of fuel for SPK50 and SPK100, respectively, in relation to conventional jet fuel [239]. Elgowainy et al. report a slightly higher combustion efficiency for SPK50 and SKP100 in relation to conventional jet fuel of about 0.15% and 0.3%, respectively [224]. Both mixtures reduce the emission of nitrogen oxides (NO<sub>x</sub>), particulate matter (PM<sub>10</sub><sup>12</sup>) and sulphur oxides (SO<sub>x</sub>) in cruise, landing and take-off mode: NO<sub>x</sub> emissions are reduced by less than 10%, PM<sub>10</sub> between 10 and 92% depending on fuel mixture and operation mode, and SO<sub>x</sub> up to 100% in case of SPK100 and by 49% in case of SPK50 [224]. Lobo et al. report a reduction of PM<sub>10</sub> mass by 39 ± 7% and 62 ± 4%, for SPK50 and SPK100, respectively [240]. A reduction in emission of these pollutants might improve local air quality due to a reduction in adverse effects for human health, especially at airports and in close proximity [241, 242]. The change in exhaust gas composition affects the formation of contrails and aircraft induced clouds (AIC), as well as optical properties of the latter [243]. Stratton et al. [244] assessed the change in radiative forcing due to a change in emission patterns and found an increase in radiative forcing due the use of SPK biokerosene. This is mainly due to an increase in water vapor, in contrails and AIC, as well as a decrease in SO<sub>x</sub>. SO<sub>x</sub> scatters short-wave radiation and thus exerts a negative climate forcing. Consequently, a positive climate forcing results from a reduction in SO<sub>2</sub> emissions [242, 245]. The formation of AIC takes place at altitudes and environmental conditions under which, naturally, no cirrus clouds form and might increase cloud cover [246, 247]. AIC reflect outgoing long-wave radiation [248]. As a consequence, AIC exert a positive climate forcing. Stratton et al. [244] quantify that SPK100 with a 100% GHG reduction, results only in 48% reduction of climate change impacts on a 100-year time horizon: The combustion of conventional jet fuel emits 73.2 gCO<sub>2</sub>/MJ but impacts the climate by non-CO<sub>2</sub> emissions as emitting 151.3 gCO<sub>2</sub>/MJ, a factor of 2.07. The combustion of SPK100 emits 70.4 gCO<sub>2</sub>/MJ and affects the climate as emitting 2.22 times that amount. It should be noted that high uncertainties are associated with the determination of the radiative forcing of contrails and cirrus clouds as well as with the formation of contrails and AIC from conventional and biofuel mixtures [244, 246]. These findings show, however, that non-CO<sub>2</sub> emission related effects on global warming might play an important role and might partly offset positive effects due to CO<sub>2</sub> emission reductions.

### 2.3.1.8. *Biodiversity*

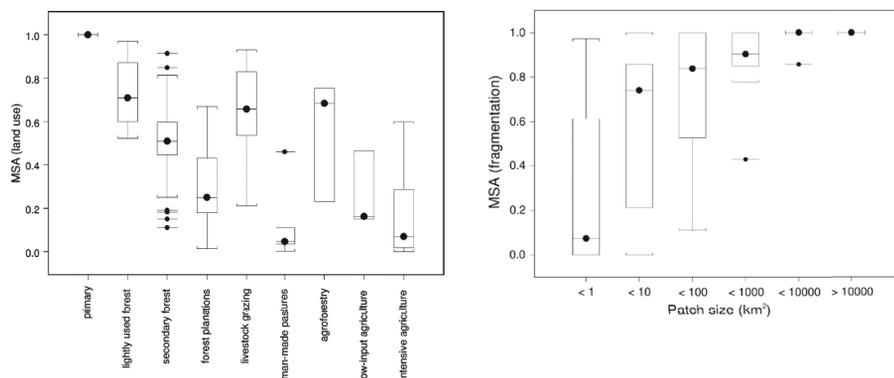
The provision of biofuels can be associated to a direct or indirect conversion of land. Whether the effect on biodiversity (or other aspects, as discussed above) is negative or positive depends on previous and new land use. A conversion of degraded land can result in positive effects,

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<sup>12</sup> PM<sub>10</sub> denotes particulate matter with a maximum diameter of 10 μm.

e.g. sequestration of carbon, increased biomass production, etc. However, the demand for agricultural commodities, socio-economic structures and the regulatory framework often result in a conversion of native environments to agricultural areas. An extensive review of published literature reveals mostly negative impacts on biodiversity related to the provision of biofuels [249]. An extensive review by Immerzeel et al. [249], encompassing 53 publications, reveals solely negative effects of first generation biofuels concerning habitat loss, species abundance and composition, species richness and species distribution at local, regional and continental scale. 2G biofuels can result in neutral or positive effects regarding these indicators, depending on specific circumstances, e.g. previous land use. The main drivers for negative impacts on biodiversity are changes in land cover, which cause habitat loss and fragmentation of landscapes, pollution and the introduction of invasive species. There is a difference in impacts reported for tropical and temperate climates: in 88% of studies, negative effects are reported in tropical regions, whereas in temperate regions 47% of studies reported negative and positive or neutral impacts; 31% reported negative results and the remainder described positive effects. Only few crops result in positive effects (miscanthus, switchgrass, short rotation coppice and other 2G biofuel feedstocks), while most other feedstocks result in predominantly negative effects, in particular corn, oil palm and soy. Oil palm plantations, for example, are reported to inhabit only about 15 to 25% of species recorded in primary forests [147, 250]. The mean species abundance (MSA) is strongly dependent on land use category and patch size (Figure 2-5). Alkemade et al. [251] report MSA for different land-use categories and patch-sizes based on a literature review and found much lower MSAs in managed agricultural systems compared to primary vegetation. There is a high variability in MSA in different ecosystems. However, even upper values of reported MSAs indicate significant differences to primary vegetation. These results show that intensive agriculture, forestry and fragmentation of large ecosystem areas result in a loss of the majority of species. Additionally, the introduction of nutrients into ecosystems, presents another trigger of MSA loss and change in species composition in various ecosystems [251, 252]. It should be kept in mind that these problems are triggered by many factors, such as an increasing demand for agricultural products in general, not biofuels specifically, and other socio-economic conditions. In 2010, for example, only 5% of global palm oil consumption was used for energy purposes; 71% was consumed as food and the remaining 24% was used for industrial purposes [253]. Kline et al. [254] argue that land is not the limiting factor concerning food and bioenergy production and that political and social conditions are often main drivers of deforestation and should thus be addressed. Consequently, the issue of land requirement, land conversion and biodiversity conservation need to be discussed in a wider scope than with regards to biofuels alone.

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**Figure 2-5** Mean species abundance (MSA) for different land-use categories (left) and different patch size categories (right) [251] - reprinted with permission under the CC BY-NC license.

### 2.3.1.9. Land requirements

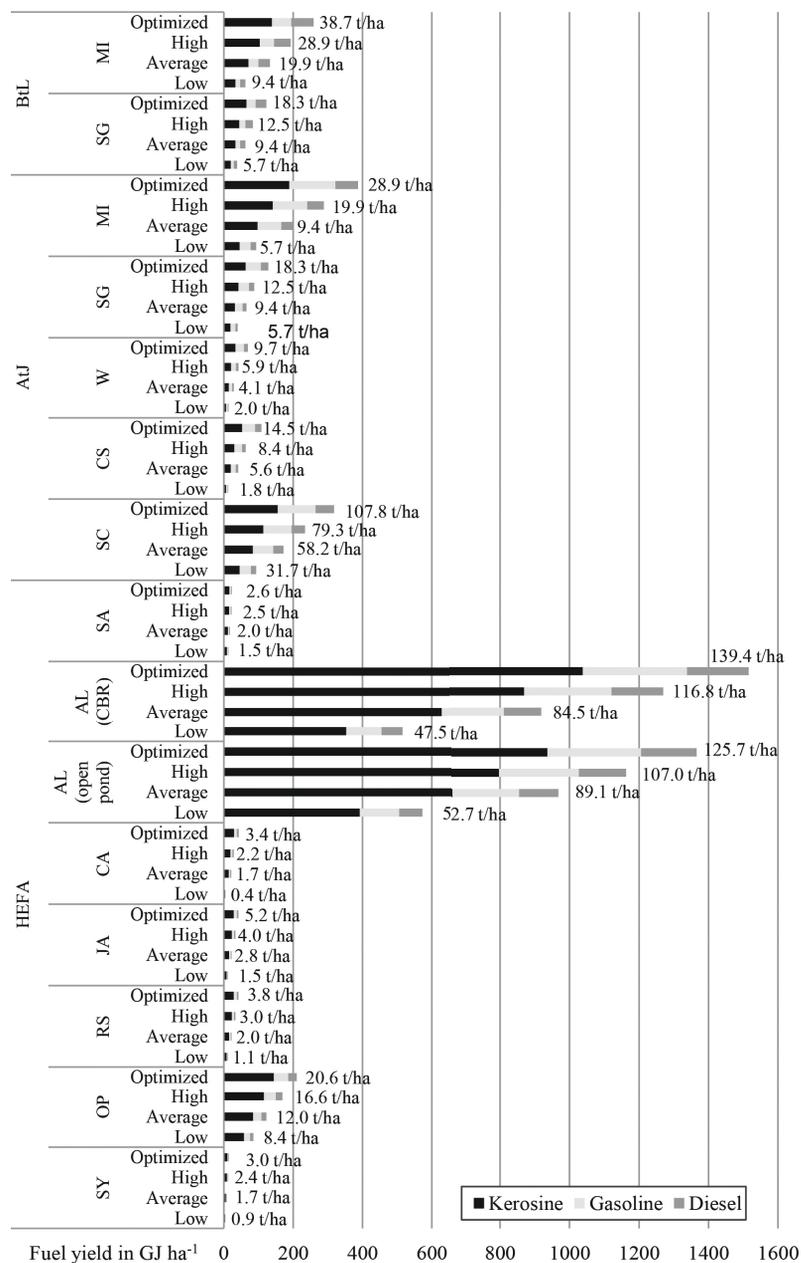
Future demand for agricultural products for food, fiber and industrial needs, including biofuels, will inevitably increase due to a growing world population, changing consumption patterns and the need to find alternatives to fossil fuel-derived fuels and products [255, 256]. An increase in demand for agricultural products by 70 to 80% until 2050 is expected [257, 258]. This will be accompanied by an expansion of arable land [257, 259]. Yield increases observed in the past, are expected not to fulfil the increase in demand. Furthermore, there is statistical evidence that an increase in yield does not necessarily result in a reduction of cultivated land, especially in industrialized countries [260]. Consequently, the conversion to arable land can be expected in the decades to come. Global efforts to promote biofuels as a measure to reduce GHG emissions will ultimately contribute to this trend at least to some extent, considering that biofuels only account for a minor share of agricultural production [256, 261].

The future demand for biokerosene that is not met by residual feedstocks or wastes can be fulfilled by an increase in productivity, by a change in cultivated crop, the change in use of the cultivated crop (potentially resulting in iLUC) or the conversion of land (dLUC). The land requirements for biokerosene production strongly depend on the chosen feedstock (Figure 2-6). Yields of soybean, oil palm, rapeseed, sugarcane, corn and winter wheat are based on FAOSTAT data from 2005 to 2014 for all covered countries [126]. Yields of switchgrass and miscanthus are based on a meta study that summarizes reported yields from six and eight countries<sup>13</sup>, respectively [262]. Productivity of open pond and closed bioreactor algae cultivation stem from a meta study assessing 13 and 11 studies for of open pond and closed bioreactor systems, respectively [263]. Most of these yields present extrapolated yields that have not been proven in reality at commercial

13 Yields of switchgrass stem from Belgium, England, France, Germany, Japan and US from 1983 to 2011; miscanthus yields are reported from Belgium, England, France, Germany, Italy, Poland, US, Wales from 1992 to 2011 [262].

scale. For all these data sets, low and high yield estimates are based on the first and fourth quintile and give an indication of low and high yields that are achieved under average global conditions. The 95%-quantile reflects yields that can be achieved under optimized conditions. Yields of the remaining feedstocks stem from field experiments in the US, Mexico and on a global scale in the case of camelina, salicornia and jatropha, respectively [157, 225, 264–266]. The HEFA and BtL-FT process yield 32.0 and 6.7 GJ/t fuel (kerosene, diesel and gasoline) of oil and biomass, respectively [211]. The AtJ process yields 2.95, 7.91, 7.95, 7.99, 6.37 7.03 and 10.00 GJ/t fuel per t of sugarcane, wheat grain, wheat straw, corn grain, corn stover, switchgrass and miscanthus, respectively, based on ethanol yields from the respective feedstock [124, 267–272]. Results presented for wheat and corn assume a biorefinery concept, which converts starch and lignocellulose, i.e. grain and straw or stover, respectively. In case of lignocellulosic feedstock, fermentation of pentose and hexose is assumed. The sustainable potentials of wheat straw and corn stover are 33 and 28%, respectively [273, 274]. As detailed process models or industry data of AtJ processes are missing, a conversion efficiency of ethanol to fuel of 90% is assumed. The product slates consisting of kerosene, diesel and gasoline are 68, 12, 20; 54, 25, 21 and 48, 17, 35%, for HEFA, BtL-FT and AtJ, respectively [211, 275]. In Figure 2-6 the fuel output comprising of all three products is presented: even if shares of products vary due to a different technical setup, total fuel output remains in about the same range. Results show that HEFA-fuel from algae is by far the most area-efficient way of providing biokerosene. However, it should be kept in mind that reported yields have not been achieved on commercial scale yet. Among the other options, miscanthus, sugarcane and oil palm are most area-efficient. Several crops that are already extensively used to provide biofuels, i.e. corn, wheat, rapeseed and soybean, yield comparably low amounts of fuel per hectare. Jatropha, often praised as a promising feedstock, shows comparably low yields. However, jatropha as well as salicornia can be cultivated on degraded soil or in saline environment, thus, on land that is otherwise not or barely suitable for agriculture. To make use of this positive aspect, it needs to be assured that plants are not grown on fertile land that could be used for other purposes. If fertile land is used, oil palm is the better choice due to significantly higher yields and suitability for similar climatic conditions [146, 276]. Apart from those feedstock presented in Figure 2-6, residues and wastes offer an alternative to provide fuels without any additional land requirement. Consequently, these results indicate that a transition towards lignocellulosic feedstocks or algae is advisable in terms of land requirements. The aspect of land investments, often referred to as “land grabbing”, is discussed in a socio-economic perspective in chapter 2.3.2.3.

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**Figure 2-6** Area-specific fuel yield of a selection of feedstocks. Low, high and average estimates present the first quintile, fourth quintile and the average of reported yields, or estimations based in experiments and meta-studies (see text). The optimized value presents an estimate based on high feedstock yields achieved under optimal conditions. Conversion efficiency and fuel product slates are constant. The data labels present feedstock yields in t/ha. Wheat and corn yields include grain yields plus sustainable potentials of straw and stover, respectively. Feedstocks: algae (AL), camelina (CA), corn stover (CS), jatropha (JA), miscanthus (MI) oil palm (OP), rapeseed (RS), salicornia (SA), sugarcane (SC), switchgrass (SG), soybean (SY) and wheat (W).

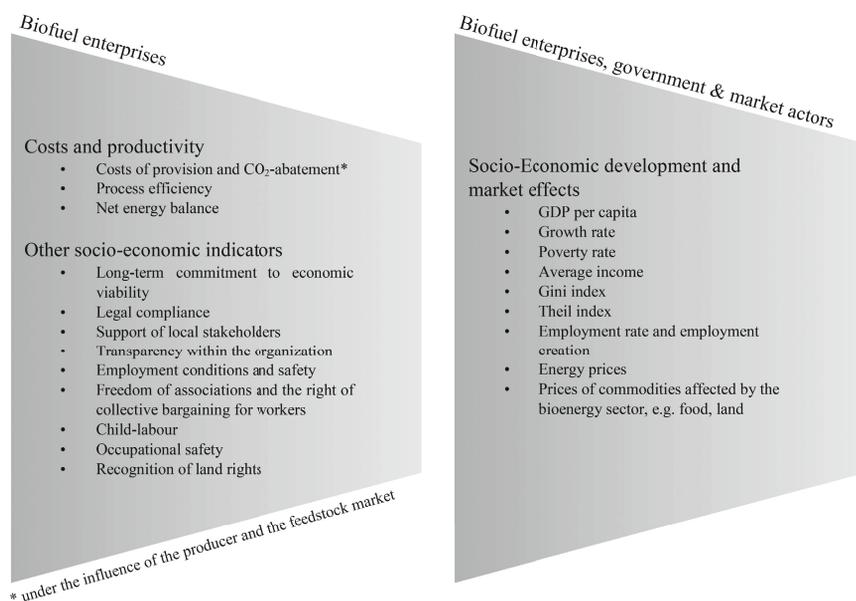
### 2.3.2. Socio-economic dimension

The economic and social dimensions of sustainability are closely linked to each other due to many aspects that affect both. The economic dimension comprises the economic viability of biofuel provision as well as impacts on the economic system, e.g. by employment creation and impacts on other commodity markets. Social consequences of biofuel projects are closely linked to economic aspects: the creation of employment, working conditions as well changes in land-use rights have economic and social implications. Figure 2-7 presents a selection of indicators concerning the socio-economic dimension of sustainability that are either under direct control of enterprises along the biofuel provision chain or that are under influence of other actors such as governmental institutions and other market actors as well. Enterprises providing fuels have direct influence on production modalities and efficiencies. They are furthermore responsible for legal compliance, recognition of land-use rights as well as fair working conditions etc. According to Cramer et al. [277] working conditions, human rights, prosperity rights, social circumstances of local population and integrity are aspects that contribute to social-wellbeing. Other indicators in Figure 2-7 present the socio-economic performance at a national level and can only be partly influenced by a single enterprise or industry sector. The establishment of a biofuel industry sector can lead to a change in these indicators, e.g. by creating employment, increasing per gross domestic product (GDP), lowering the poverty rate etc. In this chapter, three important aspects regarding the socio-economic dimension of sustainability are discussed in detail:

1. Costs of biokerosene production
2. The effect of biofuels on food prices and price volatility and consequences, and
3. Implications of investment in land (often referred to as “land grabbing”).

Furthermore, more general impacts on the socio-economic system are briefly discussed.

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**Figure 2-7** Selection of indicators concerning the economic dimension of sustainability, partly based on [278–280].

### 2.3.2.1. Minimum fuel selling price of biokerosene

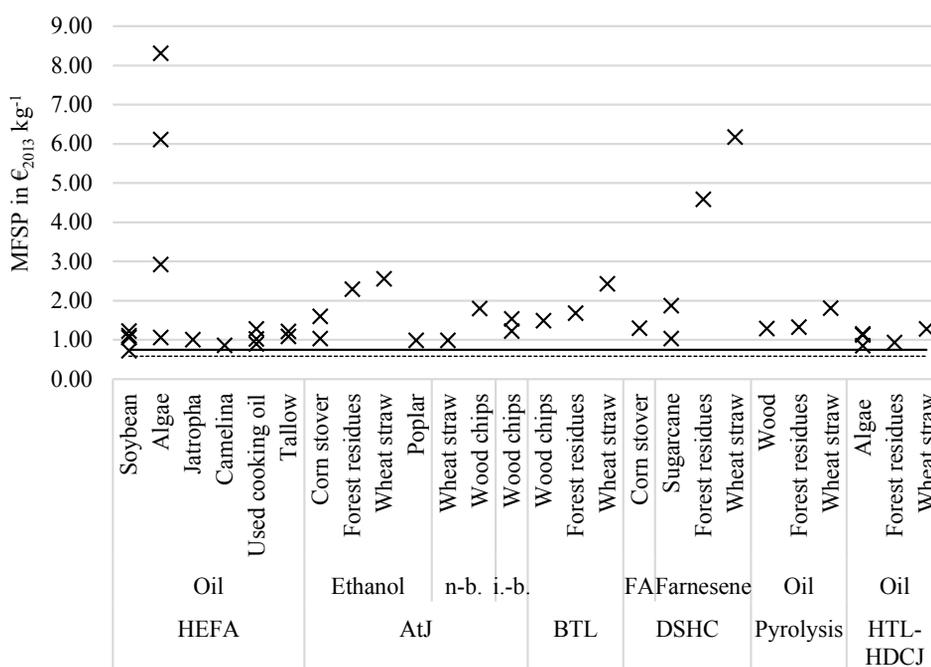
In order to allow a market penetration of biokerosene, novel biofuel technologies need to be suitable to be used in existing infrastructure and aircrafts due to slow replacement rates of existing infrastructure and high costs of the infrastructure and aircraft fleet replacement. Current estimates show that most biokerosene provision pathways are not able to compete economically with fossil kerosene (Figure 2-8). The literature review of minimum fuel selling prices (MFSP) is based on data from industrial facilities and techno-economic models, mostly assuming commercialized production ( $n^{\text{th}}$  plant conditions<sup>14</sup>). Basic assumptions like e.g. feedstock prices, discounting rates, interest rates and technical parameters differ among the available studies. The review is thus rather thought to serve as a preliminary assessment of costs. In case of HEFA-biokerosene, camelina and soybean result in lowest price estimates. Feedstock cost accounts for the highest share of cost in case of soybean [282]. The assumed price of soybean is about 2.5 times higher than that of camelina, which results in lowest prices in case of camelina [282, 283]. The MFSP of HEFA biokerosene from used cooking oil is among the lowest of compared studies [284, 285]. Despite being a residue, feedstock costs account for around 70% of the overall costs. There is a high variation in algae-derived fuel due to technical specifications of open pond and closed bioreactors concepts: the costs of closed bioreactors is about 17.5 times higher than the installation of an open pond system [286]. The authors see the highest potential of cost reduction in optimizing algae productivity and lipid content. Klein-Marcuschamer et al. [287] estimate comparably high costs

14  $n^{\text{th}}$  plant assumptions imply mature technology (no pioneer plant) and assumes that other plants with similar specifications are or have been in operation on a commercial scale [281].

for HEFA from algae grown in open pond systems due to high investment costs for ponds and harvesting equipment. Atsonios et al. [288] assessed different pathways to synthesize n-butanol and iso-butanol via hydrolysis and fermentation as well as syngas fermentation. In all cases, total installation costs account for about 50% of total costs. The resulting price of renewable jet fuel is higher than that of conventional kerosene in all assessed cases. However, short-chained products, i.e. butanol, butane and C<sub>8</sub> to C<sub>16</sub> olefins, could be sold at a competitive price. Among compared AtJ pathways, the acetone-butanol-ethanol (ABE) fermentation from corn stover [288], at which ethanol and butanol are further converted to biokerosene, results in lowest prices. The process has significantly lower capital costs and double the operating costs compared to the other pathways and benefits from revenues from acetone. Among DSHC pathways, there is no clear picture to be drawn from reported prices: Davis et al. [289] reported a MFSP of around 1,775 €/t that can be achieved using n<sup>th</sup> plant technology to produce biokerosene via fatty acids. Davis et al. [289] emphasize the importance of creating valuable co-products, e.g. from lignin and acetate, in order to reach lower fuel prices. Klein-Marcuschamer et al. [287] estimate MFSP of 2560 and 1410 €/t to produce biokerosene via farnesene; the low estimate presents prices of future optimized conditions. Raw materials account for 70% of costs in case of standard cost estimations. Compared to the former results, de Jong et al. [284] estimate comparably high prices for DSHC biokerosene from forest residues and wheat straw. The difference between the two originates from feedstock costs: the price of wheat straw (190 €/t) is twice as much as that of forest residues. The MFSP of DSHC biokerosene lies above prices of the other pathways to obtain fuel from forest residues and wheat straw that are assessed by de Jong et al. [284]: AtJ 3253 and 4731 €/t, BtL 2334 and 3377 €/t and HTL 1290 and 1781 €/t for forest residues and straw, respectively. HTL and pyrolysis benefit from high yields and comparably low total purchased equipment costs (TPEC). The MFSP of pyrolysis is slightly higher due to higher upgrading requirements and slightly higher TPEC. In both cases, the share of operational expenditures constitutes a high share of total costs. None of the considered cases reaches a fuel price that is comparable with conventional jet fuel. De Jong et al. [284] even argue that renewable fuel production from DSHC and AtJ pathways create opportunity costs due to more favorable market conditions for the intermediate products, i.e. farnesene, or ethanol and butanol, which could be used for many other industrial purposes, e.g. cosmetics, fragrances, biopharmaceuticals, etc. MFSP of biokerosene production in pioneer plants are likely to exceed MFSP of production under n<sup>th</sup> plant conditions: De Jong et al. [284] assessed the increase in MFSP in case of production in a pioneer plant and estimate an increase in MFSP by 1, 64 to 86, 57 to 82, 77 to 105 and 63 to 87% in the case of HEFA, AtJ, BtL, pyrolysis and HTL, respectively. The HEFA pathway shows the lowest difference due to the maturity of technology. Consequently, immature technologies face larger differences between pioneer facilities and under n<sup>th</sup> plant conditions.

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The literature review shows no clear advantage for any conversion pathway or feedstock. Modelled estimates are uncertain due to missing technical parameters and uncertainty about future technical improvements. Still all studies assume a mature technology and consider conditions not achieved yet in many pathways. The majority of assessed concepts produce biokerosene at a much higher cost than that of fossil kerosene. The production in pioneer plants might result in much higher MFSP than reported in Figure 2-8 [284]. To increase competitiveness, the production of high value co-products is essential [284, 290]. Furthermore, the introduction of a monetary burden on fossil fuels seems inevitable to make biokerosene financially competitive considering current price estimates and fossil fuel prices.



**Figure 2-8** Minimum selling price of biokerosene in EUR2013/kg for different production pathways and platform compounds produced in nth plant facilities. The dashed and solid lines present the average and 90%-percentile monthly price of conventional jet fuel between August 2011 and July 2016 [205]. Sources, partly obtained from [291]: HEFA – soy [282, 292], algae [286, 287, 293], jatropha [294], camelina [283], used cooking oil [284, 285], tallow [285]; AtJ – corn stover [288, 295], forest residues [284], wheat straw [284, 288], poplar [296], wood chips [288]; BtL – wood chips [288], forest residues [284], wheat straw [284]; DSHC – corn stover [289], sugarcane [287], forest residues [284], wheat straw [284]; Pyrolysis – wood [297], forest residues [284], wheat straw [284]; HTL-HDCJ – algae [298]. Abbr.: FA – fatty acids, i.-b. – iso-butanol, n-b. – n-butanol.

### 2.3.2.2. Food, feed, fiber, fuel – increasing demands and limited resources

The competition for land and the effect on food prices is a frequently discussed aspect in the context of biofuels and presents the most popular critique against them. Fertile land and agricultural

productivity is inevitably limited (even considering yield improvements). This ultimately results in the question of how fertile land could be used in the most productive and sustainable manner while serving the needs of a growing world population, changing consumption patterns, increasing demands for energy and biogenic products as well as the need for nature conservation. The rapidly growing demand for biofuels in the past decade was therefore accompanied by a public and scientific debate on the effects of biofuels on food prices and food security. Several aspects propelled this debate:

- Increasing and volatile food prices (Figure 2-9): Price indices indicate a strong relation between crude oil price and prices of agricultural commodities. Increasing prices and a high volatility of prices can be observed in the past 20 years. The so called “food crisis” in 2007/08 triggered a large debate on factors influencing food prices. The demand for biofuels, the fossil fuel price, increasing demand, exchange rates, financial speculation, on the demand side and relatively low production increases, low investments preceding the crisis, low stocks, trade impediments and decreasing exports on the supply side, are named as probable causes for the sharp increase in food prices in 2007/08 [299–301]. Wright [301] emphasizes the importance of stocks and that biofuel mandates magnify occurring increases in prices due to a decrease in supply at low stocks.

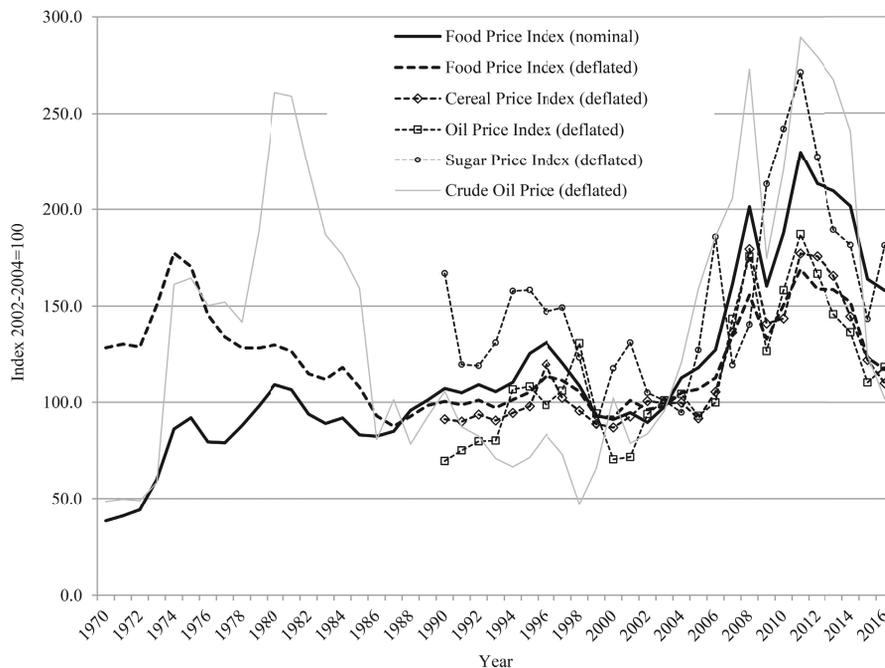
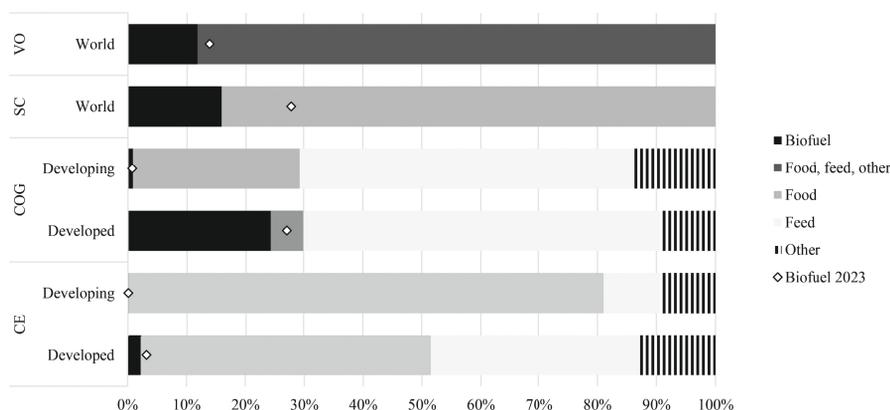


Figure 2-9 Indices of food prices and crude oil [302, 303].

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- On the demand side: a growing world population, changing diets and the use of agricultural products for other purposes (e.g. bioenergy and biofuels) increase the need for agricultural commodities. In the years to come, the growth in demand due to biofuels is expected to prevail but to slow down due to blending walls that are reached in the US and EU [256]. Currently, most first generation fuels are produced from feedstock suitable as food or feed or feedstock that is grown on land that could be used to provide food and feed. Still, the majority of most feedstocks used for bioethanol and biodiesel production are used for other purposes than biofuel production (Figure 2-10). These shares are not expected to change significantly on large scale in the upcoming decade. On a regional scale, shares of commodities used for fuel production could be significantly higher [256]: In the US 44% of maize is converted to bioethanol and around 38, 41 and 69% of vegetable oil consumed in the EU, Thailand and Argentina, respectively, are used for biofuels.



**Figure 2-10** Share of consumption of cereals (CE), coarse grains (COG), sugarcane (SC) and vegetable oil (VO) used for biofuel production and other purposes 2011 to 2013 and 2023 [256].

- On the supply side: yields are increasing year by year, but yield increases are declining, e.g. wheat yields increased in average by about 2.1%/a from 1961 to 2007 and are expected to increase by about 0.7%/a from 2007 to 2050 [304].

Based on these aspects two main questions arise that present the core of the food vs. fuel debate:

1. What is the impact of biofuels on commodity prices?
2. What is the linkage between staple food prices, poverty and food security?

To what extent biofuels influence commodity prices is of major concern, especially since the food crisis in 2007/08 and a steadily increasing demand for biofuels. Hochman and Zielberman [305] analyzed 43 studies and found that there is a (limited) effect of biofuels on food and fossil fuel

prices. On average, US corn prices increased by 17.54 €<sub>2007</sub>/t (SD=18.69), while fossil fuel prices decreased to a small extent. The effect on fossil fuel prices seems to be constant, despite increasing ethanol production. According to Hochman et al. [306], economic growth and entailed changes in consumption patterns contributed by more than 50% to the increase in price. Another literature review by Condon et al. [29] lists increases in corn prices from -0.2 to 72% that were reported in 19 studies. This yields a study-weighted average increase of corn prices of 0.24% per 1% increase in ethanol production. Most of the variation in price increase among studies can be explained by modelling framework, assumed and predicted ethanol production, projection year and the inclusion of the production of other biofuels. Kretschmer et al. [307] analyzed 7 studies and found an increase in commodity prices of 8 to 20, 1 to 36 and 1 to 22% in case of oilseeds, vegetable oils and cereals, including maize, respectively as a consequence of EU biofuel mandates. Another 5 studies report price increases 2 to 7, 35 and 1 to 35% for the same feedstocks as a consequence of global biofuel mandates. Persson [26] reviewed 121 studies dealing with the impact of biofuels on commodity prices on a global scale. The review yields an average increase in US corn price of 36%/(EJ a)<sup>15</sup> of increase in bioethanol production. This equals 11 to 43% of price increase of corn in the US between 2000 and 2008. During that period, bioethanol production increased by 0.68 EJ. In the EU, the price increase of oilseeds triggered by an increase in biofuel production is 25%/(EJ a)<sup>16</sup>, equaling about a third of the price increase observed in the EU between 2000 and 2008 considering the biodiesel production increase during that period. The author emphasizes that current assessments assume rather small biofuel demand shocks that are much lower than future predictions and targets. Facing larger demand shocks, demand and supply behave in a non-linear manner so that demand becomes more inelastic due to physical and agronomical limits, e.g. limited land resources, declining yield increases. Hence, price increases might be larger. Based on reviewed literature, Persson [26] concludes that a positive feedback of prices triggered by biofuel demand. Still, a better knowledge of elasticities of supply and demand, the functioning of land markets as well as of market transmission is needed to accurately predict price increases. Other literature claims that current biofuel policy links food and energy markets and thereby increases price volatility [28, 308, 309]. In contrast to these studies, Kline et al. [254] argue that agricultural land is not the limiting factor and, thus, that food and fuel do not compete. Biofuels could help to reduce price volatility by a flexible biofuel production. Setting flexible biofuel mandates that are adapted to the prevailing market situation, instead of fixed blending rates, could alleviate pressure on food markets as the latter presents an inelastic demand [28, 254, 309, 310]. Available review literature yields a heterogeneous picture of potential price changes due to biofuel mandates. However, almost exclusively increasing prices are reported. The extent of increase is highly variable and a matter of high variation among studies. Kretschmer et al. [307] conclude from their review that oil crops are more strongly influenced than cereal crops. This

15 SD=18%/(EJ a), n=218

16 SD=25%/(EJ a), n=25, one outlier removed

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might be due to larger quantities of biodiesel consumed, due to the market structure and due to the high share of vegetable oils used for biodiesel production.

Thus, what is the effect of rising food prices? – Increase in income or increase in poverty? There has been a vital debate on the effect of food prices on poverty with many actors presenting contradictory arguments throughout the discussion [31]. Before the 2007/08 food crisis, many organizations, e.g. NGO, the FAO, the World Bank and other institutions, promoted the idea that low staple food prices, supported by export subsidizes of developed countries, increase poverty by reducing revenue for rural farmers in developing countries. After the crisis, high staple food prices were often criticized for pushing low-income consumers into poverty [31]. Idan [311] reviewed 19 studies and reports that an increase in food staple prices creates winners and losers: Net food producers usually profit from high prices, while net consumers face negative effects. The extent of negative effects is alleviated by changes in consumption patterns, welfare benefits triggered by those profiting, e.g. by providing employment, etc. The market linkage of global and local food markets varies across countries and some markets for certain commodities appear to be mostly disconnected from world markets while others transmit changes of world market prices to local markets to a larger extent. The impact of higher commodity prices can be especially severe for countries that depend predominantly on imports [310]: A price increase of 0.20 US\$/kg of cereals results in costs for imports equaling up to 9.5% of the GDP in the top ten cereal-importing countries in Africa. Most of the reviewed studies indicate an increase in poverty due to increasing food prices due to a higher decrease in welfare of net consumers opposed to welfare benefits of net producers. Ivanic and Martin [32] report similar findings from 9 low income countries. The effects and magnitude effects vary for different commodities, among countries and within a country considering rural and urban population as well as income. The negative consequences for net consumers outweigh positive consequences for net producers. Other studies from around the world report as well that the poorest share of the population is affected negatively by increasing food prices due to similar reasons, while net food producers profit [312–316]. Producers could profit from increased income, which could in turn promote investment in agriculture [317]. Thereby yield improvements could be achieved.

The increase in food prices often results in a reduction of quality of food that is consumed [318]. This finding is supported by an analysis by Green et al. [33], who analyses 136 studies that reported price elasticities from 162 countries. The authors found a decrease in demand by 0.61, 0.55 and 0.43% per 1% increase of cereal price in low, middle and high-income countries, respectively<sup>17</sup>. The demand for vegetable oil decreased by 0.60, 0.54 and 0.42%, respectively,

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17 The 95% confidence intervals for cereals and fats and oils are -0.66 to -0.56, -0.61 to -0.41, 0.48 to 0.36 and -0.65 to -0.45, -0.60 to -0.47, -0.48 to -0.35%, in case of low, middle and high income countries, respectively.

per 1% increase in vegetable oil price<sup>17</sup>. These findings indicate a stronger impact of food price increase in low-income countries. Several studies reviewed by Indan [311] focus on the impact of price volatility and most studies report a substitution of commodities facing volatile prices with uncorrelated commodities by consumers, while net producers, in contrast, face more negative consequences. Biofuels could however stabilize markets and reduce price volatility [254, 317]: biofuel production can be increased during low price periods and significantly lowered at high feedstock prices. This has a levelling effect on commodity prices, even though the overall demand for feedstock might contribute to an increase in feedstock prices. Other authors argue that there can be a positive feedback between food prices and productivity: increasing prices might promote investment and thereby increase yields [317].

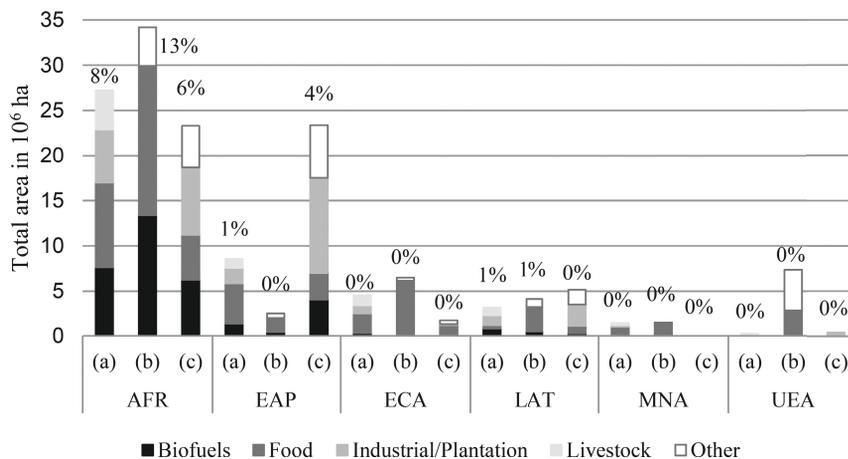
To summarize, it can be concluded that the introduction of biokerosene will affect food commodity markets, if realized by food crops or on land that could otherwise be used to provide food and feed. All literature reports increasing commodity prices due to feedstock demand for biofuel production, but the estimated extent of increase varies. The linkages between global and local food markets are difficult to assess and depend heavily on market integration [34, 319]. Review studies report predominantly negative consequences of increasing food prices and price volatility. Both increase the risks of increasing the poverty gap as poor people are most affected by increasing prices. It should be kept in mind that other drivers, e.g. yield variations, population growth, change in diets, speculation etc., contribute (possibly to an even larger extent) to increasing prices and price volatility. Flexible biofuel policies and blending rates are a mechanism to reduce price volatility. The promotion of biofuels based on residues or from feedstock grown on land that is not suitable for food production is a way to mitigate and alleviate negative effects of increasing demands for agricultural products, regardless of their use.

### 2.3.2.3. *Land acquisition and direct investment – land “grabbing” or investment stimulating economic and social development?*

The debate on direct investment in land is held as controversially as the food vs. fuel debate. Land acquisition by purchase, lease or joint venture is either considered as an investment that creates employment and offers access to technology and financial resources, or as a land “grab” that increases poverty and ignores the interests of rural farmers, while serving the global demand for agricultural commodities and the interests of international enterprises [320]. Much public attention was drawn to the topic after the announcement that Daewoo Logistics Corporation, a South Korean company, signed a 99-year agreement to rent 1.3 million hectare of land in Madagascar [321], an area that amounts to about of half of all arable land in Madagascar. After protests from Madagascan citizens that turned violent, NGO, media, the public i.a., the contract was cancelled. Still, foreign investment has not come to a halt. Most of the investment in land takes place in Africa (Figure 2-11). A peak in the number of agreements can be observed in 2009,

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following the 2007/08 food crisis [322]. The largest areas affected by agreements that have been verified are located in the Philippines, Madagascar and Ethiopia. The share of areas designated for agriculture amounts to 81%. The largest share of land acquired is forest land, 31% of the total area, followed by crop land, 22%, and scrubland, 17%. The breakdown of intended uses shows a rather small contribution of biofuels. Around 73% of non-food projects are designated to jatropha production, most of which are located in East Africa. Projects in Asia rather focus on other commodities such as rubber. Yet, 26% of all areas presented in Figure 2-11 are designated to grow “flex crops”, which can be used for food, feed and fuel, e.g. soybean, oil palm, sugarcane. It is therefore difficult to assign these areas to any specific category. Flex crops alleviate the risk of price volatility as crops can be used for food, fuel production and other purposes [254, 322]. This however requires a significant reduction in biofuel production at high prices and thus, a flexible biofuel policy. Due to their flexible use and suitability to different markets, they are especially attractive to investors [323]. They, however, bear the risk of increasing food prices in case of inflexible demands for other use than food (see chapter 2.3.2.2). Souza et al. [317] emphasize that there is a huge potential of land that can be used for bioenergy provision even when all other needs, such as food and feed, are fulfilled. A better understanding of the drivers of land scarcity, LUC and land conversion is required in order to reduce negative effects and to promote synergetic effects of food and biofuel provision [254].



**Figure 2-11** Land projects in Sub-Saharan Africa (AFR), East Asia and Pacific (EAP), Eastern and Central Europe (ECA), Latin America (LAT), Middle East and North Africa (MNA) and US, EU and Australia (UEA). The percentage value presents the share of land used for biofuel projects. Graphic based on data reported in [320]. Data stem from (a) media reports, that reported land deals between October 2008 and August 2009 by the NGO *GRAIN* ([www.farmlandgrab.org](http://www.farmlandgrab.org)), (b) historical data on signed agreements collected from by Alomar and Cousquer [324] and (c) agreements that have been verified on ground, spanning from 2000 to 2010 [322].

The impact of land investments is a matter of debate. Collier and Venables [325] argue that pioneer investors, as opposed to speculators, can facilitate an increase in productivity. Deininger [326] reports socio-economic benefits as well as negative consequences from different countries around the world. Positive results were: increase in productivity, improvement of cultivation through research, reduction of environmental damages, training and qualification of workers, improvement of infrastructure and an increase in profitability through economies of scale. Negative impacts were: conversion of native vegetation, low employment generation due to high mechanization, low poverty reduction, infringement of land rights, disregard of local population's interests, weakening of political institutions [326]. Often, marginal land is praised for its potential to provide large areas for biofuel production. However, marginal and degraded lands often present the base of subsistence for the local population and their conversion can have severe impacts on the local population [327]. It is a matter of market conditions, infrastructure, political structures and management whether investment in land results in positive or negative consequences. On a local scale, the impact of changes in land-use and land ownership can be severe for local population, due to loss of agricultural land, access to forest resources and, consequently, a decline in livelihood of people directly affected by plantations as well as people living in proximity, e.g. [328]. Several case studies report that the change in landownership and land-rights resulted in conflicts within communities, between communities and with companies, often due to a lack of transparency or a breach of contract [328–330]. This might produce mistrust in future biofuel projects.

#### 2.3.2.4. *Other impacts on the socio-economic system*

The biokerosene industry can provide employment, income in rural areas, investment and shareholder opportunities. The EU, for example, considers the provision of income and the creation of employment opportunities as a core motivation of biofuel production [122]. In 2012, the bio-economy sector provided 18.3 million jobs, 9% of jobs in the EU [331]. The bioenergy and biofuel sector created around 5% of the annual turnover. The largest share of jobs can be found in the primary biomass production sector, whereas the biofuel and bioenergy sectors provided approximately 128,000 jobs in the EU-28 in 2013. On a global scale, it is estimated that  $7.7 \cdot 10^6$  people are directly or indirectly employed in the renewable energy sector of which 23% can be found in the liquid biofuel sector [332]. There are many studies from around the world that imply a high potential of renewable energies and biofuels to promote employment creation, e.g. [333–338]. However, opposing opinions can be found as well that argue that high energy prices and subsidies reduce jobs in other sectors [339]. On a local scale, the picture is often more complex. In Indonesian oil palm plantations, employment creation and change in working conditions benefited some workers by granting them higher salaries and a regular income [328, 329], while others face a reduction in income and quality of living [328]. Van Eijck reviewed 39 studies and reports mostly positive socio-economic impacts of jatropha cultivation due to employment creation and

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increased income; however, some locations faced only marginal or no profitability [340]. The discontinuity of some projects created insecurity and high financial risks for local farmers.

A third rationale, next to the reduction of GHG emissions and the creation of jobs and income, is energy security. Biofuels present a way to increase the diversity of energy sources, allows the production of energy from feedstock that can be sourced around the globe, reduces dependency on fossil energy with its geographically and economically limited access and might provide a financially competitive source of energy in future. The implementation of biofuels into a national transport system is, however, connected to costs if supported by subsidies. Often, biofuels are subsidized via tax-exemptions. In developing countries, tax revenues from fuel can account for up to 25% of state revenues [341]. The introduction of blending quotas and tax exemptions could thus reduce state revenue by a considerable share as long as the price of fossil fuels is below that of biofuels. This aspect might thus present an obstacle for developing countries to introduce biofuels [342]. However, the demand of feedstock for biofuel production and fuel conversion can provide markets for agricultural products, employment as well as investment in infrastructure and technological improvements. It can thereby contribute to a sustainable economic development if permanent and local workforce is promoted instead of seasonal and casual labor [280]. The status of workers should be improved by associations and the allowance of collective bargaining. Additionally, the benefits of local stakeholders should be increased by cooperation with local communities, the formation of cooperatives and the provision of affordable energy. Cooperation can be strengthened by shareholding options, local ownerships, joint ventures and partnerships of globally acting biofuel producers as well as local farmers and communities. Whether developing countries gain access to biofuel markets in the EU and US or not, is a matter of economic competitiveness, market integration and trade restrictions [343]. Often, import tariffs ensure competitiveness of producers within the industrialized countries while it presents obstacles for developing countries to export their products.

### 2.4. Concluding remarks

In the course of this work, several key aspects of sustainability in the context of the provision and use of biokerosene were discussed. From an environmental perspective, biokerosene offers the chance to reduce GHG emissions and emissions of other harmful substances, e.g. particles, sulfur containing compounds, etc. If there is any reduction in GHG emissions, is a matter of cultivation practice, conversion technology and, most important, of LUC. DLUC and iLUC bear a high risk of emitting substantial amounts of GHG resulting in a net increase in GHG emissions compared to conventional kerosene. Land-use change furthermore threatens native vegetation and biodiversity. A substantial loss of native landscapes has taken place in the last decades, mostly triggered by agricultural activities, the expansion of urban areas and other socio-economic factors. These factors need to be better understood in order to avoid conversion of native vegetation and

to promote a sustainable use of land for food and fuel provision. Feedstock provision also poses risks to soil and water quality: The application of industrial fertilizers and pesticides potentially reduces soil and water quality. Excess nutrient concentrations can be observed all around the world as a consequence of excessive use of fertilizers. Many of these negative consequences can be alleviated by:

- Heterogeneous plantations such as LIHD can have positive effects on biodiversity and soil properties [170, 176].
- Plantation design and management might reduce negative effects (by a very limited extent), e.g. the retention of forest patches within or in proximity of monoculture plantations [344, 345].
- Buffer zones established at the edge of a plantation could increase biodiversity to some extent and filter nutrients and contaminants.
- The efficient use of fertilizers by crop-rotation, timing of fertilization and introduction of fertilizer-efficient species can help to reduce the loss of nutrients and the emission of eutrophying and otherwise contaminating substances [346].
- Crop rotations result in an increase in soil quality and yields compared to mono-cropping [177, 347].
- The use of lignocellulosic material as feedstock such as grasses or short rotation coppice can result in positive effects on soil and water quality.
- Some plants, e.g. jatropha and salicornia, can be used on land that is not suitable for other crops. They thereby provide an additional source of revenue without competing with food crops.

From a socio-economic perspective positive outcomes can be generated while negative consequences can and should be minimized by proper management and adequate economic and political structures. Biofuel provision has created employment opportunities around the world and thus contributed to local income as well as increased state revenues. Feedstock provision can generate a continuous source of income in rural and poor areas. The recognition of land-rights and fair working conditions are key aspects of socio-economic sustainability in rural areas. Presented literature reviews indicate an increase in commodity prices that can be attributed to the demand for biofuels. It should be kept in mind that only minor share of agricultural products serves as feedstock for biofuels on a global scale and other factors such as a growing population, changing consumption patterns, market speculation, etc. play an important role in the increase in prices, which has taken place in the past decade. Still, it is undeniable that the introduction of biokerosene, if based on food or flex crops, bears the risk of contributing to increasing food prices and price volatility, if market structures are not adapted appropriately. The effect of increasing prices has been discussed controversially in the past and the majority of scientific work reports

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an increase in poverty due to high food prices. The negative effects faced by net consumers outweigh positive effects experienced net producers. The impact of biofuels on price volatility is mostly a consequence of biofuel policy: flexible biofuel production and blending can reduce volatility, while fixed mandates and blending rates are likely to contribute to price volatility. Again, the use of (lignocellulosic) residues is the way forward to reduce competition with food and feed. It reduces pressure on commodity markets and increases public acceptance for biofuels. Another obstacle is the price of biokerosene provision: current estimates of future biokerosene production, even assuming large-scale and commercially operating production, show that the minimum fuel selling price of biokerosene is by far not competitive with its fossil counterpart. The production of valuable co-products and taxation of fossil fuels present a way forward to increase competitiveness and to facilitate market introduction of biokerosene.

Many of those environmental and socio-economic impacts presented here are merely impacts of agriculture in general, rather than specifically originating from the provision and use of biokerosene. In case of biofuels used for road transportation, legislative sustainability requirements, such as the RED [129, 130], the Renewable Fuel Standard (RFS) [348] and the Californian Low Carbon Fuel Standard [349], are in place. There are numerous voluntary certification schemes dealing with a wider range sustainability aspects of biofuel and biomass production, see e.g. [350]. In terms of sustainability requirements in place, biofuels are ahead of other commodities: None of the regulatory sustainability requirements is binding for other agricultural products than those used as biofuel. This provokes a paradox situation: many crops, i.e. flex crops, can be used as food, feed or fuel and only the ultimate use of the product defines whether sustainability requirements need to be adhered to or not and not the impact of and the potential risk entailed by the production itself. Consequently, the introduction of a mandatory scheme for agricultural products, regardless of their final use, covering a wider range of sustainability aspects is needed to reduce negative impacts.

## Sustainability aspects of biokerosene

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# Life cycle assessment of bioethanol from wheat and sugar beet discussing environmental impacts of multiple concepts of co-product processing in the context of the European Renewable Energy Directive

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Buchspies B, Kaltschmitt M (2016) Life cycle assessment of bioethanol from wheat and sugar beet discussing environmental impacts of multiple concepts of co-product processing in the context of the European Renewable Energy Directive. *Biofuels* 7(2): 141–153. doi: 10.1080/17597269.2015.1122472. The article can be found online at: <http://www.tandfonline.com>. Minor corrections and modifications were made to align the format and the nomenclature.

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### Abstract

The environmental performance of biofuels is often assessed comparing multiple feedstocks while implications of different co-product processing options are neglected. This study presents a life cycle assessment (LCA) of several co-product processing concepts of wheat- and sugar beet-based ethanol production in Germany. Inventory data are first-hand industry data presenting state-of-the-art plants. The methodology defined by the RED is applied.

The cradle-to-gate investigation shows that the co-production of fodder results in lowest impacts allocated to ethanol: 37 g CO<sub>2</sub>-eq. per MJ of ethanol from sugar beets. Total impacts are lower in case of sugar beet-based ethanol in impact categories, which are dominated by emissions from cultivation, such as eutrophication and acidification. Biogas co-production results in lowest total emissions but in higher emissions allocated to ethanol. A sensitivity analysis shows how certain assumptions, such as using a different energy carrier, grain drying, etc., influence these results.

Results indicate that the environmental impacts of different co-product processing concepts differ. Consequently, special attention should be given to this aspect when the environmental impacts of biofuels are compared. It is furthermore advised to apply a method accounting for the utility and benefits of co-products when allocating emissions, as opposed to the RED methodology.

### 3.1. Introduction

A strongly growing energy demand, the striving for a reduction of GHG emissions and the increasing dependency on fossil fuels from politically less stable countries have supported an increase in biofuel production in the past decade [101]. As a consequence, a vast variety of feedstock and conversion technology combinations for the production of biofuels can be found. Thus, the assessment of entailed environmental consequences of these concepts is required to identify the most eco-efficient concepts. Life Cycle Assessment (LCA) has been identified as an effective methodology to assess potential environmental impacts of product systems and its results are used to compare products, recognize potentials for the reduction of environmental impacts and as a support tool for policy recommendations [64, 65]. LCA has been widely applied to biofuel production systems with a strong focus on GHG emissions and consumption of (finite) fossil energy carriers. However, solely focusing on these two indicators is not sufficient for an overall environmental assessment of biofuel production and provision systems [351, 352].

Bioethanol is a biofuel with a growing production volume on a global scale in the recent two decades. This development might continue due to increasing demand for transportation fuels [102]. In numerous studies the environmental performance of bioethanol production from different feedstocks is assessed [353–355]. In most cases, alternatives are compared by assessing a single possible production concept for each feedstock mostly neglecting implications of co-product processing.

In the present study, several production concepts of wheat- and sugar beet-based ethanol yielding different co-products are assessed in a cradle-to-gate LCA. Applied data is first-hand industry data and feedstock cultivation is assumed to take place in Germany. The assessment is conducted according to the methodology defined by the Renewable Energy Directive (RED) that presents the legislative framework for biofuel certification in Europe [54]. A crucial point of the RED methodology is the handling of co-products and applied allocation principles [356–358]. Therefore, results are used to discuss differences among analyzed concepts as well as implications of the applied methodology.

### 3.2. Methodology

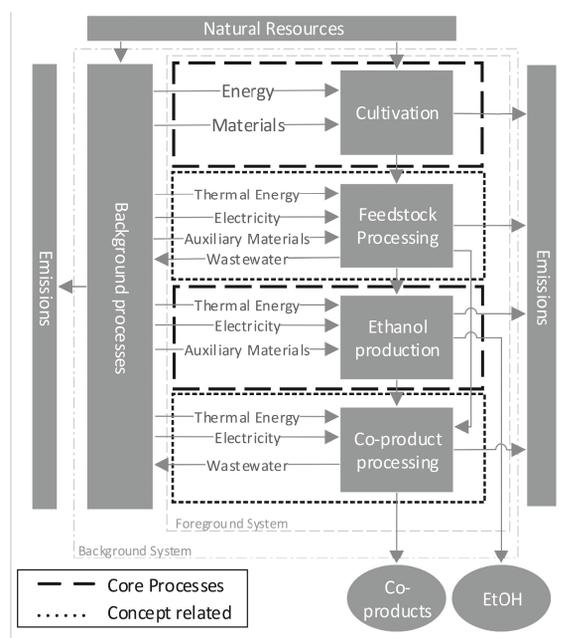
The software-based assessment of various bioethanol production concepts is based on LCA methodology [359]. The LCA is conducted with Umberto NXT LCA v7.1 [360].

#### 3.2.1. Goal and scope definition

The selection of a specific production concept is a decision based on market aspects and prospects taking the legislative framework into consideration. For these reasons, different ethanol production concepts can be found in Europe. Wheat and sugar beet present the most important feedstocks used for bioethanol production in Europe [361]. Their use allows for the production of numerous co-products, such as fodder and food products, energy (carriers), fertilizers, etc.

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The goal of this study is to assess potential environmental impacts related to the production of bioethanol and to discuss implications of co-product processing concepts under current legislative conditions (i.e. RED methodology). This is accomplished by an attributional cradle-to-gate LCA with a functional unit of 1 MJ of anhydrous ethanol (0.03% H<sub>2</sub>O). Feedstock cultivation and the subsequent production of ethanol takes place in Germany and all relevant material and energy flows related to feedstock cultivation, ethanol production, transport, wastewater treatment as well as material and energy provision are considered (Figure 3-1).



**Figure 3-1** System boundaries of the assessed production system. Depicted system boundaries delimit the product system and the background system, which represents processes for the provision of energy, auxiliary materials, agricultural activities, wastewater treatment etc. Core processes are technically identical in all concepts whereas concept related processes differ depending on production modalities and desired co-products. Abbr.: EtOH – Ethanol.

### 3.2.2. Co-product handling according to the RED

The RED presents the European legislative framework for biofuel certification [54] and is intended to facilitate GHG emission reduction from energy provision and fuel use. By 2020, a 10% share of energy in the transport sector is supposed to originate from renewable sources. In Germany, this goal is envisaged to be achieved indirectly via GHG reduction targets of fuel use: The mineral oil industry is obliged to reduce GHG emissions from the production and use of its fuel by 3.5, 4 and 6% as of 2015, 2017 and 2020, respectively [362]. This can be achieved by admixing biofuels, whose provision and use need to reduce GHG emissions by at least 35% compared to a fossil fuel comparator, as of 2017 by at least 50%. Apart from GHG reduction, additional sustainability

criteria are defined by the RED: suppliers need to ensure that feedstock does not originate from areas with high biodiversity or from land with high carbon stocks in soil or vegetation.

In order to quantify GHG emissions released during the provision of biofuels, a calculation methodology is laid down by the RED: GHG emission quantification need to account for emissions from feedstock cultivation, biofuel production and transportation of fuel as well as all intermediate products and materials. GHG emissions from fuel combustion are considered carbon neutral due to the biogenic origin of carbon.

The handling of co-products presents a crucial aspect of GHG emission quantification due to its methodological constraints and large impact on results and thereby on the establishment of specific production concepts. The methodology laid down by the RED to handle multiple output systems is a combination of allocation and substitution:

- Inputs and outputs are allocated to each product according to each product's energy content, expressed as the lower heating value (LHV) of wet material;
- The system is credited for feeding excess electricity into the grid, except when the used fuel is a co-product other than an agricultural residue. The credit given equals the impacts caused by generating the equal amount of electricity using the same energy carrier. Furthermore, credits are given for capturing biogenic CO<sub>2</sub> that replaces fossil-derived CO<sub>2</sub> in industrial applications;
- Electricity generated using biomass that is a co-product of ethanol production is considered as a co-product.
- The system boundary is to be drawn at the point at which no feedback loops of materials and energy occur [363].

### 3.2.3. Life cycle inventory

The analysis includes all relevant material and energy flows from cradle-to-gate. Inventory data of ethanol production stem from a major European ethanol producer as well as from literature and is presented below. Inventories of background processes are modelled with the Ecoinvent database [364] as well as additional data from scientific literature and industry reports.

### 3.2.4. Life cycle impact assessment

A total of six indicators are applied at mid-point level: global warming potential (GWP) for a 100 year time horizon [365], cumulative fossil energy demand (CED<sub>fossil</sub>) [366], terrestrial acidification potential (TAP), photochemical oxidant formation (POFP) as well as marine (MEP) and freshwater eutrophication potential (FEP) [367]:

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- The assessment of GWP is the core motivation of the RED and is consequently assessed. Emissions are related to the radiative forcing of CO<sub>2</sub> and presented in CO<sub>2</sub> equivalents (CO<sub>2</sub>-eq.) [365];
- The analysis of CED<sub>fossil</sub> gives an indication of the depletion of finite fossil resources and on the energy efficiency of the system [366];
- The assessment of impacts related to feedstock cultivation, such as TAP, MEP and FEP, is important in case different types of agricultural feedstock are assessed. Emissions are expressed as sulphur dioxide equivalents, nitrogen equivalents and phosphorus equivalents (SO<sub>2</sub>-eq., N-eq. and P-eq., respectively) [367];
- The presence of photochemical oxidants can result in the formation of summer smog. Emissions contributing to this mechanism are covered by the impact category POFP and are expressed as non-methane volatile organic compound equivalents (NMVOC-eq.) [367].

Land-use change is not considered in the context of this study. This is justified by the fact that (i) the extent of cultivated land slightly decreased and (ii) that the yearly hectare-specific yields have increased by 1 to 2% in the past decade in Germany [368]. Therefore, it can be assumed that dLUC plays only a negligible role in case of the investigated product system. Indicators evaluating water consumption are excluded from the assessment because it is presumed that wheat and sugar beets are not irrigated [369].

Uncertainty ranges, representing 95% confidence intervals of applied emission factors, are plotted to give an estimation of the variability of direct field emissions. Uncertainty ranges of emission factors are taken from the respective literature source of the emission factor. Estimation of emissions from technical processes is based on industry data and is subject to smaller variations. Correlated uncertainties are not discussed in the context of this study.

### 3.3. Life cycle inventories of investigated concepts

Inventories with relevant input and output streams are explained individually for feedstock cultivation, wheat- and beet-based ethanol.

#### 3.3.1. Feedstock cultivation

Table 3-1 summarizes main inputs for the cultivation of wheat and sugar beet in Germany. Wheat straw and leaves from sugar beets remain on the field in order to increase nutrient availability and thus, to help maintain the humus content of soil. Consequently, all inputs and emissions due to agricultural production are allocated to the main product (i.e. cereal, sugar beet). The quantity of applied fertilizer is based on nutrient extraction by harvest [370]. Wheat and sugar beet plants are fertilized by mineral fertilizer (i.e. ammonium nitrate). Land is not irrigated and plant protection is applied. Agricultural activities, such as tillage, pesticide application, harvesting etc., are considered [371]. Wheat grains are harvested at a dry matter (DM) content of 86%, thus

drying is not required [372]. Wheat and sugar beets are averagely transported 120 and 60 km, respectively, by truck[369].

Erosion, phosphate leaching and nitrogen oxide formation are estimated using methods described by Nemecek et al. [373]. Ammonia volatilization from mineral nitrogen fertilizer is assumed to amount to 2.5% of nitrogen input [374]. Nitrate leaching is calculated based on fertilizer inputs, precipitation as well as plant and soil characteristics [375]. Nitrous oxide emissions are assumed to be 1.75% of nitrogen input, that presents an emission factor valid for Northern Germany [376]. Jungkunst et al. [376] emphasize the importance of using local emission factors instead of generic emission factors, as provided by the IPCC [376].

**Table 3-1** Key inputs for feedstock cultivation in Germany. Data taken from [370, 371]

Input	Unit	Wheat	Sugar beet
Yield	t/ha	7.9	77.6
Fertilizer (N/P <sub>2</sub> O <sub>5</sub> /K <sub>2</sub> O/MgO)	kg/ha	118.9/25.1/34.0/8.2	139.4/31.0/163.0/38.9
Pesticides	kg/ha	2.7	2.2
Seeds	kg/ha	180	2.1

### 3.3.2. Ethanol production

Ethanol production from wheat and sugar beet is assessed by comparing environmental impacts of ten production concepts yielding various categories of co-products, such as feed, energy (carriers) and feed plus gluten are assessed in order to cover the most important feedstock and production concepts (Table 3-2).

**Table 3-2** Assessed production concepts of wheat- and sugar beet-based ethanol production and concept-specific co-products.

Wheat <sup>†,‡</sup>		Sugar beet <sup>†,‡,§</sup>	
Name	Main co-products	Name	Main co-products
W1.1	Stillage	Thick juice as feedstock	
W1.2	DDGS	S1.1	Pressed beet pulp, vinasse
W2.1	Electricity (DDGS combustion)	S2.1	Biogas <sup>§</sup> , digestate, ammonium sulfate
W2.2	Biogas <sup>§</sup> , digestate, ammonium sulphate	Raw and thick juice as feedstock	
W3.1	Wet gluten, bran, stillage	S1.2	Pressed beet pulp, vinasse
W3.2	Dry gluten, bran, CDS	S1.2	Biogas <sup>§</sup> , digestate, ammonium sulphate

<sup>†</sup> Fusel oils are a co-product in all concepts.

<sup>‡</sup> Surplus electricity is fed to the grid in concepts W1.2, W2.1, W2.2 and all S concepts.

<sup>§</sup> Internally used for heat and electricity provision.

<sup>¶</sup> All beet-based ethanol concepts yield carbonation lime.

Abbr.: CDS – Condensed distillers solubles; DDGS – Dried distiller's grains with solubles.

Ethanol production from any of the two feedstocks requires sulphuric acid, ammonium hydroxide and sodium hydroxide, 0.02 kg each per kg of ethanol [369]. Enzyme and yeast production is

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neglected in the assessment due to the very low quantity required and low emissions resulting from their production [377].

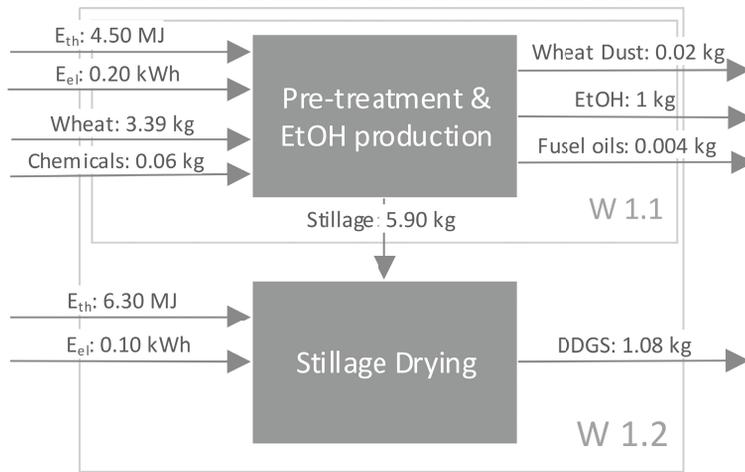
Volatile organic compounds (VOCs) might be emitted during fermentation, distillation and co-product processing (e.g. stillage drying) [378]. In the assessed production systems, evaporated water from stillage drying is recycled and not released into the atmosphere in order to reduce energy costs and wastewater to be treated [369]. Thus, VOC emissions are assumed low and are neglected. Nevertheless, the inclusion of VOC emissions reported for different conditions are discussed in the sensitivity analysis.

Process heat and electricity are provided by a natural gas-fired boiler equipped with a back-pressure turbine. Heat and electricity generation are coupled and might result in a surplus of electricity fed into the grid depending on the heat and electricity demand, which is the case for concepts W1.2, W2.1, W2.2 and all S concepts. The efficiency of energy conversion is 88% (i.e. 72.5% for thermal and 15.5% for electric energy). Energy provision for sugar beet processing has a similar total efficiency, but thermal efficiency is 69% due to a different pressure level of steam. In concepts with biogas production, biogas and natural gas are used to fulfil the energy demand. The effect of using lignite and wood is additionally assessed in the sensitivity analysis. All emissions from energy provision comply with legal requirements (in Germany) [362].

### 3.3.2.1. Ethanol from wheat

Firstly, grains are milled in a dry-milling process and starch is subsequently hydrolyzed, converted to sugars and fermented. These steps are accomplished by the aid of 3 g enzymes (i.e.  $\alpha$ - and  $\beta$ -amylase) and 0.005 g yeast per kg of ethanol [369]. Subsequently, ethanol is separated from the remaining water, fibers, proteins and unfermented sugars by distillation and rectification. Ethanol is further dried using molecular sieves to provide dehydrated ethanol. Stillage is processed according to the type of desired co-product. In the present assessment, three concepts, each comprising two sub-concepts, are investigated:

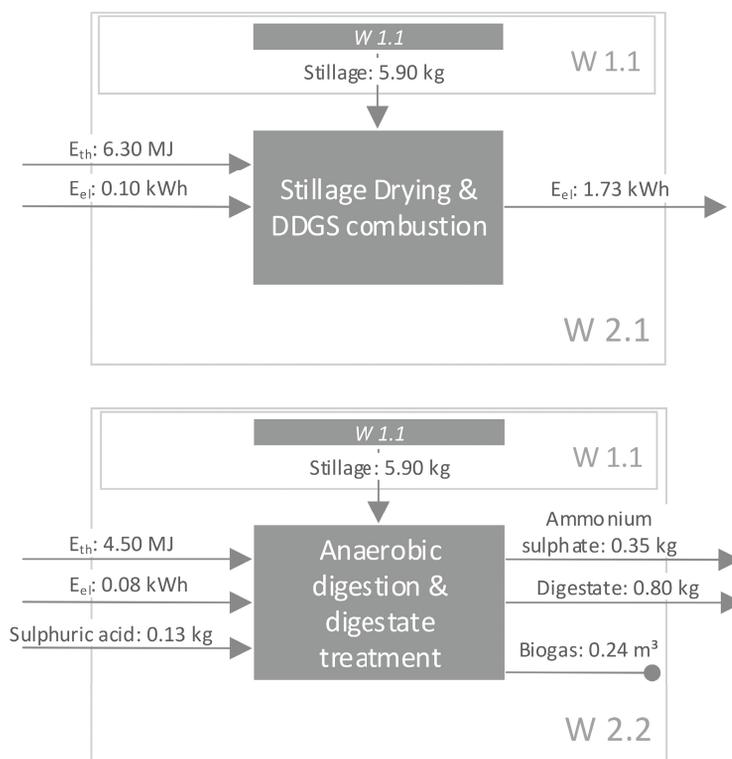
*Concept W1 – Feed as a co-product.* Stillage can be directly sold as animal feed or in the form of DDGS (Figure 3-2). In concept W1.1, drying is accomplished by centrifugation and succeeding evaporation of the remaining moisture. In concept W1.2, stillage is dried to a DM content of 90% to increase storability and pelletized afterwards to provide a marketable product.



**Figure 3-2** Key parameters of concepts W1.1 and W1.2. Depicted concepts present wheat-based ethanol production with co-production of raw stillage (W1.1) and production of DDGS (W1.2). Abbr.:  $E_{ei}$  – Electric energy;  $E_{th}$  – Thermal energy; EtOH – Ethanol; DDGS – Dried distiller’s grains with solubles; W – Wheat. Data obtained from [267].

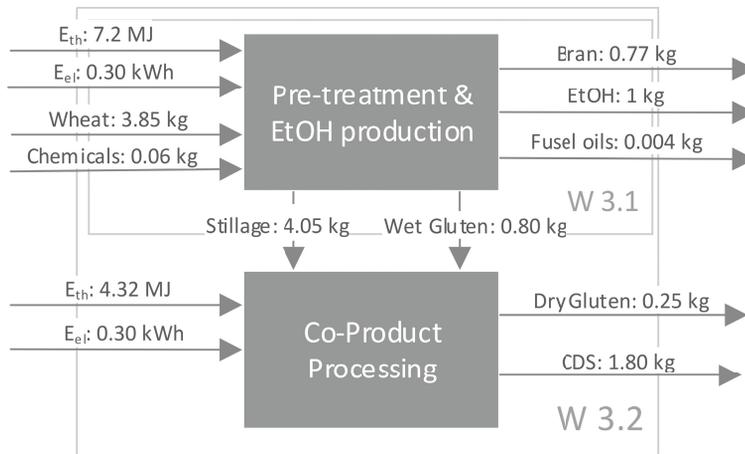
*Concept W2 – Energy as a co-product.* The combustion of DDGS allows the production of “green” electricity. This might be an option in case of favorable market conditions and having adequate DDGS production facilities in place (Figure 3-3). In concept W2.1, an electrical generation efficiency of 30% is assumed, resulting in 1.73 kWh per kg of ethanol.  $NO_x$  emissions are controlled by selective non-catalytic  $NO_x$  reduction with an efficiency of 50%. Anaerobic digestion of stillage constitutes another production concept. The resulting biogas can either be used as an energy carrier within the ethanol production system or can be purified and fed as bio-methane into the existing natural gas grid. Biogas composition is calculated based on literature data [370, 379]. In concept W2.2, internal use of biogas for the provision of process heat and electricity is assumed (Figure 3-3). Gas loss is assumed to be 1% [380]. As stillage is hot after distillation, no surplus heat is needed for anaerobic digestion [381]. Digested stillage contains nutrients and can be used as a soil quality enhancer. However, the handling of large quantities of digestate presents a challenge as year-round field application of digestate is not permitted in Germany due to environmental reasons (e.g. nitrate leaching). Therefore, storage and transportation costs are reduced by dewatering of digested stillage by means of mechanical separation of the liquid and solid phases and subsequent thermal dewatering. Furthermore, ammonia is stripped from the liquid phase to obtain ammonium sulfate (40%  $(NH_4)_2SO_4$  in  $H_2O$ ). The quantity of ammonium sulphate is calculated based on the nitrogen content of feedstocks, nutrient composition of the solid and liquid phase of digestate and an ammonia stripping efficiency of 80% [370, 379, 382]. The production and use of anti-foam agents is not considered. In addition, fertilization of wheat with digestate is assessed in the sensitivity analysis.

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**Figure 3-3** Key parameters of concepts W2.1 and W2.2. Depicted concepts present the production of electricity (W 2.1) and biogas, which is internally used as an energy carrier (W 2.2). Both concepts present a way of processing occurring stillage after ethanol production and separation of ethanol and raw stillage (W1.1). Abbr.:  $E_{el}$  – Electric energy;  $E_{th}$  – Thermal energy; DDGS – Dried distiller’s grains with solubles; W – Wheat. Data obtained from [267, 400].

*Concept W3 - Gluten and feed as co-products.* Wheat bran, which can be used as fodder or as an energy carrier, is separated before milling in this concept. In the subsequent wet-milling process, gluten is separated. Gluten mainly consist of proteins and partly of lipids and has numerous applications in food and chemical products [383]. The following simultaneous hydrolysis of starch and fermentation of sugar as well as rectification and drying of ethanol is technically similar to concept W1.1 but differs in energy requirements. The remaining stillage is low in fibers and high in proteins. Analogously to concepts W1.1 and W1.2 two concepts are discussed: Export of unprocessed gluten and stillage (concept W3.1) and drying of gluten and thickening of stillage (concept W3.2) to obtain dry gluten and condensed distiller’s solubles (CDS) (Figure 3-4).

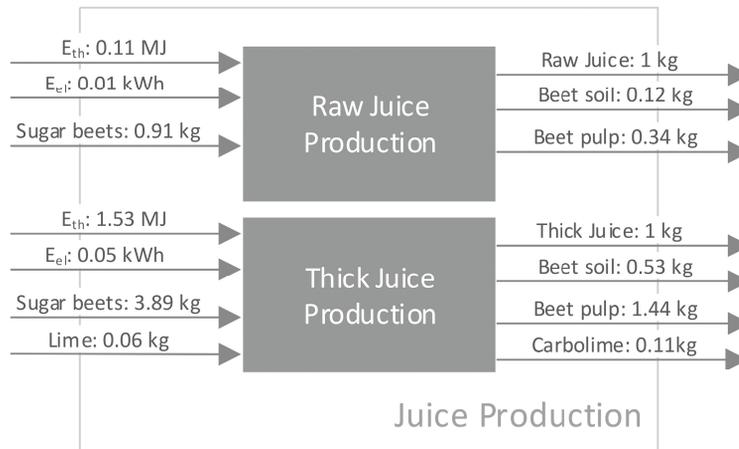


**Figure 3-4** Key parameters of concepts W3.1 and W3.2. Depicted concepts present wet milling of wheat and subsequent production and separation of ethanol. Stillage and gluten are either exported unprocessed (W3.1) or respectively thickened and dried (W3.2). Abbr.: CDS – Condensed distiller’s solubles;  $E_{el}$  – Electric energy;  $E_{th}$  – Thermal energy; W – Wheat. Data obtained from [267].

### 3.3.2.2. Ethanol from sugar beet

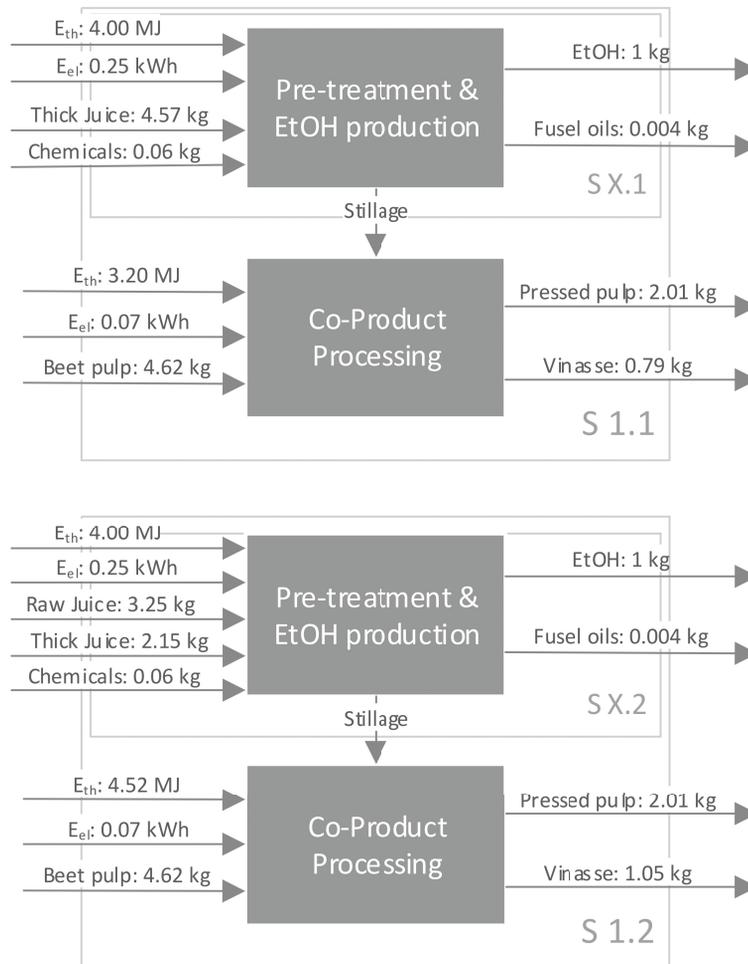
Sugar beets are harvested during the beet campaign which lasts from mid-September to mid-November. Beets are transported, cleaned, sliced and processed to raw juice in extraction columns using hot water at 70°C [384]. The resulting raw juice contains about 16% sucrose and about 2% impurities, which are removed with the aid of lime and carbon dioxide. Further thickening of the raw juice prolongs storability and allows the production of ethanol throughout the year. The resulting thick juice contains 30% water and 65% sucrose. Beet processing additionally yields beet pulp, carbonation lime and beet soil (Figure 3-5). Carbonation lime is sold as a fertilizer product and beet soil is returned to the field. To facilitate the fermentation of juice, 0.005 g yeast are added per kg of ethanol. Afterwards, ethanol is separated and dehydrated by rectification and subsequent dewatering with molecular sieves. Two feedstock variants are discussed: The production of ethanol solely from thick juice (concepts S1.1 and S2.1) and production from raw juice during the beet campaign and thick juice out of campaign (concepts S1.2 and S2.2). For both variants, co-production of feed and production of biogas are analyzed.

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**Figure 3-5** Key parameters of raw and thick juice production. Sugar beets are processed to raw and thick juice, which is subsequently fermented. Raw juice can serve as a feedstock for ethanol production during the beet campaign whereas thick juice can be stored for use throughout the rest of the year due to its storability. Abbr.:  $E_{el}$  – Electric energy;  $E_{th}$  – Thermal energy. Data obtained from [267].

*Concept S1 - Feed as a co-product.* Extracted beet pulp is dewatered by pressing to a DM content of 30% and vinasse is thermally thickened to a DM content of 33%. Vinasse can be used as an additive in animal feed or as a soil quality enhancer due to its nutrient content. Key parameters of concepts S1.1 and S1.2 are depicted in Figure 3-6. In variant S1.1, thick juice serves as feedstock, whereas thick and raw juice are used in concept S1.2.

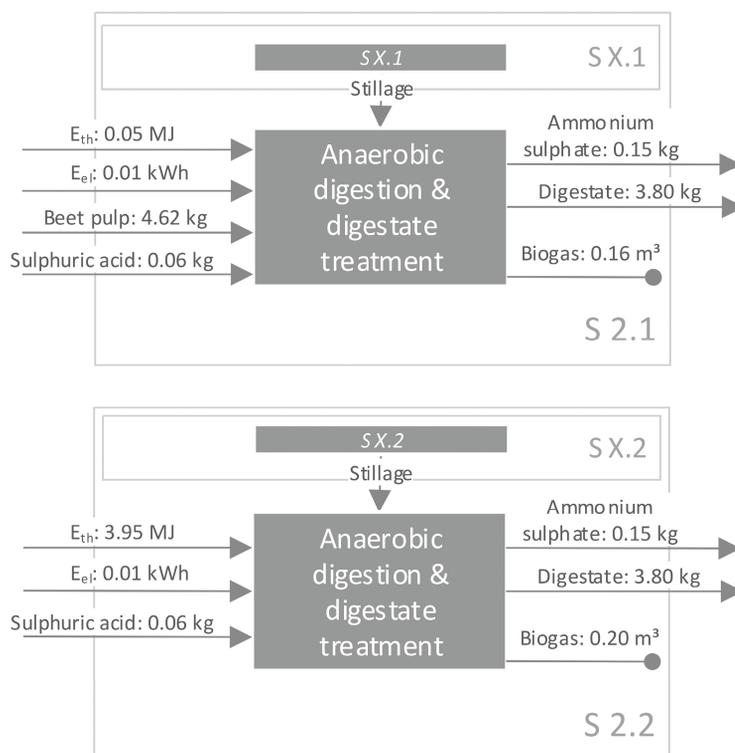


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**Figure 3-6** . Key parameters of concepts S1.1 and S1.2. Depicted concepts present the fermentation of thick juice (SX.1) and thick and raw juice (SX.2) with subsequent separation of ethanol and stillage, as well as beet pulp dewatering and stillage thickening either following the fermentation of thick juice (S1.1) or the fermentation of raw and thick juice (S1.2). Abbr.:  $E_{el}$  – Electric energy;  $E_{th}$  – Thermal energy; EtOH – Ethanol; S – Sugar beet. Data obtained from [267].

*Concept S2 – Energy as a co-product.* Beet pulp and vinasse are anaerobically digested to obtain biogas (Figure 3-7). Pulp is ensiled for preservation before being used as biogas substrate. Analogously to concept S1, two variants are assessed: Production of ethanol from thick juice (concept S2.1) and from raw and thick juice (concept S2.2)

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**Figure 3-7** Key parameters of concepts S2.1 and S2.2. Concepts present the production of biogas from stillage and beet pulp after fermentation of either thick juice (S2.1) or raw and thick juice (S2.2). In- and Outputs of the fermentation of thick juice (SX.1) and raw and thick juice (SX.2) is presented in Figure 3-6. Abbr.:  $E_{el}$  – Electric energy;  $E_{th}$  – Thermal energy; S – Sugar beet. Data obtained from [267, 400].

### 3.4. Results

Below, firstly, impact scores of concepts previously outlined are presented. Various influencing factors are additionally discussed in a sensitivity analysis. Presented results refer to the production of 1 MJ of anhydrous ethanol, produced in Germany.

#### 3.4.1. GHG emissions

Total GHG emissions before allocation range from 44 to 90 g CO<sub>2</sub>-eq. (Figure 3-8).

Wheat cultivation accounts for more than half of total GHG emissions within concepts using wheat as feedstock (i.e. 57 to 75% of GHG emissions). These emissions are mainly caused by fertilizer induced nitrous oxide emissions and the production of fertilizers, each contributing by around a third to GHG emissions from cultivation. Direct field emissions account for 11 to 26% of total GHG emissions depending on the concept. Using wheat straw as fodder and scant or as

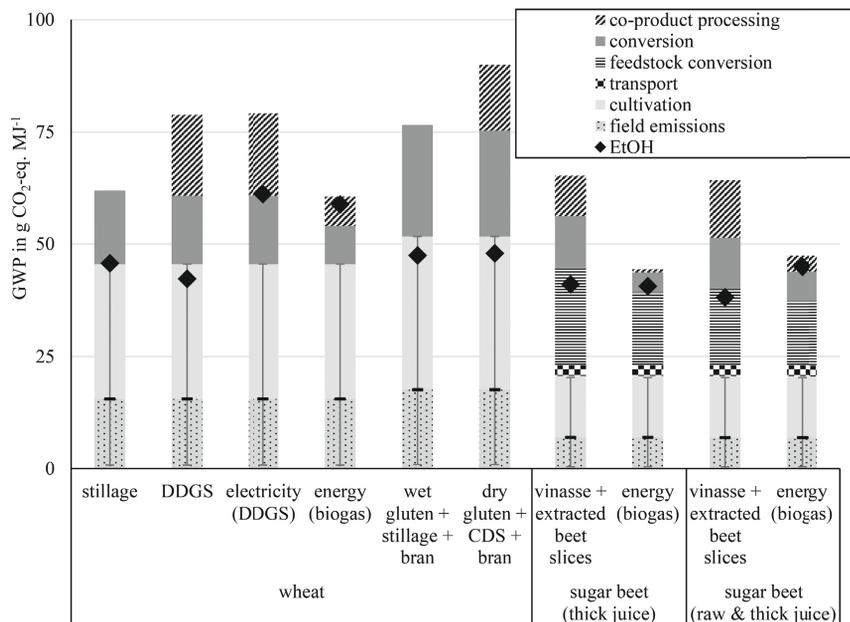
feedstock for lignocellulose biorefineries could benefit the performance of cereal-based ethanol due to an additional allocation to be applied in order to allocate emissions to cereals and straw;

Sugar beet cultivation causes less emission due to higher yields and, in consequence, lower specific fertilizer requirements. Even though beet cultivation results in lower GHG emissions per MJ of ethanol, beet-based concepts do not result in significantly lower GWPs due to the fact that emissions from juice production, that account for around 30% of total GHG emissions, cancel out low emissions from cultivation.

Whiskers, representing a 95% confidence interval of applied emission factors, confirm a high variability of direct field emissions. At the upper end of the uncertainty range, GWP of direct field emissions nearly equals the GWP of cultivation using the average emission factors plus all other sources of GHG such as fertilizer production and agricultural activities.

GHG emissions of ethanol production are dominated by energy provision: Less than 5% of emissions originate from the provision of auxiliary materials required for ethanol production. Emissions from methane leakage contribute around 16% to GHG emissions of co-product processing in concepts with biogas production but are negligible in view of total emissions. Comparing all concepts, beet-based ethanol production with internal use of biogas shows the lowest total GHG emissions. All concepts that use biogas as an energy source result in considerably lower emissions than other concepts due to the partly coverage of the energy demand by biogas.

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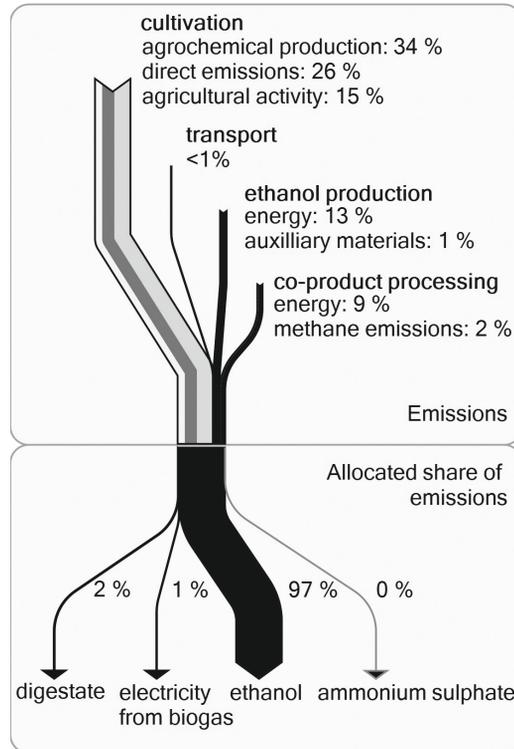
**Figure 3-8** Total and allocated GWP per MJ of ethanol. Allocated GWP is depicted by diamond symbols. Whiskers present minimum and maximum GWP resulting from direct field emissions according to 95% confidence intervals of applied emission factors. Abbr.: CDS – Condensed distiller’s solubles; DDGS – Dried distiller’s grains with solubles; GWP – Global warming potential.

Allocated emissions are lowest in case of ethanol and feed production: 38 and 42 g CO<sub>2</sub>-eq. per MJ (concepts S1.1 and W1.2, respectively); these are the lowest emissions allocated to ethanol among all concepts. All concepts in which a high calorific co-product is missing, result in high emissions allocated to ethanol:

- Total GHG emissions of concepts with biogas production and use are low, as opposed to allocated emissions, even though fertilizer is produced which substitutes mineral fertilizer. This benefit is not accounted for by the RED methodology due to allocation based on the LHV. Fertilizer production and stillage dewatering accounts for 11% of emissions but barely any of these emissions are allocated to co-products (Figure 3-9);
- Electricity generation from DDGS shows nearly similar total GHG emissions as DDGS production but results in much higher emissions allocated to ethanol;

In concepts W1 and W3, the effect of dewatering of stillage is investigated. Emissions allocated to ethanol show opposing tendencies: The production of DDGS leads to a decrease of allocated

emissions compared to the production of raw stillage, whereas the production of CDS does not benefit the performance of ethanol. The surplus energy demand of CDS and gluten drying, being around 15% higher than the energy demand of DDGS production, does not result in a reduction of emissions allocated to ethanol. In this case, the increase in LHV does not compensate additional emissions entailed to co-product processing.



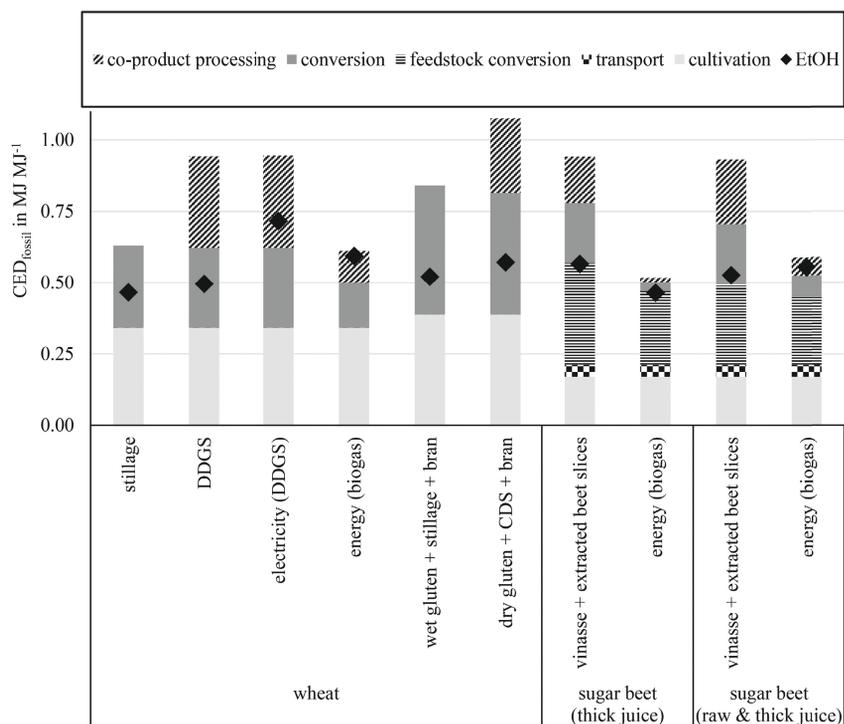
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**Figure 3-9** Distribution of emissions and allocated share of emissions of concept W2.2. The upper part depicts the origin of GHG emissions of wheat-based ethanol production with co-production of biogas. The lower part shows how these emissions are apportioned to products.

Allocated  $CED_{fossil}$  amounts to around 0.5 MJ per MJ in most concepts (Figure 3-10). Feedstock cultivation contributes to indicator scores by a smaller share than in all other impact categories. Beet-based concepts with biogas production and internal use result in lowest fossil energy requirements. Sugar beet cultivation requires significantly less energy per kg product than wheat cultivation due to higher yields. Transportation of beets results in a higher energy demand compared to wheat due to differing transportation distances and a higher quantity of feedstock to be transported per MJ of ethanol. Obviously, concepts with low energy requirements (concepts

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W1.1 and W3.1) require less fossil energy than concepts with energy-intensive co-product processing.

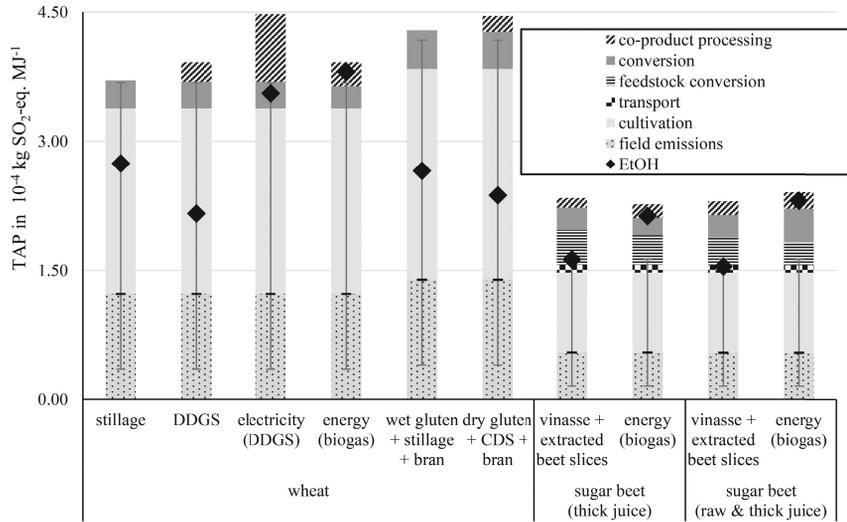


**Figure 3-10** Cumulative energy demand. Total and allocated cumulated energy demand (diamond symbol) per MJ of ethanol. Abbr.: CDS – Condensed distiller’s solubles; DDGS – Dried distiller’s grains with solubles.

### 3.4.2. Eutrophying and acidifying emissions

MEP and FEP range from 0.9 to 2.4  $10^{-4}$  kg N-eq. and 0.5 to 0.9  $10^{-4}$  kg P-eq., respectively. Feedstock cultivation dominates both impact categories:

MEP is mainly caused by emissions from cultivation: 85% of total MEP in wheat-based and around 60% in beet-based ethanol concepts. Nitrate leaching to groundwater is the most dominant contributor: 85% of MEP originates from nitrate emissions. Ammonia and nitrogen oxides play a minor role; FEP is mainly caused by phosphate emissions.



**Figure 3-11** Acidification potential. Total and allocated TAP per MJ of ethanol to ethanol. Allocated AP is depicted by diamond symbols. Whiskers present minimum and maximum TAP resulting from direct field emissions according to 95% confidence intervals of applied emission factors. Abbr.: CDS – Condensed distiller’s solubles; DDGS – Dried distiller’s grains with solubles; TAP – Terrestrial acidification potential.

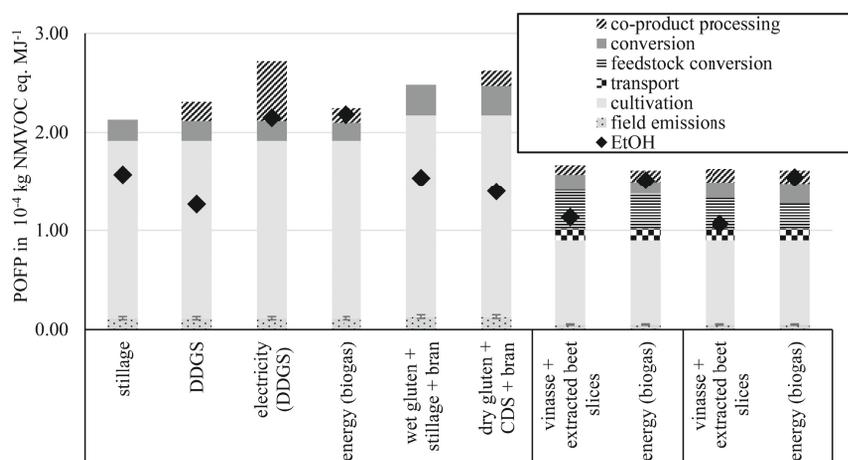
TAP ranges from 2.3 to 4.5 10<sup>-4</sup> kg SO<sub>2</sub>-eq. (Figure 3-11). TAP of cultivation originates from ammonia, sulphur dioxide and nitrogen oxide emissions, accounting for 31, 27 and 25%, respectively. Ammonia emissions are fertilizer induced, whereas sulphur dioxide and nitrogen oxide emissions stem from fertilizer production and from agricultural activities, such as harvesting and tillage. Direct field emissions account for around 32% and 23% of total TAP of wheat and beet-based concepts, respectively. A change in direct field emission factors strongly influences results. Sugar beet cultivation results in much lower acidifying emissions than wheat cultivation. Consequently, sugar beet-based ethanol results in lowest TAP: Concepts S1.1, S1.2 and S2.1 result in TAPs of 1.5, 1.6 and 2.2 10<sup>-4</sup> kg SO<sub>2</sub>-eq. per MJ. Due to the high contribution of cultivation related emissions, ethanol production and co-product processing play a minor role and concepts in which co-products with a high LHV is produced show lowest TAP allocated to ethanol. Ammonia and nitrogen oxides emissions of DDGS combustion for electricity generation (concept W2.1) result in highest indicator scores among all concepts.

### 3.4.3. POFP

POFP of ethanol production lies between 1.6 and 2.7 10<sup>-4</sup> kg NMVOC-eq. Again, at the lower end of the range, sugar beet-based concepts can be found. Concepts S1.1 and S1.2 result in 1.1 10<sup>-4</sup> kg NMVOC-eq. allocated to ethanol. Concept W2.1 results in highest impact scores among

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all concepts due to emissions originating from DDGS combustion (Figure 3-12). As previously, concepts yielding a high calorific co-product result in lowest impact scores allocated to ethanol. Cultivation-related impacts consist by 80% of nitrogen oxide emissions of which 75% stem from agricultural activity. The remaining emissions result from fertilizer production and direct field emissions. POFP from ethanol production and co-product processing is dominated by nitrogen oxides and NMVOC emissions, accounting for 51 and 32% of indicator scores of concept W1.2 for example, respectively.



**Figure 3-12** Total and allocated POFP per MJ of ethanol. Allocated POFP is depicted by diamond symbols. Whiskers present minimum and maximum POFP resulting from direct field emissions according to 95% confidence intervals of applied emission factors. Abbr.: CDS – Condensed distiller’s solubles; DDGS – Dried distiller’s grains with solubles; POFP – Photochemical oxidant formation potential.

### 3.4.4. Sensitivity analysis

The impact of changes in yield, additional drying of grains, a closed nutrient cycle (i.e. assuming wheat fertilization with digestate from biogas production), inclusion of direct VOC emissions and of a higher biogas leakage is assessed for concepts using wheat as a feedstock to give an indication of the result’s sensitivity due to changes in these aspects:

**Yield.** A decrease in yield of 20% results in an increase in TAP, MEP, FEP, POFP and GWP of 7, 47, 14, 16 and 6% per kg of wheat, respectively. MEP is most sensitive to an increase in yield: MEP per kg of wheat decreases of 25%, whereas all other indicator scores decrease by less than 10%. Consequently, MEP of ethanol is very sensitive to a change in yield as cultivation accounts for 85% of the impact score. Concepts with high energy demands tend to be less sensitive on

a relative basis, such as GHG emissions due to the lower contribution of emissions originating from feedstock cultivation;

**Grain drying.** In case wheat grains contain a lower DM content than 86%, drying is required [372]. A DM content of 82% at harvest results in an average increase in TAP, MEP, FEP, POFP and GHG emissions allocated to ethanol of around 20, 5, 6, 17 and 15%, respectively. Changes in indicator results decrease linearly with increasing DM content of harvested cereals;

**Closed nutrient cycle.** Thickened digestate is rich in nutrients, even after ammonium sulfate removal. Application of digestate is assumed to be accomplished by a trail hose in order to reduce ammonia losses. Emissions from digestate storage and application are considered, as well as the availability of organically bound nitrogen [385–387]. Digestate fertilizing results in an increase in GWP, TAP, POFP and FEP of 9, 104, 8 and 7%, respectively, per kg of wheat. MEP and fossil CED decrease of 8 and 16%, respectively. The resulting increase in indicator scores originates from increased emission rates, whereas a decrease is a consequence of lower mineral fertilizer requirements;

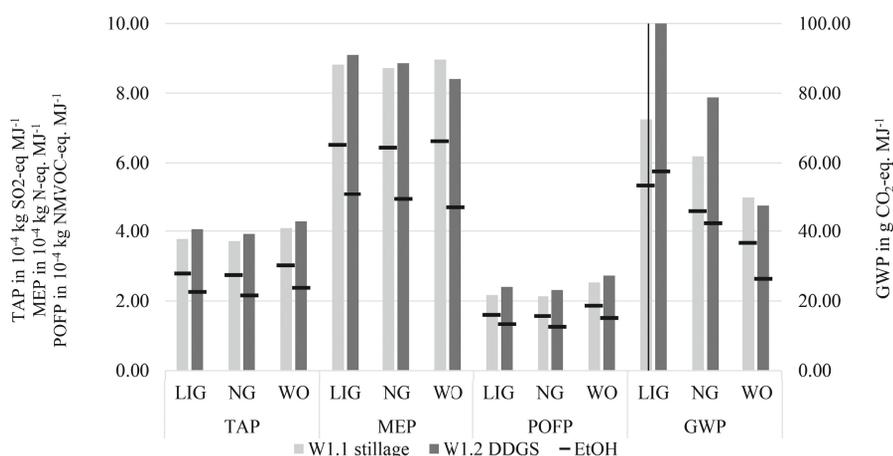
**Direct VOC emissions.** Ethanol production could result in emissions of VOCs. In the present assessment, these emissions are excluded because exhaust gas streams, presenting a potential source of VOC emissions, are used as feeding air for the combustion of natural gas. However, as not all plants, are designed in this manner, the inclusion of VOC emissions is assessed: Direct VOC emissions of  $6.7 \cdot 10^{-4}$  kg NMVOC-eq. per kg of ethanol have been reported from bioethanol plants operated in the US [388]. Dominating emissions of ethanol processing are acetaldehyde, ethyl acetate and ethanol, accounting for 34, 29 and 24% of total VOC emissions [389]. These emissions correspond to a POFP of  $0.2 \cdot 10^{-4}$  kg NMVOC-eq., which is considerably lower than POFP from agriculture and energy provision;

**Biogas leakage.** Assuming gas leakages of 2.5 and 5% instead of 1% increases TAP by 2 and 5%, GWP by 2 and 6%, respectively. This indicates that results are not very sensitive to a change in gas leakage;

**Energy carrier.** Additionally, the use of lignite and wood for energy provision are assessed besides natural gas. The efficiency of energy conversion from lignite and wood is assumed to be 85% (i.e. 72% for thermal and 13% for electric energy provision). The use of natural gas leads to lowest acidifying emissions (Figure 3-13). Lignite and natural gas show lower indicator results in terms of POFP. GWP is lowest in the case of wood combustion, followed by natural gas and lignite. The higher the energy demand of a certain concept, the greater the absolute difference between the respective energy sources, due to the fact that energy provision is gaining more

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relative importance. The inclusion of stillage drying, as opposed to the export of raw stillage, emphasizes differences among energy carriers: In case lignite is used, stillage drying (DDGS production) results in an increase of GHG emissions allocated to ethanol compared to the export of undried stillage. All other impact categories show an opposing tendency: production of a co-product with a higher LHV, such as DDGS, outweighs the emission increase related to a higher energy demand and consequently benefits ethanol. In case wood is used, GHG emissions related to electricity drawn from the national grid gains importance: Total emissions are lower if DDGS is produced due to the fact that an increased heat demand results in a self-sufficient electricity generation, whereas electricity needs to be drawn from the grid in case of stillage production, entailing a higher GWP.



**Figure 3-13** TAP, MEP, POFP and GWP of concept W1 using lignite, natural gas and wood as energy carriers. The left axis refers to TAP, MEP and POFP, the right one to GWP. The horizontal black line presents indicator scores allocated to ethanol. Abbr.: DDGS – Dried distiller’s grains with solubles; EtOH – Ethanol; GWP – Global warming potential; LIG – Lignite; MEP – Marine eutrophication potential; NG – Natural gas; NMVOC – non-methane volatile organic compound; POFP – Photochemical oxidant formation potential; TAP – Terrestrial acidification potential; WO – Wood.

### 3.5. Discussion

In the present case study, several concepts of co-product processing are compared by LCA in the context of the RED using first-hand industry data. The assessment of wheat- and sugar beet-based ethanol produced in Germany reveals differences among investigated concepts concerning total and allocated indicator scores:

- Concepts using sugar beet as feedstock result in lower TAP, MEP, FEP and POFP mostly due to higher area specific yields of sugar beet;

- Total impact scores are lowest in concepts in which biogas is produced and internally used within the ethanol production facility due to lower demand for fossil energy carriers and impacts related to their combustion.
- Ethanol performs best concerning all indicators when dry fodder is produced as a co-product due to allocation based on the LHV;
- Co-products lacking a heating value (e.g. mineral fertilizer) are not considered by RED methodology and allocation based on the LHV does furthermore not account for specific uses of co-products as all products are treated as energy carriers.
- The utilization of different energy carriers shows opposing effects depending on the concept and impact category.

These findings point out that an assessment solely based on feedstock type is not sufficient to compare the environmental performance of biofuels. Results emphasize that it is crucial to include co-product processing options and modalities in the assessment of different biofuels in order to allow a more comprehensive comparison of environmental impacts of biofuel production.

Furthermore, co-product handling, as regulated by the RED, does not account for specific uses of a co-product (e.g. ammonium sulfate as fertilizer or the benefit of replacing fodder production), nor allows it the inclusion of all co-products due to an allocation based on the LHV, as discussed in literature [356]. It thereby neglects utilities of substituted goods and consequently underestimates benefits of investigated concepts. It does not support the implementation of cascade utilization of biomass and a more efficient resource use, for example by nutrient cycling due to fertilizer production.

### 3.6. Future perspective

The results show that current legislative practice in Europe, namely the RED, promotes the production of dried co-products and does not adequately consider products lacking a heating value. It thereby inhibits the establishment of biorefineries yielding a variety of products allowing a more efficient use of resources. In future, it should be clarified if an impartial and applicable method to apportion emissions to all co-products exists which reflects distinctive functions and utilities of co-products in an appropriate way.



# The influence of co-product handling methodology on greenhouse gas savings of biofuels in the European context

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**Buchspies B, Kaltschmitt M (2017) The Influence of Co-product Handling Methodology on Greenhouse Gas Savings of Biofuels in the European Context. Bioenerg Res 10(1): 167–182. doi: 10.1007/s12155-016-9790-7. Minor corrections and modifications were made to align the format and nomenclature.**

## Chapter 4

### Abstract

The handling of multi-output systems presents a crucial aspect of GHG emission calculation as well as the certification of biofuels, and finding a robust and applicable method that accounts for distinctive characteristics of and benefits generated by all products is a challenge. In this work, GHG emission savings of eleven biofuel production concepts are assessed and the implications of methodological assumptions are discussed by applying the methodology defined by the RED, allocation based on physical parameters, two hybrid approaches, as well as six variants of substitution. GHG emission savings according to RED methodology range from 35% to 57%. Sugar beet-based ethanol shows highest savings. Results reveal that *GHG savings* according to the RED methodology present, in sum, a relatively good approximation of emission savings occurring due to substitution effects under given assumptions. An introduction of credits for products that are barely or not considered by the RED methodology due to allocation based on the lower heating value, i.e. fertilizers and wet feed co-products, reduces the difference between RED results and results based on substitution. If displacement mechanisms are considered by substitution, sugar beet-based ethanol, ethanol production by wet milling of wheat and sunflower biodiesel result in highest emission savings under given assumptions if oil that needs to be supplied due to occurring displacement mechanisms stems from rapeseed. The implementation of a method that supports concepts with high emission saving potential, e.g. allocation based the lower heating value of dry material, could promote emission reductions from biofuel provision.

## 4.1. Introduction

The EU promotes biofuels as a measure to reduce GHG emissions and the dependency on fossil fuels as well as to support economic development in rural areas. Biofuel production allows the joint provision of fuel and a variety of co-products, such as different types of feed, food, fertilizers, energy and chemicals. The emergence of novel biorefinery concepts allows a diversification of these products while increasing revenue and optimizing the use of biomass. Apart from a few restrictions on land use and biodiversity, politics selected GHG emissions as the main indicator of sustainability. The assessment of GHG emissions from biofuel provision consequently became an important aspect of biofuel legislation and certification. In the EU, biofuel producers are obliged to provide GHG intensities according to a methodology as laid down in the RED [54]. The applied methodology is based on Life Cycle Assessment (LCA) methodology but focuses solely on GHG emissions. LCA presents an assessment method that is used for certification purposes, to assess environmental impacts of product system or services, to facilitate the identification of environmental hotspots and potentials for the reduction of environmental impacts [64, 65]. Multi-output product systems present a challenge of LCA methodology and the chosen method to handle multiple-output systems is crucial for the outcome. The methodology has far reaching impacts on GHG emissions, the shape of the biofuel industry as well as other markets, such as for agricultural products, food and feed. It is consequently of uttermost importance that the applied method to apportion emissions among all products appropriately reflects the benefits of a biorefinery by considering emission savings entailed to the provision of each product, and if it stimulates the reduction of environmental impacts by promoting more efficient biorefinery concepts. There is an ongoing scientific debate in which the implications of existing methods are discussed considering a variety of biofuels and feedstocks [390–394], for novel integrated biorefineries [395]. New methodological approaches that are specifically intended to be applied to biogenic energy carriers were recently developed [84, 396].

The goal of this study is to assess GHG emission savings of biofuel provision in a European context with regards to the applied methodology. Allocation based on mass, dry mass and energy, two novel hybrid approaches, RED methodology as well as substitution are applied. Six variants comprising various combinations of substitutes are defined that cover a wide range of average and most likely occurring substitution effects at a marginal increase of biofuel production. Emission saving estimations based on all methods are compared with a strong focus on the RED methodology as it presents the current legislative framework. A comparison of RED methodology with substitution results is performed in order to demonstrate whether “emission savings”, as named and estimated by RED methodology, present a fairly adequate estimation of emission savings due to substitution effects or not.

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### 4.2. Methodology

A description of the assessed system, the delimitation of reference systems and underlying methodology is explained in chapter 4.3, as the applied methodology is concept- and product-specific. In this study, the terminology *GHG savings* refers to the RED definition (Eq. 4-1) [54]:

$$GHG\ savings = \frac{E_f - E_b}{E_f} \quad \text{Eq. 4-1}$$

Emissions from biofuel provision,  $E_b$ , are compared with a fossil fuel comparator,  $E_f$ , of 83.8 g CO<sub>2</sub>-eq. MJ<sup>-1</sup> [54]. To be eligible to be sold as biofuel, emission savings must sum up to at least 35% and as of 2018 to at least 50% [43]. The terminology “*GHG savings*” might be misleading as values calculated by Eq. 4-1 do not reflect real emission savings due emission reductions in the production process or due to substitution effects related to the provision of co-products. In this study, “emission savings” according to equation are compared to emission saving based on substitution and displacement effects. The estimation of emissions related to the provision of biofuels is strongly dependent on the method to apportion emissions among all products. The ISO 14044 standard addresses this problem by provision of a hierarchy of methods to be applied [397]: avoidance of allocation by subdivision of unit processes, (2) avoidance of allocation by system expansion, (3) allocation based on physical relations and (4) allocation based on other relations.

#### 4.2.1. Avoiding allocation by system expansion/Substitution

According to ISO 14044, allocation should be avoided, whenever possible by subdivision of the respective unit process into sub-processes. Another approach to avoid allocation is the expansion of system boundaries in order to compare an equal set of products: Functions and processes are added to each product system in a way that a comparable quantity of products is provided by each product system. Substitution is closely related to this principle: the impacts caused by the production of co-product(s) by alternative processes are subtracted from the total impacts in order to gain the impacts of the product of interest. An equivalent product or service that fulfils the same function and that is provided by an alternative (“reference”) system is consequently replaced by co-products of the assessed product system. Emissions from providing these products or services in the respective reference systems are subtracted from total emissions of the assessed system (Eq. 4-2):

$$I_{FU} = \sum_{i=1}^N I_i - \sum_{j=1}^M (R_j I_{j,ref}) \quad \text{Eq. 4-2}$$

$R$  denotes the quantity of product  $j$  provided by a reference system that is replaced by a co-product of the assessed system, and  $I_{j,ref}$  denotes the impact per unit of product  $j$  in a reference system.

Substitution is commonly applied in cLCA studies, which assess changes due to a marginal change in the system with respect to the whole market that is affected.

#### 4.2.2. Allocation

If allocation cannot be avoided, allocation is to be accomplished based on physical relations between products. If no such physical relation exists, allocation should be based on other relationships, e.g. monetary value. Let  $P_i$  be the quantity of product of process  $i$  that is needed to produce the functional unit,  $I_i$  denote the total impact of process  $i$  per output of  $P_i$ , and  $\alpha_i$  the allocation factor of  $P_i$  in process  $i$  with a total number of  $N$  processes, it follows that  $I_{FU}$ , the total impact per functional unit, can be expressed by Eq. 4-3:

$$I_{FU} = \sum_{i=1}^N \alpha_i P_i I_i \quad \text{Eq. 4-3}$$

The allocation factor  $\alpha$  of product  $P_u$  of a process delivering  $M$  products is determined by Eq. 4-4

$$\alpha_u = \frac{\varepsilon_u P_u}{\sum_{u=1}^M (\varepsilon_u P_u)} \quad \text{Eq. 4-4}$$

$\varepsilon_u$  denotes the parameter on which the allocation is based on, e.g. heating value, price, etc., of product  $P$ , and  $P$  the output quantity of each product. Allocation is commonly applied in aLCA studies, where emissions of a certain system are to be apportioned between products.

#### 4.2.3. Hybrid methods

Two assessed hybrid methods combine allocation and a reference system [84, 396]. For each product of the assessed system, a reference system providing an equivalent product or service is chosen. In the first method, by Cherubini et al. [84], allocation factors reflect the relative contribution of emissions entailed to the provision of the respective product in the reference system to the sum of emissions entailed to the provision all products or services by reference systems. Let  $I_{u,ref}$  denote the impact per unit of product  $P_u$  in a reference system, and  $P_u$  the quantity of product produced in a reference that is substituted by a respective product of the assessed system, the allocation factors of  $M$  products provided by the assessed system can be calculated by Eq. 4-5 [84]:

$$\alpha_u = \frac{I_{u,ref} P_u}{\sum_{u=1}^M (I_{u,ref} P_u)} \quad \text{Eq. 4-5}$$

Highest allocation factors are assigned to products whose production in a reference system results in high emissions. Another hybrid method by Sandin et al. [396] assigns the lowest allocation factor to those products contributing the most in a reference system (Eq. 4-6):

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$$\alpha_u = \frac{\sum_{u=1}^M (I_{u,ref} P_u) - I_{u,ref} P_u}{\sum_{u=1}^M (I_{u,ref} P_u)} \quad \text{Eq. 4-6}$$

The underlying idea is that those products that would result in high emissions in the respective reference systems have the greatest potential for impact reduction. Consequently, their allocation factors should be low to promote their use.

### 4.2.4. Handling of multi-output systems according to the RED

The methodology laid down in the RED to handle multiple-output systems is a combination of allocation and substitution depending on the type of co-product.

- Inputs and outputs are allocated between products by their energy content, expressed by the lower heating value (LHV) of wet material.
- The system is credited for feeding excess electricity into the grid, except when the used fuel is a co-product other than an agricultural residue. The credit given equals the emissions caused by generating the equal amount of electricity using the same energy carrier. Furthermore, credits are given for capturing biogenic CO<sub>2</sub> that replaces fossil-derived CO<sub>2</sub> used in commercial products and services.
- Electricity from biomass that is a co-product of ethanol production is treated as a co-product.

### 4.3. Scope of the assessment

The assessment of GHG emissions of biofuel provision considers the overall provision chain comprising biomass production, transportation, biofuel production, its distribution, as well as emissions originating from the provision of energy and auxiliary materials [54]. The functional unit of the assessment is 1 MJ of fuel produced in Germany. The assessment focuses solely on GHG gases [398]. GHG intensities of substitutes are provided in Table A - 1.

### 4.4. Description and data inventory of assessed biofuel pathways

In order to assess the implication of co-product handling, a total of eleven biofuel pathways are assessed which present nine different combinations of feedstock and co-product processing modalities. Out of these eleven pathways, five are based on standard data, which is provided by the biograce model additionally to the RED to standardize calculation procedures [398]; six cases are based on first-hand industry data [399], as well as literature data (Table 4-1). Standard biograce data is used additionally to industry data to cover a wider range of concepts and feedstocks and to facilitate the assessment of applied methodologies, as many stakeholders are familiar with RED standard values.

Table 4-1 Inventory of assessed concepts [369, 370, 379–381, 398–402].

Feedstock	Bioethanol						Biodiesel				
	Wheat		Sugar beet		Corn		RS	SF			
Process	Dry milling	Dry milling	Wet milling	Dry milling +biogas	Dry milling	Wet milling	Biogas	Dry milling	Wet milling		
<b>Feedstock inputs</b> (kg MJ <sup>-1</sup> )											
Feedstock	0.128	0.126	0.143	0.128	0.128	0.128	0.451	0.415	0.125	0.073	0.068
<b>Chemical inputs</b> <sup>a</sup> (10 <sup>-3</sup> kg MJ <sup>-1</sup> )											
Chemicals	1.28	1.28	1.28	1.28	1.28	1.28	1.27	0.08		1.50	1.49
Methanol										81.84	81.84
<b>Energy Inputs</b> (MJ MJ <sup>-1</sup> )											
Natural gas	0.950	0.557	0.594	0.291	0.291	0.291	0.436	0.439	0.038	1.273	0.493
Electricity			0.009				0.011				
Diesel											
<b>Co-products</b> (kg <sub>DM</sub> MJ <sup>-1</sup> or MJ MJ <sup>-1</sup> ) <sup>b</sup>											
DDGS	0.032	0.036								0.052	
CDS			0.018								
Bran			0.025								
Gluten			0.009								
Fusel oil		0.0001	0.0001		0.0001	0.0001	0.0001	0.0001	0.0001		
Ammonium sulfate					0.005	0.005		0.002			
Digestate					0.006	0.006		0.011			
Vinasse								0.013			
Beet slices							0.026	0.032			
Beet tailings							0.001	0.001			
Beet soil							0.037	0.037			
Carbo-lime							0.006	0.006			
CGM										0.006	
CGFM										0.029	
CGO										0.003	

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Table 4-1 Continued

Feedstock	Bioethanol			Biodiesel		
	Wheat	Sugar beet	Corn	RS	SF	
Seed cake				0.036	0.032	
Glycerin				0.003	0.003	
Electricity	0.258	0.018	0.007			
<b>Data source</b>	RED <sup>e</sup>	IND <sup>d</sup>	IND <sup>d</sup> LIT <sup>b</sup>	RED <sup>c</sup>	IND <sup>d,f</sup>	IND <sup>d</sup> , LIT <sup>b</sup> , RED <sup>d</sup>

<sup>a</sup> A detailed inventory of used chemicals can be found in Table A - 2.

<sup>b</sup> Electricity in MJ MJ<sup>-1</sup>; all other products in kg<sub>DM</sub> MJ<sup>-1</sup>.

<sup>c</sup> [398]

<sup>d</sup> [369]

<sup>e</sup> [370, 379–381]

<sup>f</sup> [400]

<sup>g</sup> [401, 402]

Abbr.: CDS: Condensed Distillers Solubles; CGM: Corn gluten meal; CGFM: Corn gluten feed meal; CGO: Corn germ oil; DDGS: Dried distiller's grains with solubles; IND: Industry data; LIT: Literature data; RS: Rapeseed; RED: Renewable Energy Directive (biograce standard data); SF: Sunflower seed.

#### 4.4.1. Feedstock provision

Feedstock provision is based on standard values provided by *the JEC E3* database (Table 4-2) [398]. In practice, fertilizer inputs are dependent on plant nutrient demand, fertilizer losses, crop cycles, soil properties etc. Dinitrogen monoxide emissions are calculated with an emission factor of 1.0% of applied N [398, 403]. Sugar beet is transported 30 km by truck, all other feedstock 50 km [398]. In Germany, the extent of arable land decreased while yields slightly increased in the past decade [368, 404]. Furthermore, biofuel production is not projected to increase significantly in years to come [405]. Therefore, it is assumed that no dLUC occurs due to cultivation of feedstocks in Germany. DLUC of substitutes is included in the respective emission factors (see literature in Table A - 1).

**Table 4-2** Inventory data for feedstock provision [398].

	Wheat	Sugar beet	Corn	Rapeseed	Sunflower
N-fertilizer (kg N ha <sup>-1</sup> year <sup>-1</sup> )	109.3	119.7	51.7	137.4	39
CaO-fertilizer (kg CaO ha <sup>-1</sup> year <sup>-1</sup> )		400	1600	19	
K <sub>2</sub> O-fertilizer (kg K <sub>2</sub> O ha <sup>-1</sup> year <sup>-1</sup> )	16.4	134.9	25.8	49.5	22
P <sub>2</sub> O <sub>5</sub> -fertilizer (kg P <sub>2</sub> O <sub>5</sub> ha <sup>-1</sup> year <sup>-1</sup> )	21.6	59.7	34	33.7	30
Pesticides (kg ha <sup>-1</sup> year <sup>-1</sup> )	2.3	1.3	2.4	1.2	2
Seeds (kg ha <sup>-1</sup> year <sup>-1</sup> )	120	6		6	6
Diesel (MJ ha <sup>-1</sup> year <sup>-1</sup> )	3717	6331	3600	2963	2963
Yield (kg FM ha <sup>-1</sup> year <sup>-1</sup> )	5208	68860	3883	3113	2440

#### 4.4.2. Fuel provision

Fuels are assumed to be transported 150 km to a depot and another 150 km to the filling station [398]. In all cases, energy is provided by a combined heat and power (CHP) generation fueled by natural gas, except for the RED standard concepts 'ethanol from sugar beet' and both biodiesel concepts, in which heat is provided by a boiler and electricity is drawn from the grid [398]. Schemes of production concepts can be found in chapter A.1.

##### 4.4.2.1. Bioethanol from wheat

Three concepts of ethanol production from wheat are assessed: dry milling with feed production, dry milling with biogas production and wet milling. Dry milling is a simple grinding and milling of grains. After fermentation, distillation and rectification the remaining stillage is dried and sold as DDGS or being used to produce biogas. Biogas is assumed to be internally used. Biogas is produced by wet fermentation without artificial heat requirements, as stillage is hot. Gas leakage is assumed to be 1% [370, 379–381]. All emissions are considered biogenic emissions. The remaining digestate is thickened to a DM content of 20% and ammonium sulfate is stripped to obtain a marketable mineral fertilizer product [379]. The ammonia stripping efficiency is assumed to be 80% [379]. Ammonia emissions from closed storage and spreading of digestate with a trail hose are 2.3 and 27% of contained NH<sub>4</sub>-N, respectively [385]. Emissions of N<sub>2</sub>O, CH<sub>4</sub>, H<sub>2</sub>S, NO<sub>x</sub> and

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NMVOs are assumed to be 0.03, 0.20, 0.28, 0.02 and 0.24 kg per t digestate [386]. Wet milling of wheat grains allows the separation of bran and gluten, which is dried. Subsequent to fermentation and distillation, thermally dewatered stillage is sold as CDS.

### 4.4.2.2. *Bioethanol from sugar beet*

Beets are harvested and processed to beet juice in order to increase storability. During the beet campaign, which typically lasts from mid-September to mid of January, ethanol is assumed to be produced from raw juice. At all other times of the year, production is realized from thick juice. The former contains 16% and the latter 65% sucrose [384]. Co-products of beet processing are beet pulp, carbonation lime, which is a product of impurity removal by lime as well as beet soil; the latter is returned to the field. Stillage that remains after fermentation is dewatered to yield vinasse, a feed product or soil quality enhancer. Two different concepts are assessed: Mechanical dewatering of beet pulp and thickening of vinasse, or production of biogas using both as substrates. In the latter case, pulp is ensiled for preservation purposes. Pulp is ensiled in plastic foil with an assumed loss of 6%. Biogas is internally used for energy provision.

### 4.4.2.3. *Bioethanol from corn*

Analogously to wheat, corn grains can be processed by dry and wet milling. Stillage resulting from fermentation of dry-milled grains can be dried to yield DDGS. Wet milling of corn yields corn gluten meal (CGM), corn gluten feed meal (CGFM) and corn germ oil (CGO) [402, 406]: Firstly, grains are steeped and degermed. Additionally bran is removed. CGO is extracted using hexane as a solvent. Subsequently, corn grains are milled and starch and proteins are separated. Drying of separated proteins yields CGM, a high protein feed. Fermentation residues, steepwater, germ meal and bran are mixed and dried to yield CGFM.

### 4.4.2.4. *Biodiesel*

To produce biodiesel from rapeseed and sunflower seeds, oil is extracted using hexane as a solvent [384, 407]. The oil is refined using a sodium hydroxide solution and citric acid. In the subsequent transesterification, methanol, sodium hydroxide and hydrochloric acid are used to obtain fatty acid methyl ester (FAME).

## 4.5. Co-product handling

The methods presented in chapter 4.2 are applied to all analyzed concepts.

### 4.5.1. Allocation, hybrid methods and RED methodology

Allocation based on wet mass, dry mass, LHV of wet material and dry material as well as the metabolizable energy (ME) of material is applied (product characteristics are listed in Table A - 3. LHV of wet material considers the heat needed to evaporate the water contained in the product.

ME is the maximum energy available for animals and is defined as the gross energy contained in feed minus fecal energy, urinary energy and the energy contained in produced methane [408]. According to RED methodology, agricultural residues are not considered as co-products. In case of biodiesel production, where seeds are first processed to meal and oil, the latter being further processed to fuel, allocation is applied at two stages: Emissions from feedstock cultivation are allocated between oil and seed meal. Subsequently, oil is processed to biodiesel and emissions from fuel production and the share of emissions from cultivation that was previously allocated to oil are allocated between biodiesel and glycerin. Data of co-product handling according to RED methodology is taken from the biograce calculation tool [398]. The allocation factors of hybrid methods are based on GHG emissions entailed to the provision of all products in a respective reference systems: allocation factors for co-products of biofuel production are based on similar reference systems as applied in the substitution approach; allocation factors of biofuels comprise fossil fuel provision and combustion [84, 396]. Price as an allocation was not considered: price fluctuations makes allocation based on prices difficult. In practice, long-term average prices could be used. This requires average long-term prices to be defined and kept as criteria for allocation for a long period of time to ensure the long-term planning security required ensuring investments into biofuel technologies. Bioethanol prices fluctuated by the factor of five in the past 10 years, thus, prices used for allocation might differ significantly from actual prices, which would make this approach very vulnerable to criticism.

#### **4.5.2. Delimitation of reference system boundaries and definition of substitutes**

Substitution is applied in this study as it might give an indication of changes in emissions in the whole market due to displacement of products by co-products of biofuel provision. In this study, average inventory data is applied. The use of average data and the omission of other market effects is not entirely accurate from the methodological point of view in case of consequential modelling. For further information on the implications of aLCA and cLCA [75, 77, 78, 409].

##### *4.5.2.1. Fertilizers and chemical products*

Presented concepts yield fertilizers, i.e. ammonium sulfate, digestate, beet soil and carbonation lime as well as fusel oil and glycerin. The estimation of emissions from the production of mineral fertilizers is based on marked shares of different types of NPK and Mg fertilizers in 2012 [410]. It is assumed that the market volume of mineral fertilizers that can be substituted by co-products is not limited due to the fact that fertilizer demand has been increasing significantly in recent years and is projected to continue to do so in all regions of the world [411]. The nutrient composition of digestate, beet soil and carbonation lime are provided in Table A - 4. Digestate replaces mineral fertilizer according to its nutrient content and plant availability of nutrient compounds, expressed by the mineral fertilizer equivalent (MFE). MFE of  $N_{\min}$ ,  $N_{\text{org}}$ , P, K and Mg contained in digestate are 1, 0.15, 0.84 and 1, respectively [387, 412–418]. Fusel oil is composed of a mixture

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of alcohols, such as isoamyl, ethyl, amyl, propyl and butyl of which isoamyl alcohol presents the main constituent [419, 420]. The composition depends on feedstock and process parameters. It is assumed that fusel oil replaces fossil-derived isoamyl alcohol. Glycerin production and market supply are dominated by the production of biodiesel: fossil-derived glycerin accounts for 17% of produced glycerin [387, 421, 422]. Glycerin is a co-product from biodiesel production and is assumed to replace synthetic glycerin. It should be noted, though, that glycerin supply from biodiesel production has exceeded demand for glycerin at certain times in the past [421]. Under these circumstances, no displacement of fossil glycerin production takes places.

### 4.5.2.2. Feed and food products

DDGS, CDS, CGM, CGF, vinasse, rapeseed cake and sunflower cake replace a combination of high-protein and high-energetic feed in order to account for energy and protein content. Replacement ratios are calculated by solving the linear Eq. 4-7 and Eq. 4-8 [423].

$$nXP_{co-product} = \lambda nXP_{protein\ feed} + \mu nXP_{cereal} \quad \text{Eq. 4-7}$$

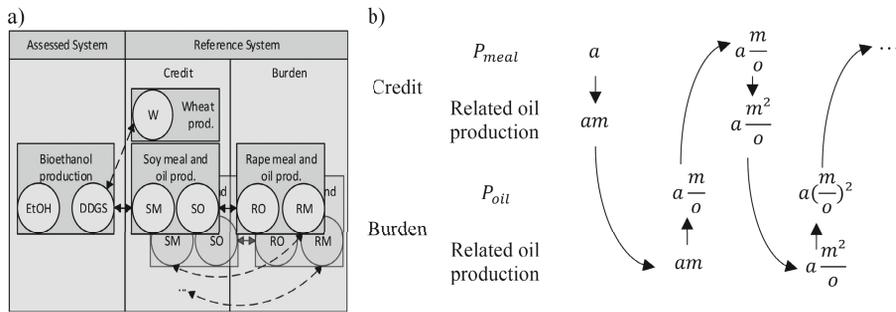
$$ME_{co-product} = \lambda ME_{protein\ feed} + \mu ME_{cereal} \quad \text{Eq. 4-8}$$

$nXP$  denotes the digestible protein content and  $ME$  the metabolizable energy for cattle of cereal, protein feed and the respective co-product;  $\lambda$  and  $\mu$  denote the displacement ratios [423]. Sugar beet pulp, beet tailings and bran are used as animal feed due to their energy content and crude fiber content. The substitution ratio is calculated analogously to the other feed products by Eq. 4-7 and Eq. 4-8 using the fiber content and energy content. The production of seed meal is coupled with the production of oil [424, 425]. If the biofuel system is credited for the production of feed which replaces seed meal, it has to be ascribed a burden for the production of oil that needs to be produced in order to replace the missing oil (Figure 4-1) [426]. As the oil, in turn, is a product of joint production, feed is produced as well:

$$P_{meal} = \sum_{i=0}^n a \left(\frac{m}{o}\right)^i \Rightarrow P_{meal} = \lim_{n \rightarrow \infty} \sum_{i=0}^n a \left(\frac{m}{o}\right)^i \Rightarrow P_{meal} = \frac{a}{1 - m/o} \text{ for } m/o < 1 \quad \text{Eq. 4-9}$$

$$P_{oil} = \sum_{i=1}^n a \left(\frac{m}{o}\right)^i \Rightarrow P_{oil} = \lim_{n \rightarrow \infty} \sum_{i=1}^n a \left(\frac{m}{o}\right)^i \Rightarrow P_{oil} = \frac{a m/o}{1 - m/o} \text{ for } m/o < 1 \quad \text{Eq. 4-10}$$

$P$  denotes protein production substituted by the feed co-product ( $P_{meal}$ ) and coupled to the oil production that needs to be produced in order to compensate the missing oil production ( $P_{oil}$ ).  $m$  and  $o$  denote the oil content per protein and  $a$  denotes the starting quantity of protein that is substituted. Integrating Eq. 4-9 and Eq. 4-10 into the linear system of Eq. 4-7 Eq. 4-8 allows the calculation of the appropriate amount of feed that is substituted while accounting for ME, digestible protein, as well as occurring feedback loops.



**Figure 4-1** a) Feed-oil-loop, exemplarily for DDGS production (substitution variant I) (adapted from [425]). Boxes depict processes, dashed arrows depict displacement/substitution and circles depict products. b) Mathematical expression of the feed-oil-loop. Variables are explained in text. Abbr.: EtOH: Ethanol; DDGS: Dried distiller’s grains with solubles; W: Wheat; RM: Rapeseed meal, RO: Rapeseed oil; SM Soybean meal; SO: Soybean oil.

In total, six combinations of different displacement mechanisms of feed are assessed (Table 4-3). Variant I to III present a variation of feed crops and oil plants. Variant I presents the most commonly used commodities in the EU (Figure 4-2). Variant II presents the most commonly used feed meals and oil source with the highest growth rates globally [427]. The prices of palm oil and soybean oil have been decreasing in the past five years and the price palm oil has been lower than that of soybean oil which propels the use of palm oil [428, 429]. At the same time, soybean meal consumption as feed has decreased in Germany from 2010 to 2015 while rapeseed meal consumption increased [430]. It is assumed that feed as a co-product from biofuel production is contributing to this trend in the long term. Due to these facts, it can be assumed that a marginal increase of biofuel product results in a displacement of commodities covered by variant I or II. In recent years, rapeseed oil has been more expensive than palm oil [429, 431]. This might result in a more likely occurrence of variant II. Mechanisms covered by variant III could be take place if feed supply from biofuel production reduces the consumption of rapeseed. However, current market behavior shows opposing patterns.

4

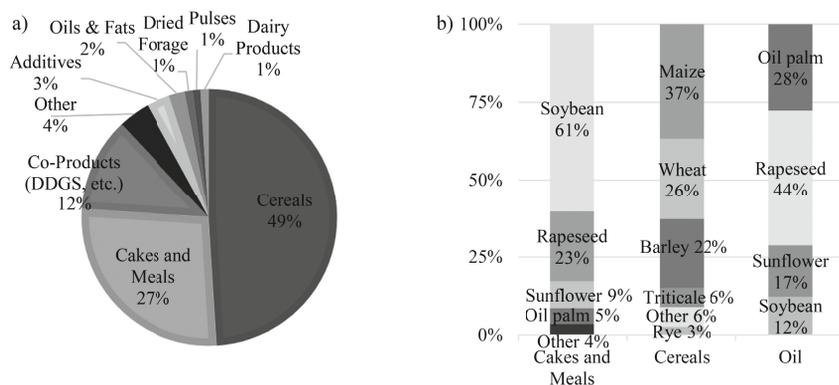
**Table 4-3** Assessed substitutes for high protein feed products.

Variant	Feed replaced by co-products	Oil source
I	Soy & Wheat	Rapeseed
II	Soy & Wheat	Oil Palm
III	Rapeseed & Barley	Oil palm
IV	Feed market mix & cereal market mix	Rapeseed
V	Feed market mix & cereal market mix	Oil palm
VI	Feed market mix & cereal market mix	Oil market mix

Variants IV to VI are based on market data and reflect the average market composition in 2013 in the EU [432–434] (Figure 4-2). It should be noted, though, that market composition of feed

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markets change over time. As projected demand for and production of bioethanol and biodiesel is not expected to change significantly in the upcoming years in Europe, no significant changes in market mechanisms are expected to be triggered by co-products from biofuel production [405]. A change of emission factors of the provision of feed according to the assessed market mix is contained in the sensitivity analysis (see chapter 4.6.6). The assessed change of emission factors by 10% covers changes in market composition to a certain extent.

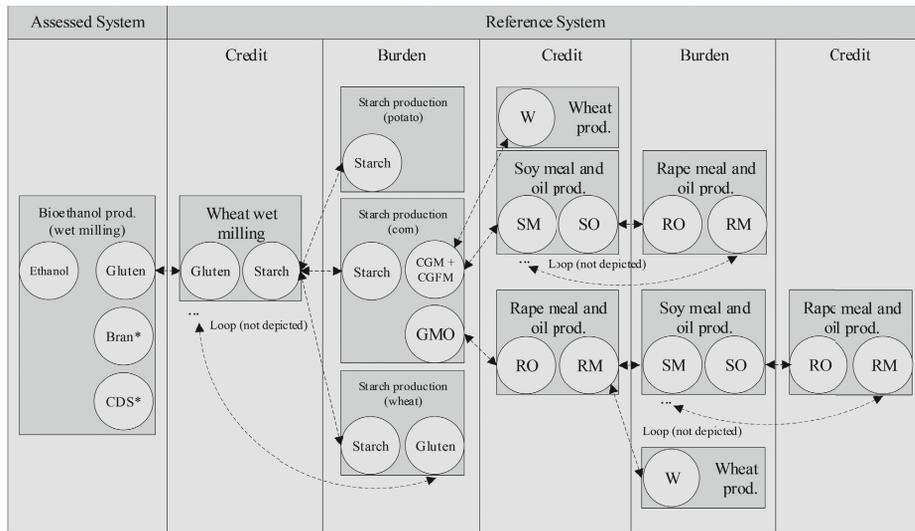


**Figure 4-2** Market share of feed (a)), cakes and meals, cereals and vegetable oil (b)) in the EU in 2013 [432–434].

For simplification, the following other feeds, cereals and meals are omitted: All feed except *cereals* and *cakes and meals* (feed market shares), *other* cakes and meals (feed market share of cakes and meals), as well *triticale*, *other cereals* and *rye* (feed market share of cereals). Market shares are adjusted accordingly. Feed co-products, such as DDGS, are not considered as a substitute as their market supply is controlled by the main product and they are consequently not substituted by feed co-products of biofuel provision.

The production of gluten is modelled analogously to other feed products: Ethanol production with co-production of gluten is credited for the cultivation and wet milling of wheat to obtain an equal amount of gluten, which is coupled with starch production (Figure 4-3). Ethanol production from corn by wet milling is modelled as depicted in Figure 4-3 starting from starch production (corn) and incorporates a feed loop, e.g. wheat, rapeseed and soy production (variant I, Figure 4-1) and an oil loop. Starch is assumed to be replaced by starch from wheat, corn and potato, according to the market share of each feedstock in Germany in 2012: 38, 48 and 14%, respectively [435]. Wet milling of corn yields CGM, CGFM and CMO. CGM and CGFM are modelled as previously described (Figure 4-1). It should be noted, though, that this is based on the assumption that gluten as a co-product of biofuel production replaces gluten by wet milling of wheat. As long as wheat is more expensive than corn, gluten as a co-product from bioethanol production might lead to a shift from wet milling of wheat to corn: increasing supply of gluten will result in a decrease in gluten

price and consequently profitability of wet milling of wheat. In case the wet milling industry is only driven by the starch market, hence independent of the gluten price, or if feedstock prices of other starch-containing feedstocks (e.g. potato or corn) turn out to be higher than that of wheat, gluten as a co-product from biofuel production might not lead to a significant reduction in wet milling of wheat at all. Beet pulp is used as a feed due to its calorific value as well as fiber content. It is assumed that beet pulp replaces barley and oats in all variants. Replacement ratio is calculated according to Eq. 4-7 and Eq. 4-8, replacing the protein content by the crude fiber content.



\*Not depicted: Replacement of bran and CDS

**Figure 4-3** System model of displacement mechanisms due to gluten production (based on substitution variant I). Boxes depict processes, dashed arrows depict displacement/substitution and circles depict products. Abbr.: CDS – Condensed distiller’s solubles; CGFM – Corn gluten feed meal; CGM – Corn gluten meal; DDGS – Dried distiller’s grains with solubles; EtOH – Ethanol; GMO – Germ meal oil; RM – Rapeseed meal; RO – Rapeseed oil; SM – Soybean meal, SO – Soybean oil; W – Wheat.

#### 4.5.2.3. Electricity

In Germany, electricity is fed into the grid according to a merit order curve: Electricity production is ranked by price in an ascending order and the demand and price regulate which electricity source is allowed to provide electricity to the market. Renewable energy sources always get access to the market and are placed at the lower end of the merit order curve. Electricity demand that cannot be met by renewable sources is supplied by nuclear power, coal and gas fired power plants based on the price of each source. Gas fired plants provide electricity at a higher price than most other sources and can consequently found at the upper end of the merit order curve. Thus, it is assumed that surplus electricity which is fed to the market from co-generation replaces conventional natural gas power plants, which corresponds to 159 g CO<sub>2</sub>-eq. MJ<sup>-1</sup> [364]. This effect was observed in recent years.

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### 4.6. Results and Discussion

At first, results of allocation, RED methodology and hybrid methods are discussed. Subsequently, *GHG savings* according to the substitution variants are discussed and compared to results according to RED methodology.

#### 4.6.1. Results of RED methodology and allocation methods

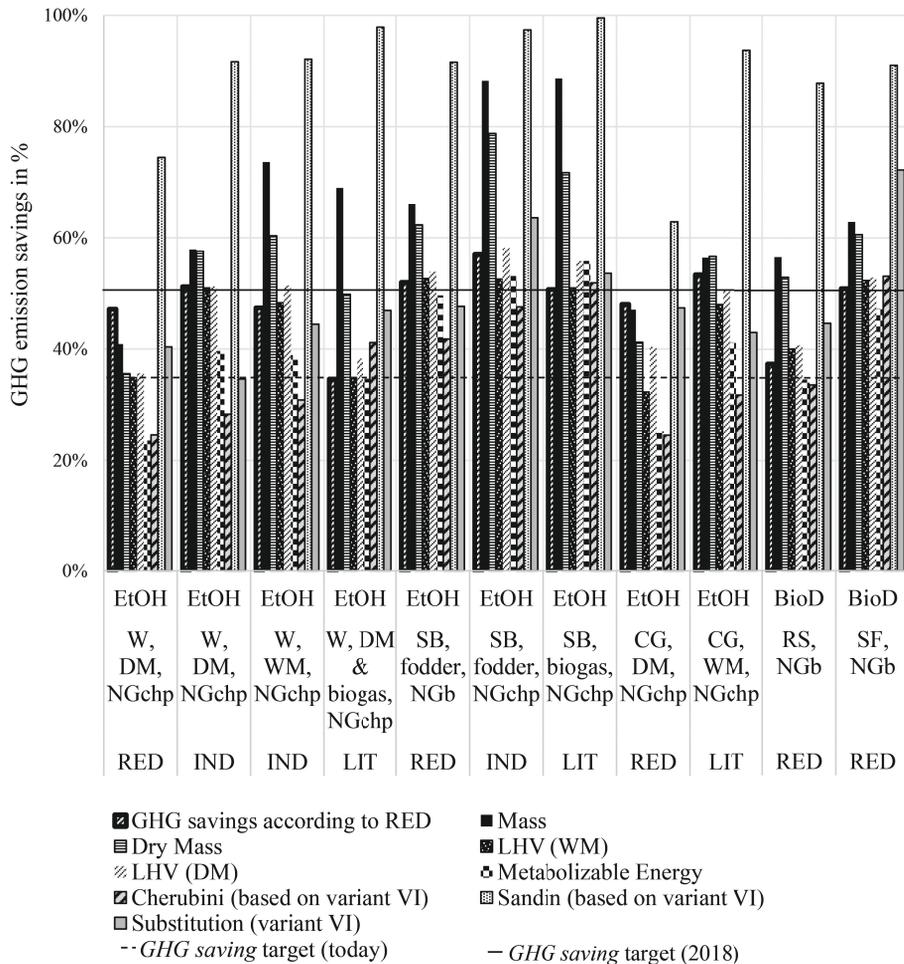
All analyzed concepts achieve GHG emission savings of at least 35%, as currently mandatory, when RED methodology is applied (Figure 4-4). All analyzed sugar beet-based ethanol concepts, as well as ethanol from corn by wet-milling and biodiesel from sunflower even reach an emission saving based on RED methodology of more than 50%, as mandatory of 2018. Sugar-beet based fuel benefits from high feedstock yields, entailing comparably low field emissions. Wet and dry milling of wheat and subsequent ethanol production result in emission savings of around 47%. Wet milling causes around 15% higher emissions due to an increase in feedstock demand per MJ of fuel output as well as higher emissions emitted at the processing stage, albeit a lower allocation factor compensates this effect. Corn-based ethanol shows a quite similar profile as ethanol from wheat. In case of biodiesel, the influence of the agricultural stage is not as prominent, as compared to ethanol, due to the fact that an allocation is applied after seeds are de-oiled. Consequently, 39 and 34% of emissions originating from cultivation are apportioned to rapeseed meal and sunflower meal, respectively.

Mass- or energy-based allocation result in highest GHG emission savings in concepts with low total emissions, e.g. 43 g CO<sub>2</sub>-eq. MJ<sup>-1</sup> of ethanol from sugar beet with biogas production, or concepts with large quantities of co-products with comparably low total emissions, e.g. beet-based ethanol with feed production.

Sugar beet-based concepts result in highest emission savings regardless of the applied allocation methodology due to high agricultural yields and thus lower emissions from feedstock provision. Beet-based ethanol requires more energy at the processing stage than wheat-based ethanol; however benefits from high yields compensate this effect. As electricity is not accounted for when mass-based allocation is applied, emission reductions are lower in case of biograce data than in case of industry data due to the difference in electricity production. A comparison of similar concepts based on industry data and on biograce data furthermore gives an indication of the influence of accounting for all co-products: Beet-based ethanol yields several other co-products apart from beet pulp that are not considered in biograce standard data (Table 4-1). This results in lower emission savings due to a higher allocation factor of ethanol. Considering applicability, dry mass-based allocation is to be preferred compared to wet mass-based allocation, as it does not allow any manipulation of results by dilution of co-product streams. Results show small

differences in emission savings in those concepts with nearly dry co-products, e.g. DDGS, oil seed meals, as opposed to wet co-products, e.g. CDS.

A comparison of all methods and concepts reveals that sugar beet-based ethanol production with co-production of feed and FAME from sunflower results in highest emission saving potentials. This is in both cases due to low emissions from agriculture combined with a large quantity of co-produced feed.



**Figure 4-4** GHG emission savings per MJ of fuel. Bars depict emission savings according to the respective methodology. Dashed line presents current *GHG saving target*, solid line target as of 2018 according to RED [43, 54]. Abbr.: BioD – Biodiesel; CG – Corn grain; DM – Dry mass (allocation) / dry milling (concept); EtOH – Ethanol; GHG – Greenhouse gas; IND – Industry data; LHV – Lower heating value; LIT – Literature data; NGb – boiler; NGchp – natural gas combined heat and power; RED – Renewable Energy Directive (biograce standard data); RS – Rapeseed; SB – Sugar beet; SF – Sunflower seed; W – wheat; WM – Wet mass (allocation) / wet milling (concept).

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All assessed allocation criteria fail to account for specific uses of co-products, e.g. feed is not used as an energy carrier. Several products are even neglected at times, e.g. electricity in case of mass allocation or all products that lack a heating value, such as fertilizer or products with a high water content, in case of energy allocation.

### 4.6.2. Results of hybrid methods

The production of co-products with high emission saving potential, e.g. gluten, results in a much lower allocation factor of ethanol (62%) as opposed to concepts without co-products with a high emission saving potential, e.g. biogas production (87%), when the approach of Cherubini et al. [84] is applied. However, the provision of such co-products entails further emissions, which negate the aforementioned effect. Thus, highest emission savings are achieved in concepts with lowest total emissions, not by concepts providing co-products whose substitute's provision entails high emissions.

Hybrid methods result in lowest (Cherubini [84]) and highest (Sandin [396]) emission savings among analyzed methodologies. The approach of Cherubini et al. [84] assigns high allocation factors to products whose provision in a reference system (and use, in case of fuels) entails high emissions. Thus, a high allocation factor is assigned to biofuels. This mechanism results in high allocation factors assigned to biofuels, even though biofuels replace fossil fuels entailing high emissions and thus having a high potential to mitigate emissions [396]. In both methods, emissions from fossil fuel combustion in the fossil reference system are considerably higher than emissions from the production of substitutes in the respective reference system. Consequently, fuel combustion dominates both methods.

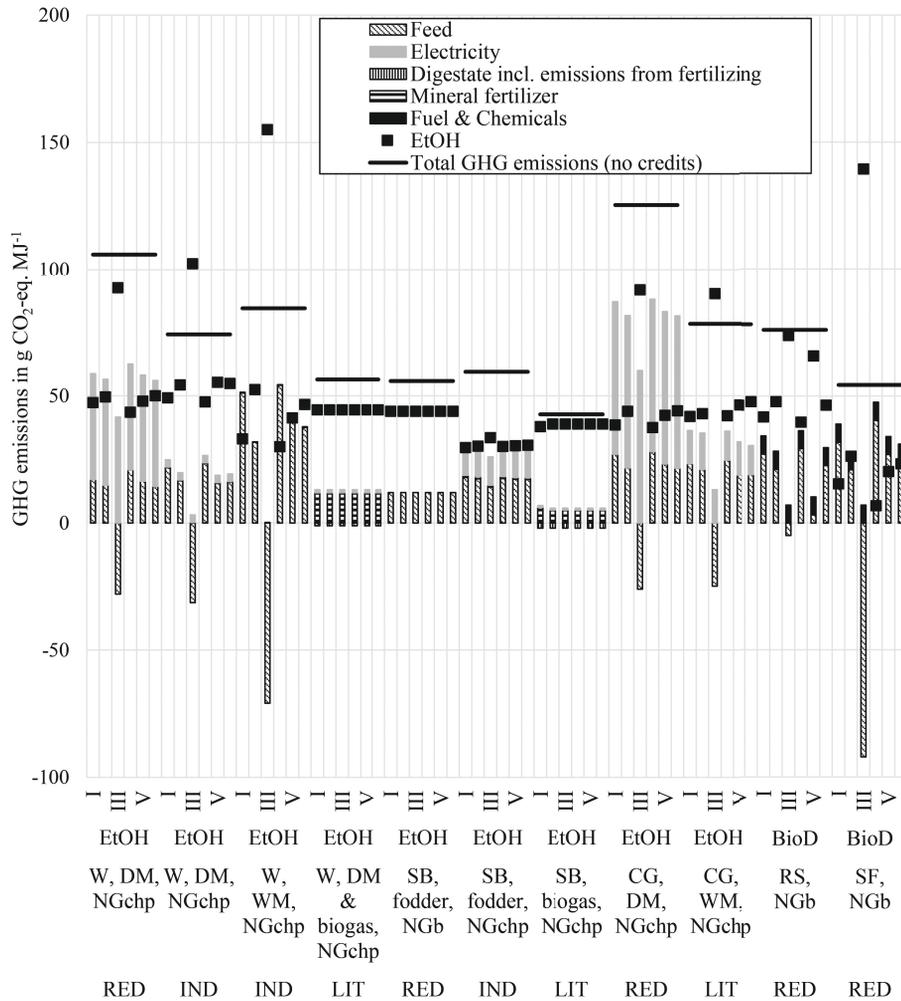
The method of Cherubini et al. [84] could be used to set a more demanding methodology. This will most likely foster more efficient fuel production systems. However, this could also be achieved by adapting *GHG saving* targets in the current RED methodology. Consequently, an application of this method for biofuel certification aiming at this effect in the current European legislative context is obsolete. The approach of Sandin et al. [396] works vice versa and can be potentially used to set appropriate incentives as it supports the introduction of products that potentially substitute products entailing high emissions. However, the assignment of high allocation factors to minor product streams is a major shortcoming that could be overcome by the definition of clear cut-off criteria as well as an adaption of reduction targets.

### 4.6.3. Results of substitution variants

In variant I, highest emission savings are achieved by ethanol from wet milling of wheat and from sugar beet with co-production of feed as well as biodiesel from sunflower: 61, 65 and 82%, respectively (Figure 4-5). Variant I, reflecting most used feed and oil in Europe, results in higher

credits than variant II which reflects the most used feed and oil globally: the largest difference can be observed in case of wet milling of wheat due to a complex market mechanisms underlying gluten supply. In all concepts, higher emission savings are achieved in case oil is supplied by rapeseed (variant I) instead of palm fruits (variant II). Differences range from 4 to 38% in case of ethanol from sugar beet and wet milling of wheat, respectively. In the long term, substitution effects as presented by variant II can be expected as long as the price for palm oil remains below that of rapeseed oil (chapter 4.5.2.2). Substitution variant III generally leads to negative credits due to high quantities of palm oil to be produced to compensate for missing rapeseed oil. In case of sunflower biodiesel, a substitution of rapeseed meal and linked oil provision from palm fruits (variant III), results in high quantities of rapeseed meal that are substituted by sunflower meal. Due to the high oil content of rapeseeds, large quantities of palm oil need to be supplied, resulting in high burdens assigned to sunflower biodiesel. Due to current market trends and the low amount of rapeseed meal consumed as feed in the EU, an extensive substitution of rapeseed meal by co-products of biofuel production is not likely (chapter 4.5.2.1).

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**Figure 4-5** Results of six substitution variants per MJ of fuel. Bars depict credits due to displacement mechanisms, solid lines reflect total emissions resulting from feedstock cultivation and biofuel production of each concept and squares depict emissions per MJ of fuel after subtraction of credits. Abbr.: BioD – Biodiesel; DM – dry milling; CG – Corn grain; EtOH – Ethanol; GHG – greenhouse gas; IND – Industry data; LIT – Literature data; NGb – Natural gas boiler; NGchp – Natural gas combined heat and power; RED – Renewable Energy Directive (biograce standard data); RS – Rapeseed; SB – Sugar beet; SF – Sunflower seed; W – wheat; W – wet milling.

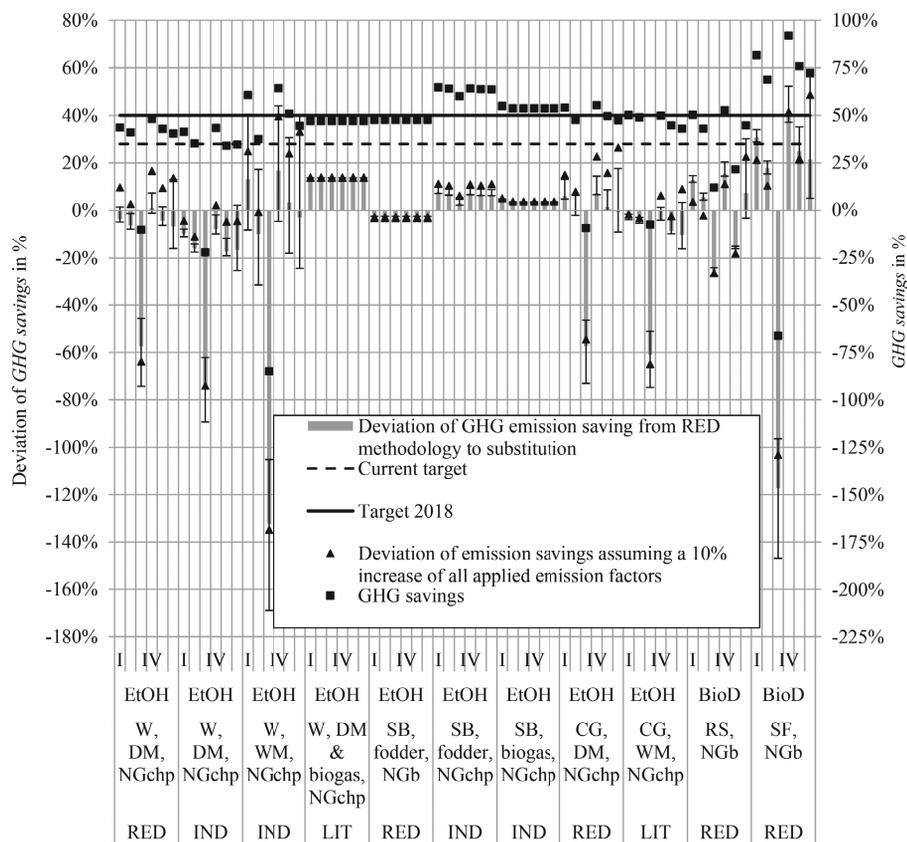
A similar effect, as observed comparing variants I and II can be observed when variants IV and V are compared: Variant IV, in which missing oil is supplied by rapeseed, results in higher emission credits for feed products than variant V, in which oil is supplied by palm fruits: the difference ranges from 2 (ethanol from sugar beet) to 89% (biodiesel from rapeseed). The highest difference can be observed at biodiesel from rapeseed due to oil contents of both oil seeds and resulting replacement ratios. In all other cases in which feed is produced, the difference is below

33%. As in variant I, highest savings are achieved in variant IV by wet milling of wheat and from sugar beet with co-production of feed as well as biodiesel from sunflower: 64, 64 and 92%, respectively (Figure 4-6).

In general, highest emission reductions are achieved due to the provision of electricity. Concepts based on biograce data receive high credits for electricity due to a surplus electricity generation, which is, however, accompanied by higher emissions. Industry data indicate optimized concepts that emit fewer emissions and result in about the same GHG intensity per MJ of fuel. Credits given for other co-products, such as fertilizer and feed, are lower. Among all concepts highest total emission reductions due to displacement mechanisms occur in case of dry milling of corn and wet milling of wheat, ranging from 34 to 88 g CO<sub>2</sub>-eq. MJ<sup>-1</sup> and from 32 to 54 g CO<sub>2</sub>-eq. MJ<sup>-1</sup>, respectively (Figure 4-5). Concepts with biogas production show a smaller variation among variants due to the fact that fertilizer substitute the same mineral fertilizer in all variants. Sunflower-based biodiesel shows high variations among variants due to the high protein content and quantity of sunflower meal combined with a high oil content. Due to the latter fact, the oil source gains importance and strongly influences results.

Furthermore, seed meal production is way less emission-intensive than other co-product processing technologies, i.e. drying of liquid product streams, and, thus, results in low total emissions and consequently high emission savings. This aspect holds true for other concepts as well: beet-based ethanol concepts show high emission savings, even though other concepts result in higher absolute emission credits due to the provision of co-products. Consequently, emission reductions due to displacement effects by co-products are of minor importance compared to total emissions from providing the respective biofuel and associated co-products.

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**Figure 4-6** Difference between *GHG savings* based on RED methodology and results of substitution variants (left axis) and *GHG savings* based on the respective substitution variants (right axis). Left axis: Grey bars depict deviation of substitution results from RED results. Positive differences indicate higher emission savings estimated by substitution than savings based on RED methodology. Values present an absolute difference in percent points, e.g. emission savings from displacement of feed according to substitution variant VI are 9%-points lower than estimated by RED methodology of concept W DM DDGS, NG chp, RED: 38%, as opposed to 47% (Figure 4-4). Whiskers present the maximum and minimum difference between *GHG savings* according to RED and substitution in case of an increase of a single GHG intensity (Table A - 4) by 10%. Triangles present the effect of a simultaneous increase of all GHG intensities by 10%. Right axis: Dashed line presents current *GHG saving* target, dashed line target as of 2018 according to RED [43, 54]. Black squares depict GHG emission savings per MJ of fuel. Abbr.: BioD – Biodiesel; CG – Corn grain; DM – dry milling; EtOH – Ethanol; GHG – Greenhouse gas; IND – Industry data; LIT – Literature data; NGb – Natural gas boiler; NGchp – Natural gas combined heat and power; RED – Renewable Energy Directive (biograce standard data); RS – Rapeseed; SB – Sugar beet; SF – Sunflower seed; W – wheat; WM – wet milling.

### 4.6.4. Comparison of methods

A comparison of results based on allocation, hybrid allocation and RED methodology with results from substitution shows that the methodology defined by RED and allocation based on dry LHV are, in average, closest to emission savings according to displacement of other products assuming

displacement of market shares (Figure 4-4). Allocation based on the LHV of dry material results in slightly higher emission savings as compared to wet material-based energy allocation. Largest differences in savings can be observed in concepts that yield wet products: The difference between *GHG savings* by allocation to those obtained by substitution variants that reflect possible occurring market mechanisms decreases in case of vinasse production and both biogas concepts. Using ME as basis for allocation increases the allocation factor of wet materials, such as CDS, but results in lower allocation factors for other materials. In seven out of eleven cases, results from RED methodology are closest to results obtained by substitution (variant II). In order to assess how robust these findings are, the deviation of *GHG savings* calculated using RED methodology from several substitution variants (Table 4-3) is assessed. In 60% of cases, considering all substitution variants but variant III, emission saving potentials calculated with the RED methodology differ by less than 10%-points from emission savings based on substitution; in 73% of cases and variants by less than 15%-points (Figure 4-6). Deviation of results obtained by RED methodology from substitution results (variant II), presenting substitution effects at a marginal increase of biofuel production, is 10%-points or less in all concepts except dry milling of wheat (industry data) and sunflower biodiesel. In variants VI, presenting average substitution effects, deviation from emission savings according to the RED from the substitution approach is less than 10%-points, except for dry milling ethanol (industry data), ethanol with biogas production and sunflower biodiesel. In case of DDGS production, the RED methodology results in *GHG savings* by 17%-points higher than estimated savings obtained by considering substitution effects. In the other two cases, emission savings are underestimated by 12 and 21%-points, respectively.

#### 4.6.5. Introduction of additional credits to the RED methodology

In the current RED methodology, credits are given for co-generated electricity. According to the RED methodology, only few or no GHG emissions are allocated to certain products streams with low or no LHV due to the allocation principle based on the LHV. The omission of certain product streams such as mineral fertilizers or wet feed products might result in an underestimation of GHG emission savings. In order to test how credits for such products influence results, credits were tested in case of the provision of mineral fertilizer and wet feed. The introduction of credits for all fertilizer products, i.e. ammonium sulfate and digestate, results in a reduction of GHG emissions of around 11 and 4 g CO<sub>2</sub>-eq. MJ<sup>-1</sup> in case of wheat- and beet-based ethanol with coupled biogas production, respectively. These credits lead to an increase of GHG emission savings by 12%-points in case of wheat and 5%-points in case of sugar beet-based ethanol. Including these credits into RED methodology, *GHG savings* are about the same as estimated by substitution variant VI (Figure 4-6): The absolute difference between *GHG saving* by RED methodology and savings based on substitution decreases from 12 to 0%-points and from 3 to 2%-points, in case of wheat-based and sugar beet-based ethanol, respectively. The effect is smaller in case of beet-based ethanol due to a lower nutrient content of digestate. A credit based on substitution variant VI

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for wet feed products, i.e. CDS and vinasse, results in an increase of the overestimation of *GHG savings*: the absolute difference between *GHG savings* based on RED methodology and results obtained by substitution increases from 10 to 18%-points in case of CDS production. Introduction of a credit for vinasse results in a decrease of the absolute difference from 3 to 2%-points.

### 4.6.6. Sensitivity analysis

In order to find how robust these findings are, co-product characteristics and emission factors are altered (Figure 4-6). In order to cover a wide range of possible variations of GHG intensities caused by changes in specific input parameters, e.g. yields, conversion efficiencies, market compositions etc., the effect of a variation of GHG intensities and feed characteristics by  $\pm 10\%$  is assessed. Direct links of changes in a specific input parameters and GHG intensities of fuels are reported in literature, e.g. [354, 436, 437]. In 75% of cases, considering both, the maximum effect due to an increase of single emission factor or sum of effects of all emission factors increasing by 10%, the absolute deviation from unchanged results remains below 15%-points. The deviation remains below 10%-points in 70% of cases. The effect of variation of feed characteristics, i.e. ME, digestible protein, crude protein content, by 10% has an even smaller effect on results. Sensitivity results show the dependence of the estimation of savings on GHG intensities and indicate that a small variation can have significant impacts in terms of the ability of biofuel certification methodology to reflect occurring emission reductions. The definition of a calculation methodology as well as minimum saving targets suggests a certainty that does not exist. GHG reduction originating from substitution effects might differ to a significant extent from *GHG savings* based on RED values (or values obtained by any other methodology). The meaningfulness of those values is thus limited as occurring estimation of savings are strongly dependent on assumptions made as well as varying conditions in practice and do not necessarily reflect emissions savings occurring in reality.

## 4.7. Conclusion

Results show that the estimation of emissions related to the production of biofuels and the subsequent comparison to a fossil fuel comparator, usually referred to as *GHG savings*, are strongly dependent on the applied method to account for co-products. Allocation based on mass or energy, as well as RED methodology (using energy allocation and credits for surplus electricity production) fail to reflect specific *GHG savings* due to displacement mechanisms. Apart from these methods, two novel hybrid approaches, which take all products and their emission saving potential into account, were tested as well. The approach of Sandin et al. [396] might help to set the right incentive needed to promote biofuels with high potentials of GHG emission reduction. The use of a hybrid method could help to promote a diversification of biorefineries producing a wide range of co-products. Hybrid approaches require the definition of reference product systems and substitutes for all co-products from biofuel production by a legal institution for being applicable

in biofuel certification. Cut-off criteria need to be defined and emission saving thresholds need to be adapted accordingly. Several substitution variants show that the displacement of electricity results in higher emission reduction than achieved by provision of any other co-product provided by typical production concepts, e.g. feed. When *GHG savings* based on substitution are compared with all other methodologies, the RED methodology results are closest to results obtained by various substitution variants. An introduction of specific credits, e.g. for fertilizers or wet feed products, reduces differences between the RED methodology and results from substitution. Results furthermore indicate that allocation factors based on physical properties, as tested in this study, do not result in a fairly accurate estimation of savings resulting from the displacement of the respective reference product. It should be kept in mind that results are strongly depend on production modalities and assumptions. As a way forward, regulative framework of biofuel certification should focus on setting a methodological framework that promotes those concepts with highest potentials to reduce GHG emissions. The latter need to be assessed and discussed in respect of potentially occurring displacement effects, e.g. by substitution methodology and cLCA approaches, not by allocation. Regarding assessed concepts, ethanol from wet milling of wheat, sugar beet-based ethanol with co-production of feed and biodiesel from sunflower result in highest emission savings when soybean meal is substituted by feed co-products while vegetable oil from rapeseed is used to compensate missing oil. Setting an adequate regulative framework, i.e. applying allocation based on the LHV of dry material, can help to promote biofuel technologies with highest emission saving potentials. This holds true for assessed conditions and made assumptions: different production modalities or a significant change in production volumes can influence emission patterns as well as substitution mechanisms. Once other novel biorefinery concepts are developed that yield a variety of biochemical products, emission savings entailed to the provision of these biochemicals need to be assessed, e.g. by substitution and cLCA studies. Afterwards, an adequate and applicable method, e.g. allocation, should be chosen that promotes those concepts with highest saving potentials.



# A consequential assessment of changes in greenhouse gas emissions due to the introduction of wheat straw ethanol in the context of European legislation

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**Buchspies B, Kaltschmitt M (2018) A consequential assessment of changes in greenhouse gas emissions due to the introduction of wheat straw ethanol in the context of European legislation. *Applied Energy* 211: 368–381. doi: 10.1016/j.apenergy.2017.10.105. Copyright Elsevier. Minor corrections and modifications were made to align the format and nomenclature.**

## Chapter 5

### Abstract

Until today, 1G biofuels dominate the market for alternative fuels. The European Commission decided to cap 1G biofuels and promote 2G biofuels with the intention to reduce GHG emissions, to limit the competition of food, feed and biofuels, as well as to improve societal approval. The assessment of consequences entailed to a shift from 1G to 2G biofuels is required to judge whether such a shift is advisable or not. According to the renewable energy directive (RED), *GHG savings*, need to be determined for all biofuels. By the end of 2020, fuel blends need to achieve a GHG reduction of 6%. Thus, *GHG savings* will determine the quantity of biofuel to be blended with fossil fuels and thereby eventually define the demand for biofuels. In this paper, the consequences of a shift from a 1G to a 2G biofuel is assessed by the example of bioethanol from wheat grains and straw. In total, three concepts of 2G ethanol production from wheat straw are considered: fermentation of C6-sugars with (1) co-production of feed, (2) coupled with biogas production and (3) co-fermentation of C5- and C6-sugars with co-production of feed. To determine the effect of the introduction of 2G ethanol, *GHG savings* according to RED are calculated first, and, in a second step, consequences of the shift from 1G to 2G ethanol are assessed by accounting for substitution mechanisms and emissions from dLUC and iLUC. *GHG savings* of these 2G concepts according to RED methodology range from 103 to 105%. The shift from 1G ethanol to these 2G concepts is assessed by two scenarios: (1) additional production of 2G ethanol and (2) the replacement of 1G ethanol by 2G ethanol. Results indicate that GHG emissions decrease in scenario 1 if all surplus ethanol replaces fossil fuels. Under the given assumptions, the reduction in emissions ranges from 9.0 to 12.1 kg CO<sub>2</sub>-eq. /GJ ethanol-gasoline blend. If 1G ethanol is replaced by 2G ethanol, GHG emission increase in a range from 7.5 to 16.5 kg CO<sub>2</sub>-eq. /GJ fuel blend. This is mainly due to the provision of feed that needs to be supplied as a consequence of the shift in production: 1G ethanol production provides a high protein feed that needs to be provided by other means. Hence, the main driver for an increase in emissions is the provision of soybean meal and entailed emissions from LUC. A sensitivity analysis shows that these results are robust regarding input parameters and LUC assumptions. These findings point out that it is of utmost importance to assess changes induced by the introduction of novel fuels rather than assessing them isolated from market conditions. Based on these findings, it can be concluded that current and proposed legislation might trigger effects opposed to those intended.

## 5.1. Introduction

As a consequence of the crude oil crises in 1973 and 1979/80, the production of liquid biofuels was expanded with the purpose of reducing the dependency on fossil fuels. In recent decades, the search for non-fossil alternatives has been propelled by the objective to reduce anthropogenic GHG emissions. Fuels based on vegetable oil, starch and sugar crops, named 1G biofuels, were the first biofuels that were brought to market maturity. Simultaneously, an increasing world population and changing consumption patterns have led to an increase in demand for agricultural commodities. As a consequence, 2G biofuels obtained from organic residues and wastes were strongly promoted as an alternative to 1G biofuels. The European Commission decided to cap the use of 1G biofuels to promote their phasing out [43, 438]. In order to facilitate a reduction in GHG emissions, the European Commission decided that biofuel-fossil fuel blends are required to achieve a reduction in GHG emissions of 6% by 2020 [56]. The quantity of a biofuel to be blended with fossil fuel to achieve this target is determined by the *GHG savings* that are estimated through a calculation method defined in the RED [54]. As of 2017, only Germany has adopted this mechanism, while other countries still rely on fixed blending rates [439]. However, in the future, other European countries will transpose this mechanism into national legislation. At the moment, the European Commission is revising the RED for the period of 2021-2030 and the current draft indicates that a reduction in the share of 1G biofuels is envisaged [438]. In contrast, minimum targets of 2G biofuels are implemented and a trajectory is defined to facilitate an increase of the share of 2G/advanced biofuels. The predicted decrease in the energy demand of the transport sector by 7% from 2015 to 2030 should therefore result in a replacement of 1G biofuels with its 2G counterpart [440]. Among 2G biofuels, straw-based bioethanol presents one of the most promising concepts [441].

In this context, the present paper assesses the transition 1G to 2G biofuels, using the example of bioethanol production from wheat grains and straw cultivated in Germany. Thereby, the implications of the blending regulation based on *GHG savings*, as well as the proposed transition from 1G to 2G bioethanol, are discussed.

## 5.2. Literature overview and motivation

Recent political decisions have been accompanied by the interest to evaluate the environmental impacts of 1G and 2G biofuels (among other means of providing energy for transportation). In recent years, numerous studies addressed the environmental impacts of 2G biofuels by life cycle assessment (LCA). The reviews of Gerbrandt et al. [80], Morales et al. [81] and Borrión et al. [82], analyzing studies on bioethanol production from lignocellulosic feedstock covering for the time period from 1999 to 2015, indicate a reduction in GHG emissions due to the use of 2G bioethanol in comparison to fossil fuel. The studies comprised in these reviews show a high variation of important parameters such as the quantity of fertilizer that is applied, N<sub>2</sub>O emissions resulting

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thereof, as well as ethanol and co-product (mainly electricity) yields [80–82]. Furthermore, the application of different LCA methodologies leads to complication when comparing various studies. The handling of arising co-products, the selection of a reference system and the functional unit have the highest impacts on results among methodological aspects. The chosen methodology usually depends on the type of analysis that is conducted: On the one hand, an aLCA seeks to analyze the environmental impacts of a specific product system or service and to provide an evaluation of environmental implications of different stages of the life cycle of a product [67]. The analyzed system is limited to the assessed product system. On the other hand, a cLCA seeks to assess changes in environmental impacts as a consequence of a change in a product system or as a result of a specific decision [67, 68]. In this case, the analyzed system is expanded and accounts for market effects and other consequences that might occur.

In recent years, the focus has shifted to the use of LCA as a means to support (political) decision making [74]. This trend, reflected in the increased interest in cLCA studies, has been a driver and a consequence of the discussion on (i)LUC triggered by biofuel demand. A vital debate evolved that revolves around the key question: which method is best to support robust (political) decision making? Due to its ability to reflect potential consequences of certain decisions, cLCA is considered by some to be a useful method to support policy making, cf. [75, 76]. However, the fact that cLCA cannot accurately account for all market effects, that its results and hypotheses cannot be confirmed or falsified, and that emission reductions predicted by cLCA do not result in emission reductions if not accompanied by appropriate political measures, has led to criticism [77, 78]. In practice, the distinction between these two models is not that clear and a constructive dialogue leading to modeling frameworks that allow better support of decision making is needed [79].

This debate reflects the need for investigations that discuss both approaches in the context of political decision-making. Recent studies on novel fuel production concepts applying aLCA or the RED methodology, mainly presenting an aLCA approach, report a reduction in GHG emissions in comparison to fossil reference systems [273, 442–445]. However, the omission or inconsistent inclusion of substitution effects and other consequences on connected markets inhibits the drawing of a conclusion as to whether an introduction of the analyzed fuel is likely to result in a reduction in GHG emissions. The aLCA of straw-based fuel and energy production conducted by Whittaker et al. [444] and Weiser et al. [273] present detailed discussions of methodological aspects regarding straw removal. In both cases, authors concluded that changes in energy and agricultural markets need to be addressed by means of cLCA to improve the understanding of consequences entailed to the analyzed system. Monteleone et al. [446] provide such a cLCA of straw-based electricity production in Southern Italy. A comparison of two conventional (agro-ecological and energetic valorization of straw) and one “innovative” concept (no-tillage practice,

crop rotation) yields that the latter is the most preferable in terms of GHG emissions and the reduction of fossil energy demand. Lopes de Carvalho [447] assessed environmental impacts of the production of bioethanol in Brazil and its effect on the Brazilian economy and show that positive effects induced by 1G and 2G ethanol production can be counterbalanced by negative effects occurring elsewhere in the economy. Hamelin et al. [448] assessed the consequences of the production of biogas in Denmark and found a reduction in GHG emissions due to a shift from a fossil reference system to the production of biogas. Tonini et al. [449] conducted a detailed cLCA of bioelectricity, biomethane and bioethanol from 24 substrates produced in Northern Europe. The assessment of 1G and 2G substrates considers emissions from feedstock provision to the final use of the energy carrier in case of biofuels. The results indicate that only ethanol from household wastes and agricultural residues reduce GHG emissions. The substitution of fossil gasoline and 1G ethanol produced in Brazil has been assessed. In the latter case, emission reductions and increases, in case of 2G and 1G bioethanol respectively, are less pronounced. Bos et al. [450] conducted a cLCA of the coupled production of biodiesel, biopolyol and bioresin. This assessment is one of very few examples in which other co-products than energy or feed are considered. The assessment neglects the use of fuels and LUC effects. All products result in a decrease in emissions when fossil counterparts of co-products are replaced. Another cLCA of biodiesel from oil palm, soy and rapeseed by Corré et al. [2] showed GHG emissions ranging from 22 to 56 g CO<sub>2</sub>-eq./MJ biodiesel without considering LUC emissions. Escobar et al. [451] compared biodiesel from soy cultivated in Brazil with biodiesel from used cooking oil and found that the 2G fuel resulted in an emission reduction in contrast to soy-derived biodiesel. The main contributor is LUC in both cases. The cultivation of soy results in LUC emissions, whereas the production of biodiesel from used cooking oil reduces the demand of vegetable oil resulting in avoided LUC emissions. The assessment of iLUC emissions as a consequence of an increase in biofuel demand in Spain conducted by Garraín et al. [452] reveals iLUC emissions ranging from 16 to 56 g CO<sub>2</sub>-eq./MJ for bioethanol and from 22 to 52 g CO<sub>2</sub>-eq./MJ for biodiesel. Triggered iLUC effects are highly dependent on feedstock and the assumed substitutes. Therefore, the authors concluded that generic iLUC factors, as proposed by the European Commission, do not reflect these high variations. All these studies present assessments of consequences related to the provision of (co-)products of the analyzed biofuel system. However, due to the limitation of system boundaries excluding the production or use of fuel [442, 449–452], the omission of LUC emissions [2, 442, 447, 450] or inconsistent handling of co-products (e.g. mixture of aLCA and cLCA, as required by the RED) [442, 445], most results do not allow to draw conclusions as to whether the use of a specific fuel is advisable in terms of GHG emissions or not. Furthermore, only one of these studies accounts for the implications on existing biofuel markets ([449]), while none considers the fuel-blending mechanism implemented by the European Commission.

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In contrast to the available studies, the current work assesses the introduction of novel fuel concepts in the context of current legislative practice and envisaged political targets by analyzing a shift from an existing conventional 1G ethanol production from wheat grain to 2G ethanol from wheat straw. The current assessment comprises of market-driven effects entailed to the provision of co-products as well as consequences of current blending legislation that needs to be transposed by European member states. This paper addresses these aspects, which have not been addressed elsewhere, and discusses them based on aLCA and cLCA methodology, thereby contributing to the ongoing debate concerning the capability of LCA to support political decision-making. The following questions are answered using the example of 1G and 2G ethanol production in Germany:

1. What are the emission hot-spots of producing bioethanol from wheat grain and wheat straw?
2. How do the assessed concepts perform in regard to current legislative practice?
3. What are possible consequences in GHG emissions of a shift from 1G to 2G bioethanol (envisaged by political measures) if potential market mechanisms are included?
4. Is an assessment based on current legislative practice capable of reflecting these consequences?
5. Will proposed legislation facilitate an overall reduction in GHG emissions?

In the light of the current revision of the RED, as well as the envisaged reduction of 1G biofuels and increase of 2G biofuels, the answers to these questions will provide detailed insights into possible implications of current political-decisions that will eventually shape the European and global biofuel industry for the upcoming decades.

### 5.3. Methodology

A two-step approach is followed to assess potential consequences of the introduction of 2G bioethanol from wheat straw:

In a first step, *GHG savings*<sup>18</sup> are estimated based on the methodology laid down by RED. These *GHG savings* of any biofuel produced in a facility in operation before 1 January 2017 must amount to at least 50%. According to the RED methodology, emissions are allocated to all co-products, except for electricity for which a credit is given. Thereby, the RED methodology represents a

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18 The terminology „*GHG savings*“, here and hereafter, exclusively refers to the value calculated by RED methodology (Eq. 5-1). The terminology “GHG reduction” refers to the political target of reducing emissions compared to a fossil fuel comparator by 6% in 2020. Both cases do not present a change in emissions, as the applied RED methodology is not able to reflect these. In contrast, terms like “decrease” or “increase in GHG emission” refer to estimations of changes in emissions based on the consequential approach, thus respecting occurring changes in emission due to changes induced by the change in the (product) system, i.e. the introduction of 2G biofuel.

mostly aLCA approach that disregards changes in emissions that occur due to the provision of co-products or due to other market driven effects that result from the introduction of a specific fuel.

In a second step, emission changes resulting from the introduction of 2G ethanol are estimated by applying a consequential model that considers changes in blending quantities (based on the RED methodology), occurring substitution mechanisms, market effects, LUC etc. As of the end of 2020, the final biofuel-fossil fuel blend must achieve a GHG reduction of 6% [43]. Thus, the quantity of biofuel to be blended with a fossil fuel is defined by *GHG savings* determined by the RED methodology.

The calculation of GHG intensities was conducted with openLCA 1.4.2. GWP, as defined by the RED [54] and the IPCC [453], were applied for the determination of *GHG savings* according to RED methodology and for the consequential approach, respectively (Table B - 1).

### 5.3.1. RED methodology

Regardless of the type of biofuel, its provision and use is regulated by the RED [43, 54] and the fuel quality directive [56]. The RED, representing the most important political instrument, defines sustainability criteria for biofuel provision. Aside from GHG emissions, sustainability aspects, such as biodiversity and dLUC, are also addressed. Additionally, the RED defines a methodology to quantify GHG emission savings from the use and provision of biofuels. As of the end of 2020, the quantity of biofuels to be blended with fossil fuels is dependent on the achieved GHG emission savings based on the RED methodology (Eq. 5-1):

$$GHG\ savings = \frac{GHG_f - GHG_b}{GHG_f} \quad \text{Eq. 5-1}$$

where  $GHG_f$  represents the fossil fuel comparator of 83.8 g CO<sub>2</sub>-eq./MJ reflecting GHG emissions of fossil fuel provision and combustion and  $GHG_b$  presents the GHG emissions related to the provision of the biofuel [3]. Emissions originating from the combustion of biofuels are considered to be carbon neutral due to the biogenic origin of carbon. Emission reduction per MJ of fuel blend must amount to at least 6% compared to the fossil baseline comparator of 94.1 g CO<sub>2</sub>-eq./MJ [43, 58]. According to the legislation, both comparators are not fuel-specific and thus do not distinguish between diesel and gasoline. They are applied for all liquid fuels.

GHG emissions of biofuel provision comprise of: emissions from feedstock cultivation, the provision of energy and auxiliary materials, transport of materials and fuel distribution. In the case of several co-products of a product system, emissions and input are apportioned to all products.

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- Inputs and outputs are allocated to products based on their lower heating value (LHV).
- Credits are given for feeding excess electricity into the grid, except when the used fuel is a co-product other than an agricultural residue. The credit equals the emissions caused by generating the respective amount of electricity using the same energy carrier.
- Credits are also provided for capturing biogenic CO<sub>2</sub> that replaces fossil-derived CO<sub>2</sub> used in commercial products and services.
- Electricity from biomass that is a co-product of the production process is treated as a co-product.

Allocation is accomplished in the following manner: Let  $P_i$  denote the quantity of product of process  $i$  that is needed to deliver the functional unit,  $I_i$  denote the total impact of process  $i$  per output of  $P_i$ , and  $a_i$  the allocation factor of  $P_i$  in process  $i$  with a total number of  $N$  processes, it follows that  $I_{FU}$ , the total impact per functional unit, can be expressed by Eq. 5-2:

$$I_{FU} = \sum_{i=1}^N \alpha_i P_i I_i \quad \text{Eq. 5-2}$$

$$\alpha_u = \frac{\varepsilon_u P_u}{\sum_{u=1}^M (\varepsilon_u P_u)} \quad \text{Eq. 5-3}$$

The allocation factor  $\alpha$  of product  $P_u$  of a process delivering  $M$  products is determined by Eq. 5-3. In Eq. 5-3  $\varepsilon_u$  denotes the parameter on which the allocation is based on, i.e. LHV.

### 5.3.2. Consequential approach

A consequential life cycle assessment (LCA) reflects changes induced by marginal changes in the assessed production system or market [454]. Occurring changes due to displacement mechanisms are accounted for by estimating potential emission changes as a consequence of changes in demand of (co-)products and the respective reference products as well as induced emissions from LUC effects. Substitution mechanisms and LUC emissions are case-specific and will thus be explained in Table 5-3 and Table 5-4 subsequent to the description of scenarios, case-specific co-products and related substitution mechanisms described in chapter 5.4.2.1 to 5.4.2.3. Occurring LUC is estimated with a deterministic model through identification of marginal suppliers under consideration of legislative frameworks, trade statistics, market environments and past developments.

### 5.3.2.1. Feed as a co-product

The provision of feed as a co-product substitutes other feed products. In case of protein feed, a linear equation system is used to reflect the substitution of protein and feed energy. The replacement ratio is calculated with Eq. 5-4 and Eq. 5-5 [423]:

$$nXP_{co-product} = \lambda nXP_{protein\ feed} + \mu nXP_{cereal} \quad \text{Eq. 5-4}$$

$$ME_{co-product} = \lambda ME_{protein\ feed} + \mu ME_{cereal} \quad \text{Eq. 5-5}$$

Where  $nXP$ ,  $ME$ ,  $\lambda$  and  $\mu$  denote the digestible protein content, the metabolizable energy for cattle and the displacement ratios, respectively [423]. The production of meal for animal consumption is coupled with the production of vegetable oil [424–426, 455]. When feed co-products reduce the demand for seed meal, resulting in a decrease in supply of meal that is substituted, seed oil production is reduced as well. In this case, oil will be supplied by another marginal supplier. By providing the respective quantity of oil to the market, meal will be supplied as well. The corresponding feedback loop and mathematical description of it is explained in the chapter B.1.2.

### 5.3.2.2. Land-use change

The change of land-use results in changes in SOC and aboveground vegetation. The respective changes in GHG emissions are estimated based on Eq. 5-6 and Eq. 5-7 [89, 91]:

$$\Delta C_{mineral} = \frac{(SOC_0 + C_{veg_0}) - (SOC_{0-T} + C_{veg_{0-T}})}{D} \quad \text{Eq. 5-6}$$

$$SOC = \sum_{c,s,i} (SOC_{REF,c,s,i} F_{LU,c,s,i} F_{MG,c,s,i} F_{I,c,s,i} A_{c,s,i}) \quad \text{Eq. 5-7}$$

Where:  $\Delta C_{mineral}$  denotes the annual change of carbon (C) stocks in mineral soils and in above-ground biomass,  $SOC_0$  the SOC stock in the last year of an inventory time period  $SOC_{0-T}$  SOC at the beginning of the inventory time period,  $C_{veg_0}$  and  $C_{veg_{0-T}}$  the carbon stocks in above-ground biomass in the last year and the beginning of the inventory period,  $T$  the number of years over a single inventory time period in years,  $c$  the climate zone,  $s$  the soil type,  $i$  the set of management systems,  $SOC_{REF}$  the reference carbon stock,  $F_{LU}$  the stock change factor for the respective land-use systems,  $F_{MG}$  the stock change factor for the management regime,  $F_I$  the stock change factor for the input of organic matter, and  $A$  the assessed area. A time period,  $D$ , of 20 years is chosen.

## 5.4. System description

The production of 1G cereal grain ethanol and 2G wheat straw ethanol is assessed by hypothetical production facilities with a capacity of 150000 m<sup>3</sup> ethanol per year, i.e. facilities of medium production capacity. This capacity is chosen in order to reflect theoretical 2G ethanol facilities

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at the early stages of market maturity. Feedstock cultivation and fuel production is assumed to take place in Germany.

### 5.4.1. GHG savings according to RED methodology

Ethanol production comprises feedstock provision, feedstock conversion, fuel distribution, transport activities as well as the provision of energy and auxiliary materials. The reference year is 2020.

#### 5.4.1.1. *Wheat cultivation*

Conventional wheat cultivation in Germany is assumed. Between 2005 and 2014, the yield of wheat fluctuated between 6.9 and 8.6 t/ha [456]. A slight positive trend in yields can be observed. In the present study a yield of 7.9 t/(ha a) is assumed [370]. The DM content of grains and straw ranges from 83 to 94% [457]. DM contents of 86% and 90% are assumed for grains and straw, respectively [370, 458, 459]. Fertilizer is applied according to nutrient extraction. Without straw removal, 118.9 kg ammonium nitrate-N, 25.1 kg phosphate-P, 34.0 kg K<sub>2</sub>O-K and 8.2 kg Mg are applied per hectare and year. Nitrous oxide emissions from fertilizer application are estimated by the IPCC Tier 1 method [403]. Ammonia-N emissions are assumed to be 2.5% of applied N [374]. Nitrate emissions are estimated based on fertilizer input, soil and plant characteristics as well as annual precipitation [460].

The quantity of straw that can be harvested is based on the sustainable straw potential in Germany, assuming soils in good condition and adequate supply of N [273, 461]. The assumed grain/straw ratio is 0.8 [273]. The calculated sustainable straw potential is 44.7% available straw (chapter B.2.1). The N, P, K, Mg and S content of straw is 0.55, 0.13, 1.45, 0.12 and 0.23% of fresh matter, respectively [462]. In case of straw removal, these nutrients are supplied by mineral fertilizer.

Grains are transported 120 km by truck [369]. The design of straw handling depends on straw requirements of the respective 2G ethanol facility. Straw is transported 3.6, 3.6 and 2.9 km by tractor to the intermediate storage and 93, 93 and 76 km by truck to the ethanol production facility in case of concept I, II and III, respectively (concepts are explained in chapter 5.4.1.3, straw handling and the estimation of transport distances are described in chapter B.2).

#### 5.4.1.2. *Ethanol production from wheat grains*

Preceding starch hydrolysis and transformation to sugars by the aid of enzymes, wheat grains are dry milled. Resulting sugars are fermented to yield ethanol. The purification of ethanol is accomplished by distillation / rectification. Finally, ethanol is dehydrated to a purity of 99.7% by molecular sieves. Aside from ethanol, the overall process yields wheat dust, fusel oils and stillage. The stillage is dried to a DM content of 90% to yield DDGS, a high protein feed. The applied data

are from operating facilities (Table 5-1). Emissions related to the provision of auxiliary materials and energy provision are based on Ecoinvent v.3.2 data [364]. Energy is supplied by a natural gas boiler with a steam turbine; the electric and thermal efficiencies are 12.5 and 72.5%, respectively. Emissions of volatile organic compounds are estimated based on measurements [389]. CO<sub>2</sub> originating from the fermentation process is captured. This intercooled 5-stage compression process requires 0.43 MJ electricity/ kg CO<sub>2</sub> [463]. Finally, ethanol is transported 150 km by truck from the production facility to the depot and another 150 km to the filling station [464].

**Table 5-1** Inventory data for 1G ethanol production from wheat grains.

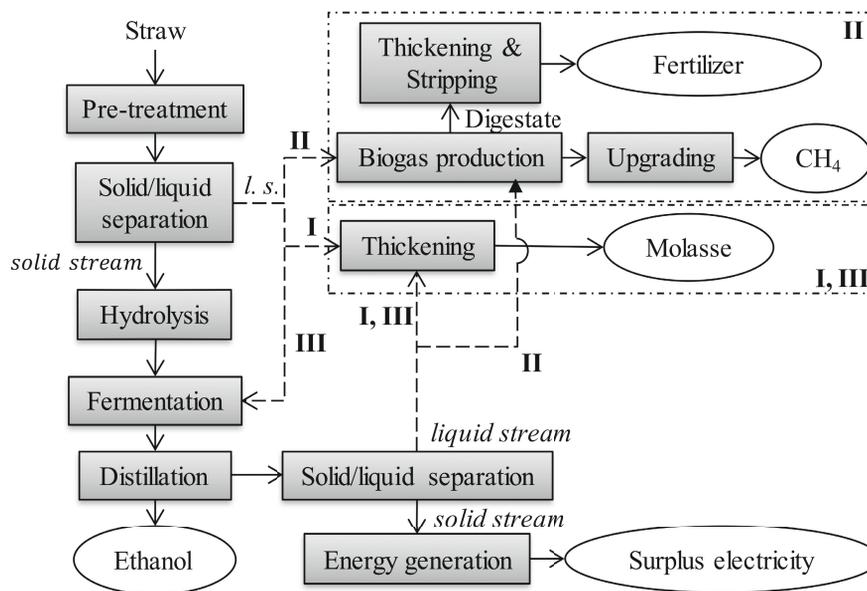
Input	Unit	Value	Reference	Output	Unit	Value	Reference
Wheat grains	kg	3.39	[369, 399]	Ethanol, 99.7%	kg	1	
Heat	MJ	10.80	[369, 399]	DDGS, 90% DM	kg	1.08	[369, 399]
Electricity	kWh	0.47	[369, 399, 463]	Electricity	kWh	0.05	
Sulfuric acid	kg	0.02	[369, 399]	Fusel oils	kg	0.004	[369, 399]
Sodium hydroxide	kg	0.02	[369, 399]	Wastewater	L	4.82	[369, 399]
Ammonia	kg	0.002	[369, 399]				
Enzymes	kg	0.003	[369, 399]	Emissions			
				Acetic Acid	kg	5.05E-05	Estimation based on [389]
				Ethanol	kg	1.52E-04	
				Ethyl Acetate	kg	1.85E-04	
				Lactic Acid	kg	2.70E-05	
				2-Furaldehyde	kg	3.37E-06	
				Acetaldehyde	kg	2.19E-04	
				Acrolein	kg	3.37E-06	
				Formaldehyde	kg	3.37E-06	
				Methanol	kg	3.37E-06	

#### 5.4.1.3. Ethanol production from wheat straw

Three concepts of ethanol production from wheat straw are assessed (Figure 5-1).

- I. C6 fermentation and co-production of feed
  - fermentation of C6-sugars to yield ethanol
  - thickening of C5-sugars to produces C5-molasses (DM 60%), a feed product
- II. C6 fermentation and biogas production
  - fermentation of C6-sugars to yield ethanol
  - production of biogas from C5-sugars
  - purification and upgrading of biogas to natural gas quality
  - production of fertilizer products from digestate
- III. Co-fermentation of C5- and C6-sugars with co-production of feed
  - co-fermentation of C5- and C6-sugars
  - thickening of residues, which can be sold as a feed product (DM 60%)

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**Figure 5-1** Assessed ethanol production concepts using wheat straw. Bold roman numbers indicate process steps that belong to a specific concept. Abbr.: l. s. – liquid stream.

Dry wheat straw consists of 39.2% cellulose, 24.8% xylose, 22.4% Klason lignin, 2.7% arabinose, and 2% other sugars [459]. The moisture content before pre-treatment is 10%. The wheat straw is pre-treated by steam explosion, yielding a liquid phase rich in C5-sugars, e.g. xylose, arabinose and a solid stream rich in lignin and C6-sugars, e.g. glucose. Steam explosion is conducted at 190 °C for 10 minutes. The conversion efficiencies and the composition of wheat straw are listed in Table B - 2. This setup is chosen due to its low yield of inhibiting compounds [465]. The following hydrolysis requires 20 mg enzymes/ g of cellulose [466]. The yields of glucose, xylose, arabinose and galactose are assumed to be 86, 68, 94 and 100%, respectively (Table 5-2) [465, 467]. The ethanol yield from glucose, xylose and arabinose are 98, 93 and 54%, respectively [369, 468]. Ethanol fermentation requires 3 g enzymes/ t ethanol [369].

In all concepts, stillage is separated after fermentation into a liquid phase containing dissolved unfermented sugars and a solid stream mainly consisting of lignin and unfermented solid sugars. The solids are used to provide process heat and electricity. Emissions for energy generation from lignin are taken from the probas data base [469]. The efficiency of energy generation is optimized to provide heat and electricity according to process demands. Surplus electricity, if available, is a co-product. In all cases, CO<sub>2</sub> is captured as in case of IG production.

In concepts I and III, the liquid stream is thickened to a DM of 60% to provide a feed product. It is assumed that 50% of the process water can be recycled. The remaining water is treated in

a wastewater treatment facility. In concept II, stillage containing 8 g volatile solids/ kg is used to produce biogas with a CH<sub>4</sub> content of 50% [470–472]. It is assumed that no additional heat is required as stillage contains latent heat when leaving the ethanol production process. Gas leakage of biogas production is assumed to be 1% [380, 473]. Biogas is de-sulfurized by activated carbon before being purified by pressure swing adsorption; this cleaning process requires 2.1 10<sup>-4</sup> kg activated carbon and 1.5 10<sup>-4</sup> kg lubricant oil per m<sup>3</sup> purified gas [385]. Waste gas is flared and all emissions are accounted for as well. The methane slip (unburnt methane) that leaves the waste gas flare is 0.2% of the waste gas stream [474]. Bio-CH<sub>4</sub> is compressed and the energy content is adjusted to meet grid requirements by adding propane (0.013 m<sup>3</sup>/ m<sup>3</sup> CH<sub>4</sub>) [475].

Additionally, ammonium sulfate is stripped from the digestate (nutrient content according to [470]). Nitrogen stripping efficiency is 80% [379]. Afterwards the digestate is dewatered through centrifugation and subsequently dried to a DM content of 20%. The resulting thickened digestate still contains nutrients and can thus be used as a fertilizer. Thickening requires 0.69 kWh electricity/ t digestate treated in a decanter and 1.16 MJ heat/ kg of water that is evaporated in a two-step evaporation column [476].

The production of 2G ethanol from wheat straw as well as biogas provision from the remaining stillage presents a challenge that has not been realized at a fully competitive industrial scale yet. Therefore, conversion efficiencies and process data considered here present an estimation of possible future lignocellulosic ethanol production according to the level of technology expected in 2020.

Similarly to 1G ethanol, ethanol is transported 150 km by truck from the production facility to the depot and another 150 km to the filling station [464].

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**Table 5-2** Inventory data for 2G ethanol production from wheat straw.

Concept		I	II	III		
Fermentation		C6 feed	C6 biogas	C5 & C6 feed		
Co-product						
<b>Input</b>	Straw	kg	7.09	7.09	4.68	
	Water	kg	8.07	13.90	5.93	
	Enzymes	kg [369, 466]	0.05	0.05	0.03	
	Corn steep liquor	kg [467]	0.06	0.06	0.06	
	Diammonium phosphate	kg [467]	0.01	0.01	0.01	
	Heat	MJ	31.27	25.13	20.84	
	<i>Pre-Treatment</i>	[477]	11.89	11.89	7.85	
	<i>Distillation</i>	[477]	6.00	6.00	6.00	
	<i>Molasses thickening</i>	[38]	13.38		6.99	
	<i>Digestate thickening</i>	[38]		7.24		
	Electricity	kWh	1.45	1.61	1.00	
	<i>Pre-Treatment</i>	[477]	0.35	0.35	0.23	
	<i>Ethanol production</i>	[477]	0.98	0.98	0.65	
	<i>Biogas production</i>	[478]		0.02		
	<i>Digestate thickening</i>	[476]		0.03		
	<i>Pressure swing adsorption</i>	[56]		0.10		
	<i>CO<sub>2</sub> capturing</i>	[463]	0.11	0.11	0.11	
	Electricity	MJ	0.60		0.21	
	<b>Output</b>	Ethanol	kg	1.00	1.00	1.00
		C5-Molasse, 60% DM	kg	2.89		1.01
Stillage to biogas		kg		14.57		
Lignin to energy generation		kg	1.85	1.85	1.24	
Biogas		MJ		9.78		
Electricity		MJ		5.07		
Digestate, 20% DM		kg		5.74		
Ammonium sulfate		kg N		0.02		
Wastewater		kg	9.94	6.32	5.50	
Direct emissions			see Table 5-1			
<b>Parameter</b>		Efficiency of energy generation		0.80	0.80	0.80
		Thermal efficiency		0.71	0.56	0.70
	Electric efficiency		0.10	0.24	0.10	

### 5.4.2. Consequential system model

In the consequential approach, the effect of an introduction of 2G ethanol from wheat straw is assessed based on two scenarios:

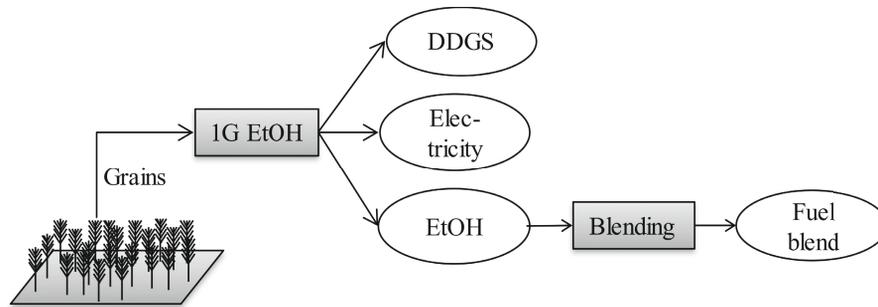
1. the additional production of 2G ethanol from wheat straw; and
2. the shift from 1G ethanol to 2G ethanol.

In these cases, ethanol production takes place in Germany. Therefore, market data for the evaluation of occurring substitution effects refers to the respective markets in Germany. A basic

assumption is that the German/European ethanol market is saturated. This assumption is justified by the existence of a blending rate that ties ethanol demand to fossil fuel consumption and by the fact that ethanol exports from the EU increased slightly in recent years [405]. The quantity of ethanol to be blended with a fossil fuel depends on *GHG savings* according to the RED methodology of the respective provision concept and the envisaged reduction of GHG emissions of the fuel blend (chapter 5.3.1).

#### 5.4.2.1. Business as usual scenario

The business as usual (BAU) scenario describes 1G ethanol production from wheat grains. (Figure 5-2). The process yields ethanol, DDGS, electricity and compressed CO<sub>2</sub>. Ethanol is blended with gasoline according to the *GHG savings* achieved by the RED methodology in order to achieve a 6% reduction in GHG emissions from fuel provision and use.



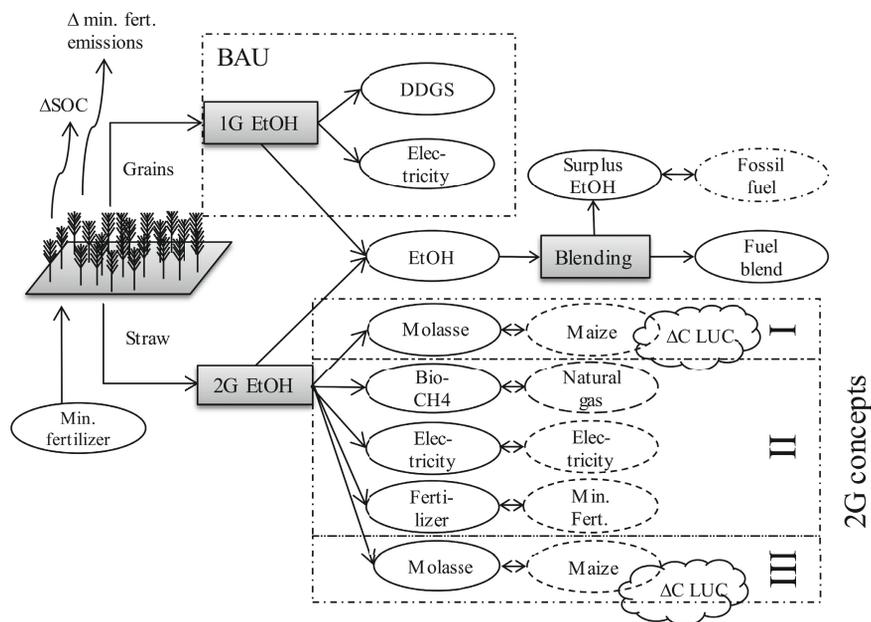
**Figure 5-2** Business as usual (BAU) scenario. Captured CO<sub>2</sub> is not depicted. Abbr.: 1G – first generation; DDGS – dried distiller’s grains with solubles; EtOH – ethanol.

#### 5.4.2.2. Scenario 1 “1G and 2G ethanol”

Scenario 1 describes the simultaneous production of 1G and 2G ethanol (Figure 5-3). The production of 1G ethanol takes place analogously to the BAU scenario. Additionally, straw is removed resulting in a change in SOC as well as a removal of nutrients. The latter are replaced by mineral fertilizer resulting in additional emissions. The methodological approach to assess the change in SOC and LUC is described in chapter 5.3.2.2 Product-specific substitution mechanisms as well as related emission estimations from LUC are described in Table 5-3 and Table 5-4. Alternative LUC scenarios are assessed in the sensitivity analysis.

The mixture of 1G and 2G ethanol results in higher *GHG savings* based on the RED methodology. Consequently, a lower quantity of fuel is blended to achieve the envisaged reduction in GHG emissions by 6%, as mandatory by 2020. The required quantity of ethanol to be blended is based on the average *GHG saving* of 1G ethanol and the respective 2G production concept. Surplus ethanol is assumed to be exported and to replace fossil fuel.

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**Figure 5-3** Scenario 1 “1G and 2G ethanol” (three concepts of 2G ethanol production are assessed (chapter 5.4.1.3); solid ellipses present products and dashed ellipses present substitutes of these products whose markets are affected (affected processes are not shown in Table 5-3; clouds indicate changes in land use that are considered (Table 5-4). Captured CO<sub>2</sub> and substitution mechanisms of the BAU scenario are not depicted. Abbr.: 1G – first generation; 2G – second generation; BAU – business as usual scenario, DDGS – dried distiller grains with solubles, EthOH – ethanol, LUC – land-use change, min. fert. – mineral fertilizer, SOC – soil organic carbon.

### 5.4.2.3. Scenario 2 “Shift from 1G to 2G ethanol”

Scenario 2 describes a complete shift from 1G to 2G ethanol (Figure 5-4). As a consequence, 1G ethanol is no longer produced and thus DDGS, compressed CO<sub>2</sub> and electricity from this process are no longer supplied to the market. Therefore, these missing products have to be provided by substitutes (Table 5-3). As in scenario 1, surplus bioethanol becomes available as a consequence of the shift from 1G to 2G ethanol due to the blending regulation based on *GHG savings* according to the RED. Two possibilities concerning how this surplus ethanol can be used are considered here: replacement of fossil fuels (scenario 2.1) and additional replacement of 1G ethanol (scenario 2.2). The choice of LUC scenarios and entailed emissions are explained in Table 5-4. Substitution quantities and LUC emissions are calculated based on chapter 5.3.2.3 Alternative LUC scenarios are assessed in the sensitivity analysis.

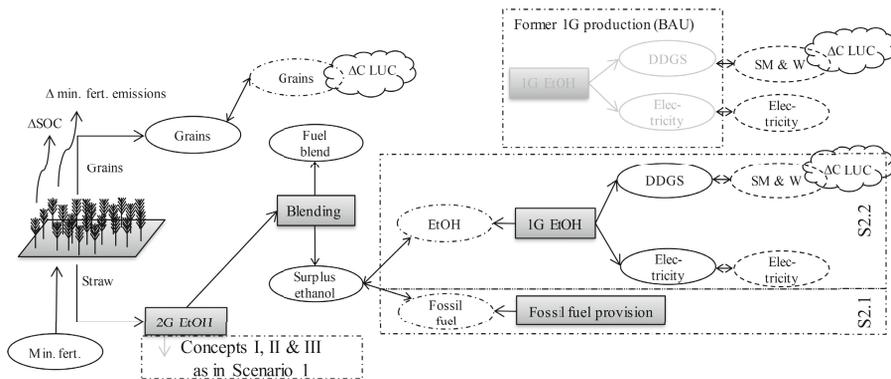
## 5.5. Results and discussion

First, *GHG savings*, determined by the RED methodology are presented. These values serve as an input to consequential assessment: *GHG savings* calculated with the RED methodology

determine the quantity of biofuel to be blended with a fossil fuel. In the year of reference, 2020, the fuel mixture needs to reduce GHGs by 6% compared to the baseline of 94.1 g CO<sub>2eq</sub>/MJ [58]. GHG intensities of processes and substitutes as well as emissions from LUC can be found in Table B - 3 and Table B - 4. A brief summary of the sensitivity analysis is presented in the following chapters. The detailed sensitivity analysis is presented in Chapter B.3.3. All presented results rely on the assumptions previously presented.

**5.5.1. GHG savings according to the RED methodology**

**Results and discussion.** All assessed 1G and 2G concepts reach the required *GHG savings* of at least 50% (Figure 5-5): 1G and 2G ethanol production with the production concepts I, II and III result in GHG emission savings of 57, 103, 105 and 103%, respectively. In the case of 1G ethanol production, the largest contributor to the GHG emissions are wheat cultivation and transport with about 34 g CO<sub>2</sub>-eq./MJ ethanol<sup>19</sup>. Ethanol production and co-product processing, i.e. stillage drying, results in 21 g CO<sub>2</sub>-eq./MJ ethanol. Thereof, 95% originate from energy provision by natural gas. The remaining GHG emissions stem from the provision of auxiliary materials. CO<sub>2</sub> capture and surplus electricity result in a credit of 20 g CO<sub>2</sub>-eq. /MJ ethanol, whereof electricity accounts for 2.3%. In case of 2G ethanol, concept III results in highest savings. This is due to the co-fermentation C5- and C6-sugars and thus lower energy and feedstock requirements per fuel output. Straw is considered a residue and thus its cultivation is not considered by the RED methodology, except for its handling and transport. GHG emissions from straw handling and transport activities range from 2 to 3 g CO<sub>2</sub>-eq./ MJ ethanol. In case of lignin-fired energy generation, non-CO<sub>2</sub> emissions, e.g. N<sub>2</sub>O, play the most important role.



**Figure 5-4** Scenario 2 “Shift from 1G to 2G ethanol” (as a consequence of the shift, 1G ethanol production is stopped; three concepts of 2G ethanol production are assessed (chapter 5.4.1.3). Solid ellipses present products and dashed ellipses present products whose markets are affected (affected processes are not shown in Table 5-3). Clouds indicate changes in land use that are considered (Table 5-4). Abbr.: EthOH – ethanol; LUC – land-use change; min. fert. – mineral fertilizer; SM – soybean meal; SOC – soil organic carbon; W – wheat.

19 All reported values present results after allocation based on the LHV, if not stated otherwise.

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**Table 5-3** Substitution mechanisms.

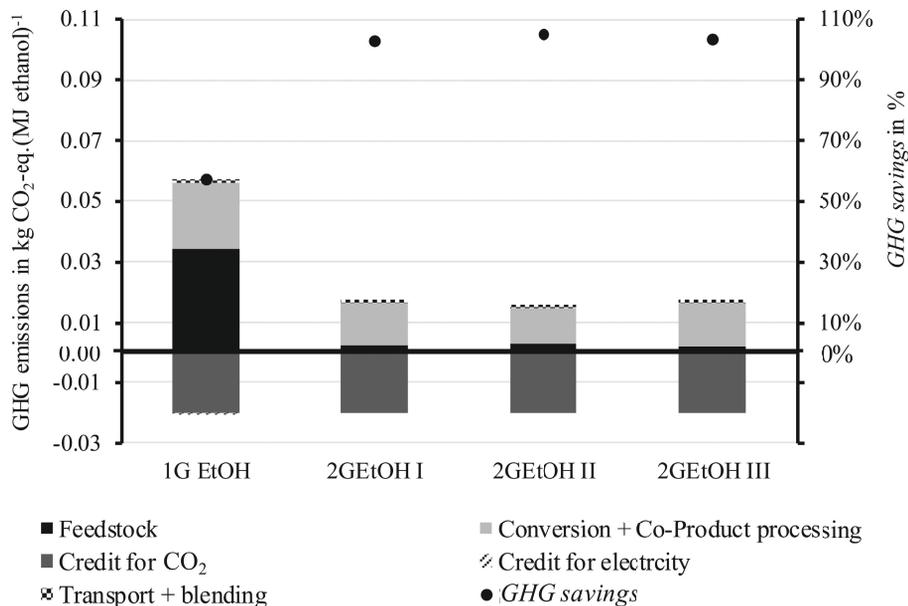
<b>Product (Scenario)</b>	<b>Substitution mechanism</b>
Electricity (S1, S2)	In 2020, bituminous coal, will constitute a major part of the base and middle load supply in Germany [479]. 1G ethanol production and 2G concept II provide electricity. The lack of the former in scenario S2 and the existence of the latter in scenarios S1 and S2 result in a change in electricity supply. Due to the constant supply of electricity from ethanol facilities, electricity from bituminous coal is considered the marginal electricity.
DDGS (S2)	DDGS is substituted by a combination of protein feed and cereals. Vegetable oil completes the substitution mechanism (chapter 5.3.2.1). In Germany, 4 million t of rapeseed meal and 3.9 million t of soybean meal were fed to animals in 2015 [480]. The former showed an increase by 25% and the latter a decrease by 13% between 2011 and 2015 [480]. In the same period, imports of rapeseed meal to the EU and Germany increased by 39 and 98%, respectively, whereas soybean meal imports to the EU decreased by 16% [481]. Rapeseed meal is a co-product of biodiesel production and its supply is predominantly controlled by biofuel production and not by feed demand. Consequently, it is assumed that DDGS is a substitute for soybean meal and vice versa. Additionally, wheat grains complement the nutrient and energy demand. In 2015, 55% of soy meal in Germany was imported from Brazil, followed by the Netherlands (21%) and Argentina (19%) [482]. In 2015, soy meal imported to the Netherlands predominantly originated from Brazil (57%), Argentina (45%) [480]. Thus, around 68% of soybean meal used in Germany in 2015 originates from Brazil. In case of soybeans, 45 came from the US and 39% from Brazil. Between 2000 and 2014, developments in yields and planted areas indicate a stable development in the US, while yields and planted area of soybean increased considerably in Brazil (Figure B - 3). It is therefore assumed that Brazil is the marginal supplier of soy. The majority of Brazilian soybean (meal) is exported from Paranaguá (36%), Santos (25%), Rio Grande (1%) and Vitória (8%) [483]. The averaged shipping distance from these ports to Hamburg, Germany, is 10,723 km. Palm oil presents the most used vegetable oil world-wide and the price of palm oil has been lower than that of rapeseed and soybean oil in the past 5 years [429, 431, 481]. Therefore, it is assumed that palm oil is the oil that complements the feed substitution mechanism. The major exporters of palm oil are Indonesia and Malaysia, providing 49% and 40% of global palm oil exports in 2014/15, respectively [481]. Consequently, Indonesia and Malaysia supply 55% and 45% of palm oil to the European market (adjusted shares), respectively. In Indonesia, 96% of palm oil is produced in Sumatra (75%) and Kalimantan (21%) [484]. It is assumed that palm oil is shipped from Port Klang, Jakarta and Pontianak in case of production in Malaysia, Sumatra and Kalimantan, respectively. The averaged shipping distance to Hamburg, Germany, is 13,958 km. Subsequently road transport by trucks for another 300 km is assumed for soybean meal and palm oil.
Molasses (S1, S2)	Molasses, a co-product from 2G concepts I and III, is assumed to substitute maize according to the metabolizable energy. Maize is assumed to be cultivated in Germany as 85% of domestic maize consumption is provided by domestic production [485]. Maize is assumed to be transported 300 km by truck.
Biomethane (S1, S2)	Biomethane, a product of 2G concept II, replaces the provision and combustion of the equivalent amount of natural gas.
Fertilizer (S1, S2)	Thickened digestate and ammonium sulfate, co-products of biogas production of 2G concept II, replace mineral fertilizer according to their nutrient content. A transport distance of 300 km is assumed.
Wheat grains (S2)	In scenario S2, wheat grains become available due a shift from 1G to 2G ethanol and needs to be supplied due to missing DDGS as part of the DDGS replacement scheme (chapter 5.3.2.1). Wheat is assumed to be transported 300 km by truck.
Ethanol (S2)	Surplus ethanol as a consequence of blending regulation is either exported whereby it replaces fossil gasoline provision and use (S1, S2.1), or substitutes 1G ethanol in Germany (S2.2). The fuel efficiency of (low) fuel blends, as currently common in the EU, is considered equal to that of pure gasoline [486].
CO <sub>2</sub> (S1, S2)	Captured CO <sub>2</sub> is assumed to replace fossil derived CO <sub>2</sub> .

**Table 5-4** LUC mechanisms and related carbon stock changes over 20 years.

Mechanism (Location)	Description and parameters (Eq. 5-6 and Eq. 5-7)
Straw removal (Germany)	The sustainable straw potential is 44.7% of the overall available straw. Straw is harvested and processed according to chapter B.2.2. The assumed soil is a Luvisol / Avisol ( $SOC_{REF} = 95 \text{ t/ha}$ ) [89]. The cultivation system is a long-term cultivation in moist temperate climate with full tillage ( $F_{LU} = 0.69$ , $F_{MG} = 1$ , $C_{veg_{0,T}} = C_{veg_0} = 0 \text{ t/ha}$ ). All of organic input is converted to carbon if straw is not removed ( $F_I = 1$ ); if straw is removed, 92% are converted ( $F_I = 0.92$ ). Straw removal results in a carbon loss of $0.26 \text{ t C/ (ha a)}$ .
Conversion from / to cropland (Germany)	In scenario 2, wheat grains become available and reduce domestic wheat production. Additional wheat is required to substitute missing DDGS. The corresponding LUC is a conversion from or to fallow land ( $F_{LU} = 0.82$ , $F_{MG} = 1.1$ , $F_I = 0.95$ , $C_{veg_0} = 6.8 \text{ t/ha}^a$ ) [89]. An alternative LUC mechanism is assessed in the sensitivity analysis.
Soybean cultivation (Brazil)	In 2013/14, 52% of Brazilian soy was cultivated in the Central West and 27% in the South [487]. Between 2001 and 2005, the expansion of land used for soy cultivation took place on rainforest land (26%) and on scrubland (74%) [164]. In the subsequent four years, the conversion occurred mainly on scrubland (91%). Only 22% of increasing demand was fulfilled by intensification, whereas the rest was provided by extensification [164, 488]. Thus, it is assumed that this trend continues and that, consequently, land conversion for soy cultivation occurs on scrubland/ grassland; this also reflects the current Brazilian policy, e.g. Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm). It is assumed that soy cultivation takes place in Central-West Brazil on low activity clay soils ( $SOC_{REF} = 47 \text{ t/ha}$ ) [89, 483, 489]. Soy is cultivated in a full-tillage system with medium inputs ( $F_{LU} = 0.48$ , $F_{MG} = F_I = 1$ , $C_{veg_{0,T}} = 53 \text{ t/ha}$ ) [89, 489]. It is assumed that an averagely degraded savanna is converted ( $F_{MG} = 0.97$ , $F_{LU} = F_I = 1$ , $C_{veg_{0,T}} = 53 \text{ t/ha}$ ). The conversion results in carbon loss of $3.8 \text{ t C/ (ha a)}$ . Other LUC mechanisms and cultivation practices are assessed in the sensitivity analysis.
Oil Palm cultivation (Indonesia)	In Indonesia, forest cover decreased from 130 million ha in 1975 to 91 million ha in 2005. About half of this decrease can be attributed to palm oil plantations [145]. In Sumatra and Kalimantan, where 95% of total land used for palm oil cultivation in Indonesia is located and 96% of Indonesian palm oil is produced. In these areas annual forest cover loss is 2.5%; this is significantly higher than the overall level in Indonesia (1.9%) [145, 484]. Forest land presents the land use category with the largest decreases, while others, e.g. permanent pastures, decreased to a much lower extent in absolute terms. It is therefore assumed that insular native forest is converted ( $F_{LU} = 1$ , $C_{veg_{0,T}} = 230 \text{ t/ha}$ ) to palm oil plantations ( $F_{LU} = F_{MG} = F_I = 1$ , $C_{veg_0} = 60 \text{ t/ha}$ ) [89]. A low activity clay soil is assumed ( $SOC_{REF} = 60 \text{ t/ha}$ ). The conversion results in carbon loss of $8.5 \text{ t C/ (ha a)}$ . Note: In 2016, a five-year moratorium on new palm plantations was issued. It prohibits the establishment of new plantations on forest land. A conversion of permanent cropland to oil palm plantations and the establishment of a plantation on peatland in Indonesia is assessed in the sensitivity analysis.
(Malaysia)	Historical data from 1989 to 2013 shows that deforestation and oil palm expansion show similar growth patterns [490]. Oil palm cultivation showed an expansion from 0.1 to 5.5 million ha between 1975 and 2005. During the same period, forest land and other permanent crops showed a large decrease by 4.6 and 1.4 million ha, presenting a decrease by 20 and 45%, respectively [145]. It is therefore assumed that 76.7% of land conversion to palm oil plantations ( $F_{LU} = F_{MG} = F_I = 1$ , $C_{veg_{0,T}} = 60 \text{ t/ha}$ ) takes place on continental forest land ( $F_{LU} = 1$ , $C_{veg_{0,T}} = 185 \text{ t/ha}$ ) while the remaining 23.3% takes place on permanent crop land ( $F_{LU} = F_{MG} = F_I = 1$ , $C_{veg_{0,T}} = 34.3 \text{ t/ha}$ ) [89, 145]. A low activity clay soil is assumed ( $SOC_{REF} = 60 \text{ t/ha}$ ). This results in carbon loss of $4.5 \text{ t C/ (ha a)}$ . In the sensitivity analysis, a complete conversion of permanent crops, e.g. rubber, to palm oil plantations as well as the establishment of plantations on peatland is assessed.

<sup>a</sup> The carbon content of grassland is taken to estimate the carbon content in set-aside land.

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**Figure 5-5** GHG emissions (left axis) and GHG emission savings (right axis) according to RED methodology. Abbr.: 1G – first generation; 2G – second generation; EtOH – ethanol; GHG – greenhouse gas.

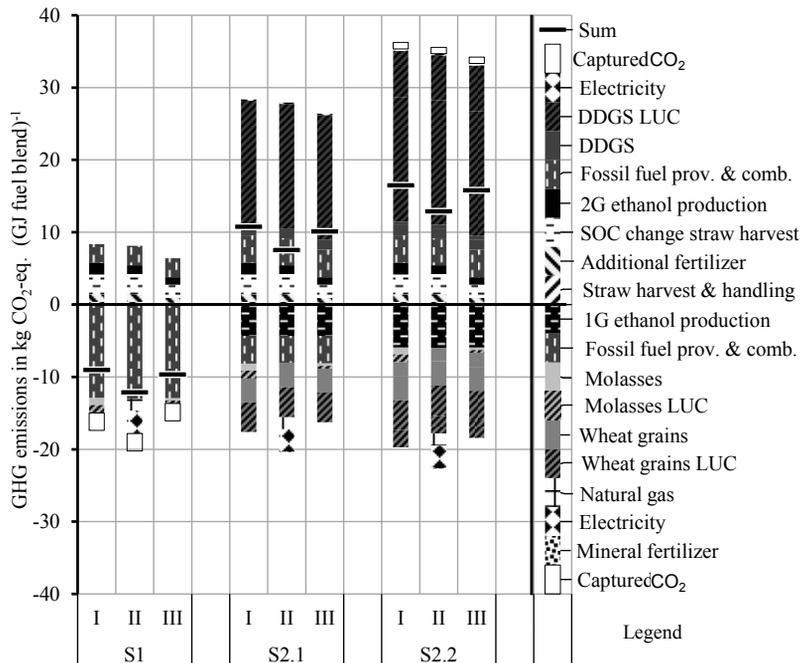
**Sensitivity analysis.** The sensitivity analysis reveals that the magnitude of change in *GHG savings* is lower than the magnitude of a change in energy (heat) demand of 1G and 2G ethanol production (Figure B - 4). A change in conversion efficiency has an even smaller effect on *GHG savings* according to RED methodology (Figure B - 5).

### 5.5.2. The consequential approach: From 1G to 2G ethanol

**Results and discussion.** Based on *GHG savings* according to RED methodology, 98, 61, 63 and 62 MJ of ethanol needs to be blended with gasoline per GJ of fuel blend in case of 1G, 2G concepts I, II and III, respectively, in order to achieve the envisaged GHG reduction of 6%. Accordingly, 32660 GJ of fuel energy each containing 98 MJ ethanol, can be supplied by the 1G ethanol facility with an annual capacity of 150000 m<sup>3</sup> (BAU scenario). The absolute quantity of fuel blend to be sold on the market is not affected by the shift from 1G ethanol to 2G ethanol, whereas the quantity of ethanol required to be blended with fossil fuel changes according to *GHG savings* according to RED methodology and the envisaged reduction in GHG emissions by 6%. All surplus ethanol that is not required to supply these 32660 GJ is either exported where it replaces fossil fuel energy (scenarios 1 and 2.1) or it substitutes domestic production of 1G ethanol (scenario 2.2). Results indicate that the introduction of 2G ethanol leads to a decrease in GHG emissions if 2G ethanol is additionally produced to 1G ethanol (scenario 1, Figure 5-6). The decrease ranges from 9.0 to 12.1 kg CO<sub>2</sub>-eq./GJ fuel blend. 2G ethanol production combined with biogas production (2G concept II) results in highest decreases due to credits for the substitution

of natural gas provision and combustion by biomethane as well as due to surplus electricity generation substituting electricity in the market (Table 5-3). Molasses, a co-product of the other two concepts, results in a small decrease in GHG emissions due to the replacement of maize. The largest contributions to emission savings, in total around 13 kg CO<sub>2</sub>-eq./GJ fuel blend, stem from the replacement of fossil fuels due to the saturated market conditions, the doubling of production capacities in scenario 1 and the assumption of a substitution of fossil fuels by surplus ethanol. Thus, results of scenario 1 rely on the assumption that surplus ethanol fully substitutes fossil fuels. Additionally, the quantity of captured CO<sub>2</sub> doubles. Moreover, the likewise amount of fossil derived compressed CO<sub>2</sub> is replaced.

The shift from 1G to 2G ethanol (scenario 2) results in an increase in GHG emissions. This increase ranges from 7.5 to 10.8 and from 12.9 to 16.5 kg CO<sub>2</sub>-eq./ GJ ethanol in case of a replacement of fossil fuel (scenario 2.1) and in case of a replacement of 1G ethanol (scenario 2.2) by surplus ethanol, respectively. The surplus in scenario 2 originates from lower blending requirements as a consequence of higher *GHG savings* according to the RED requirements. In case surplus ethanol replaces 1G ethanol, the respective co-products from 1G ethanol need to be provided by other substitutes (i.e. feed, CO<sub>2</sub> and electricity, Table 5-3).

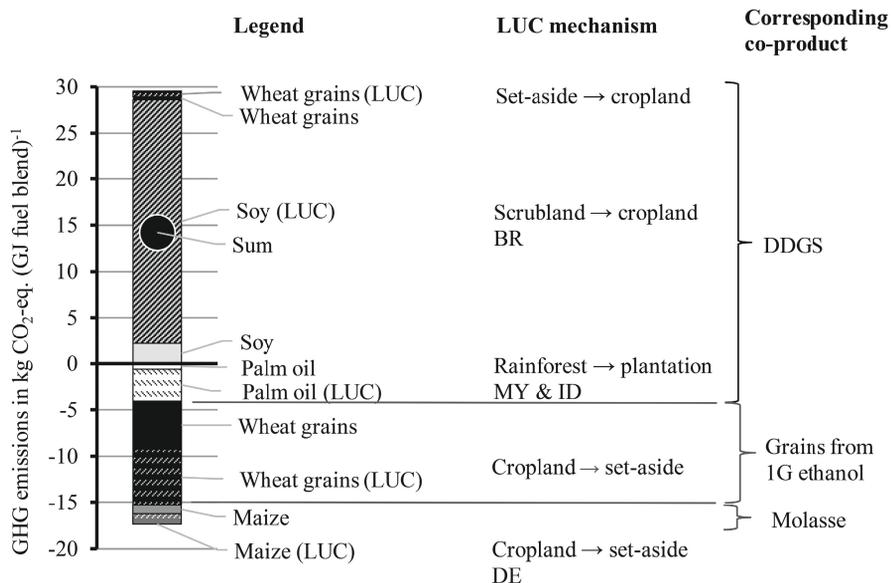


**Figure 5-6** Changes in GHG emission due to the introduction of 2G ethanol per GJ fuel blend (a total of 30644 GJ fuel blend is supplied to the market based on the BAU scenario. Roman numbers denote 2G concepts according to chapter 5.4.1.3. Abbr.: 1G – first generation; 2G – second generation; DDGS – dried distiller’s grains with solubles, LUC – land-use change, SOC – soil organic carbon.

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As an additional consequence of shifting production from 1G to 2G ethanol is that DDGS and electricity are no longer supplied through this process. The provision of feed replacing DDGS results in emissions of around 25 kg CO<sub>2</sub>-eq./ GJ ethanol, of which 93% stem from LUC (Figure 5-7). The largest contributors are soy cultivation and related LUC. This is due to relatively low yields and high carbon stock changes. The sum of emissions related to the substitution of feed products is around 14 kg CO<sub>2</sub>-eq./ GJ ethanol. The provision of feed is a major reason for an increase in emissions if 1G being replaced by 2G ethanol. Consequently, the provision of feed entailing lower emissions presents a major lever to reduce negative effects if political targets are put into practice.

These outcomes are highly relevant in the context of the current ongoing revision of the RED: the proposed reduction of the share of 1G biofuels and increase of the share of 2G biofuels will eventually trigger the replacement of the former by the latter (if the absolute energy demand in the transportation sector decreases as predicted) [440]. Thus, proposed legislation might trigger an increase in emissions. The magnitude of the increase in emissions is emphasized by the fact that certain 2G biofuels are at an advantage in the revised RED by considering their provision carbon-neutral up to the point of their collection, thereby resulting in higher *GHG savings*. Past works confirmed that this is not justifiable from a scientific point of view, cf. [273, 446]. As a consequence of an additional lowering of *GHG savings*, higher quantities of 1G fuel will be displaced by lower quantities of 2G biofuel resulting in higher shares of fossil fuels contained in the fuel blend.



**Figure 5-7** GHG emissions from agricultural production and LUC of substitutes of 2G ethanol production concept I (scenario 2.2). Abbr.: 1G – first generation; BR – Brazil; DDGS – dried distiller’s grains with solubles, DE – Germany, ID – Indonesia, LUC – land-use change, MY – Malaysia.

Based on these findings, two options are given to prevent or lower an increase in emissions due to the introduction of 2G fuels. Firstly, legislation should promote the production of 1G and 2G ethanol and ensure the displacement of fossil fuel (scenario 1). It should be noted that this does not imply an increase in production of 1G ethanol. Secondly, if the replacement of 1G by 2G ethanol is turned into practice as proposed, protein feed entailing low GHG emissions should be supplied from land that becomes available to prevent iLUC.

**Sensitivity analysis.** The sensitivity analysis shows that a change in heat demand or a change in conversion efficiency only slightly affects changes in emissions due to the simultaneous production of 1G and 2G ethanol or due to the shift from 1G to 2G ethanol (Figure B - 4 and Figure B - 5). Apart from a change in *GHG savings* as a key input parameter of the consequential approach, a change in heat demand and conversion efficiency affect the quantity of co-products that are provided, i.e. electricity and molasses. In certain cases, an increase in energy demand or a decrease in conversion efficiency will even lead to a (minor) decrease in emissions compared to the reference case. A change in *GHG savings* ranging from -15 to + 15% without a change in the quantity of co-products, e.g. due to a change in emissions from feedstock provision, results in a maximum relative change in results by 40% and a maximum absolute change in results by 2.8 kg CO<sub>2</sub>-eq./GJ fuel blend (Figure B - 6). Within the assessed range of changes in parameters, emission decreases (scenario 1) and emission increases (scenario 2) remained a decrease and an increase in emissions, respectively.

Emissions from LUC contribute a large extent to emissions (Figure 5-6 and Figure 5-7). The assessment of alternative LUC variants shows that:

- The increase in GHG emissions due to a shift from 1G to 2G ethanol will be lower, if land that becomes available due to the availability of wheat grains in scenario 2 turns into forest and settlement area. Such a LUC was observed in Germany between 2004 and 2014. The change in emissions ranges from 2 to 23% (Figure B - 7).
- A change in cultivation practice of soybean (reduced or no-tillage) has only a minor effect on results (Figure B - 8).
- A change in cultivation location and biome where LUC of soybean cultivation occurs can result in lower emissions than in the reference case. If moderately or severely degraded savanna is converted to soybean plantations in Southern Brazil, scenarios 2.1 and 2.2 will result in a (slight) decrease in overall emissions. In recent years, extensification of agricultural land has slowed in Brazil. However, in the Central West, where most of Brazilian soy is cultivated, extensification and intensification took place in parallel [488, 491]. Assuming that no LUC occurs, emissions will be reduced by a larger extent (Figure B - 8).

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- The conversion of peat land or native forest to oil palm plantations results in high LUC emissions. However, recent trends observed in Malaysia, as well as the moratorium on new oil palm plantations that was passed in Indonesia, indicate that LUC mechanisms might change. A change in LUC mechanisms of oil palm cultivation results in an increase in overall emissions if less CO<sub>2</sub> is emitted by the land conversion (Figure B - 9). This is due to the fact that soy bean feed, that needs to be supplied as a consequence of a shift from 1G to 2G ethanol production, supplied oil to the market. This oil is assumed to reduce the demand for palm oil. Thus, the decrease in emissions attributed to the system are lowered, if emissions entailed to the provision of palm oil are lower than assumed in the reference case.

Caveat: in case the substitution effects are too small to trigger changes in palm oil demand (due to low oil quantities of soy beans and low shares of DDGS in the overall feed market), the increase in emissions due to shift from 1G to 2G ethanol ranges from 20 to 28% among all concepts and scenarios.

**Limitations.** The assessment of consequences as a result of changes in production patterns requires the consideration of substitution mechanisms and changes in market behavior. Several aspects are not or only partially covered in this study, e.g.:

- The production of 2G ethanol from wheat straw as well as biogas from remaining stillage presents a challenge and has not been realized at a competitive scale yet.
- No decrease in grain yield due to straw harvest was assumed.
- No rebound effect of fossil fuel prices and resulting change in demand is considered. Other studies indicate a substantial rebound effect, cf. [492].
- The change prices of commodities will affect supply and demand of products and co-products.
- In certain cases, average production data (e.g. yield) is used. The marginal change in production might result in different conditions.
- A simplified model is applied to account for LUC and related emissions, which are part of a complex global agricultural commodity system: where and to what extent LUC, extensification and intensification occurs is estimated by a deterministic model.

The assessed scenarios could therefore be considered to present two extremes: In scenario 1, it is assumed that surplus ethanol fully replaces fossil fuel and in scenario 2, it is assumed that the demand for protein feed will be fully met by soybean meal and wheat grains stimulating agricultural expansion.

## 5.6. Conclusion

The current paper demonstrates how the introduction of novel liquid biofuels can be assessed in the context of the European legislation to support robust decision-making. Future studies can build thereupon and expand the analysis by including other fuels and extend the understanding of potential market mechanisms. A generalized framework that is valid in the context of the European legislation and markets and that can be applied to all fuel and mobility concepts, e.g. for biofuels and e-mobility alike, should be developed.

Under the given assumptions, the simultaneous production of 1G and 2G ethanol results in a decrease in emissions if surplus ethanol (from a doubling of production capacities plus minor surplus quantities due to blending regulations) replaces fossil fuels elsewhere. In contrast, the shift from 1G to 2G ethanol might increase GHG emissions:

- Emissions increase regardless of the 2G concept. The choice of the production concept of 2G ethanol is not of high importance regarding total changes in emissions that are triggered. Even higher conversion efficiencies or lower energy requirements do not change these findings.
- Direct emissions from 2G ethanol production play a minor role in comparison to changes in GHG emissions due to occurring substitution mechanisms. This is the case, if 1G ethanol is replaced by 2G ethanol under given assumptions: the provision of protein feed that is required to supply the market demand for feed might increase emissions. The largest source of emissions is LUC. The negative LUC emissions resulting from the occurring availability of wheat grains are, by far, outweighed by LUC emissions entailed to the supply of protein feed.
- A shift from a fuel with relatively low *GHG savings* (here: 1G ethanol) to a fuel with higher savings (here: 2G ethanol concepts) results in lower quantities of biofuel to be blended with fossil fuel and thus, higher quantities of fossil fuel contained in the blend.

It can be concluded, that the existing terminology “*GHG savings*”, as defined by the RED, is misleading: according to the RED’s terminology, 2G ethanol results in a decrease in GHG emissions, but the analysis of consequences of an introduction of 2G ethanol shows the opposite. The application of the RED methodology can serve the purpose of certification as it might give an indication of concepts emitting low emissions in the production phase but the methodology does not reflect occurring changes in emissions triggered by substitution mechanisms as a consequence of the introduction of a novel fuel. The analysis of these effects reveals that an increase in emissions might be triggered. The revised RED will eventually shape the European (and global) biofuel industry for the upcoming decades. The current draft of the RED indicates that mechanisms similar to those assessed in the current work will be promoted if total energy

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demand in the transport sector decreases. It can be concluded, that the new RED, if turned into practice as proposed, might not facilitate a reduction in GHG emissions while falsely claiming to do so.

A change in the demand for biofuels affects global food and feed markets and legislation should therefore target emissions (and other effects) of agricultural commodities in general, independently from their use as food, feed, fiber or fuel in order to avoid a shift of emissions from one market (e.g. biofuels) to another (e.g. feed). Likewise, a reduction in absolute GHG emissions can only be achieved by the coordination of concepts serving the needs for food, feed, fiber and fuel. It is therefore suggested to develop legislation that comprehensively addresses these demands and promotes those production concepts that entail lowest emissions while contributing to the fulfillment of the demands.

Consequential GHG balance of 2G bioethanol



# Potential changes in GHG emissions arising from the introduction of biorefineries combining biofuel and electrofuel production within the European Union – A location specific assessment

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Buchspies B, Kaltschmitt M, Neuling U (2020) Potential changes in GHG emissions arising from the introduction of biorefineries combining biofuel and electrofuel production within the European Union – A location specific assessment. (submitted)

## Chapter 6

### Abstract

In the upcoming decade, biofuels made from agricultural residues, wastes and by-products will most likely present an integral part of biofuel provision to achieve GHG reduction targets. But novel biorefineries using lignocellulosic biomass can provide multiple other products aside from fuel. To identify concepts that can contribute the most to reduce anthropogenic GHG emissions, it is important to evaluate potential changes in GHG emissions arising from the introduction of alternative fuel concepts. To this end, potential changes in GHG emissions arising from the introduction of 36 bioethanol concepts combining biorefineries and electrofuel production providing a broad spectrum of products (e.g. fuels, chemicals, feed and food additives) are assessed. A detailed analysis comprises feedstock and energy supply, as well as marginal displacement effects for 26 EU member states. The potential changes in GHG emissions arising from the introduction of these concepts range from -206 to 135 and from -221 to -17 g CO<sub>2</sub> per MJ of bioethanol provided from wheat grains and wheat straw, respectively. The analysis reveals a high variability in GHG intensities related to marginal feedstock and energy supply as well as displacement effects between countries. These wide variations arising thereof indicate that local conditions should be considered when long-term policy targets of alternative fuel provision are developed. The analysis furthermore shows that the methodology used within the EU to evaluate GHG emissions provided by the RED (II) excludes many concepts and production modalities that bear the potential to decrease GHG emissions.

## 6.1. Introduction

In recent years, governments world-wide implemented measures to promote the introduction of alternative technologies to provide non-fossil-based products and services. Steered by political decisions, most of these technologies had a clear focus on the energy and transportation sector. This ongoing transition towards non-fossil-based energy systems motivated by the need to reduce anthropogenic GHG emissions and to reduce the dependency on fossil resources has led to the advent of technologies that interlink sectors that were formerly mostly unconnected. For example, the introduction of biofuels provided by feedstock that is used as feed and food, so-called 1G biofuels, has interlinked fuel provision with the agricultural sector and thus with the global agricultural commodity markets. The recently introduced RED II [47] will additionally promote the introduction of renewable energy and alternative fuels within the EU for the period from 2021 to 2030. Beside this, the RED II aims at promoting biofuels made from agricultural residues, wastes, and by-products, so-called 2G biofuels.

At present, most conventional biorefineries that are currently providing biofuels and feed products. Novel biofuel production concepts bear the potential to provide multiple products beside energy, fuels and feed [61, 493]. Apart from organic components, CO<sub>2</sub> streams arising in fermentation and anaerobic digestion processes are suitable for many additional applications within the transportation sector and the chemical industry [494]. There are many assessments available evaluating potential environmental implications of such integrated biorefinery concepts providing manifold different products (e.g. [81, 495–497]). There are also several studies addressing the use of CO<sub>2</sub> or biogas for a subsequent production of methanol or other liquid and/or gaseous products [498, 499]. However, assessment of integrated biorefineries converting biomass arising CO<sub>2</sub> that comprehensively address the overall provision chain from biomass to fuel provision and beyond are scarce. The introduction of these concepts entails effects that go beyond the production chain itself by affecting local and global commodity markets. The impact of their market introduction therefore depends on the location and concept of the facility, the location where the feedstock is sourced and the local, regional, and/or international markets to which the respective products are provided to. So far, there are no studies available that evaluate changes in GHG emissions resulting from the introduction of novel biorefinery concepts that combine biofuel production with carbon capture and utilization of arising carbon streams as well as multiple other processes that convert side-streams to (base-)chemicals and food additives.

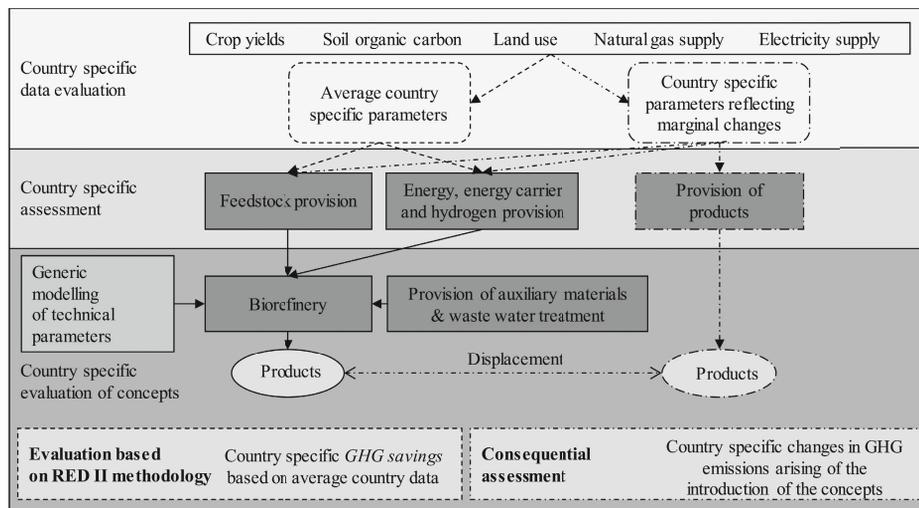
Therefore, the aim of this paper is to provide an in-depth assessment of the implications of the introduction of novel biorefinery concepts combining biorefinery processes with various additional processes ranging from electrofuel production to the provision of chemicals. To this end, a total of 36 concepts (four 1G concepts and eight 2G concepts plus additional CO<sub>2</sub> liquefaction, methanation or methanol synthesis) located in 26 EU member states are assessed. The evaluation

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considers potential changes in GHG emissions arising from the change in demand for feedstock and supply of provided products. This is accomplished by conducting a consequential GHG balance based on cLCA methodology [500]. Additionally, concepts are evaluated by the GHG assessment methodology provided by the RED II permitting access to the European biofuel market. This analysis is complemented by a sensitivity analysis comprising parameter variation and Monte Carlo simulation evaluating the sensitivity of results to the variability in biological parameters.

### 6.2. Materials and methods

The analysis evaluates potential changes in emissions resulting from a shift from straw incorporation (and present market supply of all other products that are potential substitutes of products provided by biorefineries) to biofuel production. For each of the 26 countries, the marginal energy supply and feedstock provision are assessed and used as an input to the biorefinery model. Furthermore, marginal suppliers are identified and GHG intensities are determined for all substitutes of products provided by the assessed biorefinery concept. The determined potential changes in GHG emissions are compared with *GHG savings* determined by the methodology provided by the RED II (Figure 6-1).



**Figure 6-1** Schematic depiction of the evaluation process. Dashed elements are contained in the assessment based on the RED II methodology applied to estimate *GHG savings*. Dash-dotted elements are part of the consequential approach that evaluates potential changes in GHG emissions arising from the introduction of the evaluated concepts; solid elements are contained in both analyses.

#### 6.2.1. Assessment of changes in GHG emissions

The analysis of changes in emissions uses GWP according to the IPCC [501]. Emissions of to the provision of auxiliary materials and energy are based on the ecoinvent database [502].

6.2.1.1. Marginal supply of feedstock provision: LUC

The change of land use results in changes in SOC and above-ground vegetation. The respective changes in GHG emissions are estimated based on Eq. 6-1 and Eq. 6-2 [89, 91]:

$$\Delta C = \frac{(SOC_0 + C_{veg_0}) - (SOC_{0-T} + C_{veg_{0-T}})}{T} \quad \text{Eq. 6-1}$$

$$SOC = \sum_{c,s,i} (SOC_{REF_{c,s,i}} F_{LU_{c,s,i}} F_{MG_{c,s,i}} F_{I_{c,s,i}}) \quad \text{Eq. 6-2}$$

The average annual change in carbon stocks ( $\Delta C$ ) of carbon contained in mineral soils and in aboveground biomass is determined by subtracting the SOC and carbon contained in biomass ( $C_{veg}$ ) after the land conversion from carbon stocks before the land conversion (Eq. 6-1). The overall change in carbon stocks is evenly distributed over a period ( $T$ ) of 20 years [89]. The SOC content is determined based on a reference carbon stock ( $SOC_{REF}$ ) and other factors ( $F_{LU}$ ,  $F_P$ ,  $F_{MG}$ ) accounting for land use type and land management under specific environmental conditions (e.g. climate, soil) (Eq. 6-2). The applied data and factors as well as resulting change in SOC that is attributed to feedstock provision and the production of displaced feed products are listed in Table C - 1 and Table C - 2. The removal of straw furthermore results in a decrease in SOC (or an avoidance of SOC formation). The applied methodology to determine the change in GHG emissions arising thereof is explained in a forthcoming publication [503].

6.2.1.2. Marginal supply of feed

Certain concepts provide feed displacing other feed products. A linear equation system is used to reflect the substitution of protein and metabolic energy content of feed. The replacement ratio is calculated by Eq. 6-3 and Eq. 6-4 [423]:

$$nXP_{co-product} = \lambda nXP_{protein\ feed} + \mu nXP_{cereal} \quad \text{Eq. 6-3}$$

$$ME_{co-product} = \lambda ME_{protein\ feed} + \mu ME_{cereal} \quad \text{Eq. 6-4}$$

The variables  $nXP$ ,  $ME$ ,  $\lambda$  and  $\mu$  denote the digestible protein content, the metabolizable energy for cattle and the displacement ratios, respectively [423]. The production of seed meal is coupled with the production of vegetable oil [424–426, 455]. When feed co-products displace supply of feed meal, seed oil production also ceases. This might trigger an increase in demand for vegetable oil that might be met by another marginal supplier. The supply of vegetable oil again might provide feed. This creates a loop of meal and oil supply. The methodology to account for this feed loop is explained in detail in [504].

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### 6.2.1.3. Marginal supply of energy and energy carriers

The provision of alternative fuels and energy carriers reduces the demand for conventional energy resources. For each product, the most likely marginal supply was determined on trade statistics and market analyses [505, 506]. Therefore changes in imports of natural gas and in electricity supply by source from 2012 to 2016 were analyzed. These were combined with GHG intensities of the respective fuel and electricity supply [502, 507].

### 6.2.2. GHG savings according to RED II methodology

The RED II provides a methodology to calculate *GHG savings* of biofuels. These determined *GHG savings* based on this mandatory approach comprise GHG emissions from feedstock provision, fuel production and use, as well as the provision of auxiliary materials and energy required within the overall conversion process. The multifunctional character of biorefineries is accounted for by allocating GHG emissions to all co-products, except for surplus electricity and captured CO<sub>2</sub> replacing fossil derived CO<sub>2</sub> in commercial products and services. In these two cases, credits are granted. The GHG emissions allocated to the evaluated fuel ( $GHG_f$ ) are finally compared to a reference value of 94 g CO<sub>2</sub>/MJ ( $GHG_p$ ) [47]:

$$GHG\ savings = \frac{GHG_f - GHG_b}{GHG_f} \quad \text{Eq. 6-5}$$

The allocation factor for each product is determined by dividing the energy content provided by the respective product (based on the lower heating value) by the total energetic output of the process. GWP of 1, 298 and 25 kg CO<sub>2</sub>-eq. per kg CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>, respectively, are applied. The directive sets minimum thresholds for (new) installations of 50, 60 and 65% for facilities in operation before 2015, as of 2015 and 2021, respectively. The RED II capped the use of 1G biofuels and promotes the use of residues, by-products, and wastes as feedstock for biofuel production by defining minimum quantities for fuels derived from 2G feedstock. Furthermore, agricultural by-products, such as straw, are considered residues to which no emissions from cultivation are allocated. The RED II methodology uses average production data. Therefore, average feedstock and energy supply were determined for all countries.

### 6.2.3. Sensitivity and uncertainty analysis

Statistical uncertainty (i.e. parameter variability) and model uncertainty are accounted for by Monte-Carlo simulations and a sensitivity analysis, respectively. Monte-Carlo simulation is a stochastic simulation technique generating parameter values randomly following predefined probability distributions [508]. Here, 5000 runs are computed for each model. Based on this approach the variability of most important biogenic parameters and parameters related to the conversion of biogenic material (e.g. pretreatment efficiencies, enzymatic hydrolysis and fermentation yields) is evaluated. Statistical distributions were derived from an extensive literature

research and subsequent statistical analysis (Table C - 4). Inventory data obtained from modelling is uncertain as well as no measurements of hypothetical facilities can be obtained. To assess the result's sensitivity to these model outputs, a sensitivity analysis is conducted that assesses the relative change in GHG emissions in response to a change in the most influential parameters.

### 6.3. System description

In total 36 concepts are analyzed. All concepts are based on a 1G ethanol facility using wheat grains or 2G facilities using wheat straw. For both types, standard concepts as well as elaborated concepts providing additional products are assessed (Table 6-1, Figure 6-2):

- 1G concepts – dry milling (concept abbreviation: **DM**) and wet milling (**WM**)
- 2G concepts – steam explosion (**SE**) and organosolv (**OS**) pre-treatment

In case of 1G facilities, 2 concepts to process arising side streams are evaluated for each concept:

- Feed production: DDGS (**DDGS**) and CDS (**CDS**)
- Anaerobic digestion to produce biogas (**BG**)

In case of 2G facilities, 4 concepts to process unfermented sugars were assessed for each pre-treatment method:

- Feed production: thickening of unfermented sugars to yield molasses (**MOL**)
- Anaerobic digestion to produce biogas (**BG**)
- Food additives: fermentation of xylose to produce xylitol (**XYL**)
- Co-fermentation: co-fermentation of pentose and hexose (**COF**)

The provided biogas is either upgraded or further processed to methane or methanol. In all concepts, biogenic CO<sub>2</sub> and is either liquefied or further processed to methane or methanol. Required hydrogen is provided through alkaline electrolysis. A CHP unit provides process energy. As a base case, energy provision of natural gas is assumed. Additional demands for electricity are fulfilled by electricity from the grid. In an alternative scenario, the CHP unit uses wheat straw and additional electricity is taken from renewable sources. All steam explosion concepts use lignin for energy provision.

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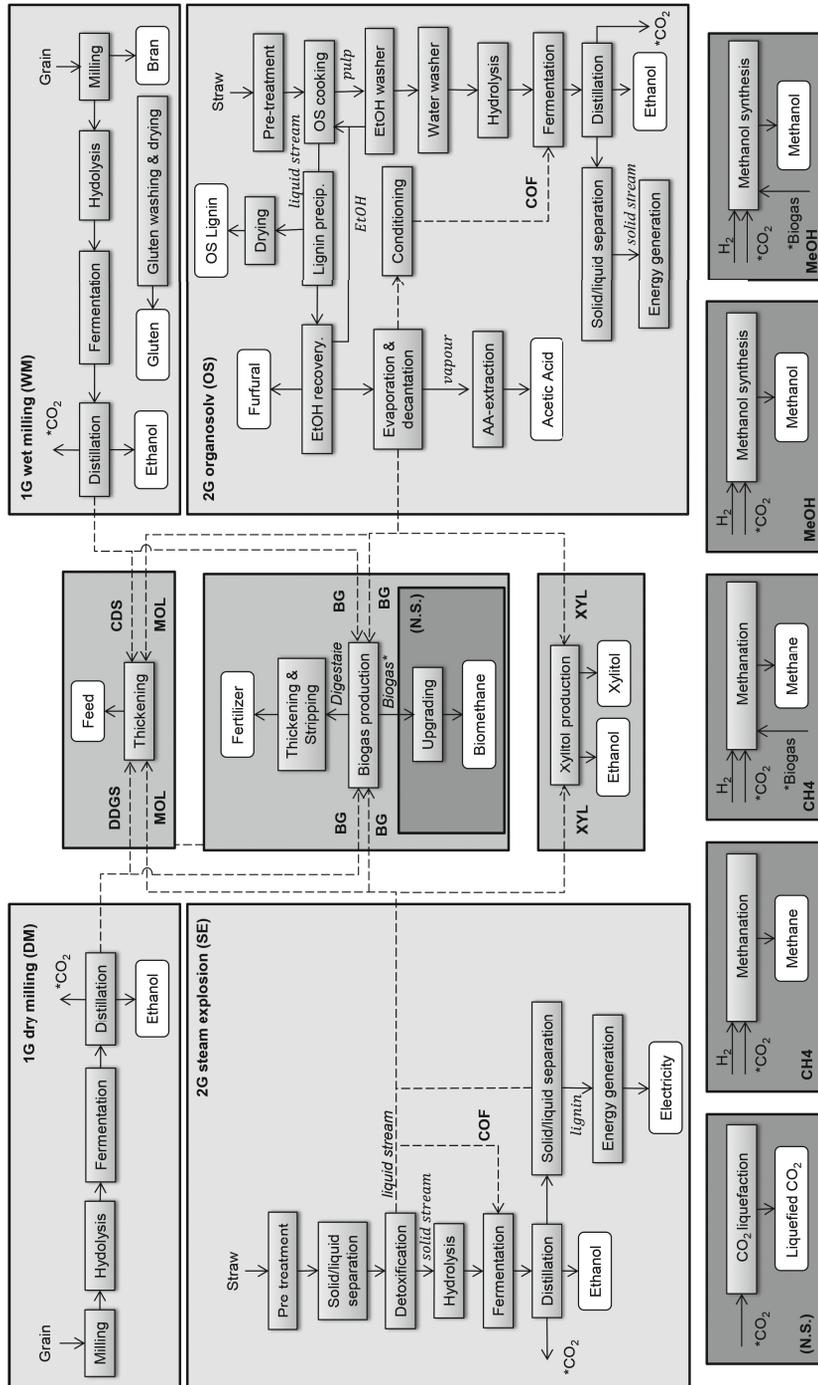
**Table 6-1** Ethanol production and CO<sub>2</sub> utilization concepts. In all cases, only glucose is fermented, except co-fermentation concepts.

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<b>First generation concepts</b>	
<i>Standard concepts: dry milling</i>	
1G DM DDGS	- drying of stillage to produce DDGS
1G DM BG	- stillage anaerobically digested to produce biogas
<hr/>	
<i>Elaborated concepts: wet milling</i>	
1G WM CDS	- bran separation, gluten washing and drying - Thickening of stillage to produce CDS
1G WM BG	- as 1G WM CDS but stillage is used to produce biogas
<hr/>	
<b>Second generation concepts</b>	
<i>Standard concepts: steam explosion</i>	
2G SE MOL	- steam explosion of wheat straw - thickening of C5 sugars to produce molasses
2G SE BG	- as 2G SE MOL but stillage is used to produce biogas, incl. upgrading and fertilizer production
2G SE XYL	- as 2G SE MOL but xylose is used to produce xylitol
2G SE COF	- as 2G SE MOL but co-fermentation of C5 and C6 sugars
<hr/>	
<i>Elaborated concepts: organosolv</i>	
2G OS MOL	- analogously to SE concepts but organosolv pretreatment, incl. production of OS
2G OS XYL	lignin, acetic acid and furfural
2G OS BG	
2G OS COF	
<hr/>	
<b>Additional processes for biogas and CO<sub>2</sub> utilization</b>	
1G DM BG	- biogas upgrading and mineral fertilizer production (ammonium stripping and solid
1G WM BG	organic fertilizer production)
2G SE BG	
2G OS BG	
+ CH <sub>4</sub>	- methanation of CO <sub>2</sub>
+ MeOH	- methanol synthesis from CO <sub>2</sub> and biogas (in BG concepts)

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Consequential GHG balance of 2G bioethanol with focus on location



**Figure 6-2** Assessed production concepts. Each concept consists of a combination of processes depicted in light, medium and dark grey boxes (one each). Bold abbreviations indicate the respective denomination of concepts as presented in Table 6-1.

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### 6.3.1. Feedstock cultivation and provision

The analyzed 1G and 2G concepts use wheat grain and wheat straw as feedstock, respectively:

- Wheat is cultivated in a conventional, intensive agricultural system. Yields, moisture, nutrient composition (N, P and K) and the grain to straw ratio are determined by statistical analysis (Table C - 3). Nutrients extracted through harvest are replaced by the application of mineral fertilizer. Wheat grains contain  $1.96 \cdot 10^{-2}$  kg N,  $3.44 \cdot 10^{-3}$  kg P and  $9.08 \cdot 10^{-3}$  kg K per kg DM. In 14 countries out of the overall assessed EU countries a (slight) decrease in cultivated land was observed between 2009 and 2015. In contrast, 8 countries report an increase in agricultural land [509]. Also, in many EU countries there is still a potential to increase yields [510]. The intensification of agriculture through additional fertilizer application bears risks to result in negative environmental consequences (e.g. GHG emissions, eutrophication). Compared to that, in countries, where production already operates at or near the optimum, further increase in yields seem unlikely. Additionally, increasing yields do not necessarily result in a reduction of cultivated land [260]. Thus, in the case of an increase in production of 1G fuels, the conversion of fallow land to wheat production is therefore assumed. The GHG emissions of the resulting LUC effects are listed in Table C - 2.
- Wheat straw contains  $5.96 \cdot 10^{-3}$  kg N,  $8.04 \cdot 10^{-4}$  kg P and  $6.97 \cdot 10^{-3}$  kg K per kg DM (Table C - 3). Again, these nutrients are replaced by mineral fertilizer. The harvestable straw taking sustainability criteria into consideration is 44.7% [273]. Due to the shift from straw incorporation to biofuel production, straw does not contribute any more to SOC formation. This results in a decrease in SOC due to a reduced SOC formation. The decrease in SOC amounts to 145 kg CO<sub>2</sub> per t DM of straw [503].

### 6.3.2. Biorefineries

The process elements comprised in the 36 evaluated concept setups are described below. Energy is provided by a natural gas boiler with a subsequent steam turbine. An overall efficiency of 0.85 and 0.8 is assumed in case of natural gas and biomass combustion, respectively [511]. The power to heat ratio is dependent on the respective energy requirements of each process setup. A detailed description and data used for the modelling and assessment of processes can be found in chapter C.2.

#### 6.3.2.1. Ethanol production

The composition of grain (starch, gluten and bran content) and straw (lignin, cellulose and hemicellulose) were determined by statistical analysis of literature data (Table C - 3). The conversion efficiencies are presented in Table C - 4. Two concepts of ethanol production of ethanol from wheat grains (1G) are assessed (Figure 6-2):

## Consequential GHG balance of 2G bioethanol with focus on location

- **Standard concept.** Wheat grains are milled in a dry-milling process. Subsequently, the contained starch is hydrolyzed and transformed to sugars by the aid of enzymes. Afterwards, the resulting sugars are fermented to yield ethanol. Stillage that remains after the distillation step is either dried to yield DDGS (**1G DM DDGS**), or used as feedstock for biogas production (**1G DM BG**).
- **Elaborated concept.** Before milling, bran is separated from grain. After milling, gluten is extracted by washing and drying. The arising stillage is either thickened to produce CDS (**1G WM CDS**) or sent to a biogas facility (**1G WM BG**).

Likewise, two concepts of ethanol from wheat straw (2G) are assessed (Figure 6-2):

- **Standard concept.** The wheat straw is pre-treated by steam explosion (210 °C, 5 min) [465] yielding a liquid phase rich in C5-sugars (e.g. xylose, arabinose) and a solid stream rich in lignin and C6-sugars (e.g. glucan, glucose and minor quantities of other C6 sugars). The severe pre-treatment conditions result in the formation of inhibitors, such as furfural, 5-hydroxymethylfurfural, acetic acid and formic acid that inhibit subsequent process steps [512]. Thus the streams are detoxified by and resin-wafer electro-deionization and washing, in case of the liquid and the solid stream, respectively [513, 514]. Afterwards, the solid stream is sent to hydrolysis. The overall process yields a solid stream (mainly consisting of lignin), that is combusted to provide process energy. The process furthermore generates a liquid stream composed of the liquid fraction after pre-treatment and the liquid phase separated after ethanol distillation. This stream, mainly consisting of xylose and minor quantities of other pentose sugars is either thickened to be sold as molasses (**2G SE MOL**), used as a feedstock for biogas production (**2G SE BG**), for xylitol production (**2G SE XYL**) or fermented together with the solid stream (**2G SE COF**). All concepts are described below.
- **Elaborated concept.** The organosolv pretreatment conditions need account for the aim of optimizing lignin output for a subsequent use as a substitute for phenol-formaldehyde resin and the output of ethanol. An auto-catalyzed ethanol organosolv pretreatment is conducted (ethanol concentration of 60% w./w., catalyst dose  $30 \cdot 10^{-3}$  Mol  $H_2SO_4$  L<sup>-1</sup>, 190 °C, 60 min) [515, 516]. After the ethanol organosolv pretreatment, pulp containing mainly hexose sugars is washed twice (once with ethanol and once with water). Afterwards hexose sugars that are contained in the delignified and detoxified pulp are hydrolyzed and subsequently fermented. The post-pretreatment liquid stream contains mainly dissolved lignin, xylose and furfural. The latter is extracted at the ethanol recovery stage and subsequently concentrated. The hydrolysis of acetyl groups can lead to the formation of acetic acid [517] to be extracted in a subsequent step. Analogously to the steam explosion concepts, the liquid stream is either used to produce molasses (**2G OS MOL**), biogas (**2G OS BG**), xylitol (**2G OS XYL**) or ethanol through co-fermentation of hexose and pentose sugars (**2G OS COF**). After

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distillation/rectification of ethanol, the remaining suspended solids are combusted to provide process energy while the liquid stream is processed in a waste-water treatment plant (**2G OS COF**) or is treated with the pentose sugar stream (all other concepts).

In all concepts, the purification of ethanol is accomplished by distillation/rectification and molecular sieves. Wastewater is treated in a waste-water treatment facility. Ethanol is assumed to be delivered 150 km to a filling station [464]. All process inputs and outputs are presented in chapter C.2.4.

### 6.3.2.2. *Unfermented sugar utilization*

All concepts yield a side stream consisting of unfermented sugars (e.g. pentose sugars in all 2G non co-fermentation concepts) and other components (concept-dependent). Several processes are considered that are combined with the aforementioned ethanol concepts:

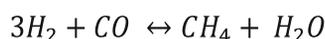
- **Feed production.** The side stream can be dried or thickened to generate feed products: DDGS, CDS, and molasses.
- **Biogas production.** The production of biogas from side streams arising from each bioethanol production concept (i.e. stillage as well as pentose sugars and unfermented hexose sugars, in case of 1G and 2G production concepts, respectively) was analyzed. The biogas potentials are 0.70, 0.74, 0.75 and 0.75 m<sup>3</sup> biogas per kg organic dry substance, in case of 1G dry milling, wet milling and 2G steam explosion and organosolv concepts, respectively, with a DM degradation of 65% [379, 470]. The methane contents of biogas are 55 and 49% in case of 1G concepts and 2G concepts, respectively. Ammonium sulfate is stripped from the digestate before it is dewatered through centrifugation and thermal drying. Conservatively, a gas leakage of 1% of the produced gas is assumed.
- **Xylitol production.** Xylitol is produced via fermentation by *Candida tropicalis* [518]. The unfermented glucose benefits the cell biomass growth and the xylitol yield. First, the liquor is de-toxified using activated charcoal, ionic resins and chromatographic separation [518, 519]. Subsequently, xylose is fermented with an output of 0.73 kg crystallized xylitol per kg xylose [518]. It is assumed that unfermented sugars from ethanol production are sufficient to sustain biomass growth and respiration. In addition, the fermentation yields CO<sub>2</sub> that is processed with CO<sub>2</sub> arising from ethanol fermentation. Xylitol is purified using ion exchange membranes and activated carbon to remove contaminants. Finally, after the removal of precipitates and subsequent vacuum distillation to increase xylitol concentration, xylitol crystallization is accomplished by adding ethanol and cooling to -20°C. The crystals are washed out and dried.
- **Ethanol production.** In case of 2G ethanol production, the co-fermentation of pentose sugars is considered (**2G SE COF and 2G OS COF**). Xylose and arabinose are fermented

with an efficiency of 93.0 and 54.0%, respectively [468, 520]. Unfermented sugars are thickened to yield feed (i.e. molasses).

### 6.3.2.3. $CO_2$ and biogas utilization: Liquefaction, methanation and methanol synthesis

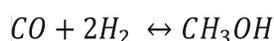
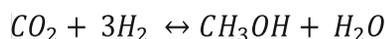
The  $CO_2$  produced by fermentation (all concepts) and anaerobic digestion (BG concepts) is a potential feedstock for additional products. In total, three concepts are assessed in combination with the aforementioned ethanol production concepts:

- **Liquefaction.**  $CO_2$  from ethanol fermentation is captured and liquefied. The product can be used in the chemical, beverage and food industry.
- **Biogas upgrading.** Biogas is cleaned and upgraded to biomethane and  $CO_2$ . Therefore, at first, biogas is de-sulfurized by activated carbon before being purified by pressure swing adsorption (PSA). Subsequently, biomethane is compressed and propane is added to meet grid requirements.
- **Methanation (+ $CH_4$ ).** Two process setups were developed for the processing of biogas and of pure  $CO_2$  captured from fermentation processes [521, 522]. The former process consists of biogas cleaning, (de-sulfurization), mixing of biogas with hydrogen, gas heating, methanation in a bubbling fluidized bed reactor and, finally, methane upgrading. In the reactor, the reverse water gas shift reaction and the methanation reaction are realized:

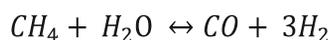
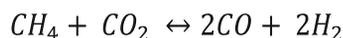


The overall methane yield is 98.7%. The required hydrogen is supplied by alkaline electrolysis.

- **Methanol synthesis (+MeOH).** The overall reaction is a combination of the reverse water gas shift reaction and the methanol synthesis from synthesis gas [523, 524]:

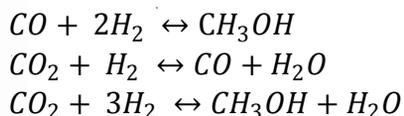


The reactor works with a molar  $H_2$  to  $CO_2$  ratio of 3 to 1 [523]. In BG concepts, methanol is synthesized directly from biogas. The data inventory is based on modelling results [525]. In these cases,  $H_2S$  is first removed. Subsequently methane is reformed (steam and dry reforming):



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After refining, methanol is synthesized:



A part of the biogas (16.3%-vol.) is used for energy provision of the reforming step. After the reforming, syngas is cleaned (water removal and a PSA to remove traces of hydrocarbons, nitrogen and CO<sub>2</sub>). Subsequently, a by-pass, a water gas shift reactor and a hybrid membrane-PSA are used to adjust the H<sub>2</sub> to CO ratio. It is assumed that the output of methanol can be increased by addition of hydrogen derived from electrolysis.

- **Electrolysis.** Hydrogen is supplied by alkaline electrolysis providing pressurized hydrogen. The applied efficiency of alkaline electrolysis is 68.6% (Table C - 5) [522].

### 6.3.3. Substitution mechanisms

In order to account for the provision of all productions provided by the biorefinery concepts, most likely marginal suppliers for all products provided by the respective concepts are identified (Table 6-2). A detailed description of substitution mechanisms and GHG intensity of the respective substitutes can be found in Tables C - 9 to C - 11. Feed products are assumed to replace a combination of feed products to complement the nutrient content (chapter 6.2.1.2).

**Table 6-2** Co-products and affected production systems.

Product	Affected production	Product	
<b>Acetic acid</b>	Acetic acid produced by methanol carbonylation	<b>Fertilizer</b>	Mineral fertilizer
<b>Biomethane</b>	Marginal natural gas supply	<b>Furfural</b>	Furfural production from corncob
<b>Bran</b>	Barley and oat	<b>Gluten</b>	Gluten from wheat and potato starch to compensate decrease in starch production from wheat
<b>CDS</b>	Soybean meal and wheat (plus additional palm oil production to compensate decrease in vegetable oil production)	<b>Molasses</b>	Corn
<b>CO<sub>2</sub></b>	Captured CO <sub>2</sub> from ammonia production	<b>Methanol</b>	Methanol from methanol synthesis of natural gas
<b>DDGS</b>	See CDS	<b>OS Lignin</b>	Phenol-formaldehyde resin production
<b>Electricity</b>	Marginal electricity supply	<b>Oxygen</b>	Oxygen production from air separation
<b>Ethanol</b>	Gasoline production from shale oil	<b>Xylitol</b>	Xylitol made from corn cob

## 6.4. Results and discussion

### 6.4.1. Changes in GHG emissions

#### 6.4.1.1. GHG intensity of energy supply

The evaluation of country-specific changes in GHG emissions arising from the introduction of the evaluated fuel concepts uses country-specific GHG intensities of marginal supply and displacement of natural gas and electricity. The analysis of GHG intensities of electricity and natural supply for all EU member states except Cyprus and Malta are presented in Table 6-3. The evaluation reveals that in most countries, there is a trend towards less GHG intensive electricity generation. The Netherlands and Czech Republic exhibit the highest marginal GHG intensities of electricity due to a high share of fossil-based electricity generation: 77 and 46% of the marginal increase of supply is derived from natural gas and bituminous coal, respectively. Interestingly, electricity supply in France shifts towards renewable sources leading to an increase in the overall GHG intensity of the marginal energy supply. This is due to the presently high share of nuclear power (entailing low GHG emissions).

The analysis of European gas trading statistics shows that in most countries, domestic supply decreases while imports from extra-European natural gas trading partners increases. The most important trading partner is Russia which supplies most of the increase in natural gas to EU member states. The results furthermore reveal that the marginal GHG intensity of natural gas supply increases in the majority of countries. The decline in domestic natural gas production from conventional sources and the increasing imports entailing higher GHG intensities are important aspects to consider when making decisions on introducing bioenergy provision concepts using natural gas for energy supply.

Caveat: that the period from 2012 to 2016 was assessed because 2016 was the last year for which all data was available. The marginal change in electricity generation might have changed since then in certain cases.

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**Table 6-3** GHG intensity of energy supply within the EU in g CO<sub>2</sub>-eq. per MJ. The reference year is 2016. Marginal suppliers were identified based on change between 2012 and 2016. The average GHG intensity of electricity was derived from [526]. Countries are abbreviated according to the International Organization for Standardization (ISO) standard 3166 [221].

	Electricity					Natural gas				
	All sources			Renewables		Average	Marginal increase	Marginal decrease	Supplier	Supplier
	Average	Marginal increase	Marginal decrease	Average	Marginal increase					
AT	23.64	8.25	249.79	47.99	7.68	33.59	RU	35.88	AT	16.80
BE	47.11	24.74	142.78	38.39	16.46	12.18	RU	35.88	QA	25.20
BG	130.61	56.75	396.04	56.55	18.73	38.81	RU	40.22	RU	40.22
HR	58.33	9.72	242.69	54.43	8.30	17.80	RU	40.22	HR	16.80
CZ	142.42	116.32	178.48	82.53	37.59	31.83	RU	35.88	CZ	16.80
DK	46.14	11.82	271.60	26.27	11.82	7.83	NO	9.33	DK	8.08
EE	227.47	144.67	662.05	20.18	12.23	18.99	RU	35.88	RU	35.88
FI	31.33	17.74	256.65	32.53	14.07	27.34	RU	28.77	RU	28.77
FR	16.25	39.39	53.62	49.77	9.91	14.17	RU	35.88	FR	18.82
DE	122.44	78.78	127.22	71.33	25.21	27.44	RU	35.88	DK	11.27
GR	173.06	48.27	330.81	53.27	17.96	36.94	RU	53.56	EG	53.56
HU	72.33	66.86	282.79	35.05	30.21	33.42	RU	35.88	HU	24.42
IE	118.03	89.62	175.93	27.36	6.88	11.27	IE	11.41	UK	11.41
IT	71.17	22.49	201.19	62.48	22.49	31.86	RU	40.22	IT	16.71
LV	29.14	22.06	40.18	56.60	22.06	32.84	RU	35.88	RU	35.88
LT	5.00	13.55	231.77	45.63	13.55	22.72	NO	12.59	RU	35.88
LU	60.92	12.37	270.59	55.65	12.37	20.33	DZ	45.14	QA	25.20
NL	140.33	215.65	158.19	53.77	15.85	14.17	RU	35.88	DK	11.27
PL	214.81	57.12	299.76	50.59	11.85	26.38	RU	35.88	PL	12.64
PT	90.19	80.98	207.48	43.48	14.32	15.27	DZ	45.14	NG	25.01
RO	85.00	30.37	290.63	50.46	13.40	22.40	RU	40.22	RO	19.87
SK	36.75	23.77	213.54	57.78	23.77	33.88	RU	35.88	SK	18.82
SI	70.58	11.88	138.53	54.81	11.88	38.02	RU	35.88	DZ	53.56
ES	73.72	16.06	230.33	38.76	12.02	14.17	DZ	45.14	TT	23.60
SE	3.69	6.96	97.08	41.00	8.08	6.63	DK	8.08	DK	8.08
UK	78.08	9.68	285.27	40.59	10.09	8.76	NO	9.33	QA	22.86

### 6.4.1.2. Base case: natural gas and grid electricity

The introduction of the analyzed biofuel concepts increases the demand for wheat grains and straw in case of 1G and 2G concepts, respectively. The change in demand for wheat grains could lead to an increase in land used for wheat cultivation. The SOC content of top-soils ranges from 45 to 156 t C per ha corresponding to GHG emissions of 0.17 to 1.6 kg CO<sub>2</sub> per kg of wheat grain (Table C - 2). As a consequence, most 1G concepts result in a lower net reduction in GHG emissions (if at all). Among these concepts, the provision of DDGS results in the highest net reductions ranging from -206 to -24 g CO<sub>2</sub>-eq. per MJ of fuel produced (Figure 6-3). The increase in production of ethanol by other 1G concepts results in net changes in emissions ranging from -86

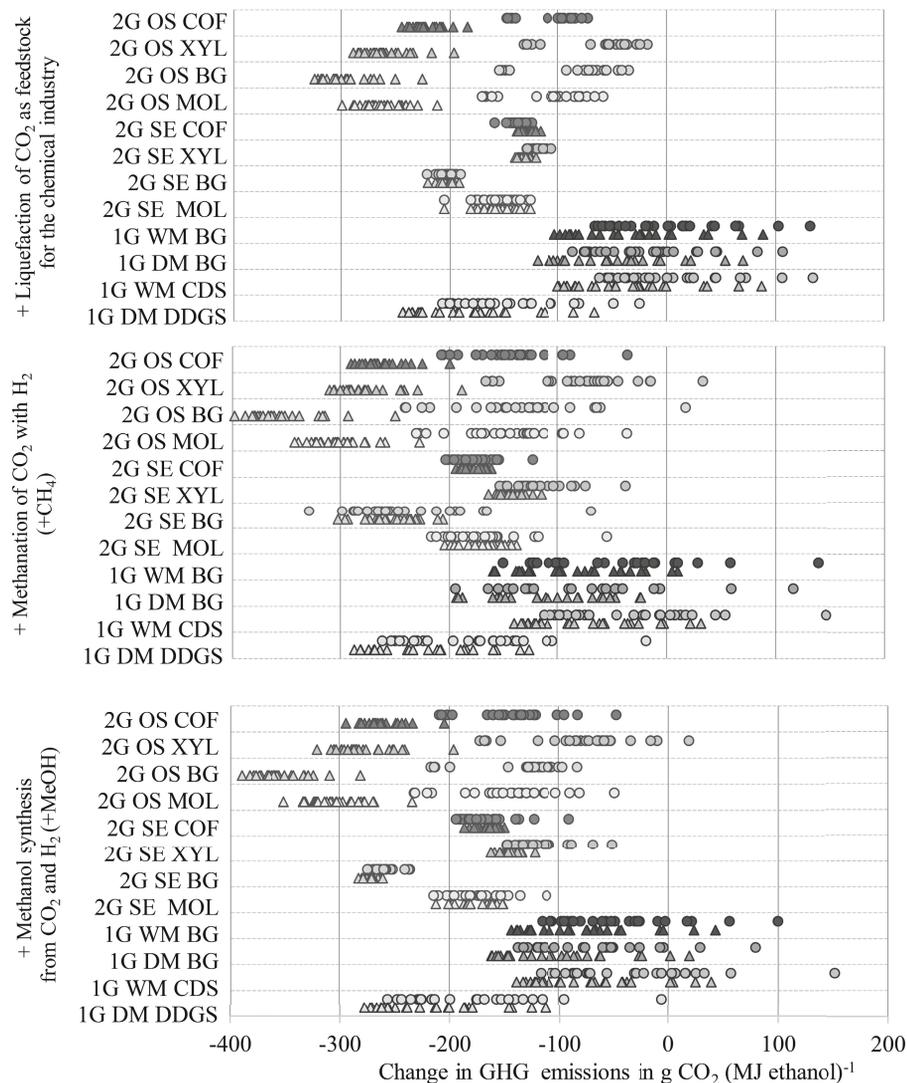
## Consequential GHG balance of 2G bioethanol with focus on location

to 135 g CO<sub>2</sub>-eq. per MJ. Highest net increases in emissions are determined for Estonia, Finland, Latvia and Lithuania. The conversion of land and arising emissions combined with comparably low wheat yields result in considerable GHG emissions. In Estonia, high LUC emissions could occur: 203 and 231 g CO<sub>2</sub>-eq. per MJ of ethanol in case of 1G dry milling (1G DM) and 1G wet milling (1G WM) concepts, respectively. Highest net reductions could potentially arise if facilities are located in Denmark, Bulgaria, Italy, Croatia and France. Denmark, as opposed to many other countries, increased natural gas imports from Norway, while in most other countries the overall share of imports from Russia constitutes the highest share of total imports. This corresponds to low GHG emissions entailed to the marginal supply of natural gas.

All of the assessed 2G concepts result in potential net decreases in emissions in all assessed countries. The highest net reductions can be achieved with steam explosion and the use of lignin as energy carrier (2G SE). In these concepts, the net reduction in emissions ranges from -221 to -105 g CO<sub>2</sub>-eq. per MJ ethanol produced. Organosolv concepts (2G OS) potentially reduce net GHG emissions between -170 and -17 g CO<sub>2</sub>-eq. per MJ ethanol. In case of 2G steam explosion concepts (2G SE), the marginal electricity mix plays a more important role because less natural gas is required. Therefore, facilities located in countries like the United Kingdom, Ireland, Lithuania, Sweden and Denmark exhibit highest net reductions in GHG emissions (Table 6-3). Certain 2G concepts (i.e. molasses production, 2G OS/SE MOL) are self-sufficient in energy supply and even export low quantities of electricity. These concepts result in lowest net GHG reductions in countries like France, Italy or Slovenia. In these countries, observed trends in electricity supply indicate that electricity entailing comparably low GHG emissions decreased within the assessed period. Thus, other countries, where electricity supply potentially contributes to the displacement of electricity generation entailing high GHG emissions, higher reductions can be observed. In contrast, the organosolv concepts have a high energy demand and lignin is not energetically used. The provision of xylitol (2G OS/SE XYL) results in the lowest reduction in GHG emissions. This is due to the fact that another (less efficient) production of a biogenic product made from residues is assumed to be replaced.

Additional methanation (+MeOH) and methanol synthesis (+CH<sub>3</sub>) results in a higher net reduction in GHG emissions for most concepts in most countries. Only in the Czech Republic, Estonia and the Netherlands, most of concepts result in lower net reductions in GHG emissions as a consequence of additional use of the arising CO<sub>2</sub> stream. This is due to comparably high GHG emissions related to marginal electricity supply and low GHG intensities of the marginal decrease in natural gas. This can even lead to an overall increase in emissions if these concepts are introduced to the market. Similar results can be observed in case of additional methanol synthesis.

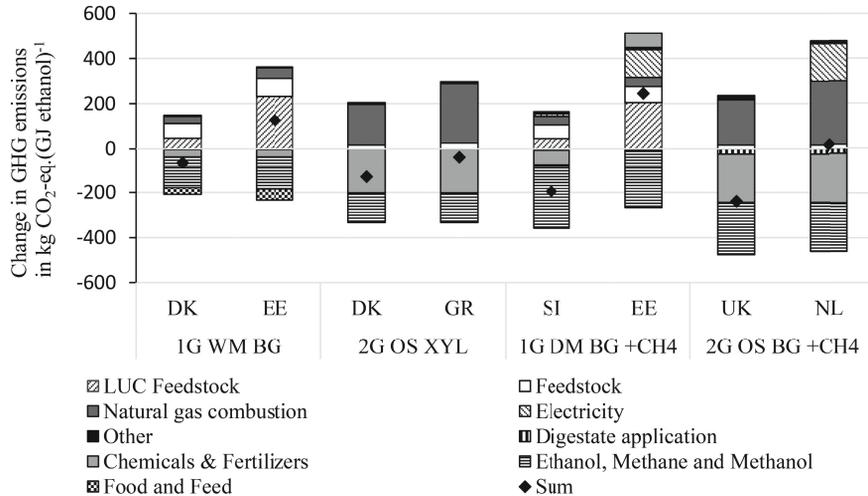
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**Figure 6-3** Change in GHG emissions resulting from the increase in production of bioethanol and respective co-products in g CO<sub>2</sub>-eq. per MJ ethanol. Circles present conventional energy supply by marginal natural gas and marginal grid electricity. Triangle present results if renewable energy is used (straw for process heat and the marginal renewable energy mix if additional electricity is required).

To illustrate the extent of LUC emissions, emissions entailed to energy provision and the influence of the marginal supplier on a selection of processes, highest and lowest cases for four selected concepts are depicted in Figure 6-4. The high variation of potential LUC emissions arises from different yields and top-soil SOC contents. The provided products partly displace products within the country of production. However, these positive effects do not outweigh the potential effects arising from feedstock provision. Furthermore, it can be seen that marginal supply of natural gas highly

influences production emissions and reductions in emissions attributed to the respective production systems. The largest emission reductions occurring at the organosolv concept mainly arise from the provision of ethanol and lignin (substitution of phenol-formaldehyde resin) contributing by 38 and 32% to overall reductions in emissions, respectively. The provision of food additives, i.e. gluten and xylitol, do not result in high reductions in GHG emissions in comparison to other products.



**Figure 6-4** Change in GHG emissions arising from the increase in production of a selection of processes and locations in g CO<sub>2</sub>-eq. per MJ ethanol. The displayed concepts exhibit the highest difference between minimum and maximum change in GHG emissions in different locations of base concepts (without electrofuel production) and with methanation (+CH<sub>4</sub>).

6.4.1.3. Renewable energy: straw and renewable electricity

If energy is supplied by renewable sources instead, potential changes in GHG emissions arising from the introduction of 1G concepts range from, -243 to -66 and from -120 to 89 g CO<sub>2</sub>-eq. per MJ of ethanol produced, in case of 1G combined with DDGS production and in case of all other 1G concepts, respectively. The effect of using renewable energy is less pronounced in case of 1G concepts due to the high contribution of feedstock provision (incl. LUC) to the overall emissions. The share of feedstock provision ranges from 52 to 64 and 59 to 72% of the overall emissions, if fossil energy is used. For this reason, concepts resulting in the lowest and highest overall net reductions are in most cases similar to those countries in case of fossil energy provision. The smallest or even counterproductive effects can be observed in case of 2G steam explosion concepts providing molasses (2G SE MOL) which are completely self-sufficient in energy supply. The lower overall efficiency of energy generation from straw (compared to natural gas) results in a less efficient energy generation and thus, less electricity which is provided by the concept. In these cases a minor increase in emissions can be observed. In all other steam explosion concepts (2G SE), the use of renewable energies only has minor effects on overall results. In contrast, 2G

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concepts using organosolv pretreatment (2G OS) result in considerably lower GHG emissions and therefore in much higher potential net reductions ranging from -324 to -184 g CO<sub>2</sub>-eq. per MJ of ethanol provided. The best locations of 2G concepts are Austria, Sweden, the United Kingdom and Ireland. These are also those countries exhibiting the lowest GHG intensity of marginal renewable electricity supply. The additional provision of methane and methanol increases the net reduction in GHG emissions in all cases. The potential benefits are smallest, in those countries in which the marginal supply of electricity considering all electricity sources is comprised by a high share of renewables. Thus, the consideration of the marginal increase in renewable electricity does not differ much from the marginal increase in the overall supply (e.g. Austria).

### 6.4.2. GHG savings according to RED II methodology

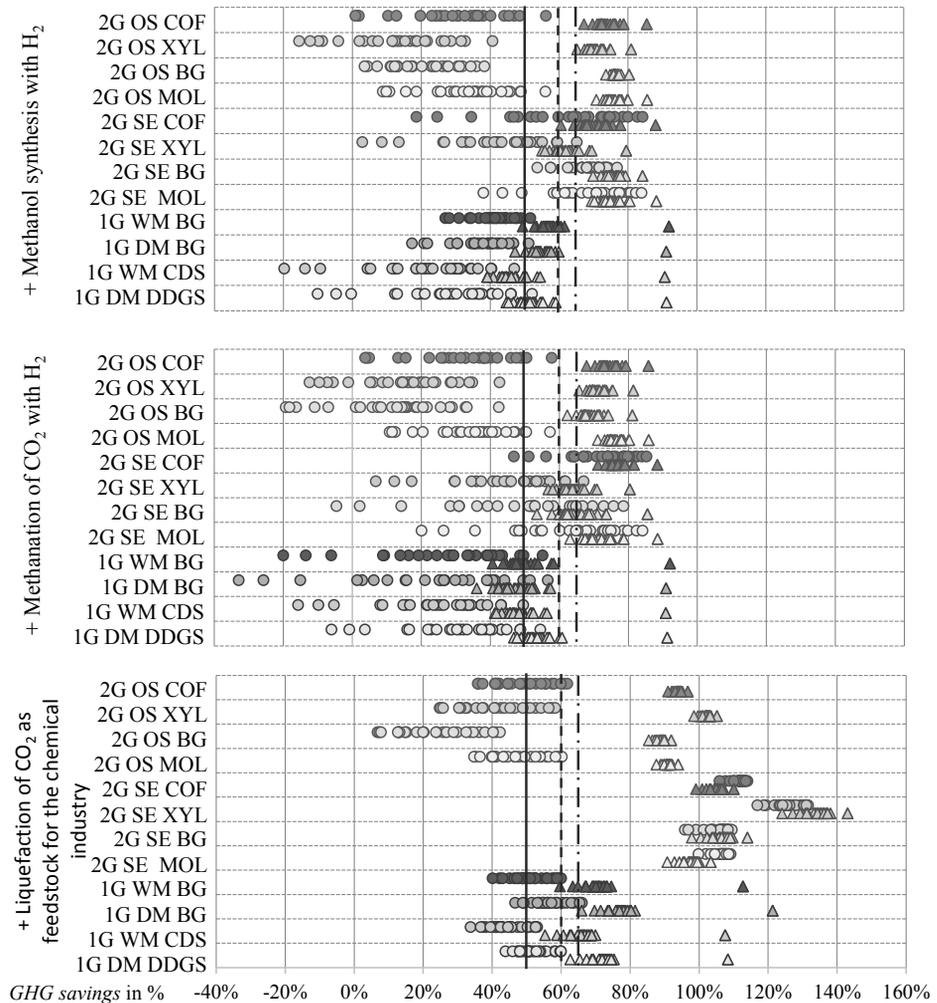
#### 6.4.2.1. Base case: natural gas and grid electricity

The RED II sets minimum *GHG saving* thresholds of 50, 60 and 65% for facilities that started operation before October 2015, facilities that started operation as of October 2015 and that will commence operation after 2020, respectively. The minimum *GHG savings* threshold defined by the RED II grants or denies access to new installations to the European biofuel market. The assessment of *GHG savings* of 1G concepts reveals a high variability among concepts in different countries: the *GHG savings* range from 44 to 60, 34 to 53, 47 to 66 and 47 to 66% in case of protein feed provision (DDGS, feed and food additives production (bran, CDS and gluten)), and biogas (based on dry milling and wet milling (1G BG DM and 1G BG WM), respectively. The most commonly applied concept to produce bioethanol within the EU to date (1G DM DDGS) complies with the minimum *GHG saving* thresholds of facilities in operation since before 2015 in 18 out of 26 countries (Figure 6-5).

Highest *GHG savings* are achieved with a similar ethanol base concept but biogas production instead of feed production. The 1G biogas concept based on dry milling (1G DM BG) reaches the minimum *GHG saving* requirements for new installations as of 2020 and 2021 in 8 and 3 countries, respectively. The extraction and processing of other valuable co-products, e.g. gluten, does not increase the *GHG savings* achieved by the respective concept. The higher energy demand of the process results in lower overall *GHG savings*. Additionally, the higher ethanol yields are achieved in dry milling concepts in comparison to wet milling concepts. The provision of wheat grains accounts for up to 77 and 87% of total emissions for dry milling and wet milling concepts, respectively. Because there is no additional electricity required, the variability of *GHG savings* of the 1G dry milling concept supplying DDGS among different countries mainly originates from wheat cultivation yields and varying GHG intensities of natural gas supply. Highest cultivation emissions and GHG intensities of average natural gas supply occur in Greece, Portugal and Estonia, as well as Slovenia, Bulgaria and Greece, respectively. Consequently, the lowest *GHG savings* are achieved in these five countries. Likewise, highest savings are reached in countries where natural gas supply

## Consequential GHG balance of 2G bioethanol with focus on location

entails low GHG emissions, i.e. the UK, Sweden and Denmark. The RED II capped the use of 1G biofuels that can be counted towards overall renewable energy targets to a maximum of 7% of the final energy consumption in each member state or at maximum 1%-p. higher than the consumption in 2021. Aside from these restrictions, minimum *GHG savings* are going to increase as of 2020 and 2021 denying access to new installations based on most 1G concepts. Only the biogas concept based on dry milling and wet milling comply with the requirements as of 2021 in eight and one countries, respectively. None of the concepts reaches minimum *GHG saving* requirements as of 2026.



**Figure 6-5** *GHG savings* according to RED II methodology for all concepts produced in 26 EU member states. The red solid, dashed and dash-dot lines present the minimum *GHG savings* for new installations starting operation before 2015, as of 2015 and 2021, respectively. Circles present conventional energy supply by marginal natural gas and marginal grid electricity. Triangle present results if renewable energy is used (straw for process heat and the marginal renewable energy mix if additional electricity is required).

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The compliance of straw-based bioethanol (2G) production with minimum *GHG savings* depends on the use of lignin: at present state of development, many 2G concepts are highly energy intensive and the provision of process energy entails high fossil GHG emissions, if it is supplied by fossil energy carriers. If lignin is processed to be used as a product for the further production of chemicals, energy needs to be supplied by other means than lignin. Consequently, the assessed organosolv concepts (2G OS) entail high GHG emissions if natural gas is used as an energy carrier. The concepts result in *GHG savings* ranging from 35 to 60, 7 to 42, 25 to 58 and 36 to 62% in case of concepts providing molasses (MOL), biogas (BG), xylitol (XYL) and the concepts using co-fermentation (COF), respectively. Only 42, 35 and 25% of all locations and organosolv concepts comply with minimum requirements as of 2015 in case of co-fermentation, and concepts providing molasses or xylitol, respectively. In light of the technical status of 2G organosolv concepts, it seems therefore questionable if such concepts will enter the biofuel market under the RED II and subordinate national legislation at all (if no significant reductions in energy demand are achieved or renewable energies are used). In contrast, assessed 2G concepts using lignin for internal heat provision result in higher *GHG savings*: 100 to 109, 96 to 110, 117 to 132 and 106 to 104% in case of 2G steam explosion concepts (2G SE) providing molasses (MOL), biogas (BG), xylitol (XYL) or concepts based on co-fermentation (COF), respectively. Thus, all concepts comprising steam explosion of wheat straw and internal heat provision by lignin comply with minimum *GHG saving* requirements as of 2021 in in all countries regardless of the location.

The additional provision of methane or methanol from the captured biogenic CO<sub>2</sub> lowers *GHG savings*, if electricity is drawn from the grid. In these cases, *GHG savings* are reduced in 98 and 61% of all possible combinations of concepts and locations in case of additional methane and methanol production, respectively. This is due to the credit that is granted for liquefied CO<sub>2</sub> by the RED II methodology. The RED II states that credits are granted for CO<sub>2</sub> that is “*used to replace fossil-derived CO<sub>2</sub> in production of commercial products and services*” [47]. A strict interpretation of this rule triggers the observed effects. If conventional fossil methane or methanol are considered as the reference, the use of arising CO<sub>2</sub> for electrofuel production should not be credited as it does not replace CO<sub>2</sub> in commercial products (it displaces the emission of CO<sub>2</sub> from commercial products). If a replacement of fossil-derived CO<sub>2</sub> in other power-to-liquid or power-to-gas processes is assumed as a reference instead, credits could be granted according to the quoted definition. This however entails several inconsistencies of the RED II methodology:

- If the biorefinery sold biogenic CO<sub>2</sub> as a feedstock for synthesis processes, credits could be granted. This however grants credits for displacements that do not occur: if biogenic CO<sub>2</sub> displaced captured fossil CO<sub>2</sub> in the synthesis processes, the fossil CO<sub>2</sub> would be emitted instead of being captured (as it is a waste gas stream and thus an inflexible “supply”). Thus,

in sum, no net reduction in CO<sub>2</sub> arises from the carbon balance. Consequently, a credit is not justifiable based on the carbon balance.

- If the synthesis processes are integrated into the biorefinery, no CO<sub>2</sub> stream arises and thus, no credit can be granted. In this case, another product arises to which emissions are allocated.

It is inconsistent to apply two different approaches depending on whether the captured biogenic CO<sub>2</sub> is sold to downstream synthesis processes or used within the biorefinery for synthesis processes. In the former case, applying credits implies displacement effects that do not occur. In the latter case, allocation emissions might even lower overall *GHG savings* of the primary products (in this case, bioethanol).

These aspects present a predicament: on the one hand, not granting credits might reduce incentives to additionally provide feedstock to synthesis processes (especially if blending mechanisms based on *GHG savings* are in place resulting in differing market values according to the achieved *GHG saving*). On the other hand, granting credits implies displacement effects that do not occur. Furthermore, this requires a revision of the allocation principle within the RED II: all products produced from arising CO<sub>2</sub> must be excluded from the allocation rule if credits are granted.

#### 6.4.2.2. Renewable energy: straw and renewable electricity

The use of renewable energies to supply process heat and electricity considerably increases *GHG savings* of all 1G and 2G organosolv concepts (Figure 6-5). The effect is more pronounced in case of organosolv because energy provision constitutes a high share of overall emissions (if supplied by fossil energy carriers). The effect is less pronounced in case of 1G concepts due to the high contribution of feedstock provision to the overall GHG emissions. Grain-based ethanol production performs best in countries with lowest emissions entailed to grain cultivation, i.e. Ireland, Netherlands, United Kingdom, Germany and Denmark. In case of 2G steam explosion concepts, only the concept providing xylitol (2G SE XYL) benefits from the utilization of renewable energies. In all other steam explosion concepts, most or all of the process energy can be supplied by lignin combustion. In general, the variability of results is lower if straw is used as energy carrier instead of natural gas due to the lower variability in emission related to the provision of the energy carrier.

#### 6.4.3. Sensitivity analysis

The sensitivity of results to changes in heat demand, GHG intensity of natural gas supply and the GHG intensity of displaced products can be summarized as follows:

- Due to the high contribution of energy supply in organosolv concepts, these concepts are most affected by changes in the GHG intensity of natural gas supply or overall heat demand

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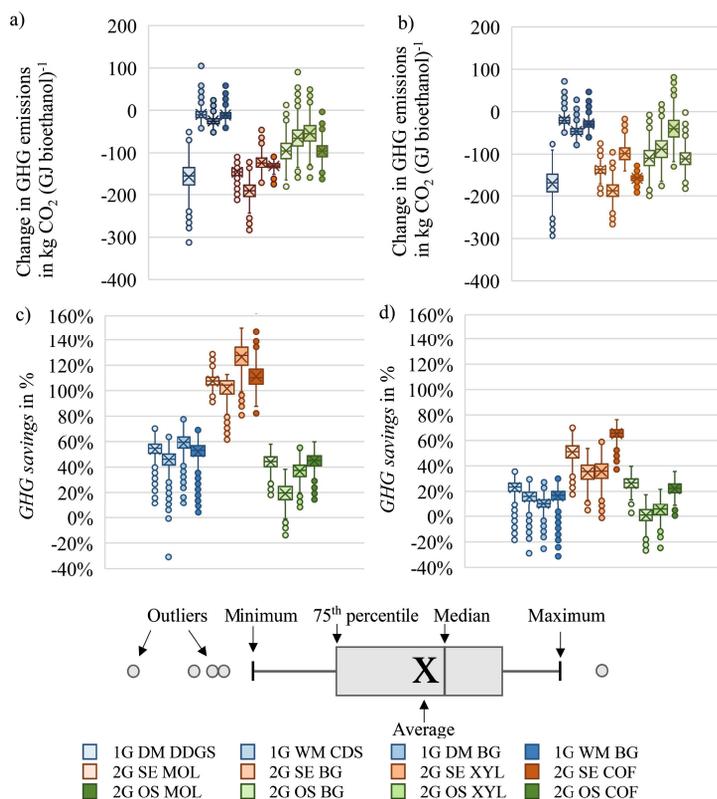
(Figure C - 1 and Figure C - 2). This is due to the high contribution of energy supply to the overall GHG emissions. The 1G concepts are less affected due to the higher contribution of feedstock supply. Only in certain cases, a change in the GHG intensity natural gas supply or in the heat demand by up to 20% changes an overall net decrease resulting from the introduction of biorefinery concepts to an increase. However, in most cases, a net reduction in GHG emissions resulting from the introduction of fuels remains a net reduction;

- A change in electricity demand or the GHG intensity of electricity supply only has little effects (Figure C - 3). In many countries, the marginal electricity supply is comprised mainly of electricity from renewables. Only in countries, where the marginal supply of electricity still contains considerable shares of electricity from fossil resources, overall results will be affected. Again, for almost all cases, a determined net reduction or increase will remain and reduction or increase, respectively, if the GHG intensity of electricity supply or the electricity demand increases.
- A change in the GHG intensity of displaced products or the quantity of products displaced has the highest effect on results (Figure C - 4). However, in most cases concepts that result in a net reduction in GHG emissions still result in a net reduction in emissions, even if the GHG intensity changes.

A Monte Carlo simulation was conducted to provide insights into the variability of results as a consequence of the inherent variability of biological parameters and processes. The analysis shows that the variability of changes in GHG emissions is highest in the 1G concept providing DDGS (Figure 6-6 a) and b)). This is due to the high influence of the GHG intensity of displaced protein feed. Less efficient fermentation processes yield higher quantities of feed and thus, displace more protein feed. The probability of 1G concepts to result in an increase in GHG emissions due to variability in biological parameters is 0, 17, 2 and 13% in case of the provision of protein feed (1G DM DDGS), food and feed additives (1G WM CDS), and biogas (dry milling and wet milling, 1G DM/WM BG), respectively. In case of 2G concepts, the highest variability arises from the energy demand per biofuel output. Therefore, there is fewer variation in concepts using steam explosion. In 2G concepts providing biomethane an even higher variation arises from the dependency of biogas on upstream processes and the variation in biogas yield. Among 2G concepts, only the organosolv concept providing biogas (2G OS BG) and xylitol (2G OS XYL) the variability of biological parameters results in low chances to result in a net increase in GHG emissions (i.e. 2 and 3%, respectively). The additional provision of methane from captured biogenic CO<sub>2</sub> lowers overall net reductions in GHG emissions. There is only a minor influence of additional methane production on the overall variability in results. The variability in *GHG savings* is highest in concepts providing biogas and xylitol (Figure 6-6 c) and d)). The other concepts only show a less pronounced variation of results. This is because emissions are allocated to all products, except

## Consequential GHG balance of 2G bioethanol with focus on location

for captured CO<sub>2</sub> and electricity. Thus, concepts providing more CO<sub>2</sub> show a higher variability in results (if no methane is additionally produced).



**Figure 6-6** Results of the Monte Carlo simulation (5000 runs) for concepts located in Germany. Parts a) and b) depict the variability of changes in GHG emissions in g CO<sub>2</sub>-eq. per MJ bioethanol with CO<sub>2</sub> liquefaction and methane production, respectively. Parts c) and d) depict *GHG savings* of these concepts. Abbr.: Pre-treatment: DM – dry milling, OS – organosolv, SE – steam explosion, WM – wet milling; Sugar stream processing: BG – biogas production, COF – co-fermentation (molasses production from unfermented sugars), MOL – molasses production from pentose and unfermented hexose, XYL – xylitol production.

### 6.4.4. Limitations

There are certain limitations to the presented results, most importantly:

- Scaling-up experiments show that yields can be substantially lower at larger scales than in lab-scale [527, 528]. In practice, yields could differ from those ones applied within this study. In order to account for this uncertainty, a Monte Carlo Simulation and a sensitivity analysis was conducted.

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- Biological production of xylitol including subsequent purification and crystallization has not been realized on large economic scales yet [519]. The purification losses applied in this study are rather optimistic in view of published experimental data [529].
- The displacement effects were identified based on observed market trends. The potential to predict future developments from these trends is limited. Furthermore, trends observed in the energy sector depend on many other decisions and agreements. Therefore, it is not certain if the supply of energy carriers or additional demand contributes to the trends. Furthermore, the most recent comprehensive data set containing all data required stems from 2016. By now, certain trends might have changed. Due to the use of past trends, results can give indications of near-term developments.
- The evaluated changes trigger changes in marginal supply and thereby in the production of affected processes. In certain cases, no marginal emission data was available. In these cases, average data was used. This is insofar incorrect, as changes in production of marginal processes might considerably differ from average data [530].

These limitations emphasize that the assumed displacement effects do not provide a fully accurate prediction of occurring effects. Instead, results give an indication on how the introduction of biorefinery concepts could potentially affect overall GHG emissions under a broad range of boundary conditions observed within different EU member states.

### 6.5. Conclusion

The analysis of a broad range of biorefinery concepts located in 26 EU member states reveals that the introduction of almost all evaluated 2G concepts using wheat straw as feedstock are likely to result in net reductions in GHG emissions. In contrast, 1G concepts using wheat grain as feedstock might result in an increase in overall GHG emissions. Most important parameters governing the overall change in GHG emissions are emissions caused by LUC, change in demand for energy as well as the supply of renewable liquid and gaseous fuels. The additional provision of methane and methanol from captured biogenic CO<sub>2</sub> presents an additional opportunity to reduce GHG emissions. Most of the determined changes in overall emissions occur outside of the provision chain (e.g. through displacement effects). It is therefore important to comprehensively assess potential changes arising from certain decisions within the energy and transportation sector. As many of these changes occurring outside of the production chain affect sectors and regions that are not regulated by the RED II (or any other European legislation), it is advised that legislation is needed that comprehensively addresses sustainability of production processes to avoid burden-shifting from regulated to less regulated sectors. In addition, the methodology provided by the RED II to evaluate *GHG savings* does not value the additional provision of fuels from captured CO<sub>2</sub> if these processes are an integrated part of the biorefinery. Likewise, certain 2G concepts (e.g. evaluated organosolv concepts) do not comply with minimum *GHG saving* thresholds, even

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though the evaluation of potential changes in emissions arising from the introduction of these fuels indicates that these concepts could result in a net decrease in emissions if introduced. These two aspects indicate that the RED II fails to account for the capability to result in reductions of GHG emissions in certain cases and that the methodology should be adopted with regards to the use of captured CO<sub>2</sub>. The results furthermore show that the magnitude of change is strongly dependent on locally prevailing market conditions. Therefore, it is advised that strategies to introduce alternative fuels concepts must be country-specific and overall targets defined by the EU should be transposed using concepts providing products that are aligned to local markets in order to maximize reduction in GHG emissions.



# Straw utilization for biofuel production: A consequential GHG assessment of bioethanol and biomethane provision with a focus on the time-dependency of emissions

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Buchspies B, Kaltschmitt M, Junginger HM (2019) Straw utilization for biofuel production: A consequential GHG assessment of bioethanol and biomethane provision with a focus on the time-dependency of emissions. This chapter presents the submitted version including some minor edits and changes. A revised version is currently under review.

## Chapter 7

### Abstract

The shift from straw incorporation to biofuel production triggers changes in GHG emissions from production, changes in SOC and through the provision of (co-)products and entailed displacement effects. This paper analyzes changes in GHG emissions arising from the shift from straw incorporation to biomethane and bioethanol production. The biomethane concept comprises comminution, anaerobic digestion and amine washing. It additionally provides an organic fertilizer. Bioethanol production comprises energetic use of lignin, steam explosion, enzymatic hydrolysis and co-fermentation. Additionally feed is provided. A detailed consequential GHG balance with in-depth focus on the time-dependency of emissions is conducted: (a) the change in the atmospheric load of emissions arising from the change in the temporal occurrence of emissions comparing two steady-states (before the shift and once a new steady-state has established) and (b) the annual change in overall emissions over time starting from the shift are assessed. The shift from straw incorporation to biomethane production results net changes in GHG emissions of (a) -979 (-436 to -1654) and (b) -955 (-220 to -1623) kg CO<sub>2</sub>-eq. per t<sub>DM</sub> straw converted to biomethane (minimum and maximum). The shift to bioethanol production results in net changes of (a) -409 (-107 to -610) and (b) -361 (57 to -603) kg CO<sub>2</sub>-eq. per t<sub>DM</sub> straw converted to bioethanol. If the atmospheric load of emissions arising from different timing of emissions is neglected in case (a), the change in GHG emissions differs by up to 54%. Case (b) reveals carbon payback times of 0 (0 to 58) and 19 (0 to 100) years in case of biomethane and bioethanol production, respectively. These results demonstrate that the detailed inclusion of temporal aspects into GHG balances is required to get a comprehensive understanding of changes in GHG emissions induced by the introduction of 2G biofuels from agricultural residues.

## 7.1. Introduction

At present, high efforts are undertaken to reduce the dependency on fossil fuels and thereby to lower anthropogenic GHG emissions. For these purposes, biofuels were promoted as a substitute for fossil energy carriers within the transportation sector in the past decades. So far, the majority of biofuels are produced from starch, sugar and oil crops that are also used to fulfill the needs for food and feed. This has led to substantial criticism of biofuels made of these kind of feedstocks [531, 532]. Thus, in recent years, the production of biofuels from alternative feedstocks was promoted and more recently policy instruments were implemented that facilitate the introduction of so-called 2G or advanced biofuels [47]. Cereal straw presents a mostly commercially unused resource that could be used to produce 2G biofuels such as bioethanol or biomethane [533].

Recently several cLCA studies on bioenergy, biomethane and bioethanol using wheat straw as feedstock were published. Of these, some do not specifically model SOC changes as a consequence of lignocellulosic feedstock removal, e.g. [534, 535], some studies use simplistic approaches and assumptions to account for changes in SOC, e.g. [504, 536, 537], while others model the (avoided) decay of lignocellulosic material or the influence of a change in organic matter supply, e.g. [538, 539]. Studies show that the production of biomethane and the subsequent application of organic fertilizer can help to increase SOC [536, 538]. None of the available literature addresses the impact of the temporal decay of SOC with regard to GHG balances. This is however of crucial importance regarding the present challenge of mitigating climate change because high efforts to decrease the emission of GHG need to be undertaken within the upcoming decades to limit global mean temperature increase. With regard to this fact, the importance of the inclusion of temporal aspects into GHG assessments is two-fold:

- A) Bioenergy systems potentially alter existing carbon stocks and aside from the absolute emission changes, the temporal pattern of the release of carbon contained in these stocks changes. As a consequence, the presence of GHG in the atmosphere changes over time in addition to the absolute change in emissions.
- B) The shift to bioenergy production (or from bioenergy provision to other ways of biomass or land utilization) involves changes in carbon stocks that change over time. This might lead to a new equilibrium state or remain changing throughout production cycles, e.g. a forest plantation that is harvested and replanted. In the present study, an equilibrium is reached after a certain period. The establishing of the new equilibrium state takes up to several years and involves a decrease in SOC and thereby an increase in GHG emissions.

The consideration of temporal aspects of emissions has been widely discussed with regards to forest biomass. Norton et al. [540] for example questioned the capability of forest biomass to mitigate climate change in view of the carbon payback times of forest bioenergy and the time

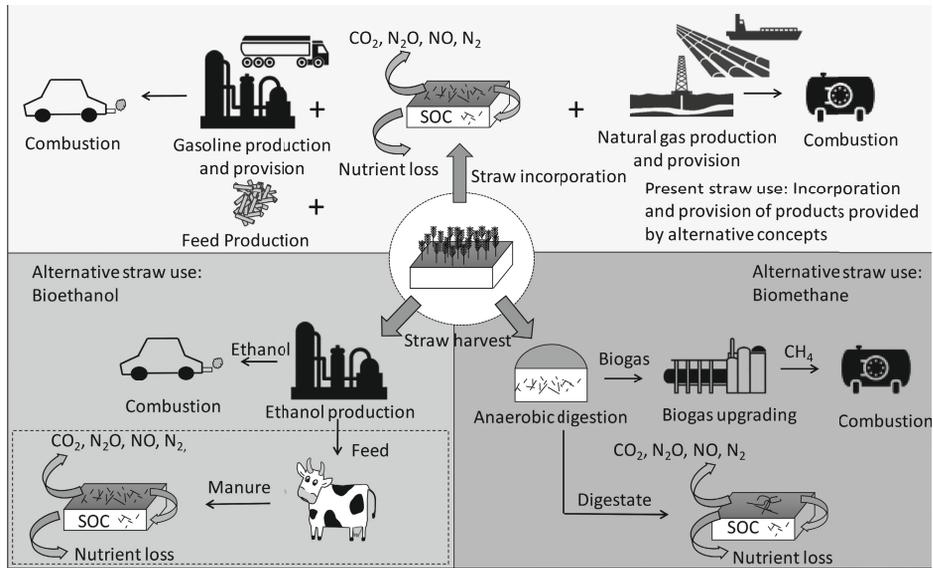
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remaining to realize a substantial reduction in (anthropogenic) GHG emissions. While forest biomass and 1G feedstocks have received attention with regard to at least one of the above mentioned aspects of the time-dependency of emissions, e.g. [97–99], studies that address other 2G feedstocks are scarce. Few studies address this aspect for 2G feedstocks other than forest biomass, e.g. [100–102]. Even fewer studies focus on the use of residues, e.g. straw, for biofuel production with consideration of the time-dependency of emissions and the impact on the GHG balance [103].

Thus, these two aspects are addressed in the context of the introduction of two 2G biofuel concepts by means of a consequential GHG balance using wheat straw as feedstock. The scope is limited to GHG emissions due to the importance of GHG emissions and their time-dependent release regarding climate change (mitigation). Temporal aspect A is analyzed by the methodology presented by [541]. The presented methodology was so far not applied to products arising from bioenergy concepts that contribute to SOC formation, e.g. organic fertilizer. Furthermore, the methodology is extended to non-CO<sub>2</sub> GHG emissions and applied for the first time within a cLCA/GHG balance of wheat straw-based bioenergy provision. The temporal change in emissions over time (aspect B) is analyzed by a detailed analysis of the temporal pattern of organic matter decomposition and SOC formation. The introduction of two near-future concepts with capacities of 150 GWh/a biofuel output located in Germany are analyzed (Figure 7-1):

- Biomethane is produced by comminuting straw and subsequent anaerobic digestion. Biogas is thereafter upgraded to biomethane by amine washing. Biomethane is subsequently injected into the existing natural gas grid. The produced digestate is dewatered to yield a solid organic fertilizer. Apart from emissions arising from the concept, several displacement effects are assessed. The produced biomethane is a substitute for fossil natural gas and digestate is processed to yield a solid organic fertilizer. Its application alters the quantity and quality of organic matter and nutrients that are applied to the field (in comparison to the previous incorporation of straw). The additional or displaced application of fertilizers results in GHG emission changes from fertilizer production and application. The organic fertilizer is sold as a product and is thus applied elsewhere to contribute to SOC formation and to provide nutrients.
- Bioethanol is produced from straw via pre-treatment by steam explosion and subsequent fermentation. Lignin is energetically used to provide process energy. The bioethanol concept provides ethanol, a substitute for fossil gasoline, and molasses, a substitute for animal feed, e.g. maize.

Only a share of straw is available for bioenergy production while the remainder is incorporated into soil to maintain SOC levels and to serve other soil quality purposes.



**Figure 7-1** Simplified depiction of the analyzed shift from straw incorporation to biomethane and bioethanol production. The temporal change in SOC due to the feed displacement is not considered. It is assumed that nutrient release from manure does not change through a shift in diet (from maize to molasses).

The shift from straw incorporation to bioenergy provision triggers changes in GHG emissions arising from the provision of biomethane and bioethanol, changes in SOC, the application and use of fertilizers, etc. These aspects are addressed by applying the proposed methodology by Petersen et al. [541] to the production of biomethane using empirical data of organic fertilizer decomposition and using literature data in case of straw decomposition. Furthermore, the methodology is extended to N-related GHG emissions. The results of the cLCA are compared with results obtained by applying biofuel evaluation method provided by the RED II [47]. The latter methodology is a mandatory instrument to certify biofuels used within the EU from 2021 onwards. This methodology allows the estimation of GHG emissions related to the provision of biofuels but does not account for effects induced by the introduction of novel biofuel provision concepts such as displacement effects occurring through the supply of (co-)products, a detailed consideration of changes in SOC and the time-dependency of emissions.

## 7.2. Methods

The change in GHG emissions entailed to the shift from present straw use to biomethane production is assessed by means of a cLCA and, for comparison, the methodology defined by the RED II. In the following chapter, the methodology of these two approaches is explained. For all cases and assessment methodologies a base case is analyzed. Furthermore, two confining scenarios are analyzed: a minimum reduction scenario using unfavorable emission factors, conversion efficiencies and decomposition rates and a maximum reduction scenario based on

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a combination of favorable parameter values and decomposition curves (Table D - 1 and Table D - 2).

### 7.2.1. Consequential GHG assessment

The shift from straw incorporation towards its use as feedstock for biomethane and bioethanol production triggers changes in other (production) systems due to additional demands (e.g. electricity) and due to the arising supply of products (e.g. natural gas, gasoline, fertilizer and feed). The marginal suppliers of the respective products and services are identified and GHG emissions of a change in demand supplied from the respective marginal supplier is determined. GHG emissions are expressed and compared by the metric GWP. In this study, a time frame of 100 years is considered regarding changes in SOC and the chosen characterization factors ( $GWP_{100}$ ). This choice is justified by the long time (up to several decades) needed until soil reaches a new equilibrium state after changes in management practice. The GWP of all relevant emissions are taken from the IPCC [542]. A critical part is the decomposition of organic matter that is left on the agricultural field as the decomposition of the organic matter (straw and organic fertilizer produced from digestate) leads to GHG emissions emitted over a period of time. Commonly, the timing of emissions is neglected in most LCA studies and GHG balances: usually, it is assumed that all emissions happen at once (at  $t=0$ ). In contrast, the shift from present straw use to bioenergy production is assessed with respect to two temporal aspects (A and B):

- A) In addition to the change in the absolute quantity of emissions released, the timing of emissions is changed through an alteration of the temporal storage and release of carbon (e.g. straw decomposition and resulting delayed emission of GHG vs. instant release of the GHG). The latter aspect changes the temporal presence of GHG in the atmosphere. The proceeding to address this aspect follows the methodology proposed by Petersen et al. [541]. According to the method, this aspect is analyzed for a specific year. The change in the temporal occurrence of emissions and the presence of GHG in the atmosphere arising thereof in the following years as a consequence of the change in carbon stocks and emissions in that specific year are considered. A brief overview of the methodology will be presented in the chapters 7.2.1.1. and 7.2.1.2. and the readers are referred to [541] for a more detailed description of the methodology.
- B) The shift from one to another system of biomass use triggers changes in emissions and carbon pools (chapter 7.2.1.1.). These changes take place instantly and over a certain period of time. The shift from straw incorporation to bioenergy production concepts assessed in this study, for example, leads to a certain transition time until a new equilibrium state establishes. It is assessed how yearly emissions change over a period of 100 years when straw is used for bioenergy production instead of incorporation during that period. A carbon

payback time is calculated to estimate the time needed to compensate potentially arising decrease in carbon stocks (chapter 7.2.1.3.).

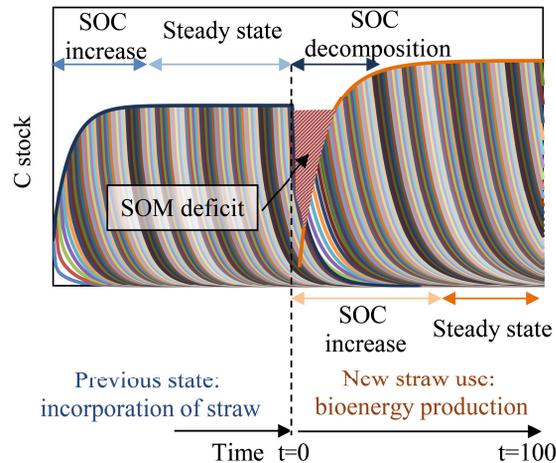
The first aspect is analyzed for a steady state that reflects a certain point in time when the changes in carbon pools and emissions are balanced. Thus, only the effect of the different timing of emissions and the presence of GHG in the atmosphere in the 100 year period following that specific year are analyzed. The second aspect is analyzed by assessing yearly emissions over a 100 year production period following the shift to bioenergy production assumingly bioenergy production throughout that period.

The decomposition of organic matter leads to the release of CO<sub>2</sub> and nutrients over time. At first, the methodology to account or the mineralization of carbon and nutrients is described. Thereafter, the determination of the carbon payback time and how the time-integrated atmospheric load of emissions can be included in a GHG balance.

#### 7.2.1.1. *Organic matter mineralization*

**Carbon mineralization.** When organic matter, such as straw, digestate or any organic fertilizer decomposes, a part of the contained carbon is retained in soil in form of SOC, while the major share is decomposed and emitted as CO<sub>2</sub> over a certain period. If organic matter is added each consecutive year, an equilibrium state between organic matter input and organic matter mineralization is reached at some point in time (Figure 7-2) [543, 544]. There is a carbon saturation state that is independent of climate and management practice [545]. In practice however, a carbon saturation can be observed at lower carbon levels due to management practices and climate. When the “effective carbon saturation” is reached, additional input of organic matter does not increase SOC under a given management regime and present climatic conditions [545]. In this study, the steady state is defined as the time when the change in SOC is less than 1% for each addition of organic matter. If organic material is supplied no longer, the SOC decreases slowly until it reaches the base level [546].

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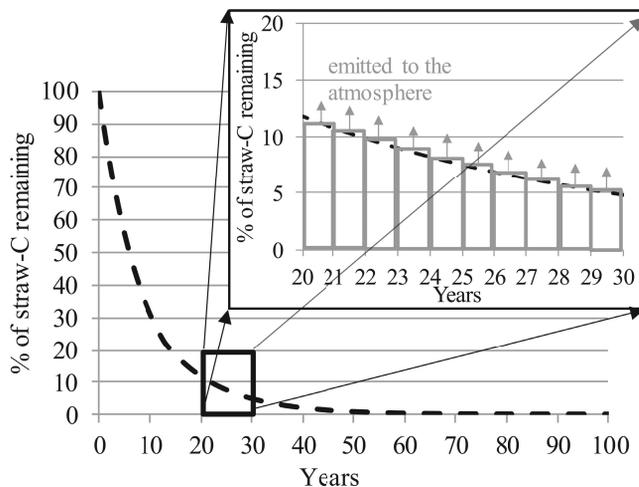


**Figure 7-2** Schematic depiction of carbon stocks before the shift from straw incorporation to bioenergy production and thereafter. In the given example, the bioenergy concept yields a source of carbon (organic fertilizer) that can be applied to agricultural land to contribute to SOC formation. The system is in a steady state before the shift and a new equilibrium state is reached after a certain transition time. The confining blue and orange curves depict the sum of carbon remaining from a yearly addition of straw and organic fertilizer, respectively. The colored curves below the blue and orange curves depict decomposition curves of organic matter that is added each year. Once straw supply ceases, straw-related carbon decomposes while at the same time carbon stocks build up due to use of organic fertilizer. During that time, a carbon deficit might arise (depending on organic matter decomposition and application rates).

Field studies show that the mineralization of organic matter depends on site conditions (e.g. climate and soil), agronomic practice and the quantity of organic matter input, cf. [543, 547]. The amount of organic matter that is mineralized decreases over time because easily degradable material is decomposed first (Figure 7-3) [548]. The mineralization of organic matter is expressed by a two-component exponential decay function [549, 550]:

$$y(t) = \alpha e^{-k_1 t} + (100 - \alpha) e^{-k_2 t} \quad \text{Eq. 7-1}$$

$y(t)$  expresses the share of organic matter remaining at time  $t$  with  $\alpha$  signifying the fraction of rapidly decomposing material.  $k_1$  and  $k_2$  are the decomposition rates of the rapidly and slowly decaying fractions. These factors were determined by a literature review in case of straw and derived by empirical data in case of organic fertilizer produced from digestate in the biomethane concept.



**Figure 7-3** Schematic depiction of straw mineralization and the assumption of yearly pulse emissions instead of constant emissions.

**Nutrient mineralization.** Nitrogen (N) contained in straw is bound within complex organic molecules. In contrast, digestate contains N organically bound and in mineral form. Organically bound nutrients contained in organic matter are mineralized over time. Mineral N (i.e. ammonium ( $\text{NH}_4^+$ )) is subject to volatilization, nitrification and denitrification [551]. Nitrifying bacteria convert ammonia ( $\text{NH}_3$ ) to nitrite ( $\text{NO}_2^-$ ) and nitrate ( $\text{NO}_3^-$ ). Subsequently, microorganisms denitrify  $\text{NO}_3^-$  and thereby produce nitrous oxide ( $\text{N}_2\text{O}$ ), nitric oxide (NO) and molecular nitrogen ( $\text{N}_2$ ). There is a complex relation between denitrification and soil texture, organic matter content, moisture, climate as well as other factors influencing these metabolic processes.

Furthermore, the composition of the (organic) fertilizer that is applied influences emissions. Several studies report that  $\text{N}_2\text{O}$  emissions are lower in case of anaerobically digested material compared to undigested organic material, [552–556], while others report opposing results [557–559].

A reduction in  $\text{N}_2\text{O}$  emissions is attributed to the reduction in easily degradable material by anaerobic digestion reducing the risk of the occurrence of anoxic microsites, which are beneficial for denitrification [552, 560]. Additionally, airborne emissions depend on the application practice: injecting (liquid) digestate shows higher  $\text{N}_2\text{O}$  emissions than emissions than on-ground application [555]. All studies that analyze the temporal pattern of  $\text{N}_2\text{O}$  fluxes indicate that highest  $\text{N}_2\text{O}$  formation occurs within the first few days or weeks after application of the organic fertilizer. Most of these studies address short-time effects of digestate application, long-term experiments are scarce.

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Apart from direct  $N_2O$  emissions following the described chain of microbial processes,  $N_2O$  formation takes place indirectly following re-deposition of volatilized  $NH_3$  or as a consequence of leaching of  $NO_3^-$  and subsequent denitrification.

Regarding  $NH_3$  emissions, studies comparing digested and undigested material report higher  $NH_3$  emissions from digested material compared to undigested material or mineral fertilizer [554, 555].  $NH_3$  volatilization occurs either shortly after application of mineral N ( $NH_4^+$ ) or as a consequence of mineralization of organically bound N. The latter occurs over a longer period of time and is dependent on the decomposition rate of the organic material [561, 562]. It is therefore assumed that the mineralization of organically bound N follows the same temporal pattern as reported for carbon (see above), whereas emissions related to nutrients in mineral form (e.g.  $NH_4^+-N$ ) occur within a short time span after application.

### 7.2.1.2. Integration of organic matter mineralization into the consequential GHG balance

**GWP of carbon mineralization.** The methodology to account for a change in the temporal occurrence of emissions applied here follows the approach proposed by [541]. The methodology allows to include the time-integrated atmospheric load of  $CO_2$  emitted over a certain period, e.g. through mineralization of organic matter, into GHG balances that use the metric GWP. The method addresses these changes for a specific year, thus after the transition time until a new steady state is established (Figure 7-2) is not part of this consideration. A fraction of any pulse emission of  $CO_2$  is absorbed by sinks, such as vegetation or the oceans, whereas the remainder remains in the atmosphere. The share of a pulse emission of  $CO_2$  remaining in the atmosphere can be estimated by the decay curve of the Bern Carbon model [563]:

$$f(t) = 0.2173 + 0.224e^{-\frac{t}{394.4}} + 0.2824e^{-\frac{t}{36.56}} + 0.2763e^{-\frac{t}{4.304}} \quad \text{Eq. 7-2}$$

$f(t)$  presents the share of  $CO_2$  remaining in the atmosphere at time  $t$ . The time-integrated share of  $CO_2$  remaining in the atmosphere that can be expressed by:

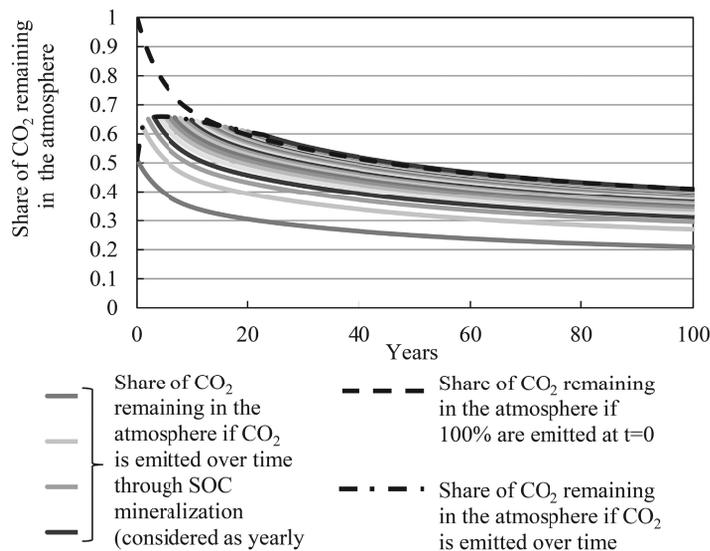
$$F(t) = \int_0^T f(t) dt \quad \text{Eq. 7-3}$$

GHG balances usually use the GWP as a metric to compare alternatives and therefore need to refer to a specific time frame (e.g. 20 ( $GWP_{20}$ ) or 100 ( $GWP_{100}$ ) years). Concerning these specific time frames, it is crucial whether a certain quantity of  $CO_2$  is emitted at once at a certain time, e.g. through biomass burning, or in parts over a longer period of time, e.g. through soil storage and mineralization. For simplification, emissions of mineralized organic matter are considered as discrete yearly pulse emissions (Figure 7-3). The share of all of these emissions remaining in the atmosphere can be determined by the Bern Carbon model's decay curve. The time-integrated

share of CO<sub>2</sub> remaining in the atmosphere as a consequence of organic matter mineralization can be derived by combining Eq. 7-1, Eq. 7-2 and Eq. 7-3:

$$S_T(t) = \sum_{i=1}^T \left( (1 - y(i)) \int_{j=1}^{T-i} f(j) dj \right) \quad \text{Eq. 7-4}$$

Figure 7-4 exemplarily depicts the share of CO<sub>2</sub> remaining in the atmosphere in case of an instant release of CO<sub>2</sub> at t=0 and in case of soil storage and mineralization (only emissions of the first 24 years are shown).



**Figure 7-4** Share of CO<sub>2</sub> remaining in the atmosphere as a consequence of a pulse release of CO<sub>2</sub> at t=0 (dashed line) and as a consequence of decomposition (only emissions of the first 24 years are shown, dot-dashed line). The dashed line depicts the share of CO<sub>2</sub> remaining in the atmosphere if 100% of CO<sub>2</sub> are emitted at t=0 according to the Bern Carbon Model (Eq. 7-2). The dot-dashed line presents the sum of CO<sub>2</sub> remaining in the atmosphere if CO<sub>2</sub> is emitted over a longer period of time (e.g. through decomposition of organic matter, Eq. 7-1), if all yearly emissions follow Bern Carbon Models decay curve (Eq. 7-2). The presence of GHG emissions in the atmosphere can be expressed by the time-integrated share of emissions in the atmosphere (Eq. 7-4).

The mineralization of organic matter and alternative use without on-site mineralization can be compared with regards to GWP<sub>100</sub> by:

$$D_T(100) = \frac{F(100)}{S(100)} \quad \text{Eq. 7-5}$$

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$D_T$  expresses the ratio of the time-integrated fraction of CO<sub>2</sub> remaining in the atmosphere resulting from a single release of CO<sub>2</sub> at  $t=0$  compared to the time-integrated fraction of CO<sub>2</sub> remaining in the atmosphere emitted through mineralization over a longer time span on a 100 year time horizon. Likewise,  $D_T$  can be used to determine the relative difference in GWP of different mineralization processes (e.g. mineralization of straw vs. decomposition of digestate) or an instant release (e.g. through straw combustion or combustion of a fuel produced from straw). The respective emissions are multiplied with  $D_T$  to gain equivalent GHG emissions that include the temporal pattern and time-integrated atmospheric load of emissions.

**GWP of N mineralization.** The same approach is chosen for N-related (GHG-) emission. N<sub>2</sub>O exhibits a decay pattern in the atmosphere. According to [453] the lifetime of a N<sub>2</sub>O perturbation is 121 years. The perturbation lifetime of N<sub>2</sub>O is lower than the lifetime of the overall atmospheric N<sub>2</sub>O burden due to feedbacks in the atmosphere. A first order decay curve is applied to model the temporal pattern of N<sub>2</sub>O residence in the atmosphere [453]:

$$g(t) = e^{-\frac{t}{121}} \quad \text{Eq. 7-6}$$

$g(t)$  and  $t$  express the share of N<sub>2</sub>O remaining in the atmosphere and the time in years after the emission, respectively.

### 7.2.1.3. Carbon payback time

A carbon payback time,  $t_p$ , is determined to assess how long it takes to compensate potential emissions arising from the shift from straw incorporation to bioenergy production. In the context of this assessment, it is defined as the time needed to compensate the avoided contribution to SOC formation from straw incorporation (forgone SOC formation):

$$\sum_{t=0}^{t_p} (C_{OF} m_{OF} y_{OF}(t) + \Delta_{GHG}) - C_S SOM_S \sum_{t=0}^{t_p} y_S(t) \stackrel{!}{\geq} 0 \quad \text{Eq. 7-7}$$

In Eq. 7-7,  $m_{OF}$  and  $SOM_S$  denote the annually added quantity of organic fertilizer and the cumulative quantity of SOC from straw that has accumulated until the moment when the shift takes place, respectively.  $C$  denotes the carbon content of straw and organic fertilizer, respectively. The first term expresses the overall change in GHG emissions arising from SOC formation and GHG emission changes (including emissions from production and substitution effects),  $\Delta_{GHG}$ , that arise every year as a consequence of the shift to biofuel production. The second term describes the contribution to SOC formation from the application and decomposition of straw. In addition, the carbon payback time is calculated only for changes in SOC (excl.  $\Delta_{GHG}$ ) to assess the time needed to compensate potential changes in SOC formation.

### 7.2.2. Assessment according to RED II methodology

The methodology defined in the RED II follows a different approach serving the purpose of certification [47]. The approach does not account for changes triggered by the shift from present straw use to bioenergy production. Thus, average data (e.g. electricity mix instead of marginal electricity supply) are used and emissions are allocated to all products based on their energy content (LHV). The results are expressed in *GHG savings* [47]:

$$GHG\ savings = \frac{E_f - E_b}{E_f} \quad \text{Eq. 7-8}$$

$E_f$  and  $E_b$  are the emissions entailed to the production and use of fossil fuel and the respective biofuel.  $E_f$  is set to 94 g CO<sub>2</sub> per MJ fuel.  $E_b$  comprises GHG emissions entailed to feedstock provision, fuel production, distribution, its use and several possible emission credits, e.g. for surplus electricity fed to the public grid, surplus heat that is used elsewhere, improved agricultural management, CO<sub>2</sub> capture and subsequent storage or utilization. All emissions and credits are allocated to all products except those for which credits are given (i.e. captured CO<sub>2</sub>, electricity and heat). Residues such as straw are not considered as products of the cultivation stage. Thus, no emissions related to feedstock cultivation are allocated to residues up to the point of collection. In this case, a credit is given that equals the emissions arising from supplying electricity using the same energy carrier. The methodology uses GWP of 1, 298 and 25 kg CO<sub>2</sub>-eq. per kg CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>, respectively. For comparison, Eq. 7-8 is applied to results of the consequential approach as well. In this case,  $E_f$  and  $E_b$  comprise the displaced fossil products (i.e. natural gas and mineral fertilizer as well as gasoline and feed in case of biomethane and bioethanol, respectively) and all changes in GHG emissions related to the biofuel concept, respectively. In this case, no allocation is applied.

#### 7.2.2.1. Change in SOC

The change in SOC is treated differently: changes in SOC are accounted for by a generalized methodology [89]. Such changes are considered over a period of 20 years and are equally assigned to all products produced within this period, i.e. the arising CO<sub>2</sub> emissions are considered as being equally distributed over a 20 year period (residues, such as straw, are not considered products according to the RED II methodology). These emissions are assigned to all products harvested within the 20 year period. Additionally, reductions in GHG emissions due to improved agricultural management can be deducted from the overall emissions. According to the directive, the credit can be granted if the change in SOC is proven by measurements conducted in regular intervals. If no other measurement than the first one is available, the change in SOC can be inferred by representative experiments and models. In the present case, empirical data from incubation experiments are available in case of organic fertilizer application from digestate in the biomethane concept. The change in SOC is determined per t of fertilizer once the steady-

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state is reached (once carbon input and carbon mineralization are balanced, Figure 7-2). Due to the lack of long-term field data, results including and excluding the consideration of the change in SOC are presented.

### 7.3. System description

The change in GHG emissions of a shift from current straw use to bioenergy production is assessed. At present the major share (approx. 85%) of cereal straw in Europe is incorporated into soil while the remaining share is used for animal bedding, animal feed or horticulture (e.g. cover for plants or substrate for mushroom cultivation) [533, 564]. In order to be eligible to receive direct payments from the EU, farmers need to show that their SOC balance is balanced by applying specific methods, e.g. [565]. Based on cultivated crops, arising input of organic material, applied (organic) fertilizer and SOC depletion arising from agricultural activities, 44% of straw in Germany can be sustainably used for bioenergy production while complying to the SOC balance requirement [273]. It is therefore assumed that (in average) 56% of straw are incorporated into soil to maintain the SOC level (as required to receive direct payments from the EU). The remainder is assumed to be available for bioenergy production.

The use of straw as feedstock for bioenergy production requires additional operations to harvest, collect and handle straw before it is further processed. The change in straw use alters carbon and nutrient cycles. These changes are considered with respect to the temporal pattern of emissions. The composition of wheat straw produced organic fertilizer (biomethane concept) and molasses (bioethanol concept) plays an important role concerning SOC formation and nutrient cycling (Table D - 6). The provision of products triggers displacement effect. The determination of marginal suppliers and related GHG intensities can be found in chapter D.2.

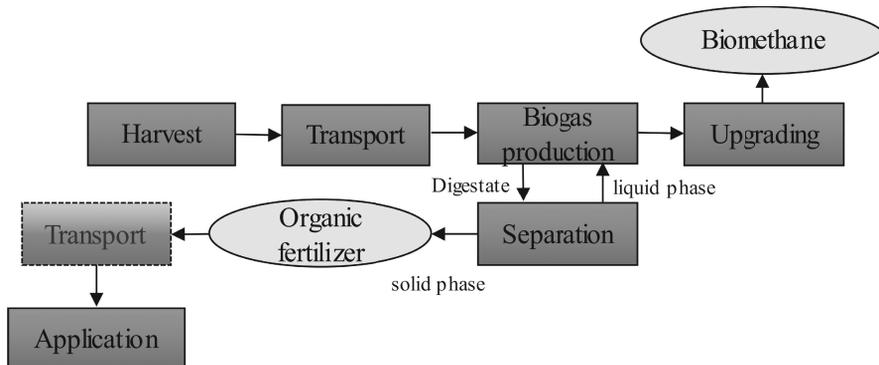
For most important parameters and decay functions, average, minimum and maximum values are given. These are applied to base case, minimum and maximum reduction scenarios in a way that these scenarios present average, minimum and maximum reductions in GHG emissions (Table D - 1 and Table D - 2).

#### 7.3.1. Present use of straw: incorporation into soil

When straw is incorporated, the major part of contained carbon and nutrients are mineralized. Based on data available in literature, decomposition curves according to Eq. 7-1 with  $\alpha=58.02$ ,  $k_1=1.53$ ,  $k_2=0.14$ ;  $\alpha=30.67$ ,  $k_1=0.07$ ,  $k_2=1.14$  and  $\alpha=0.07$ ,  $k_1=28.381$ ,  $k_2=1.67$  where derived in case of the average, maximum and minimum decomposition, respectively (Figure D - 1). The incorporation of straw triggers the emission of  $N_2O$  and  $NO_3$ , [91], and strongly reduces or even eliminates the volatilization of  $NH_3$  [561]. All applied EF are listed in Table D - 5.

### 7.3.2. Alternative straw use: biomethane production

Due to the fact that the major share of straw is presently incorporated into soil, it is assumed that the energetic use of straw displaces the incorporation of straw. The process chain is depicted in Figure 7-5. The detailed inventory can be found in chapter D.3. At first straw is harvested (besides grain) with a combine harvester. Subsequently straw baled and transported by tractors to a storage facility where it is covered in foil and stored. Later on, straw is transported by high duty vehicles to the central storage located nearby the biomethane facility. The overall process of biomethane production and co-product processing requires heat and electricity, which are supplied by biogas combustion (thermal efficiency of 90%) and from the public electricity grid, respectively. Before anaerobic digestion, straw is comminuted by a hammer mill. Thereafter, anaerobic digestion is accomplished in steel tanks, as currently applied in the only commercially running facility producing biomethane from straw in Germany. In contrast to membrane-covered tanks, the use of steel tanks drastically reduces fugitive emissions and heating requirements. Only in winter, heating is required, while throughout the year no additional heat provision is needed [566]. In the sensitivity analysis, the dependency of the results on fugitive methane emissions is assessed (chapter D.4). The average biogas yield determined by a literature review is 9.1 MJ biomethane per kg<sub>DM</sub> straw digested [567–578]. The biogas has a methane content of 60%-vol. The DM content in the fermenter is 8%. To upgrade biogas to be fed into the existing natural gas grid, biogas is first de-sulfurized using activated carbon and then purified by amine washing with monoethanolamine, reaching a purity of 99.9% [579]. Optionally, the liquefaction of arising CO<sub>2</sub> is assessed. Arising digestate is dewatered with a screw-press to yield a solid fertilizer (22% DM). The fertilizer is stored in an enclosed facility. Due to the uncertainty regarding the location where the fertilizer is applied, similar transport distances as for straw are assumed.



**Figure 7-5** Schematic depiction of the analyzed biogas production chain. The organic fertilizer is sold as a product and is thus not (necessarily) applied to the same field.

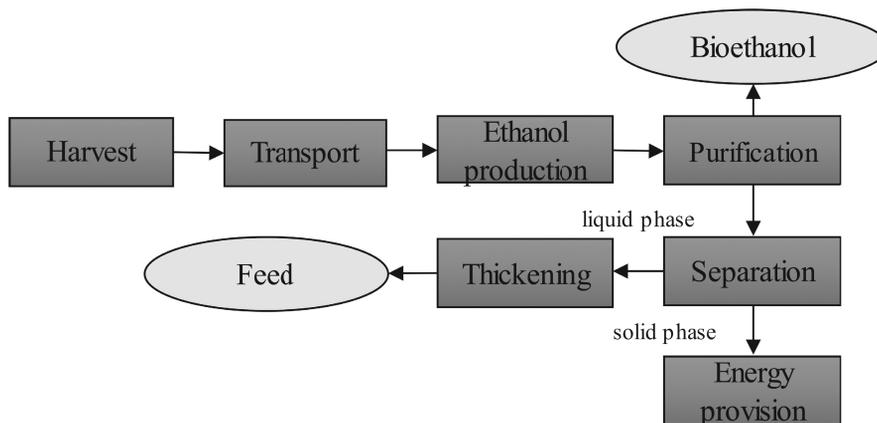
Once applied on the agricultural field, the organic fertilizer decomposes. The decay function was determined with  $\alpha=58.64$ ,  $k_1=2.03 \cdot 10^{-6}$ ,  $k_2=2.58$  (chapter D.3.3). Nutrients contained in the

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fertilizer are released. During this process, losses occur through ammonia volatilization, leaching and denitrification (Table D - 5).

### 7.3.3. Alternative straw use: bioethanol production

The assessed bioethanol production concept is comprised of a straw harvest and transportation (as described above), pretreatment, ethanol production and distillation (Figure 7-6). After the harvest, straw is pre-treated by steam explosion (210°C, 5 minutes) to yield a liquid stream that mainly consists of xylose and a solid stream that mainly consists of glucan and lignin (Table D - 8). Due to the severe pre-treatment conditions, inhibitors, such as furfural, 5-hydroxymethylfurfural, acetic acid and formic acid, are formed [512]. The liquid and the solid stream is detoxified by resin-wafer electro-deionization and washing, respectively [513, 514, 580]. Subsequently, oligomeric sugars are enzymatically hydrolyzed with efficiencies of 81.8 and 63.3%, in case of glucan and xylan, respectively [465]. In the following fermentation process, glucose and xylose are fermented with efficiencies of 95 and 93% of the theoretical maximum, respectively [468, 520]. After fermentation, ethanol is separated by distillation, rectification and molecular sieves. The remaining stream is separated into a solid phase mainly consisting of lignin and a liquid stream containing unfermented sugars. The liquid stream is dewatered to a DM content of 60% and can be used as animal feed (molasses). The solid stream is combusted to provide process energy (heat and electricity) by a CHP with a total energy conversion efficiency of 0.8. The thermal and electric efficiencies are optimized in each case (base case, minimum and maximum change scenarios) according to the respective heat and electricity demands. As for biomethane production, an optional liquefaction of arising CO<sub>2</sub> is considered.



**Figure 7-6** Schematic depiction of the analyzed bioethanol production chain.

The molasses provided by the system serve as an animal feed. It is assumed that excreta are applied to agricultural fields. The parameters of the decay function are  $\alpha=1$ ,  $k_1=3.37 \cdot 10^{-1}$ ,  $k_2=1500$

(chapter D.3.5). All other CO<sub>2</sub> (i.e. CO<sub>2</sub> from fermentation, ethanol combustion, all carbon and resulting CO<sub>2</sub> leaving the husbandry system excluding excreta) are considered to take place within the first year after ethanol production. Thus, decay curves and the atmospheric load of emissions is considered for the share of contained in animal excreta.

## 7.4. Results

All results reflect changes induced by the shift from straw incorporation to biofuel production. The parameters and values selected for the base case, minimum reduction and maximum reduction scenarios are listed in (Table D - 1 and Table D - 2). At first, results will be presented with focus on the impact of a change in timing of emissions occurring in a specific year at steady state (temporal aspect A, chapter 7.2.1). The results are presented with and without the consideration of the atmospheric load of emissions (chapter 7.2.1.2.). Subsequently it is assessed how emissions change within a period of 100 years after the shift when straw is not incorporated any longer but used for bioenergy production (temporal aspect B). A sensitivity analysis addressing the influence of crucial assumptions and important parameters can be found in the supplementary material (chapter D.4)

### 7.4.1. Temporal aspect A: Steady state and the impact of the temporal pattern of emissions

The shift from straw incorporation to bioenergy production alters the temporal occurrence of emissions. In the following chapter, results that reflect a steady state that establishes after a certain transition time following the shift to bioenergy production are discussed. Apart from absolute emission changes, the effect of the temporal occurrence of emissions is addressed by considering the time-integrated load of emissions (chapter 7.2.1.2.). If not otherwise stated, all presented values refer to one t<sub>DM</sub> straw that is converted to biomethane or bioethanol instead of incorporation into agricultural soil.

#### 7.4.1.1. Biomethane production

**Base case.** The shift from current straw use (incorporation) to biomethane production potentially reduces the GHG emissions by 979 kg CO<sub>2</sub>-eq., including the temporal pattern of GHG release and the time-integrated atmospheric load of GHG emissions following 100 years after the emission (Figure 7-7 a). The decrease in GHG emissions amounts to 998 kg CO<sub>2</sub>-eq. without consideration of the time-integrated atmospheric load of GHG emissions (net change in absolute emission quantities). The change in GHG emissions per t<sub>DM</sub> straw converted is comprised of:

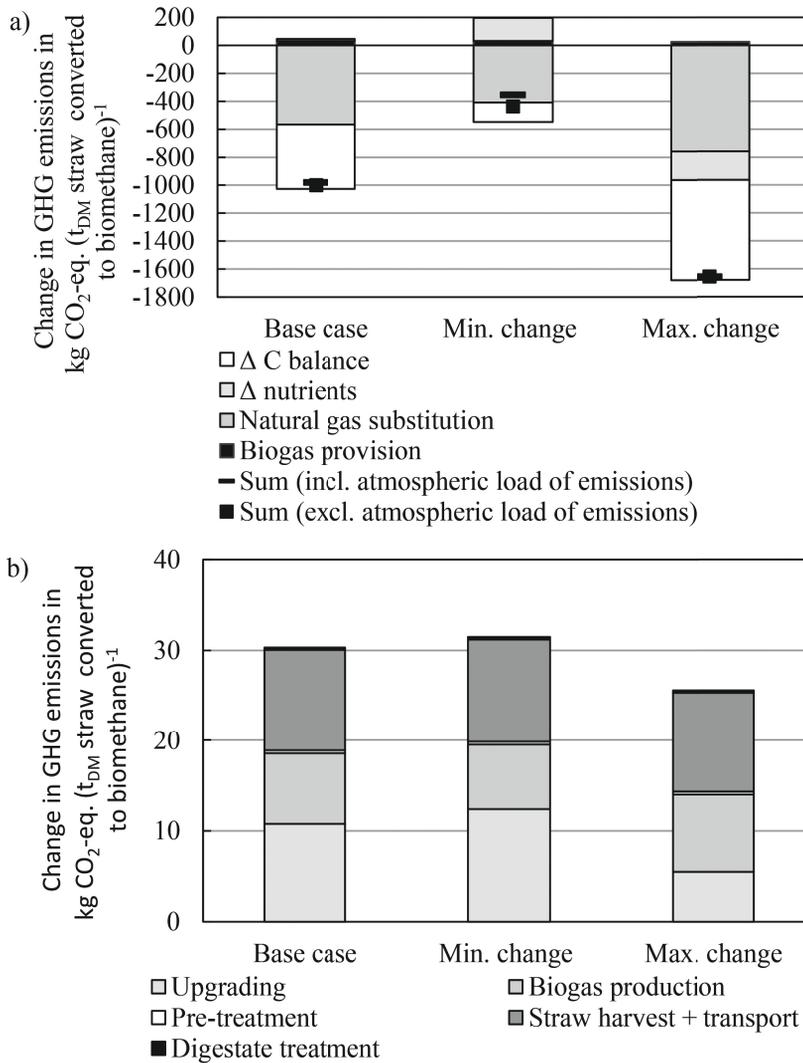
- 30 kg CO<sub>2</sub>-eq. emissions arising from the overall process of biomethane production from straw harvest to the delivery of the final products (i.e. biomethane and organic fertilizer, Figure 7-7 b). Of these, straw harvest and transportation, biogas upgrading, biomethane

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production (including pretreatment) account for 37, 36 and 27% of the GHG emissions, respectively.

- 18 CO<sub>2</sub>-eq. emissions arising from the transportation of organic fertilizer.
- A net decrease of 458 kg CO<sub>2</sub>-eq. (including the consideration of the time-integrated atmospheric load of emissions) arising from the change in carbon utilization (from straw mineralization to biomethane production and its use, fertilizer application and its decomposition). If the time-integrated atmospheric load of GHG emissions is neglected, the emission reduction due to changes in SOC amounts to 485 kg CO<sub>2</sub>-eq. This value corresponds to a SOC increase of 261 and 277 kg C per t<sub>DM</sub> of fertilizer with consideration of the time-integrated atmospheric load and without consideration of it. The inclusion of the time-integrated atmospheric load of CO<sub>2</sub> results in a lower net GHG emissions decrease (-458 vs -485 kg CO<sub>2</sub>) because biogenic CO<sub>2</sub> emissions emitted during production (e.g. emitted in the upgrading step or from combustion of CH<sub>4</sub> for internal heat provision) and by using biomethane (i.e. combustion) are released at the time of production or shortly thereafter. In contrast, carbon mineralizes slowly when straw is incorporated. Thus, the time-integrated atmospheric load of the emissions emitted during production or shortly thereafter is higher than that of mineralizing C. This results in an increase in GHG emissions relative to straw incorporation if the atmospheric load is considered. This increase outweighs the effect of the time-integrated atmospheric load of emissions released by the slower decomposition of organic fertilizer in comparison to straw decomposition.
- A part of N in the organic fertilizer derived from digestate is contained in mineral form. The higher availability of mineral N in digestate compared to nutrients bound in wheat straw increases N-losses by shifting from straw incorporation to digestate application. Additionally, digestate decomposes more slowly. Thus, less organically bound nutrients are released over the 100 year period from organic fertilizer than from incorporated straw. The overall required additional fertilizer sum up to 1.3 kg N. The provision of this mineral fertilizer and emissions arising from its application result in GHG emissions of 12 kg CO<sub>2</sub>-eq.
- The lower release of N bound in organic compounds results in lower N-related GHG emissions (most importantly N<sub>2</sub>O). This leads to a decrease in emissions of 14 kg CO<sub>2</sub>-eq.
- The substitution of natural gas results in a decrease of 568 kg CO<sub>2</sub>-eq. The combustion of natural gas accounts for 83% of this emission reduction. The remainder stems from the provision of natural gas.
- Optional: If CO<sub>2</sub> originating from ammonia production (steam reforming of methane) is substituted by captured CO<sub>2</sub> an additional 225 kg CO<sub>2</sub>-eq. can be avoided. The replacement of CO<sub>2</sub> only triggers a reduction in CO<sub>2</sub> capturing. The CO<sub>2</sub> that was formerly captured is still released because it is a waste product of steam reforming.

Consequential GHG balance of 2G biofuels with focus on temporal aspects



**Figure 7-7** Change in GHG emissions as a consequence of the shift from straw incorporation into soil to biomethane production. Results are presented per t<sub>DM</sub> straw that is converted to biomethane. Bars include the time-integrated atmospheric load of GHG emissions. Only fossil GHG emissions and changes in biogenic GHG emissions arising from the shift are shown. Organic fertilizer (produced from digestate) includes the substitution of mineral fertilizer, emissions from fertilizer application (C mineralization and N-based emissions) as well as the transport and application of the fertilizer. Natural gas substitution comprises the provision and combustion of natural gas. Biogas provision in figure a) is the sum of all process steps presented in figure b).

**Minimum and maximum changes.** Minimum and maximum changes were derived by applying a combination of minimum and maximum values of previously presented parameters (Table

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D - 1) as well as faster and slower decay functions. Parameter values and decomposition curves were applied in a way that the minimum reduction scenario reflects the lowest possible reduction in GHG emissions through the shift from straw incorporation to biomethane production (Table D - 8). Analogously, the maximum reduction scenario is based on most favorable parameters and decomposition curves and reflects the maximum possible reduction in GHG emissions as the consequence of the shift from straw incorporation to bioenergy production. These minimum and maximum reduction scenarios are extreme cases that can be considered as the boundary conditions confining the potential change in emission. In these cases, the shift from incorporation of one  $t_{DM}$  straw to the provision and use of biomethane results in the following changes in emissions:

- In the minimum GHG reduction scenario, the shift from straw incorporation to biomethane production results in net decreases in GHG emissions of 353 and 436 kg CO<sub>2</sub>-eq. with consideration of the time-integrated atmospheric load of GHG and without consideration of it, respectively. In this case, the application of organic fertilizer and its decomposition results in net changes in SOC formation of 75 and 132 kg C per  $t_{DM}$  organic fertilizer with and without consideration of the time-integrated atmospheric load of emissions, respectively. The quick decomposition of organic fertilizer and the immediate release of carbon from CH<sub>4</sub> and CO<sub>2</sub> contained in biogas in contrast to formerly slow carbon release through straw decomposition results in a lower CO<sub>2</sub>-eq. GHG emission reduction if the time-integrated atmospheric load is considered. The change in the nutrient balance arising from different decay patterns, nutrient availability and applied EF results in net increases of 164 and 187 kg CO<sub>2</sub>-eq. if the atmospheric load of emissions is considered and without consideration of it, respectively. This comprises fertilizer transportation, surplus mineral fertilizer needed to compensate nutrient losses and emissions arising from fertilizer application. An additional capture of CO<sub>2</sub> could reduce emissions by another 204 kg CO<sub>2</sub>-eq.
- In the maximum reduction scenario, overall reduction in GHG emissions amount to 1654 kg CO<sub>2</sub>-eq. with consideration of the atmospheric load of GHG and without consideration of it per  $t_{DM}$  straw converted to biomethane that was formerly incorporated. With the assumption of a fast decomposition of straw and a slow decomposition of organic fertilizer, the change in SOC is 436 and 435 kg C per  $t_{DM}$  organic fertilizer with and without consideration of the time-integrated atmospheric load, respectively. The change in nutrient availability and release results in a net decrease of 204 kg CO<sub>2</sub>-eq. (including the atmospheric load of emissions). An additional capture of CO<sub>2</sub> reduces emissions by another 235 kg CO<sub>2</sub>-eq. CO<sub>2</sub> capturing results in a higher GHG emission reduction than the worst case scenario despite lower quantities of CO<sub>2</sub> that are captured due to the lower GHG intensity of CO<sub>2</sub> capturing .

#### 7.4.1.2. Bioethanol production

**Base case.** The shift from straw incorporation to the provision of bioethanol results in net decreases in GHG emissions of 409 and 457 kg CO<sub>2</sub>-eq. with consideration of the time-integrated atmospheric load of emissions and without consideration of it, respectively (Figure 7-8). The change in emissions is comprised of:

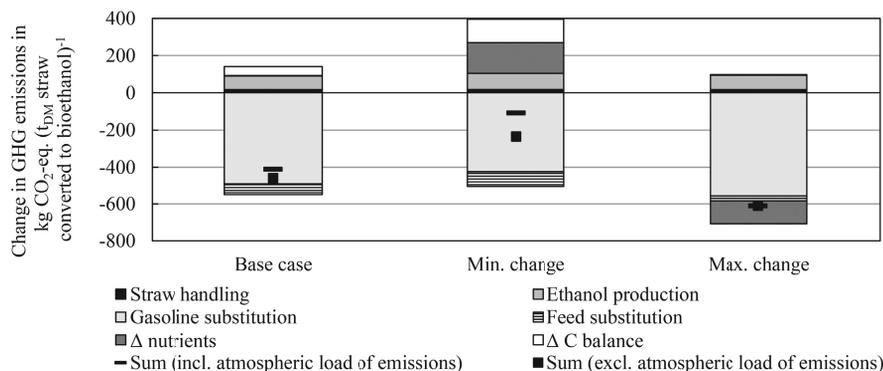
- The production of ethanol results in 73 kg CO<sub>2</sub>-eq. Of these, 60% originate from the provision of auxiliary materials (ammonia 27%, corn steep liquor 9%, enzymes and diammonium phosphate 12% each). Because the electricity demand of the overall process cannot be fully covered by the energy cogeneration, electricity needs to be drawn from the grid accounting for 25% of the GHG emissions.
- The provision of straw results in GHG emissions of 17 kg CO<sub>2</sub>-eq.
- The overall nutrient balance results in a net increase of about 3 kg CO<sub>2</sub>-eq. This contains additional fertilizer production (12 kg CO<sub>2</sub>-eq.), its application (13 kg CO<sub>2</sub>-eq.) and avoided emissions (-22 kg CO<sub>2</sub>-eq.). The avoided emissions are higher than the emissions of mineral fertilizer due to higher volatilization (NH<sub>3</sub>) of nutrients contained in organic material (Table D - 5).
- Ethanol potentially substitutes gasoline. This results in a reduction of 489 kg CO<sub>2</sub>-eq.
- Molasses can be used as animal feed. It is assumed that molasses potentially substitutes feed (maize). Thereby, emissions are reduced by 61 kg CO<sub>2</sub>-eq.
- Optional: The additional capture of CO<sub>2</sub> and replacement of fossil derived CO<sub>2</sub> reduces emissions by another 133 kg CO<sub>2</sub>-eq. can be avoided.

**Minimum and maximum change.** Minimum and maximum decreases in GHG emissions are derived by applying parameters and decay functions according to Table D - 2. The changes in GHG emissions from a shift to biomethane production per t<sub>DM</sub> straw converted to biomethane are:

- In the minimum reduction scenario, the overall reductions in GHG emissions are 107 and 235 kg CO<sub>2</sub>-eq. with consideration of the time-integrated atmospheric load of emissions and without consideration of it, respectively. The change in the nutrient balance results in a GHG emissions of 165 kg CO<sub>2</sub>-eq. if the atmospheric load and the temporal pattern of nutrient release from straw are considered. The highest contributor to these GHG emissions is emissions arising from mineral fertilizer application to compensate nutrient losses (151 kg CO<sub>2</sub>-eq.). Additional capture of CO<sub>2</sub> reduces emissions by another 88 kg CO<sub>2</sub>-eq.
- In the maximum reduction scenario, the reduction in GHG emissions is 610 kg CO<sub>2</sub>-eq. in both cases (with consideration of the time-integrated atmospheric load of emissions and without consideration of it). Due to the low and high emission factors applied to nutrients

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contained in organic fertilizer from digestate and straw, respectively, no additional N fertilizer is required. Additional CO<sub>2</sub> reduces GHG emissions by another 200 kg CO<sub>2</sub>-eq.



**Figure 7-8** Change in GHG emissions as a consequence of the shift from straw incorporation to bioethanol production. Results are presented per t<sub>DM</sub> straw converted to bioethanol. Bars include the time-integrated atmospheric load of GHG emissions. Only fossil GHG emissions and changes in biogenic GHG emissions arising from the shift are shown. Gasoline substitution comprises the provision and combustion of gasoline.

### 7.4.2. Temporal aspect B: Changes in emissions following the shift to bioenergy production

Results presented in this section address the temporal change in GHG emissions per t<sub>DM</sub> straw converted to biomethane or bioethanol over a 100 year period following the shift from straw incorporation to bioenergy production.

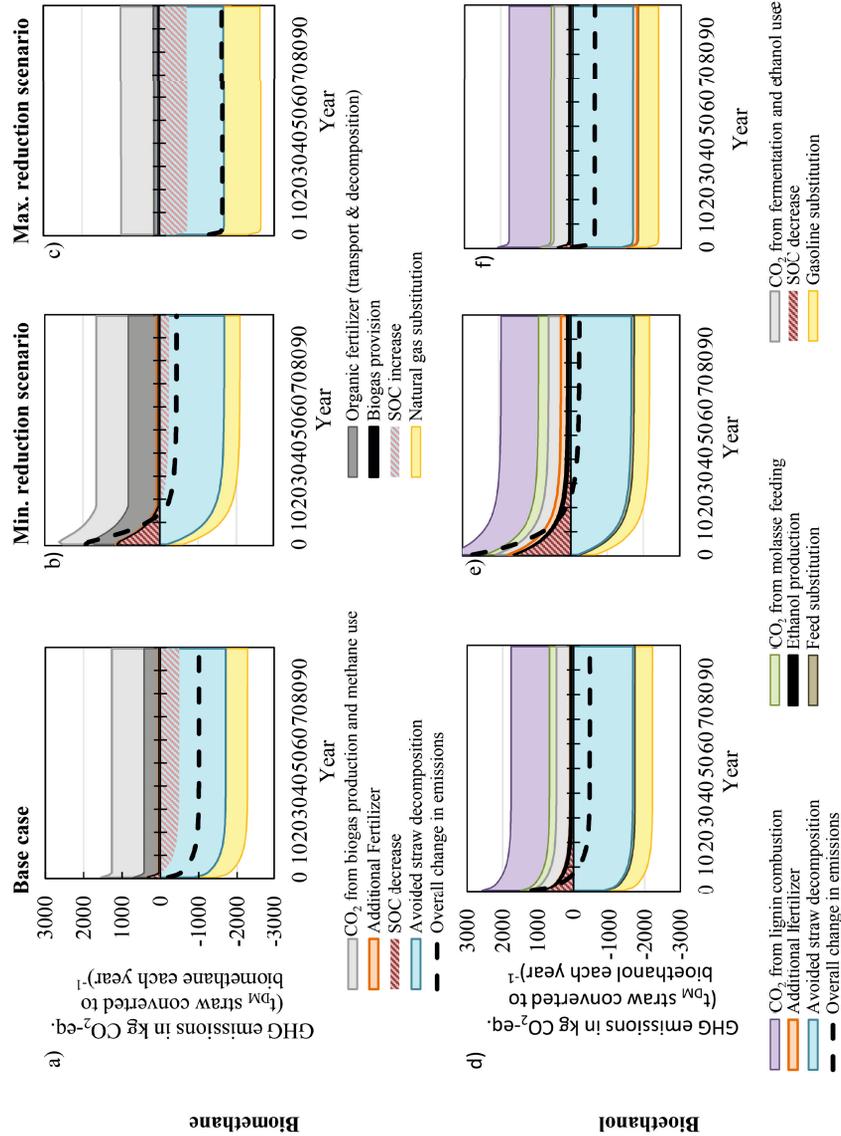
#### 7.4.2.1. Biomethane production

As a consequence of the shift from straw incorporation to biomethane production, the share of straw used for bioenergy production is not incorporated any longer and therefore does not contribute to SOC formation (exemplarily depicted in Figure 7-2). In addition, GHG emissions previously arising from straw decomposition are avoided. The supply of organic fertilizer results in the formation of SOC. Due to different decomposition rates and application quantities of straw and organic fertilizer, a certain time passes until a new equilibrium state establishes. The application of a range of decomposition curves results in carbon payback times ranging 2, 17 and 0 years if only SOC is considered in the base case, minimum and maximum reduction scenario, respectively (Figure 7-9). Once the payback time is reached, more carbon is sequestered than before the shift to bioenergy production. The overall carbon payback time (including all other changes in emissions, such as displacement effects and additional emissions from biofuel production) ranges from 0 to 58 years: no carbon payback time in the base case and maximum reduction scenario and 58 years in the minimum reduction scenario. The average changes in GHG emissions over the 100 year period are -955, -220 and -1623 kg CO<sub>2</sub>-eq. per t<sub>DM</sub> straw converted to

biomethane in the base case, minimum and maximum reduction scenario, respectively. A main factor responsible for the difference in the net GHG reductions is the decomposition of organic matter. In the minimum reduction scenario, the slow decomposition of wheat straw and the fast decomposition of organic fertilizer (after less than one year, more than half of the organic fertilizer is decomposed whereas it takes 6 years until half of the straw is decomposed) result in a slow increase in SOC through organic fertilizer application and high quantities of straw related carbon stocks that decompose.

#### 7.4.2.2. *Bioethanol production*

In case of the analyzed bioethanol provision concept no carbon source is returned to the agricultural field. Thus, SOC levels decrease towards the base level (which depends on local soil characteristics, climate, agricultural practice and other sources of organic matter as only the effect on SOC of straw is assessed in this study) and there is no newly built-up SOC. Overall carbon payback times range from 0 to no compensation of emissions arising from SOC decomposition: 0 years the maximum reduction scenario, 19 years in the base case and no compensation of GHG emissions from SOC changes within the assessed 100 year period in the minimum reduction scenario (Figure 7-9). A slow decomposition of wheat straw before the shift results in a high accumulation of SOC that is mineralized after the shift to biofuel production as a consequence of the cessation of wheat straw incorporation. Thus, very high emissions occur in the minimum reduction scenario. The average change in GHG emissions are -361, 57 and -603 kg CO<sub>2</sub>-eq. per t<sub>DM</sub> straw converted to bioethanol in the base case, the minimum reduction and the maximum reduction scenario, respectively.



**Figure 7-9** Change in GHG emissions per tDM of straw converted to biomethane (base case a), minimum reduction scenario b) and maximum reduction scenario c)) and bioethanol (base case d), minimum reduction scenario e) and maximum reduction scenario f)).

### 7.4.3. Evaluation according to RED II methodology

The biomethane concept results in slightly higher *GHG savings* according to RED II methodology than the bioethanol concept (Table 7-1). The overall efficiency of the respective concept only has a minor impact on determined *GHG savings*. This is mainly caused by the change in allocation factor (less efficient concepts yield higher quantities of co-products. The consideration of CO<sub>2</sub>, SOC formation and the consideration of the cultivation phase influence results:

- In the biogas base case concept, the SOC credit (determined at the steady state of organic matter input and its mineralization, chapter 7.2.2.1) amounts to 63.6 g CO<sub>2</sub>-eq. per MJ (without allocation), corresponding to 0.28 kg C per kg DM organic fertilizer. The allocated SOC credit is 40.6 g CO<sub>2</sub>-eq./MJ biomethane. In case of ethanol production, there is no credit for SOC formation that can be given due to the use of lignin for energy provision.
- The *GHG savings* according to RED II of the minimum reduction scenario result in a higher *GHG saving* in case of CO<sub>2</sub> capture than the base case and maximum reduction scenario due to lower conversion efficiency and thus more digestate as well a higher CO<sub>2</sub> concentration in the biogas.
- The difference between RED II and consequential results in the minimum and maximum change scenarios stem from the consideration of the cultivation phase and the nutrient balance that is included in the RED II approach. The nutrient balance results in changes in emissions ranging from -202 to 187 and -122 to 163 kg CO<sub>2</sub>-eq. per t<sub>DM</sub> straw converted to biomethane and bioethanol, respectively. The RED II approach excludes the cultivation stage.

In all cases, the assessed concepts comply with legal minimum *GHG saving* requirements.

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**Table 7-1** GHG savings according to RED II methodology and derived by applying Eq. 7-8 to results from the consequential approach (steady state, chapter 7.4.1).

	Biomethane			Bioethanol		
	Base case	Min. change	Max. change	Base case	Min. change	Max. change
RED II methodology						
Standard	93%	93%	93%	89%	88%	87%
Incl. CO <sub>2</sub> capture	120%	131%	111%	116%	122%	131%
Incl. SOC credit <sup>a</sup>	136%	119%	142%			
Consequential approach						
Temporal Aspect A						
Incl. AL <sup>b</sup> , incl. SOC	173%	92%	220%	74%	21%	104%
Excl. AL <sup>b</sup> , incl. SOC	176%	111%	221%	83%	47%	105%
Incl. AL <sup>b</sup> , excl. SOC	94%	60%	113%			
Excl. AL <sup>b</sup> , excl. SOC	93%	55%	113%			
Temporal Aspect B						
Excl. AL <sup>b</sup> , incl. SOC	168%	72%	214%	74%	18%	104%

<sup>a</sup> The inclusion of the SOC credit is reported separately as SOC credits can only be granted according to RED II if long-term studies confirm an increase in SOC (chapter 7.2.2.1). Results presented in this study rely on incubation experiments.

<sup>b</sup> AL: Time-integrated atmospheric load of emissions, time horizon 100 years.

Abbr.: AL – atmospheric load; RED II – Renewable Energy Directive II; SOC – soil organic carbon.

### 7.5. Discussion

The analysis demonstrates that the shift from the presently common use of wheat straw (incorporation into soil) to the production of biomethane and bioethanol results in a net decrease in GHG emissions. Overall, the GHG reduction of the shift from straw incorporation to biomethane production is about twice that of the shift to bioethanol production. This is mainly due to the effect of SOC increase in the biomethane concept and the loss of carbon due to lignin combustion in the ethanol concept. The contribution of digestate to SOC formation confirms previous findings [536, 538]. Alternatively, lignin could be applied to soil as well. However, if lignin is used for other purposes than energy generation, the high energy demand of 2G ethanol production could lead to a significant increase in GHG emissions of the production process if process energy is provided by fossil energy carriers. The low economic competitiveness of 2G ethanol at present is likely to stimulate the search for alternative, high-value applications of lignin [581]. In the light of these two aspects, the return of lignin to the agricultural field seems unlikely.

The benefits of both systems arise from the substitution of fossil energy carriers and in case of biomethane production, the preservation of nutrients and SOC. The substitution of fossil energy carriers serves the political targets to reduce anthropogenic GHG emissions and the dependency on (imported) fossil energy carriers. When straw is incorporated, as presently done, the largest part of carbon contained decomposes within a few years and is thus converted to CO<sub>2</sub> (and

released to the atmosphere). The production of bioenergy therefore presents a cascade use of carbon contained in straw. In case of biomethane production, an additional share of carbon otherwise mineralized can be returned to soil through the application of organic fertilizer from digestate. This contributes to the formation of SOC and closes nutrient cycles. Thereby the temporal occurrence of GHG emissions is altered. The change in the temporal occurrence of GHG emissions and its influence on the overall GHG balance was assessed with regard to two aspects (chapter 7.2.1.):

- The inclusion of the temporal occurrence of emissions of a specific year once a new equilibrium state is established (temporal aspect A, results presented in chapter 7.4.1.), shows that the consideration of this effect changes the resulting net decrease in GHG emissions of the biomethane base case, minimum change and maximum change scenario by 2, 19 and 0%, respectively. In case of the shift from straw incorporation to bioethanol production, the inclusion of the aspect into the GHG balance yields GHG reductions differing by 11, 54 and 0% from the net change in GHG emission without consideration of the temporal aspect in the base case, minimum change and maximum change scenario, respectively. The largest contributor to this effect is the decomposition rate of wheat straw. If straw decomposes slowly, emissions are released over a long period of time. In contrast, a considerable share of this carbon previously emitted through decomposition is immediately released at bioenergy production or shortly thereafter by the use of the respective biofuel. Therefore the time-integrated atmospheric load of these emissions is highest in the minimum reduction scenario in which the slowest decomposition of straw is assumed. In case of the shift to biomethane production, this effect is less pronounced due to a share of carbon is contained in organic fertilizer that is subject to decomposition as well.
- The assessment of the temporal change in emissions occurring following the years after the shift to bioenergy production (temporal aspect B) shows that a transition time occurs until a new steady state occurs. The transition time is characterized by the decrease in straw-related SOC and SOC built-up from digestate-derived organic fertilizer (only biomethane concept). In the biomethane concept it takes between 3 and 35 years until a new steady state is reached. The introduction of the bioethanol concept might ensue a transition time lasting up to 48 years. However, the overall net change in GHG emissions is negative even before the equilibrium state is reached. Depending on the decomposition of organic matter, considerable carbon payback times might occur (results presented in chapter 7.4.2). The average net changes in GHG emissions of the shift to biomethane production with consideration of the temporal change in emissions occurring over a period of 100 years are 4, 50 and 2% lower than those determined at the steady state. This is due to the higher emissions occurring within the first few years after the shift. In case of the shift to bioethanol production, the net decreases in emissions are 21 and 1% lower in the base case

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and maximum reduction scenario, respectively. In the minimum reduction scenario, the net decrease determined for the steady state turns into a net increase of 57 kg CO<sub>2</sub>-eq. per t<sub>DM</sub> straw converted to bioethanol. This is due to the high quantity of carbon formerly stored in SOC that is released following the shift to biofuel production.

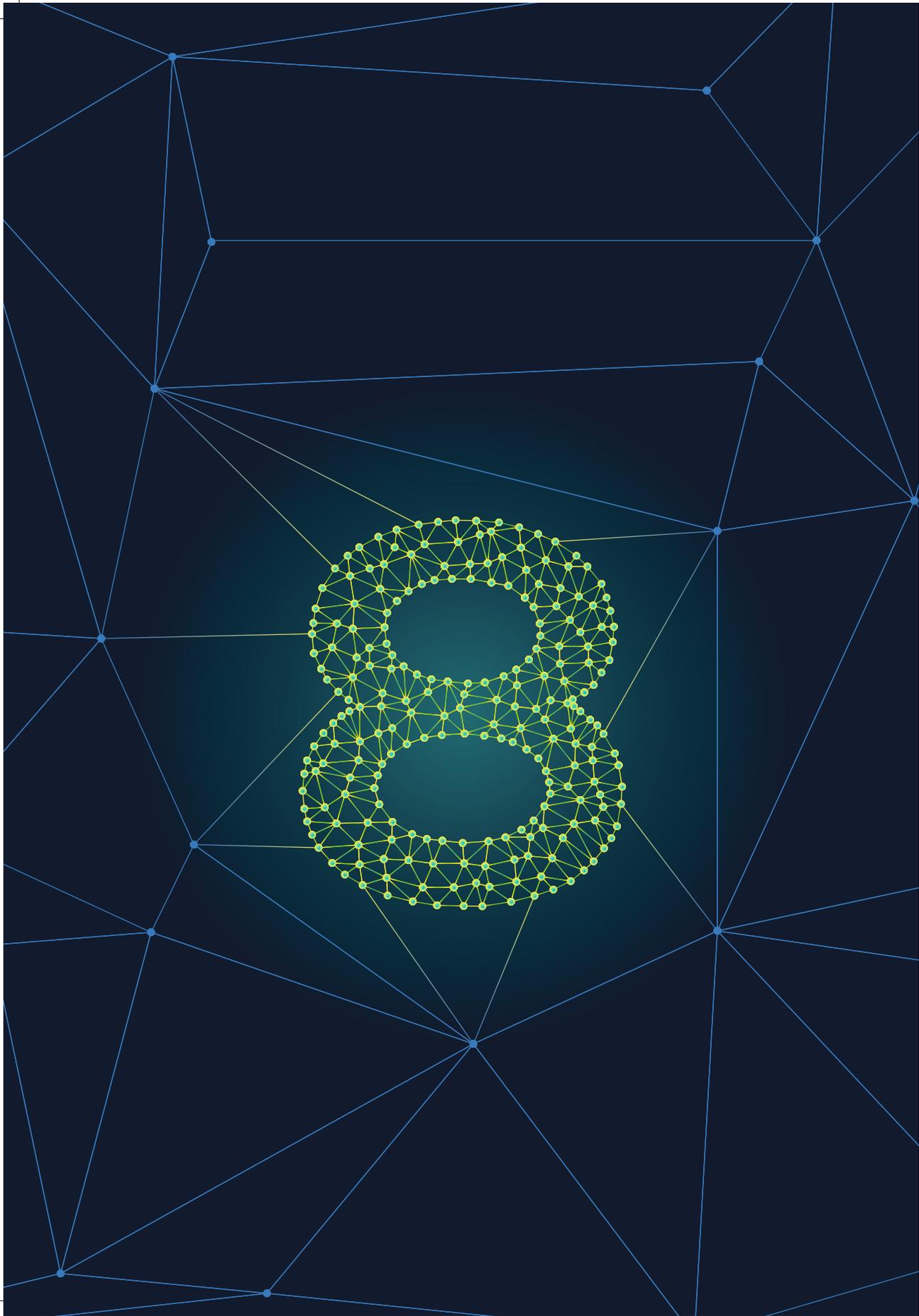
These findings show that the inclusion of temporal changes of emissions might change results considerably. In most cases, the inclusion of temporal effects leads to a lower net GHG emission reduction than determined without the consideration of the temporal pattern of emissions. On the other hand, over a 100 year time horizon, bioenergy systems lead to substantial *GHG savings* and in most cases to high net reductions in GHG emissions. The determined carbon payback times are lower than those of most forest biomass which is a widely discussed feedstock for 2G bioenergy [582, 583]. The reported payback time of forest biomass has led to questioning the capability of forest bioenergy to contribute to the needed timely reduction in (anthropogenic) GHG emissions [540]. The findings presented within this paper reveal that straw-based bioenergy on the contrary could yield reductions in GHG emissions within acceptable time-scales. Only if very high quantities of carbon are stored, long carbon payback times arise. The findings presented are connected to certain limitations:

- The change in temporal patterns of carbon release as a consequence of maize substitution is not considered. With regard to the low quantities of corn substituted, the effect is considered of minor importance.
- It is assumed that nutrient release follows the same pattern as the decomposition of organic matter. This is a simplification that does not account for complex mechanisms and biological activity involved. If these nutrients are released within days, weeks or months as estimated by the decay curve, this assumption can be considered acceptable.
- The empirical data of digestate decomposition indicate a stable fraction (as opposed to wheat straw that decomposes nearly completely within a couple of years). This stable fraction leads to higher quantities of carbon that are sequestered in SOC. As the data were inferred by incubation experiments, it can be expected that decomposition behavior in reality is different. However, long-term field studies are missing. Other literature available (incubation experiments) also reports high stable fractions of digestate that slowly decompose [584, 585].
- Biogenic CO<sub>2</sub> emissions from anaerobic digestion and especially fermentation processes may relatively easily be captured, and possibly utilized (e.g. upgraded with H<sub>2</sub> to solar fuels) or stored underground. Both could yield additional reductions in GHG emissions, but quantification is outside the scope of this paper.

Aside from these limitations, it should be noted that this study solely focuses on GHG emissions. The change in agricultural practice, the application of different types of organic fertilizers and

## Consequential GHG balance of 2G biofuels with focus on temporal aspects

the use of straw that was previously incorporated into soil as source for bioenergy results in multiple other effects on soil and soil quality than GHG emissions arising from changes in SOC. The incorporation of straw contributes to SOC formation, prevents soil erosion, increases soil porosity, influences the nutrient mobilization and immobilization and positively affects soil biodiversity. These effects need to be included to evaluate the overall sustainable straw-based bioenergy potential. Based thereon, the most sustainable concepts that allow the reduction in GHG emissions and while maintaining soil quality can be identified and measures to promote their introduction should be taken.



# Synthesis of results and conclusions

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## Chapter 8

At present, efforts are undertaken in many sectors to supply the needs of societies by more sustainable means. Among these sectors, the energy and transportation sectors together account for the majority of fossil resource use and emissions of anthropogenic GHG emissions. Therefore, efforts are undertaken to reduce GHG emissions within these sectors. To this end, legislation was enacted worldwide to gradually displace energy provision and mobility services using fossil energy carriers by non-fossil based and more sustainable alternatives. Within the EU, the RED (II) presents the most important legislation governing the introduction of renewable energy and transportation fuels by setting targets and defining certain sustainability criteria for renewable energy and transportation fuels. Among these criteria, GHG emissions were selected as the key indicator of sustainability of novel alternative fuel concepts. To this end, the RED (II) provides a methodology to estimate GHG emissions of alternative fuel production concepts, expressed as *GHG savings*<sup>20</sup>, and defines minimum *GHG savings* that need to be achieved. The methodology to determine the *GHG savings* was introduced for administrative purposes rather than for the evaluation of consequences of the ongoing and envisaged shift within the transportation sector. With regard to the ongoing and future transition towards more sustainable means of energy and fuel provision, it is therefore of crucial importance to understand the consequences that arise from the introduction of novel concepts and from mechanisms implemented in the legal framework governing the introduction of these concepts.

The aim of the presented thesis was to provide a deeper understanding of changes in GHG emissions arising from the introduction of novel biorefinery concepts and the implications of methodological choices made to evaluate these changes. To this end, the following research questions were formulated

1. What are environmental impacts and GHG emissions of biofuel concepts arising from within the production chain and which are key parameters that influence results?
2. What changes in GHG emissions are caused by the introduction of novel biofuel concepts?
3. What is the influence of a change in the temporal occurrence of emissions on the GHG balances of biofuels?

To provide answers to these questions, a selection of existing and potential future biorefinery concepts were evaluated. The assessed concepts comprise 1G and 2G concepts providing multiple other products aside from biofuels. Several approaches based on aLCA and cLCA, the RED (II) methodology as well as methods going beyond traditional LCA methodology were applied

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20 Reminder: The terminology *GHG savings* used within this chapter (and the rest of the thesis) solely expresses the value calculated by the RED (II) methodology. In order to emphasize the sole use of the expression in the context of the RED (II) methodology, and not to express any changes in emissions, the expression is written in italic. See also <sup>2</sup>.

to these concepts. Thereby a broad spectrum of potential displacement effects arising from the introduction of certain concepts is evaluated and the capabilities of different methodological approaches to evaluate changes in GHG emissions arising from changes within the biofuel industry are discussed. Table 8-1 provides an overview on the chapters in which these research questions are addressed. Chapters 8.1 to 8.3 provide a synthesis of results to provide answers to these research questions.

**Table 8-1** Overview on the evaluation of different research questions (Q) by chapter.

Chapter	Title	Q1	Q2	Q3
<b>Chapter 2</b>	Sustainability aspects of biokerosene	x		
<b>Chapter 3</b>	Life cycle assessment of bioethanol from wheat and sugar beet discussing environmental impacts of multiple concepts of co-product processing in the context of the European Renewable Energy	x		
<b>Chapter 4</b>	The influence of co-product handling methodology on greenhouse gas savings of biofuels in the European context	x	x	
<b>Chapter 5</b>	A consequential assessment of changes in greenhouse gas emissions due to the introduction of wheat straw ethanol in the context of European legislation	x	x	
<b>Chapter 6</b>	Potential changes in GHG emissions arising from the introduction of biorefineries combining biofuel and electrofuel production within the European Union – A location specific assessment	x	x	
<b>Chapter 7</b>	Straw utilization for biofuel production: A consequential GHG assessment of bioethanol and biomethane provision with a focus on the time-dependency of emissions	x	x	x
<b>Chapter 8</b>	Synthesis of results and conclusion	x	x	x

## 8.1. GHG emissions arising from the provision of biofuels and selected other environmental aspects

To answer the first research question, first a brief general overview on environmental aspects based on chapter 2 is given. Thereafter, key findings regarding GHG emissions will be presented.

### 8.1.1. Water and land demand

On a global scale, the demand for many agricultural commodities is increasing due to a growing world population and changing consumption patterns. Thus, any additional demand for these raw materials (e.g. for biofuel production) increases the already growing demand for many agricultural commodities. Additional requirements for agricultural commodities can be met either by expansion of agricultural land or by intensification of agricultural production. The expansion of agricultural land is usually accompanied by a conversion of existing land use to a new type of land use either through direct or indirect displacement of land use. Both effects affect soil properties, nutrient availability, water quality and availability, nutrient cycling and biodiversity. To provide a better understanding of the implications of different feedstocks and fuel provision concepts, comprehensive analyses were conducted to evaluate the water and land demand (chapter

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2). The analysis comprises several pathways to produce biokerosene, e.g. HEFA made from oil crops, alcoholic fermentation and subsequent processing (AtJ), direct conversion of sugars to biokerosene (DSHC) using sugar crops, as well as several methods to convert lignocellulosic material, e.g. gasification and Fischer-Tropsch-Synthesis (BTL-FT).

**Water.** The cultivation of feedstock for biofuel production, as any other cultivated crop, requires water and results in emissions of agrochemicals and fertilizers to waterbodies. Additionally, water is required for the feedstock conversion and fuel production. The analysis of water demand was conducted according to the water footprint methodology [204]. It comprises green, blue and grey water, representing evapotranspired precipitation, consumed surface and ground water as well as the water volume required to dilute pollutants to a concentration level below agreed quality standards, respectively. The analysis reveals water footprints ranging from 16 to 6405 m<sup>3</sup> per GJ of biokerosene (chapter 2.3.1.4). In all cases, the conversion step is negligible in comparison to feedstock cultivation. Among cultivated crops, rain-fed lignocellulosic feedstock (e.g. miscanthus) exhibits the lowest water demand. In general, concepts using oil crops, such as oil palm, soybean and rapeseed as well as sugar crops, such as sugar beet and sugarcane, result in a similar range of water demands (between 53 and 140 m<sup>3</sup> per GJ biokerosene). Among oil crops and sugar crops, those with highest yields, namely oil palm and sugarcane, perform better than other plants of the respective group. Interestingly, jatropha, an oil crop that has been praised an alternative feedstock to 1G feedstocks due to its ability to grow on marginal land and due to the unsuitability to be used as a food or feed crop, results in water demands that exceed other oil crops by a factor of up to seven. In addition to these conventional agricultural systems, algae are a widely discussed alternative to crops cultivated on land. The performance of concepts using algae highly depends on the system's capability of water re-use. Thus, algae derived biokerosene results in the lowest and highest water demands of all the assessed concepts depending on the recycling rate of water.

**Land demand.** The evaluation of the land demand of crops for 1G biofuel production shows that highest fuel yields can be achieved using sugarcane and oil palm, ranging from 94 to 318 and 85 to 211 GJ fuel per ha land, respectively (chapter 2.3.1.9). The lower and upper end of the ranges present low and high yielding cultivation systems and conversion efficiencies, respectively. Furthermore, the results reveal, that even the least efficient provision of biofuels from oil palm yields higher fuel quantities than the optimized cases of any other oil crop. Likewise, only few optimized production systems of sugar or cereal crops with highest yields observed globally provide fuel quantities in the range of the lower estimate for sugarcane. In addition to cultivated crops, algae present an alternative with very low land demand. In the optimized case, algae yield five times more fuel per ha than the most productive system using cultivated crops (i.e. sugarcane).

In past years, the problems connected with an increasing demand for land for the provision of agricultural commodities and space for the built environment have become apparent. Often, socio-economic structures and mechanisms exacerbated negative effects. Much criticism of these effects was directed towards 1G biofuels and have led governments to revise biofuel strategies (e.g. the cap of 1G biofuels implemented by the RED II). The presented results show that fuel provision from dedicatedly cultivated lignocellulosic material (e.g. miscanthus, switchgrass, short rotation coppice) might result in higher land demand than conventional 1G fuel provision. Furthermore, certain feedstocks for 1G biofuel production (i.e. palm oil) received much criticism for being responsible for the extensive conversion of natural forests into plantations observed in recent decades. The analysis reveals that oil palms could provide a much higher output per ha than any other feedstock except algae. It can be concluded that mechanisms and efforts to replace palm oil derived products (e.g. through legislation as the RED II or customer awareness regarding commercial products containing vegetable oils) should be backed by

- sustainability criteria that are applied to all agricultural resources regardless of their use: All assessed crops can be used for many other purposes than biofuel production. Only applying sustainability criteria to one use sector might just provoke producers to shift supply that is considered sustainable to those sectors where sustainability compliance is demanded while funneling the remainder to other sectors and markets where no such measures are in place;
- mechanisms that ensure the prevention of an increase in land demand resulting from a shift in vegetable oil crop cultivation. If certain feedstock is banned from biofuel production, e.g. palm oil, it must be ensured that palm oil is not substituted by other vegetable oils (all of which have much lower yields and thus might even worsen negative effects observed from LUC).

These considerations emphasize the need of legislation and mechanisms that comprehensively target the overall agricultural commodity market. Legislation that restricts the use of certain feedstock in the biofuel sector might not result in desired effects as long as no mechanisms are in place that prevent burden shifting.

### **8.1.2. GHG emissions arising from within the production chain**

In addition to legal requirements as defined by the RED (II), climate change has turned out to be the most important environmental aspect discussed in the scientific, political and public debate. Due to this reason, GHG emissions arising from the introduction of alternative fuel concepts were chosen as a key element to be investigated within this thesis.

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The first research question refers to GHG emissions occurring within the production chain of biofuel supply. With regard to the GHG emissions occurring within the biofuel provision chain, the conducted analyses comprised in this thesis have three foci:

1. A comparison of a wide range of 1G concepts evaluating GHG emissions and *GHG savings*;
2. A comparison of selected 1G concepts and a wide range of 2G concepts with a focus on GHG emissions and *GHG savings*; and
3. The implications of location on most important parameters and *GHG savings* of 1G and 2G concepts.

Key findings regarding these three foci presented in the following chapters are addressed in detail in chapters 3 and 4, 5 to 7, and 6, respectively. Chapters 8.1.2.1, 8.1.2.2 and 8.1.2.3 summarize the key findings regarding the first research question and the three foci. The first two aspects are discussed for biofuel production in Germany, the latter comprises biofuel production in all EU member states except Cyprus and Malta. At last, a synthesis of key findings is given to provide answers to the first research question.

### 8.1.2.1. Comparison of 1G concepts

In order to provide a deeper insight into key parameters governing the total GHG emissions and methodological aspects associated with analyzing emissions arising from within the production chain, a wide selection of biofuels from 1G feedstock was assessed in chapters 3 and 4. The analysis comprises several concepts for the production of bioethanol from different feedstock (Table 8-2).

**Table 8-2** Concepts discussed in chapter 8.1.2.1.

Feedstock	Provided co-products aside from ethanol ( <i>and milling process</i> )
Wheat grains	<i>Dry milling:</i>
	Dry protein feed production (DDGS)
	Dry protein feed (DDGS) and electricity
Sugar beet	<i>Wet milling:</i>
	Feed and food additive (Bran, CDS and gluten)
	Bioenergy (biogas that is internally used to provide process energy)
Corn	Feed (beet slices and molasses)
	Bioenergy (biogas that is internally used to provide process energy)
	<i>Dry milling:</i>
Dry (DDGS)	
<i>Wet milling:</i>	
Food additive and feed (Gluten, gluten feed meal, and corn germ oil)	

**Total GHG emissions.** The overall GHG emissions arising from feedstock provision, biofuel production, transportation processes and fuel use of these processes range from 42 to 126 g CO<sub>2</sub>

per MJ of biofuel produced. The lowest emissions occur in concepts providing bioethanol from sugar beet (42 to 59 g CO<sub>2</sub>-eq. per MJ bioethanol). Wheat and corn used as feedstock result in higher GHG emissions (56 to 79 and 78 to 125 g CO<sub>2</sub>-eq. per MJ of fuel produced, respectively). The variability of results mainly arises from feedstock cultivation and energy provision:

- Feedstock provision.** In case of 1G ethanol made from wheat grains, the overall contribution of feedstock provision ranges from 37 to 75% of overall GHG emissions. The use of sugar beet as feedstock results in lower overall emissions related to feedstock provision. This is mainly due to high yields of sugar beet. The high share of emissions attributed to feedstock provision mainly arises from fertilizer induced N<sub>2</sub>O emissions. This is especially critical concerning the high GWP of N<sub>2</sub>O, the variability of reported emission factors and the high uncertainties related to these. It is common practice to apply the IPCC emission factor of 0.01 (0.003 – 0.03) kg N<sub>2</sub>O-N per kg applied N to estimate direct emissions [230]. The broad range gives an indication of the uncertainty related to the fertilizer induced N<sub>2</sub>O emissions. In chapter 3, an emission factor for direct emissions based on measurements in northern Germany was applied. The measurements reveal higher emissions amounting to 0.0175 kg N<sub>2</sub>O-N per kg applied N [376], which is considerably higher than the emission factors provided by the IPCC. Furthermore, a high variability of emission factors is reported. The second most important contributor to cultivation emissions is mineral fertilizer production. Literature data applied in the presented analyses reveal a high variability of GHG emissions related to fertilizer provision. Differences among applied datasets amount up to about 11 g CO<sub>2</sub>-eq. per MJ of bioethanol from wheat straw.
- Energy provision.** In all analyzed concepts, energy provision presents the second most important contributor to overall emissions after feedstock provision. The higher energy requirements of sugar beet-based ethanol production partly offset the lower GHG emissions from feedstock provision. In all cases, production and internal use of biogas drastically reduces emissions compared to other concepts using natural gas, e.g. the DDGS and the biogas concepts emit between 74 and 106 and between 56 and 61 g CO<sub>2</sub>-eq. per MJ of bioethanol, respectively. Furthermore, evaluated concepts comprise two different designs of energy provision by CHP cogeneration: one concept provides energy to fulfill only its demand and supplies only low amounts of surplus electricity to the grid. The other concept provides of high quantities of surplus electricity comes at the cost of lower thermal efficiencies and is therefore connected with higher total emissions. The overall difference in these two concepts is 32 g CO<sub>2</sub>-eq. per MJ of bioethanol.

The energy demand is feedstock-dependent and depends on the overall concept setup providing specific co-products. Among concepts using wheat grain, highest emissions occur if high quantities of surplus electricity are provided aside from DDGS (106 g CO<sub>2</sub>-eq. per MJ bioethanol).

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Concepts providing DDGS without additional production of high quantities of surplus electricity emit between 62 and 79 g CO<sub>2</sub>-eq. per MJ. Alternatively, gluten and feed can be provided. This concept has higher energy requirements and therefore results in higher emissions (90 g CO<sub>2</sub>-eq. per MJ bioethanol).

Thus, depending on the co-products provided, the overall emissions might differ considerably and is important how the provision of products is accounted for.

**Evaluation based on RED (II) methodology and methodological aspects.** Several methodological approaches to account for multi-functionality of product systems exist. Apart from several pure allocation methods, the methodology provided by the RED was applied to determine *GHG savings*. According to the RED methodology, emissions are allocated to all products based on their energy content, except for surplus electricity and captured biogenic CO<sub>2</sub> that replaces fossil derived CO<sub>2</sub> in commercial products and services. In these two cases, credits are granted. In order to allow a comparability of results with the following chapters, *GHG savings* were converted to *GHG savings* according to RED II methodology (adaption of fossil reference and credits given for electricity). Among wheat- and corn-based ethanol concepts, concepts providing DDGS aside from ethanol yield highest emission savings (51 to 56%). The concepts providing electricity aside from DDGS yield *GHG savings* of 53%. The other concepts using wheat grain result in *GHG savings* of 49 and between 34 and 42%, in case of gluten provision and the production and internal use of biogas, respectively. Concepts that result in highest overall emissions also achieve higher *GHG savings* and vice versa. Similar results can be observed at sugar beet-based ethanol production: feed production emits between 55 and 64 g CO<sub>2</sub>-eq. per MJ and results in *GHG savings* between 59 and 62%, whereas the provision and internal use of biogas results in emissions ranging from 42 to 47 g CO<sub>2</sub>-eq. per MJ ethanol and *GHG savings* ranging from 52 to 56%. These results show that the RED (II) benefits additional energy expenditures in case of 1G biofuel concepts if additional dry products or electricity are provided. In case of production and internal use of biogas, the RED methodology fails to reflect the overall low emissions occurring within the production system. Furthermore, due to the allocation based on the energy content of products, additional efforts to provide products lacking a lower heating value (e.g. mineral fertilizer derived from digestate) are not valued by the RED (II) methodology.

### 8.1.2.2. Comparison of 2G concepts

In chapters 5 to 7, multiple 2G ethanol concepts were analyzed that should characteristically stand for a variety of potential options to use side-streams arising from ethanol production. In total, 24 concepts comprised of a combination of the following elements were evaluated (Table 8-3).

**Table 8-3** Evaluated 2G concepts. Each evaluated concept is comprised of one option of each concept element.

Concept element	Options evaluated
Pretreatment (2)	Steam explosion Organosolv
Processing of unfermented sugars (4)	<i>Fermentation of hexose:</i> Molasses production Biogas production (fed into the grid) Xylitol production <i>Co-fermentation of pentose and hexose:</i> Molasses production
Processing of biogenic CO <sub>2</sub> (3)	Liquefaction (base case) Methanation Methanol synthesis

The concepts use either steam explosion or organosolv pretreatment. The former concept includes the energetic use of the arising lignin stream. The latter yields high purity lignin that can be used as a substitute for fossil products, e.g. phenol-formaldehyde resin. These concepts were selected because they present a current and a potential future approach on how to use lignin. To date, most biorefineries use lignin energetically. However, alternative uses might be desired to increase profitability and to provide a renewable resource to further production processes. For both pretreatment concepts, hexose and co-fermentation of pentose and hexose are evaluated. For each of the two pretreatment options, four concepts of co-product processing are assessed: if only hexose is fermented, pentose sugars are processed to molasses, biogas (which is purified and fed into the gas grid) or xylitol. In case of co-fermentation of pentose and hexose, only low quantities of molasses are provided from the remaining unfermented sugars. For each of these eight concepts, three options to process arising biogenic CO<sub>2</sub> are evaluated: liquefaction as well as synthesis to methane or methanol using additional hydrogen from alkaline electrolysis. Two energy provision scenarios are evaluated: the provision of process energy by natural gas and electricity drawn from the grid (if the CHP unit does not provide sufficient electricity) as well as energy from renewables (straw for energy supply and renewable electricity from the grid).

**Total GHG emissions.** The total GHG emissions of 2G steam explosion concepts range from 22 to 48 g CO<sub>2</sub> per MJ of bioethanol provided. Lowest emissions arise if pentose and hexose are co-fermented. If only hexose is fermented, emissions amount to 31, 38 and 48 g CO<sub>2</sub> per MJ of fuel in case of feed, biogas and xylitol production, respectively. If organosolv pretreatment is conducted, overall emissions range from 151 to 264 g CO<sub>2</sub>-eq. per MJ of bioethanol. In this case, biogas production and co-fermentation result in the highest and lowest GHG emissions, respectively. Feed production and xylitol co-production result in overall GHG emissions of 198 and 243 g CO<sub>2</sub>-eq. The share of feedstock provision of the overall emissions ranges from 19 to 24 and from 2 to 3% in case of steam explosion and organosolv pretreatment, respectively. The share

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of feedstock in the steam explosion concepts is higher because of low overall emissions resulting from lignin combustion. In contrast, the organosolv process requires considerably more heat and does not use lignin for energy provision. This is reflected in the high share of emissions related to energy provision in organosolv concepts ranging from 91 to 94%. Additional methanation or methanol synthesis of the arising  $\text{CO}_2$  stream increases overall emissions by 40 to 127 and 20 to 73 g  $\text{CO}_2$ -eq. per MJ bioethanol produced. Highest additional emissions occur in biogas scenarios where higher quantities of  $\text{CO}_2$  are converted to methane and methanol. This again shows that energy generation presents the most important parameter governing overall GHG emissions.

**Evaluation based on RED (II) methodology and methodological aspects.** Of the two compared pretreatment concepts, only the steam explosion concepts comply with minimum *GHG saving* threshold: The *GHG savings* achieved by the steam explosion concepts providing feed, biogas, xylitol and feed (co-fermentation) are 109, 107, 128 and 113%, respectively. In case of both concepts providing feed, the low total GHG emissions are the reason for high *GHG savings* in comparison to the other concepts. The concept providing xylitol results in highest emissions and has fewer product output. However, *GHG savings* are high due to high amounts of captured biogenic  $\text{CO}_2$ . The biogenic conversion of xylose to xylitol produces  $\text{CO}_2$  that can be additionally captured. The RED (II) grants credits for the arising  $\text{CO}_2$  equaling the amount of  $\text{CO}_2$  captured. In reality however, the captured  $\text{CO}_2$  would not result in a likewise reduction in fossil  $\text{CO}_2$  as fossil derived  $\text{CO}_2$  is a waste product. Thus, even supplying  $\text{CO}_2$  would not trigger a direct reduction in  $\text{CO}_2$  emissions. If at all, GHG emissions related to the capturing of  $\text{CO}_2$  could be avoided. This mechanism thus benefits concepts providing (and capturing) large  $\text{CO}_2$  streams while not reflecting any change in emissions occurring. In addition: The RED II methodology otherwise focuses only on GHG emissions arising from within the production chain and neglects effects that occur through displacement effect from provided products. Thus, granting credits for  $\text{CO}_2$  and allocating emissions to all other products is meaningless from a conceptual point of view. If energy is alternatively supplied by renewables, *GHG savings* (and overall GHG emissions) of the respective concepts do not change. This is due to the fact that the processes are self-sufficient through lignin combustion.

The evaluated organosolv concepts result in *GHG savings* of 44, 20, 37 and 46% in case of provision of feed, biogas, xylitol as well as co-fermentation, respectively. All of these concepts fail to comply with the minimum *GHG saving* thresholds. The overall process is highly energy intensive and the provision of energy from natural gas result in high emissions. This is not compensated by lower emissions allocated to bioethanol (through the provision of an additional product – lignin). In contrast to steam explosion concepts, the evaluated organosolv concepts benefit by the use of renewable energy. If renewable energy is used, *GHG savings* range from 91 to 97%.

The additional provision of methane or methanol from the arising CO<sub>2</sub> stream lowers *GHG savings* by a high extent, if electricity is drawn from the grid. In these cases, *GHG savings* are reduced to values ranging between 30 and 50% of the *GHG savings* achieved without additional production of methane or methanol. If the German renewable electricity mix is used instead, *GHG savings* range from 58 to 80%. Thus, the additional electrofuel production lowers *GHG savings* of steam explosion concepts. In case of the organosolv concepts using renewable energy, *GHG savings* increase by a smaller extent if methane or methanol are produced instead of CO<sub>2</sub> liquefaction. This is due to the credit that is granted for liquefied CO<sub>2</sub> but not for PtX<sup>21</sup> processes. The RED II states that credits are granted for CO<sub>2</sub> that is “used to replace fossil-derived CO<sub>2</sub> in production of commercial products and services” [47]. In this case, there are several unclear and inconsistent aspects:

- If conventional fossil methane or methanol are considered as the reference, the use of arising CO<sub>2</sub> for electrofuel production should not be credited as it does not replace CO<sub>2</sub> in commercial products (it displaces the emission of CO<sub>2</sub> from commercial products).
- If a replacement of fossil-derived CO<sub>2</sub> in PtX processes is assumed as a reference, credits could be granted according to the quoted definition. This however entails several inconsistencies of the RED II methodology:
  - If the biorefinery sold biogenic CO<sub>2</sub> as a feedstock for PtX processes, credits could be granted. This however grants credits for displacements that do not occur: if biogenic CO<sub>2</sub> displaced captured fossil CO<sub>2</sub> in the PtX processes, the fossil CO<sub>2</sub> would be emitted instead of being captured (as it is a waste gas stream and thus an inflexible “supply”). Thus, in sum, no net reduction in CO<sub>2</sub> arises from the carbon balance. Consequently, a credit is not justifiable based on the carbon balance.
  - If the PtX processes are integrated into the biorefinery, no CO<sub>2</sub> stream arises and thus, no credit can be granted. In this case, another product arises to which emissions are allocated.

It is inconsistent to apply two different approaches depending on whether the captured biogenic CO<sub>2</sub> is sold to PtX processes or used within the biorefinery for PtX processes. In the former case, applying credits implies displacement effects that do not occur. In the latter case, allocation emissions might even lower overall *GHG savings* of the primary products (in this case, bioethanol).

These aspects present a predicament: on the one hand, not granting credits might reduce incentives to additionally provide feedstock to PtX processes (especially if blending mechanisms

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21 The terminology PtX signifies power-to-X. It describes processes aiming at using (surplus) electricity in production processes (e.g. production of heat, fuels, chemicals, fertilizer). Using an additional carbon source allows the synthesis of carbon-based chemicals and fuels.

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based on *GHG savings* are in place resulting in differing market values according to the achieved *GHG saving*). On the other hand, granting credits implies displacement effects that do not occur. Furthermore, this requires a revision of the allocation principle within the RED II: all products produced from arising CO<sub>2</sub> must be excluded from the allocation rule if credits are granted.

### 8.1.2.3. *The influence of location on the variability of key parameters, GHG emissions and GHG savings*

The previous two chapters pointed out that in most cases, overall GHG emissions highly depend on energy provision and feedstock supply. These GHG emissions related to these two aspects differ within European countries. Therefore, these parameters were assessed for all European countries, except Malta and Cyprus (chapter 6). Based thereon, overall GHG emissions and *GHG savings* of the 2G concepts discussed in chapter 8.1.2.2 (Table 8-3) and other selected 1G concepts (concepts using wheat grain listed in Table 8-2) were evaluated. The key results regarding GHG emissions of energy supply and feedstock provision are:

- **Electricity supply:** The GHG intensity of average electricity supply ranges from 4 to 227 g CO<sub>2</sub>-eq. per MJ. The lowest GHG intensities can be found in Sweden, Lithuania and France. Greece, Poland and Estonia exhibit highest emission intensities.
- **Natural gas supply:** The GHG intensity of average natural gas supply ranges from 7 to 39 g CO<sub>2</sub>-eq. per MJ. Lowest GHG intensities can be found in Sweden, Denmark and the United Kingdom. These countries use high shares of natural gas extracted in the Northern Sea entailing comparably low GHG emissions. In addition, the Swedish natural gas mix comprises the highest share of biogas. The highest GHG intensity of natural gas can be found in Bulgaria, Slovenia and Greece.
- **Feedstock provision:** The GHG emissions related to wheat grain supply range from 430 to 593 g CO<sub>2</sub>-eq. per kg of wheat grain. Highest emissions occur in Portugal, Estonia and Greece due to low yields.

The variation in these parameters results in considerable variation in overall GHG emissions and *GHG savings* depending on location. The assessment of *GHG savings* of 1G concepts reveals a high variability among concepts in different countries: the *GHG savings* range from 44 to 60, 34 to 53, and 47 to 66 in case of concepts providing DDGS, CDS, gluten and bran, as well as biogas, respectively. The lowest *GHG savings* of 1G concepts occur in Greece, Portugal and Estonia, confirming the high influence of energy supply and feedstock provision. The RED II provides a default and typical *GHG savings* values of 46 and 53% for cereal grain ethanol using natural gas CHP for energy provision (no specification on co-product processing). The variability of 2G concepts using steam-explosion remains below 2% because process energy supplied by lignin. In case of organosolv pretreatment, concepts providing feed, biogas, xylitol

and feed (co-fermentation) result in *GHG savings* of 35 to 60, 7 to 42, 25 to 58 and 36 to 62%, respectively. The default and typical *GHG saving* for 2G bioethanol are 85 and 83% (again unspecific regarding process setup and co-production modalities). Thus, depending on the concept and location, achieved *GHG savings* might differ considerably. If methane and methanol are produced from captured biogenic CO<sub>2</sub>, similar effects as discussed in chapter 8.1.2.2 occur. Again, *GHG savings* are lower if captured biogenic CO<sub>2</sub> is used to provide methane or methanol. In these cases, national electricity generation mixes gain importance. The variability of *GHG savings* among countries therefore increases.

The analysis confirms the high influence of energy supply and feedstock provision. Furthermore, achieved *GHG savings* vary considerably between different process setups, production modalities and locations. In contrast, the RED II only provides generic default GHG emissions and *GHG savings*. The presented findings point out that standard values, as provided by the RED II, should be location- and process-specific.

#### 8.1.2.4. *Synthesis of findings regarding GHG emission occurring within the production chain and the RED (II) methodology*

The attributional approach was applied to provide insights into the GHG emissions arising from within the biofuel provision chain. The results of the conducted analyses reveal that the GHG emissions of the assessed concepts mainly depend on two factors: feedstock and process energy supply. Due to the high influence of feedstock (especially in case of 1G concepts) and energy supply, the performance of concepts strongly depends on local conditions. The analysis of GHG emissions and *GHG savings* based on data derived from 26 EU member states reveals a high variability in results depending on the location of the facility. The overall energy demand of processes depends on the used feedstock and process setup. Increasing complexity of product processing or in pretreatment of lignocellulosic material, e.g. gluten separation and drying, xylitol production or organosolv pretreatment, considerably increase the overall GHG emissions. The *GHG savings* determined by the RED (II) methodology only partly reflect these increases in emissions. In addition, product systems that internally use most of the side streams for energy provision (e.g. biogas production and internal use of biogas for energy provision) lack co-products to which emissions are allocated. These concepts result in lower *GHG savings*, even though overall emissions are lower. If products are provided lacking a lower heating value, these are not considered by the applied allocation methodology. This approach clearly reduces the incentive to provide products other than energy carriers and/or dry products with a high energy content.

Another potential barrier in the way of the development of integrated biorefineries that seek to maximize the use of carbon contained in biomass was found regarding the provision of methane and methanol made from biogenic CO<sub>2</sub> arising from fermentation and anaerobic digestion.

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The RED (II) grants credits for captured biogenic CO<sub>2</sub> that replaces fossil CO<sub>2</sub> in commercial products. A strict interpretation of this rule implies that no credits are granted if CO<sub>2</sub> is used in PtX processes and if fossil derived counterparts (e.g. methanol or methane) are considered to be substituted. In such a case, the PtX fuel substitutes CO<sub>2</sub> resulting from the combustion of the respective fuel (and does not displace fossil CO<sub>2</sub> in a production process). If credits were given for captured biogenic CO<sub>2</sub> assuming a replacement of fossil CO<sub>2</sub> in PtX production processes instead, methodological inconsistencies arise. Such credits would be granted if the biorefinery sold the captured CO<sub>2</sub> (analogously to any other CO<sub>2</sub> that is sold to replace fossil derived CO<sub>2</sub> in conformity with the rule of the RED (II)). In contrast, the biorefinery process would not receive any credits if the biorefinery were an integrated process in which all processes are interconnected. In such a case, an additional product (e.g. methane or methanol) is provided to which emissions need to be allocated to according to the RED II methodology. Furthermore, granting credits for captured CO<sub>2</sub> equaling the amount of CO<sub>2</sub> captured disregards potentially occurring displacement mechanisms. At present, fossil CO<sub>2</sub> is a waste gas and providing biogenic CO<sub>2</sub> would not reduce any emission of fossil CO<sub>2</sub>. Even if the captured biogenic CO<sub>2</sub> replaced fossil CO<sub>2</sub> in PtX processes, the fossil CO<sub>2</sub> would still be emitted. At the most, emissions arising from the capture of fossil CO<sub>2</sub> is avoided through the supply of biogenic CO<sub>2</sub>. It is therefore questionable whether the credit for CO<sub>2</sub> serves any other purpose than increasing *GHG savings* of alternative fuel concepts while not reflecting any potential effect that could arise from CO<sub>2</sub> capturing. These aspects point out that with the rise of novel concepts using CO<sub>2</sub> as a feedstock, new methodological approaches are needed. So far, no methodology to assess sustainability of PtX processes accompanying the RED II was developed. The presented findings point out that this methodology should specifically address the interlinkage between biorefineries and PtX processes.

Conceptually, the RED (II) methodology focuses on GHG emissions arising from within the production system and use phase of fuels and excludes processes and effects outside of the life cycle of the fuel (except for surplus electricity and captured CO<sub>2</sub> for which these effects are included incorrectly reflecting potentially occurring changes). The determined *GHG savings* therefore only reflect a relative comparison of aspects occurring within the system. If future modes of transportation and fuel supply are to be assessed, it is also important to understand implications of the shift from present structures to the proposed alternatives.

### 8.2. Changes in GHG emissions arising from the introduction of biofuel concepts

The introduction of alternative fuel concepts within the EU has likely been driven by political measures, such as the RED (II). These measures are aimed at replacing the supply of fossil energy with renewable alternatives. To this end, biofuels have been introduced in recent years and 2G biofuels will be introduced under the regime of the RED II. In order to evaluate the potential

implications of a shift from present fuel provision to biorefinery concepts, a cLCA approach was applied. The consequential approach allows the evaluation of potential changes in emissions as a consequence of certain decisions. The introduction of biorefinery concepts increase the demand for feedstock, energy and energy carriers as well as all other auxiliary materials. The provision of all products potentially triggers changes in demand for the respective substitutes. These effects changing GHG emissions in the respective sectors can be attributed to the decision to introduce the respective biofuel concept. The EU allows member states to choose their own mechanism on how the quantity of biofuels to be blended with fossil fuel is determined. In these regards, two main aspects were addressed to evaluate potential changes in GHG emissions as a consequence of changes within the biofuel industry (research question 2):

1. The changes in emissions arising from the introduction of certain biorefinery concepts in 26 EU member states through blending based on the energy content; and
2. The changes in GHG emissions resulting from the introduction of biorefinery concepts through blending based on the *GHG savings*.

The first blending mechanism is evaluated in chapter 6 for a wide selection of concepts. The production and introduction of these fuels is assessed for 26 EU member states. The second blending mechanisms is addressed in chapter 5 and focuses on a smaller selection of 2G concepts.

### **8.2.1. Changes in GHG emissions resulting from the introduction of biorefinery concepts through blending based on the energy content**

Most European countries enacted legislation that regulates the blending of biofuels according to the energy content. In this case, blending mandates define a certain fixed quantity of alternative fuel to be blended with conventional fossil fuel based on the energy content. To assess changes in emissions arising from the introduction of 2G concepts under such a blending mechanism, concepts discussed in chapter 8.1.2.2 (Table 8-3) and other selected 1G concepts (concepts using wheat grain listed in Table 8-2) were evaluated. Again, two scenarios were considered: a conventional and a renewable energies scenario. The results presented in chapter 8.1 revealed that most important contributors to GHG emissions, feedstock and energy supply, show a high variability within the EU. Therefore, the change in emissions arising from the introduction of these concepts in 26 EU member states was evaluated with consideration of local differences in these parameters. Based on market statistics, the GHG intensity of marginal supply and marginal decrease in production were determined:

- **Marginal electricity supply:** GHG intensities of marginal electricity supply were determined for three cases: comprising all energy sources decreasing or increasing supply as well as a marginal supply comprising only renewable sources that increased production. The

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latter change in the market could occur if the provider acquires certificates for renewable energy that ensure an increase in renewable energy production. The GHG intensity of the marginal increase in electricity supply considering all electricity sources ranges from 8 to 215 g CO<sub>2</sub>-eq. per MJ. Low GHG intensities occur in countries in which the majority of the increase in electricity demand was fulfilled by renewable energy sources. Only in few countries, the supply of electricity from certain fossil sources increased within the assessed period (e.g. Estonia, Netherlands, Czech Republic, Germany, Poland and Portugal)<sup>22</sup>. The highest GHG emissions occur in Estonia, where a considerable share of electricity is derived from oil shale. The GHG intensity of all sources decreasing supply ranges from 40 to 662 g CO<sub>2</sub>-eq. per MJ. The highest GHG intensity of a decrease in demand occurs in Estonia where electricity generation from oil shale constitutes 86% of all sources decreasing supply. The weighted average GHG intensity of all renewable sources that increased ranges from 7 to 38 g CO<sub>2</sub>-eq. per MJ. Lowest GHG intensities occur in countries with a high increase in electricity production from wind and solar PV. This is the case in most countries, except countries in which other renewable sources increased entailing higher GHG emissions (e.g. biogas in Czech Republic and Latvia).

- **Marginal natural gas supply:** The GHG intensity of a marginal increase in production of natural gas ranges from 9 to 45 g CO<sub>2</sub>-eq. per MJ. Lowest GHG intensities can be found in countries that increase their imports of natural gas extracted in the Northern Sea entailing comparably low GHG emissions (e.g. Denmark, United Kingdom, and Ireland). In contrast, a marginal increase in demand for natural gas entails high GHG emissions in countries increasing liquefied natural gas imports from Algeria and compressed natural gas imports from Russia. Russia presents the most important trading partner of many European countries and many countries increase imports of natural gas from Russia. The GHG intensity of Russian natural gas ranges from 29 to 40 g CO<sub>2</sub>-eq. per MJ depending on the location of natural gas use. If the demand for natural gas decreases (e.g. through the supply of biomethane) and assuming that this supply in the long-term contributes to observed market trends, changes in GHG emissions range from 8 to 53 g CO<sub>2</sub>-eq. per MJ. In most countries domestic supply or supply from other EU countries decreases. Highest reductions occur in countries that reduce their imports of liquefied natural gas from Algeria (e.g. Slovenia).
- **Marginal feedstock provision:** The introduction of biofuel concepts increase the demand for feedstock. This is especially relevant in case of 1G fuels, where additional demand for sugar, starch or oil crops could potentially only be partly supplied through intensification. If an increase in demand cannot be met by intensification (and if demand stays constant), expansion of agricultural land occurs. The inclusion of potential LUC effects considerably increases the GHG emissions related to feedstock supply. The magnitude of LUC emissions

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22 Only countries are named in which the share of fossil electricity provision of the overall increase in electricity production was above 15% in the assessed period.

strongly depends on the location where LUC occurs and the entailed loss of SOC. If LUC occurs and set aside land is converted to agricultural land within the EU, the additional GHG emissions range from 0.17 to 1.6 kg CO<sub>2</sub> per kg wheat grain. This corresponds to GHG emissions ranging from 82 to 274 and from 93 to 311 g CO<sub>2</sub> per MJ bioethanol produced in case of 1G dry milling and 1G wet milling concepts, respectively.

Apart from these aspects, marginal supply of all affected products was determined. The results reveal that most 2G concepts result in overall net reductions in GHG emissions regardless of the location (Figure 8-1). The variability in changes in GHG emissions is lowest in 2G steam explosion concepts without any additional production of methane or methanol because concepts are mostly self-sufficient in energy supply. The highest variation in these concepts can be observed at concepts providing molasses. The variation stems from the provision of feed and potentially entailed emissions arising from LUC. In addition to the ranges of GHG emissions, Figure 8-1 shows the results for the locations where the lowest and highest GHG intensities of marginal feedstock supply as well as the marginal supply of natural gas and electricity occur. This shows that results of 1G concepts strongly depend on the marginal supply of feedstock. The results of 2G concepts rather depend on energy supply. Concepts with methanation of captured CO<sub>2</sub> and of biogas are furthermore dependent on the marginal displacement of natural gas (other concepts than those located in countries with highest GHG intensities of marginal supply of feedstock and process energy result in highest net reduction in GHG emissions).

In case of 1G fuels, only DDGS production results in a decrease in emissions, all other concepts result in decreases and increases in GHG emissions depending on the location. A likely substitute for protein feed (e.g. DDGS) is imported soybeans or soybean meal combined with domestically sourced cereal grains (to complement the nutrient content of feed). Trade statistics reveal a declining trend in imports from Brazil. If the supply of protein feed contributes to these trends, reduction in GHG emissions related to LUC can amount to up to 4.8 (0.1 to 18.2) kg CO<sub>2</sub>-eq. per kg DDGS supplied, corresponding to 194 (4 to 737) g CO<sub>2</sub>-eq. per MJ of bioethanol. The displacement of soybean cultivation however could increase the demand for vegetable oil because soybean oil is supplied no longer in such a case. This is likely to increase the demand for palm oil, which was identified as the marginal source of vegetable oil supply worldwide. In past years, increasing palm oil demand has led to a considerable conversion of native forests to palm oil plantations. These effects lower the potential positive effects from displacing soybean meal and cereal grains by about 0.8 kg CO<sub>2</sub>-eq. per kg DDGS corresponding to 32 g CO<sub>2</sub>-eq. per MJ bioethanol. In sum, LUC contributes by between 45 and 51% to the overall emission reductions from displacement effects of the DDGS concept. Instead of soybean meal, rapeseed meal could be substituted. Such a displacement of rapeseed potentially increases the demand for vegetable oil. If this vegetable oil is derived from oil palm cultivation, overall emissions could even increase

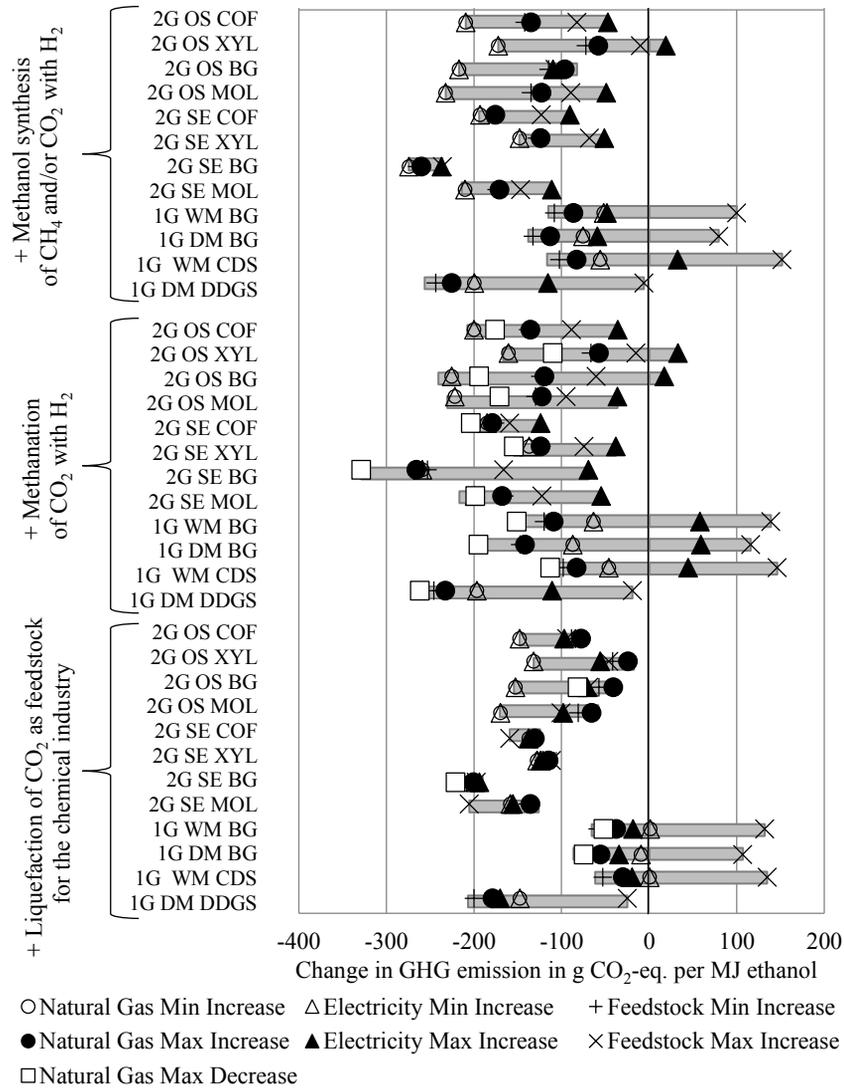
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as a consequence of the supply of DDGS due to the high oil content of rapeseed (that is supplied no longer). Other evaluated concepts also provide feed, e.g. CDS and molasses. Due to the lower nutrient content, emission changes entailed to substitution effects are smaller in these cases.

A comparison of *GHG savings* determined by the RED II methodology (chapter 8.1.2.3) with these results<sup>23</sup> reveals that *GHG savings* of the RED II strongly overestimates the *GHG savings* of all 1G concepts: in 91% of all 1G concepts (except DDGS concepts) located in all 26 countries, the RED overestimates savings. In case of DDGS production, overestimation occurs in 23% of cases (i.e. six countries). In contrast to 1G concepts, *GHG savings* of 2G concepts are strongly underestimating the potential reduction in GHG emission through the introduction of the respective concepts: in 99 and 50% of all steam explosion and organosolv concepts, respectively, *GHG savings* determined by the RED II underestimate potential GHG emission reductions. According to minimum *GHG saving* thresholds defined in the RED II, organosolv concepts could not be introduced to the European market. However, the inclusion of potential displacement effects reveals that these concepts result in overall net reductions in GHG emissions. An additional provision of electrofuels increases the variability in net changes in GHG emissions due to the increasing importance of the electricity supply. In 79 and 88% of all concepts and locations, the additional production of methane and methanol, respectively, result in a higher net decrease in GHG emissions. A comparison of determined changes in emissions and *GHG savings* reveals that the RED II methodology underestimates the reduction in GHG emissions of 1G, 2G steam explosion and 2G organosolv concepts in 60, 97, and 95%, respectively in case of methane production. In 55, 97 as 98% of cases, the RED II methodology underestimates *GHG savings* if methanol is additionally produced in case of 1G, 2G steam explosion and 2G organosolv concepts, respectively.

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23 Analogously to the RED II methodology, savings were determined by dividing the difference between emissions occurring without the biofuel concept (fossil reference) and the emissions from the biofuel concept by the fossil reference.



**Figure 8-1** Ranges of changes in GHG emissions arising from the introduction of biofuel concepts using wheat grain and straw as feedstock, including CO<sub>2</sub> utilization and taking into account location-specific feedstock provision as well as electricity and natural gas supply. Results reflect a shift from the presently existing system of product supply and straw use (incorporation into the soil) to bioenergy production. Additionally, results of countries with lowest and highest GHG intensities related to marginal supply of feedstock, natural gas and electricity are depicted. Concepts depicted are listed in Table 8-2 (only concepts using wheat grain) and Table 8-3. Abbr.: Pre-treatment: DM – dry milling, OS – organosolv, SE – steam explosion, WM – wet milling; Sugar stream processing: BG – biogas production, COF – co-fermentation (molasses production from unfermented sugars), MOL – molasses production from pentose and unfermented hexose, XYL – xylitol production. A detailed depiction of country-specific results and alternative use of renewable energy is presented in chapter 6.4.

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### 8.2.2. Changes in GHG emissions resulting from the introduction of biorefinery concepts through blending based on the GHG savings

A blending mechanism based on achieved *GHG savings* determined according to RED II methodology was proposed and was finally included in the RED II. The choice of which blending mechanism to be used was left the EU member states free to decide. The mechanism provides that the quantity of alternative fuel to be blended with fossil fuel depends on the achieved *GHG savings* determined according to RED II methodology. Certain EU member states (e.g. Germany and Sweden) implemented such legislation that regulates the quantity of biofuel to be blended with conventional fossil fuel according to the achieved *GHG savings* and overall targets of GHG reduction of the fuel blend. In Germany, the envisaged GHG reduction of the overall fuel blend in 2020 is 6%. To evaluate implications of such a mechanisms, changes in GHG emissions resulting from a shift from the present state of the biofuel market (1G production) to potential 2G concepts were assessed for biofuel production in Germany (Table 8-4).

**Table 8-4** Concepts assessed to evaluate the implications of blending mechanism based in *GHG savings* (chapter 5).

<b>Feedstock</b>	<b>Provided co-products aside from ethanol (and pre-treatment process)</b>
Wheat grains	<i>Dry milling:</i> Dry protein feed production (DDGS)
Wheat straw	<i>Fermentation of hexose sugars</i> Molasses Biogas (fed to the grid) <i>Co-fermentation</i> Molasses

When the RED II was developed, the reduction of 1G fuels was discussed widely as a response to criticism of 1G fuels. Furthermore, an increase in 2G biofuel production was envisaged. Due to increasing targets for the use of alternative fuels (including minimum quantities of 2G biofuels to be used), these intentions imply a displacement of 1G fuels by 2G fuels. The analysis was conducted for two cases:

1. The additional production of 2G bioethanol. In this case, it was assumed that 1G production remains constant and 2G biofuels are additionally produced;
2. The replacement of 1G ethanol by 2G ethanol. This case represents the discussed reduction in 1G biofuels.

In both cases, changes in emissions were determined per GJ fuel blend that is supplied to the market. The biofuel content of the blend is determined according to achieved *GHG savings* and the reduction target of 6%.

#### 8.2.2.1. Additional production of 2G bioethanol

Before the additional production of 2G bioethanol, a fuel blend needed to contain 9.8% (energy content) of bioethanol provided by a 1G DDGS concept in order to achieve the envisaged overall reduction in GHG emissions of 6%. As shown in the previous chapters, 2G concepts potentially result in higher *GHG savings* than 1G concepts. The overall quantity of bioethanol to be blended with fossil fuel decreases by about one third. Therefore, the blending mechanism based on the *GHG savings* results in a surplus of bioethanol on the market if 2G bioethanol is provided in addition to existing 1G bioethanol provision (through the quantity and through the blending mechanism). It is assumed that this surplus bioethanol additionally replaces fossil fuel elsewhere. The additional production of 2G bioethanol potentially triggers the following changes: changes in SOC due to straw removal, increase in GHG emission related to feedstock provision and biofuel production as well as decreases in emissions occurring in other sectors through the provision of products (i.e. bioethanol and co-products).

The results revealed that the additional provision of 2G bioethanol potentially results in an overall net decrease ranging from 9 to 12 g CO<sub>2</sub>-eq. per MJ fuel blend. The highest net reduction in GHG emissions are achieved by co-production of biogas (substituting natural gas). The sum of all displacement effects resulting in GHG emission reduction range from 13 to 18 g CO<sub>2</sub>-eq. per MJ fuel blend. Of these, between 51 and 64% stem from the substitution of fossil gasoline, depending on the considered 2G concept. The highest share of additional GHG emissions arising from the shift to straw can be attributed the additional agricultural activity and transportation processes to supply straw, ranging from 43 and 52% of GHG emissions occurring (incl. changes in SOC). The share of emissions included by the RED II methodology only accounts for 6 to 9% of all emissions and changes in emissions occurring. Thus, more than 90% of emissions changes are not covered by the RED II methodology.

These results indicate that, the simultaneous production of 1G and 2G ethanol can result in decreases in GHG emissions if surplus ethanol (from a doubling of production capacities plus surplus quantities due to blending regulations) replaces fossil fuels.

#### 8.2.2.2. Displacement of 1G bioethanol by 2G bioethanol

If the production of 1G bioethanol ceases, additional effects occur: Apart from those effects occurring in case of an additional production of 2G bioethanol, all products of 1G bioethanol are no longer supplied. Furthermore, wheat grains become available. The assessment shows that a shift from 1G to 2G bioethanol potentially results in net increases in GHG emissions ranging from 8 to 17 g CO<sub>2</sub>-eq. per MJ fuel blend. The cessation of DDGS and electricity supply are additional consequences of shifting production from 1G to 2G ethanol. Based in trade statistics, soybean meal was identified as the most likely substitute for protein feed. The additional supply of soybean

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meal results in a coupled production in vegetable oil. This oversupply could lead to a reduction in vegetable oil supply. The provision of feed replacing DDGS results in emissions of around 25 g CO<sub>2</sub>-eq. per MJ of fuel blend, of which 93% stem from LUC. The largest contributors are soy cultivation and LUC attributed to soybean cultivation. This is due to relatively low yields and high carbon stock changes. The sum of emissions comprising all substitution effects related to the provision of feed and cessation of grain use of biofuel production is around 14 g CO<sub>2</sub>-eq per MJ ethanol. The overall share of LUC induced emissions related to soybean production in Brazil is 61% of all substitution effects related to the provision of feed and cessation of grain use for biofuel production. Alternative LUC changes were assessed. The evaluation confirmed observed trends and revealed that in most cases, the determined increase in GHG emissions remains an increase. Consequently, the provision of feed entailing lower emissions presents a major lever to reduce negative effects if 1G fuels should be reduced.

The comparison of those emissions occurring within the production chain, (i.e. those included in the assessment by the RED II methodology) only comprises between 2 and 4% of all emissions and emission changes occurring as a consequence of the shift to bioethanol.

Caveat: The evaluated displacement mechanisms, especially the displacement mechanisms of soybean meal and vegetable oil are subject to high uncertainties. This aspect is addressed in the chapter 8.4.

### 8.2.3. Synthesis of findings regarding the evaluation of effects arising from the introduction of biofuel concepts

The evaluation of potential changes occurring as the consequence of novel biofuel concepts reveals that 2G biofuels can result in an overall net decrease in GHG emissions, if fossil fuel is replaced. The consideration of the variability of most important parameters that can be observed within the EU shows that occurring effects might differ considerably in different countries. These findings point out that it is of crucial importance to consider local conditions when planning a transition from the present use of fossil fuels to alternative fuels. At present, fossil fuels and energy carriers still constitute the major share of energy supply. Therefore, 2G concepts providing energy carriers still bear the highest potential to reduce overall GHG emissions. In the long run, other alternatives to fossil energy carriers might constitute a major share of the energy and fuel supply. Once this state is reached (if it ever happens to turn into reality), the substitution of energy carriers is no longer required and the provision of other products could provide more benefits. The presented analysis reveals that the most critical aspects are the provision of feed energy carriers:

- **Feed provision.** Several of the evaluated concepts provide feed aside from bioethanol and other products. The provision of feed potentially results in a displacement of feed production

by other means. The analysis shows that entailed changes in emissions can constitute a high share of all occurring changes in emissions. This is especially relevant for concepts using wheat grain and providing DDGS. Within the EU, the use of 1G fuels will be capped as a consequence of the criticism of 1G fuels regarding competing uses of grains for food and feed production and all consequences resulting from this competition (i.e. LUC, potential changes in staple food prices, etc.). An increase in production in 1G fuels theoretically bears the potential to result in an overall net reduction in GHG emissions, opposed to other 1G concepts assessed which might even result in an increase in emissions, depending on where and to what extent LUC occurs. This however requires that supplied DDGS replace feed from regions with high LUC emissions. As there is no way of controlling this, an increase in 1G fuel production is not advised. Special attention must be paid if the use of 1G biofuels is reduced. The cessation of these concepts also entails a cessation of co-product supply. At present, DDGS presents the most provided co-product of 1G concepts within the EU. If the cessation of these concepts is accompanied by a compensation of missing protein feed by an increase in imports of feed from regions where high LUC emission occur, the overall shift from 1G to 2G biofuels might trigger an increase in emissions. Thus, changes induced by legislation focusing on the transportation and energy sector triggers changes in emissions in sectors that fall outside of the respective legislation. A careful coordination of legislation is required to avoid burden shifting from one sector to other sectors. Furthermore, the shifted burden could take place elsewhere where there is no (legislative) control over occurring effects or where governments do not want or are not able to exercise power over mechanisms preventing negative effects (e.g. LUC occurring at present in Brazil [586]). Blending mechanisms based on *GHG savings* might aggravate these negative effects due to lower quantities of biofuels required if production is shifted from 1G to 2G fuels.

- **PtX: methane and methanol production.** Apart from feed, changes in GHG emissions arising from the provision of energy carriers were shown to be highly influential regarding the overall changes in emissions potentially occurring from the introduction of certain concepts. The provision of methane and methanol from arising biogenic CO<sub>2</sub> provides an additional opportunity to provide non-fossil fuels and base chemicals. The evaluation has shown that the present methodology provided by the RED II includes methodological inconsistencies that need to be addressed to avoid double-counting or inconsistent evaluations of *GHG savings*. In addition, potential changes in emissions occurring from concepts providing methane and methanol from biogenic CO<sub>2</sub> and from 2G concepts using organosolv pretreatment are underestimated.

These changes occurring in other sectors exceed emissions occurring within the biofuel provision chain by far. The methodology applied by the RED (II) to evaluate GHG emissions of biofuel concepts through the determination of *GHG savings* only comprises a minor share (in some

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cases even less than 10%) of potentially occurring emissions. The terminology *GHG savings* thus might only express a relative change within the production chain. The approach neglects the vast majority of effects that potentially occur. This results in *GHG savings* implying a reduction in GHG emission, even though the introduction of the respective fuel concept could increase or decrease overall emissions. Political decisions and claims of reductions in GHG emissions should thus not be based on the determined *GHG savings*.

The methodology laid down in the RED II ultimately restricts access to the market to certain concepts that were shown to potentially result in overall net reductions in GHG emissions while permitting certain concepts that were shown to even might lead to an overall increase in GHG emissions. The RED II methodology benefits concepts providing energy carriers and dry products with a high energy content. It fails to set incentives to provide complex products aside from biofuels and dry feed products. It additionally hinders the introduction of biorefinery concepts that yield biofuels just as one product out of many others. This is relevant insofar as many alternative technologies and fuels that could be used to provide non-fossil based mobility (e.g. electrification, PtX-fuels etc.) are currently under development or are already entering the market. Biorefineries could therefore provide other highly specialized products as building materials for a future bioeconomy aside from fuels (and feed). The present RED II methodology could therefore be counterproductive with regard to the need of transforming the overall economy towards non-fossil based and more sustainable supply of society's needs.

### 8.3. Change in the temporal occurrence of emissions and their inclusion into GHG balances

The introduction of bioenergy production alters feedstock demand and triggers displacement effects. This might entail a change in cultivation practice or a shift in the crop species cultivated. Resulting changes in land use or management of agricultural lands affects SOC as well as carbon contained in aboveground biomass. Such changes can occur within very short timeframes (e.g. through biomass harvest, subsequent production and use as biofuel) or over longer periods of time (e.g. decomposition of organic material or carbon uptake through biomass growth). To date, it is common practice in LCA studies to consider changes in carbon stocks resulting from 2G biofuels made from agricultural residues to happen at once (at  $t=0$ ). The net change in SOC and carbon in aboveground biomass is often allocated to the biomass production harvested within a specific period (e.g. 20 years). The magnitude of change in carbon stocks is most commonly evaluated by comparing two steady states. This approach disregards the temporal occurrence of emissions and the change in emissions over time.

So far, there has been quite some attention on temporal changes of carbon stocks in agro-forestry systems, but studies on other biofuels or bioenergy provision from lignocellulosic material are

scarce. The analysis presented in this thesis provides one of the few studies providing a detailed analysis of these aspects with regard to biofuel production from agricultural residues (chapter 7). Two concepts were selected: biomethane production via anaerobic digestion and alcoholic fermentation with hydrothermal pre-treatment. These concepts represent process setups that are available on commercial scale. They were selected because these concepts characteristically represent two types of concepts that differ in the way lignin is used: the biomethane concept provides a solid fertilizer made from digestate and the bioethanol concept uses lignin internally for energy generation. The shift from straw incorporation to these concepts was evaluated with consideration of two temporal aspects: The change in the temporal occurrence of emissions and the change in carbon stocks and emissions over time.

### 8.3.1. Assessment of the influence of the change in temporal occurrence of GHG emissions

This aspect pays regard to the fact that even if the same overall quantity of emissions occurs in the two systems that are compared, the time when these emissions occur might change. This is insofar relevant as common metrics to evaluate GHG emissions (e.g. the GWP) express the effect of emissions over a specific timeframe. With regard to the climatic effect of a certain quantity of a GHG, it makes thus a difference whether that quantity is emitted at once (e.g. at  $t=0$ ) or over a longer period of time. To account for this aspect, the Bern Carbon Model was applied [563]. The model describes the share of any  $\text{CO}_2$  emission that remains in the atmosphere in the years following its release. The remainder is taken up by sinks (i.e. oceans and biomass). The model was combined with decomposition patterns of wheat straw (taking place before the shift to any of the two concepts) and of organic fertilizer (taking place after the shift to the biomethane scenario).

The results show that net decreases in GHG emissions arising from a shift from straw incorporation to biofuel production range from -1654 to -436 and from -610 to -107  $\text{g CO}_2\text{-eq. per kg}_{\text{DM}}$  matter of straw that is converted to biomethane or bioethanol, respectively. This corresponds to emission changes ranging from -171 to -61 and -102 to -22  $\text{g CO}_2$  per MJ of biomethane and bioethanol, respectively. If the temporal occurrence of GHG emissions is neglected, these changes range from -75 to -171 and from -45 to -105  $\text{g CO}_2$  per MJ of biomethane and bioethanol, respectively. The higher difference in case of a shift to ethanol production results from the fact that before the shift, straw decomposed slowly while carbon contained in straw is released within a very short period of time after the shift to bioethanol (i.e. release of  $\text{CO}_2$  from fermentation, lignin combustion and ethanol use). In contrast, the biomethane concept provides an organic fertilizer that mainly consists of the hardly degradable lignin fraction. The application of the organic fertilizer compensates the ceased SOC formation. The contribution of organic fertilizer to overall net decreases ranges from -435 to -75  $\text{g CO}_2$  per MJ biomethane provided. The wide range presented arises from the application of different decomposition patterns of wheat straw

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and organic fertilizer. The built-up of SOC from organic fertilizer and the lower process energy requirements (which are provided by natural gas) are the main reasons for higher net reductions in GHG emissions of the shift to biomethane production.

### 8.3.2. Assessment of the change in emissions over time

A dynamic evaluation of changes in GHG emissions over time allows the estimation carbon payback times and provides a more comprehensive analysis of the temporal pattern of SOC changes. Within the first years following the shift from straw incorporation to biofuel production, GHG emissions change over time. The shift to biofuel production leads to a cessation of straw incorporation and eventually to the decomposition of SOC. The application of organic fertilizer compensates this effect. However, the built-up of organic matter is slow. Thus, within the first years, a deficit arises. The average changes in GHG emissions arising after the shift for a period of 100 years range from -1623 to -220 and from -603 to 57 g CO<sub>2</sub>-eq. per kg<sub>DM</sub> straw converted to biomethane and bioethanol, respectively. These ranges correspond to -168 to -17 and to -101 to 12 g CO<sub>2</sub> per MJ of biomethane and bioethanol, respectively. The inclusion of changes in emissions through time reveals considerable GHG emissions arising from SOC changes within the first years. In certain cases, this effect might even result in an overall net increase in emission resulting from the shift. This is due to the fact that a slow decomposition of wheat straw is assumed in a low emission reduction scenario. The slow decomposition of wheat straw results in high quantities of carbon stored in soil before the shift that decompose as a consequence of the cessation of wheat straw incorporation. The analysis reveals carbon payback times ranging of 0 (0 to 58) and 19 (0 to no compensation within 100 years) years in case of the shift to biomethane and bioethanol production, respectively. The high ranges of carbon payback times originate from different decomposition rates that were derived from literature. A slow decomposition of wheat straw before the shift resulted in a high accumulation of SOC. Thus, in the worst case, emission savings cannot compensate the decrease in SOC resulting from the shift within a 100 year period. The ranges presented here present the boundary conditions found in literature and thus present extreme cases. The carbon payback times determined for the base case are at the lower end of the range of carbon payback times of bioenergy from forest biomass [582]. These results indicate that changes in SOC can also play a critical role in biofuel production from agricultural residues.

### 8.3.3. Synthesis of findings regarding the inclusion of temporal effects

So far, the temporal aspects of carbon storage and release of CO<sub>2</sub> have been often neglected in GHG balances, LCA and certification methodologies (e.g. RED (II)). The conducted analysis has proven that the inclusion of temporal aspects can change the extent of GHG emission changes arising from the introduction of the respective fuel. The determined net reductions in GHG emissions occur within acceptable timeframes concerning political targets to reduce anthropogenic GHG emissions. Only in cases in which very high SOC quantities are stored in

soil, no shift from straw incorporation to biofuel production should be conducted. These findings imply that the overall changes in emissions highly depend on local conditions (i.e. soil, climate, management practice etc.). Without consideration of these effects, shifts towards 2G biofuel concepts could result in lower reduction in GHG emissions or, in extreme cases, in an overall net increase in emissions. In order to avoid this and to source feedstock for bioenergy production from areas with the highest potential to reduce GHG emissions, it is therefore advised to include local soil conditions and the temporal aspects of GHG emissions in the evaluation of biofuels from agricultural residues.

## 8.4. Limitations

### 8.4.1. Limitations regarding the applied consequential assessment approach

The applied evaluation of changes in emissions arising from changes in (bio)fuel supply is based on the cLCA methodology. Conceptually, cLCA seeks to evaluate changes arising from specific decisions, changes in production modalities, behavior etc. Ideally, all relevant changes are included in the assessment and the evaluation of these changes reflects real-world changes and effects. However, there are several fundamental limitations connected to the approach applied within the present thesis:

- In many cases, linear substitution is assumed. Linear and perfect substitution assumes that any additionally produced quantity of biofuel substitutes the respective fossil counterpart. No distinction was made within this thesis between the first MJ and the first TJ of biofuel produced. The evaluated substitution mechanisms were identified on current market developments. These change over time and could change if high quantities of a certain product are provided. The presented results are therefore considered valid for near-future developments and assuming supply that does not disrupt existing market structures. The applied methodology furthermore implies that the quantity of each product supplied is high enough to trigger a displacement.
- The focus on near-term mechanisms also implies that potentially arising displacement effects might differ considerably in a few years. This is especially relevant in case of the energy system where the transition towards energy provision from renewable sources is increasing (at a rapid pace). Likewise, trade flows can change quickly (e.g. as a result of trade agreements, change in price of products, changes in taxes, etc.). Over time, also consumption patterns change. This might considerably affect demands for agricultural products, especially feed.
- If such a displacement occurs depends on many factors, such as flexibility in production, prices, economic agreements etc. It is unlikely that perfect substitution occurs. For example, it is unlikely that 1 MJ of ethanol will substitute the provision and use of 1 MJ of fossil gasoline. Very likely, price changes and other rebound effects that reduce the

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overall substitution ratio are triggered. To account for potentially less efficient substitution, sensitivity analyses were conducted that evaluate the minimum quantity of fossil fuel that needs to be substituted in order to yield a net reduction in GHG emissions. Additionally, it should be noted that the substitution of fossil fuels is only effective in preventing climate change if these fossil fuels remain unexploited. The provision of renewable energy will only delay climate change if the supply of these renewables only delays the extraction and use of the respective fossil fuel. Thus, the supply of alternative energy must be backed by other measures that ensure that fossil energy carriers remain unused (or that arising GHG emissions are captured).

- The selection of substitution mechanisms (and all entailed effects, such as LUC) was based on market statistics and other observations, e.g. LUC observations. The analyses furthermore rely on the assumption of unchanging behaviors of actors. This neglects effects that could change the magnitude of emission changes resulting from substitution mechanisms. For example, increasing demand for agricultural commodities could provide incentives to farmers to invest in more efficient and environmental friendly technology, or in efforts to expand (unsustainable) production to further areas. The applied approach presents a strong simplification of the real-world commodity markets. Therefore, results should not be considered as predictions of changes in emissions that occur. Rather, results give an indication on whether certain concepts could yield net reductions in GHG emissions, if introduced and if certain mechanisms take place. If the evaluation of specific concepts yields significant GHG emission reductions under specific assumptions regarding substitution and production modalities, results give indications on which concepts and effects should be promoted (or which ones should be sought to be prevented).
- The selected substitution mechanisms only present the key substitution effects that could arise. In addition, only changes in emissions arising directly from the production and use of the respective substitute are considered. This however neglects other indirect effects, e.g.:
  - LUC changes surface albedo and the local climate. Only few studies, address this issue so far within the context of LCA, cf. [98, 587].
  - The wide-scale introduction of alternative concepts entailing low GHG emissions reduces the ongoing increase in the atmospheric GHG concentration. This in turn reduces ongoing effects that occur through warming climates such as the thawing of permafrost soils or melting of ice sheets. Thus, the shift towards less GHG intensive technologies and procedures potentially results in a reduction in the ongoing release of GHG from permafrost soils or changes in albedo from melting ice sheets.

These are only two examples of complex processes related to changes in GHG emissions that are not addressed by only assessing direct changes in emissions. These effects often include

complex cause-effect-chains that are not well understood so far. To date, these effects have not been included in cLCA studies.

In addition to these limitations regarding the applied methodology, the used metric GWP implies further limitations regarding the capability to evaluate the potential to mitigate climate change. Within this thesis, the GWP was chosen as the metric of choice due to its wide acceptance and application. There is no linear relation between the emitted quantity of a GHG and the surface temperature increase. Therefore, no conclusions on climatic effects can be drawn solely from GHG emissions expressed by the GWP. Other metrics, such as the global temperature potential, have been proposed allowing the inclusion of the mean surface temperature increase [453]. The reader is referred to [588] for further details on these metrics.

#### 8.4.2. Limitation regarding input parameters

There are several limitations regarding the applied parameters:

- Within this study, present and potential near-future biorefinery concepts were assessed based on simulations, literature and industry data. Therefore, assessed concepts present exemplary facilities. Potential real-world facilities most likely differ in their setup and, thus, in their technical specifications. However, the analyses revealed that direct emissions from the biorefinery concepts play only a minor role in the potential overall change in emissions: in most cases, arising displacement effects exceed direct emissions by far. Thus, if real-world technical specifications differ slightly from modelled ones, the overall observed trends do not change.
- Simplified approaches were used to determine GHG emissions arising from LUC. A regional analysis of carbon stored in soil shows high variations among countries and regions. Therefore, SOC emissions are likely to be highly variable in reality. Therefore, the analysis provides an indication on potential impacts. There is no way of determining global GHG emissions from LUC. However, results presented here, emphasize the existence and magnitude of these effects. Even though, these effects cannot be determined precisely, it raises the questions whether decisions should be made that bear the risk of triggering potential negative consequences.
- The evaluated changes trigger changes in marginal supply and thereby in the production of affected processes. In certain cases, no marginal emission data was available. In these cases, average data was used. This is insofar incorrect, as changes in production of marginal processes might considerably differ from average data [530]. So far this issue has been raised regarding the identification of the marginal supplying technology and the region from where the respective product is sourced [530, 589]. Within this thesis, average GHG emission of crude oil extraction and refining from unconventional sources from a specific region are

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considered (e.g. average GHG emissions of US shale oil). However, the marginal supply within that region might differ from the average supply (e.g. the marginal supply of shale oil from the US might differ from the average supply of shale oil from the US because less efficient production processes might be ceased in case of a decrease in demand). No study was found addressing such intra-variabilities of GHG intensities of marginal supply.

- The analysis conducted to answer the third research question relies on decomposition data of digestate from empirical data obtained in laboratory incubation experiments. To date, there is no data available on long-term field studies on the decomposition behavior of digestate or organic fertilizer derived therefrom. The formation of SOC depends on local climatic conditions and management practice. It takes up to decades until a new equilibrium state establishes. Thus, further long-term studies are required to confirm (or falsify) presented results.

### 8.4.3. Appraisal of results with regards to limitations

The presented limitations with regard to the applied methodology and the utilized data give indications on potential imprecision and inaccuracy of results<sup>24</sup>:

- The applied data, especially process parameters, GHG intensities of all auxiliary materials and of displaced products and GHG emissions from LUC affect the precision of results. The use of first hand industry data can help to reduce uncertainty of process parameters, but most other limitations are hard to overcome concerning the assessment of near-future concepts or the process data of the myriad processes involved in all process chains affected. In order to account for these, the sensitivity of results was assessed regarding most influential parameters in all studies. Furthermore, minimum and maximum cases representing the lower and upper range of data available were defined to provide a span of potential changes in emissions. One of the assessments (chapter 6) includes a Monte Carlo simulation that shows that the variability of biological parameters (e.g. feedstock composition) and biological conversion efficiencies change achieved *GHG savings* by less than  $\pm 10\%$ -p.
- The selection and identification of substitution mechanisms inherently implies inaccuracies. No model is able to predict accurately (and precisely) the overall changes resulting from the introduction of biorefinery concepts. General and partial equilibrium models are often applied to reduce inaccuracy. Due to the fact that these models (as the deterministic approach applied within this thesis) are not verifiable, there is no way of identifying the degree of inaccuracy of results<sup>25</sup>. The deterministic model applied (in contrast to general equilibrium models) does not seek to provide any prediction on whether these substitution

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24 Precision refers to variation of results around the true value, while accuracy refers to the representativity of results [76].

25 This aspect is one of the major points of criticism of cLCA and determination of iLUC, cf. [77, 232, 590].

mechanisms will eventually take place if a certain concept is introduced or ceased. The use of mathematically complex models (e.g. general equilibrium models), does not necessarily come along with an improvement in accuracy and the capability to predict potentially arising effects [69].

- Due to the applied methodology and data, the evaluated substitution mechanisms could present indications on potential near-term developments. Ongoing transitions in the overall economy, especially the energy sector, will affect potential implications of the introduction of the evaluated concepts. If plans to drastically reduce GHG emissions were turned into reality, process energy supply and the displacement of products through the provision of fuels could result in different effects: biofuel production will probably emit less GHG emissions and the provision of fuels or electricity might be less effective in reducing GHG emissions. Furthermore, consumption patterns and trade flows might change. There are other levers to influence these two aspects and thereby to reduce GHG emissions related the consumption of other products (e.g. meat and dairy products).

In light of discussed limitations, it is emphasized that the presented results do not intend to provide a fully accurate prediction of potential changes (in emissions) arising from analyzed changes. The analyses identify several substitution mechanisms that were observed in the past. The presented result does not intend to provide a prediction whether these substitution mechanisms will happen in future or not. Instead, the analyses provide potential changes in emissions if these mechanisms take place. Both applied approaches (detailed consideration of emissions occurring within the provision chain and evaluation of potential changes in GHG emissions) should be applied complementary to provide a more comprehensive picture of implications of the use and introduction of biofuel concepts. These results can therefore provide advice to policy makers on specific mechanisms that need to be addressed.

### 8.5. Overall conclusion

The aim of the thesis is to provide a deeper understanding of potential changes in GHG emissions arising from the introduction of a selection of novel fuel concepts. Due to the political framework of the RED II supporting the introduction of 2G biofuels, these concepts might play an important role in the near-future supply of alternative fuels. Therefore, GHG emissions both arising directly within the production chain and indirectly through displacement effects due to the introduction of several biorefinery concepts were evaluated. The following key conclusions can be drawn from the assessment:

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- **The introduction of advanced biofuel concepts bear the potential to reduce GHG emissions**
  - At present, liquid biofuels are almost exclusively produced from sugar, starch and oil crops.
  - Additional production of 1G fuels is not advised due to potential risks of LUC entailed to increasing feedstock demands.
  - The introduction of 2G biofuels made from agricultural residues can lead to a substantial net reduction in GHG emissions.
  - The displacement of 1G by 2G biofuels (or any other mean of providing fuels or mobility) bears the risk of a net increase in GHG emissions. This might be caused by the cessation of protein feed provision. If protein feed is supplied no longer (and the demand does not decrease in parallel), protein feed will be supplied by other means. If this supply of protein feed entails high GHG emissions (e.g. due to LUC), overall GHG emission could increase. Therefore, legislation is required that comprehensively addresses sustainable supply of all agricultural goods, regardless of their use.
- **Location is a key parameter influencing potential net changes in GHG emissions**
  - Agricultural yields and other cultivation parameters differ considerably depending on location, resulting in a broad range of GHG emissions arising from feedstock provision.
  - Marginal changes in energy provision and displacement effects arising from the provision of products are dependent on local market conditions and, therefore, differ in GHG emissions.
  - Biorefinery concepts should therefore be adapted to locally prevailing conditions, including local markets affected by the supply of products.
- **The methodology provided by the RED II to determine *GHG savings* entails several shortcomings to comprehend indirect effects triggered by the RED II and to stimulate the diversification of biorefineries**
  - The introduction of novel fuel concepts most likely results in displacement effects. These indirect effects can exceed the direct GHG emissions within the production chain by far. The analysis shows that these indirect emissions can amount to up to 90% of overall emissions. The changes in emissions that are (partly) triggered by targets and mechanisms of the RED II occur in other sectors (and countries), which are not necessarily regulated by the RED II (or sometimes by any other regulation). This bears the risk of unintended side effects and burden shifting.
  - The RED II allocation methodology benefits concepts providing large quantities of dry products as well as liquid or gaseous fuels by allocating overall emissions according to

the energy content. Thereby other, more complex concepts setups might result in low *GHG savings*, especially if products lacking an energy content are provided. Additional production of specialized products is not valued. This might prohibit these concepts from entering the biofuel market.

- There is a risk of creating lock-in situations that might hinder the transformation towards biorefineries that sustainably yield a wide range of products.
- **Regulations must be extended**
  - Biorefineries bear the potential to provide a broad range of products aside from fuels.
  - Legislation must set incentives for an effective cascade use of biomass that closes nutrient cycles and maximizes the material use of biomass components.
  - Legislation is needed that comprehensively addresses all sectors that are affected by biomass use and products provided from these sectors. Thus, a legislation containing energy, materials, food, feed and fiber is needed.
  - Sustainability criteria must go beyond GHG emissions and include other relevant aspects (in addition to the sustainability requirements contained in the RED). These criteria should be applied to all types of land-use and biomass utilization, regardless of the sector.

Ongoing and potential changes in the transportation sector affect processes and mechanisms in the overall economic system. The omission of potential external effects disregards main drivers regarding potential changes in GHG emissions. The results show that largest changes in GHG emissions may occur outside the production chain. The terminology *GHG savings* is often used to communicate the performance of alternative fuel concepts. Thereby changes in emissions occurring are often implied. Based on this logic, *GHG savings* are often used to calculate a reduction in GHG emissions, e.g. in governmental reports or in claims made by the biofuel industry. The application of *GHG savings* for these purposes conceals potentially occurring effects and in the worst case, leads to decisions resulting in consequences opposed to those intended.

The analysis shows that decisions within the fuel sector might trigger emissions in other sectors and regions that are not under control of the political institutions that initiated these decisions. To date, most governments define sectoral targets and evaluate emissions within specific sectors. Thereby, they might even hinder to evaluate whether an overall reduction in GHG emissions takes place as a consequence of political measures or not. In addition, the effectiveness of political measures might be drastically reduced if legislation targets single sectors only. This bears the potential of burden shifting that can be hardly prevented by legislation focusing on one sector only. Furthermore, burdens might be shifted to other regions where the legislative body that initiated the change is not able to exert power.

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The narrow focus on the energy sector and the preference of concepts yielding liquid and gaseous fuels or large quantities of dry products with a high energy content might hinder the introduction of concepts that provide a wider range of products. The RED II will shape the biofuel industry for the upcoming decade and therefore a focus on these concepts might result in lock-in situations that are hard to overcome. This might be even more critical as other alternatives to provide renewable energy and transportation fuels might enter the market and (hopefully) constitute a major share of energy and fuel provision in future. If there are no or only few fossil energy carriers to be displaced, biomass might be better used for other purposes than producing transport fuels. Biorefineries bear the potential to provide multiple other products than fuels and could therefore contribute to the efforts to provide renewable resources to all economic sectors.

It can be concluded that the narrow focus of the RED (II) on the use of biomass for energy only is insufficient with regards to the intention to reduce the general dependency on fossil resources (for the supply of all products, not just energy and energy carriers) and to mitigate climate change. The required transformation of the overall economy requires legislation that holistically encompasses the overall (bio)economy and that includes additional considerations of sustainability going beyond climate change. These sustainability requirements must be applied to all types of land use and biomass production, regardless of the final use of biomass. Otherwise, sustainably sourced biomass is provided to markets where it is required while other non-sustainable production is supplied to all other markets.

### 8.6. Outlook, recommendations and final remarks

#### 8.6.1. Policy recommendations

Based on previous findings, the following recommendations towards policy makers can be given:

- The analysis has shown that an additional increase in 1G fuel production is not advisable, if accompanied by an increase in land demand. As there are no measures to prevent this, it is strongly recommended to maintain the current cap on 1G fuels.
- A substitution of 1G biofuels by 2G biofuels might result in an increase in emissions, if the resulting increase in feed demand (resulting from the cessation of feed supply) is fulfilled by protein feed from areas where high LUC emissions occur.
- Blending mechanisms based on the achieved *GHG savings* were shown to yield counterproductive outcomes if such a displacement effects happen. Thus, implementing these measures should be only considered if negative consequences arising from the agricultural sector can be effectively prevented (which is hardly possible on a global scale);
- Current methodology supports concepts that provide energy and fuels. The RED (II) was designed for the energy and transportation sectors (which is nicely reflected by labelling all other products than fuel “co-product”). Until 2030, the RED II will be in place. Thereby,

most likely the methodological focus and privileges for concepts providing energy and fuels will be maintained.

Biomass could be used for other purposes than energy and fuels. Especially, because other alternatives targeting these markets (e.g. electrification, hydrogen, PtX etc.) could reach market maturity within the next few years. Novel biorefineries could be integrated facilities that provide multiple products of which biofuels might be just one out of many different main product. These concepts interlink many sectors and their introduction eventually effects demands within these sectors. Thereby, emissions will change in these sectors as a consequence of these novel biorefinery concepts. Therefore, legislation comprehensively targeting several sectors is needed.

- The present legal and conceptual focus on energy hinders the introduction of biorefineries that provide multiple other products than energy. This might delay the transition towards an overall transformation of the economy. Therefore, the overall focus needs to be widened and policy needs to be implemented that holistically approaches the transition of the economy by targeting all sectors.
- Numerous studies report an advancing decline in biodiversity, cf. [591–594]. Habitat loss, habitat fragmentation, the use of agrochemicals and fertilizers, invasive species as well as climate change present proven (and presumed) key drivers. Thus, limiting sustainability criteria to GHG (and the few other restrictions imposed by the RED II) might be insufficient to prevent considerable negative consequences. In general, the supply of society's needs and present land use practices must be reconsidered concerning the negative consequences arising thereof.

### 8.6.2. Science and research

The analyses and the discussed limitations indicate several aspects that should be addressed by the scientific community:

- In the presented analyses, only a narrow selection of processes was assessed. More concepts (biorefineries with diverse product portfolios) and a wider range of substitution mechanisms need to be evaluated to gain a deeper understanding of the implications of changes arising from the needed transition towards a non-fossil economy. These substitution mechanisms should also be assessed through other methods than cLCA in parallel. Subsequently, policy recommendations can be derived on what concepts and substitution mechanisms should be supported. This also goes beyond the biofuel sector.
- There are still many unresolved questions regarding the evaluation of potential effects of changes. Among these, the identification of marginal suppliers and cause-effect-chains of indirect effects need to be better understood.

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- Supporting information to policy makers needs to be provided on how the transition towards a bioeconomy (or an overall transition towards a more sustainable economy) could be facilitated. A more comprehensive regulation is needed encompassing the overall economy. Thus, the existing RED (II) methodology should be widened to include the overall (bio) economy. This implies that the methodological focus must be widened and must go beyond energy and energy carriers.
- A more comprehensive analysis of land use is needed. Globally available land resources must be allocated in a way that they allow a more sustainable provision of the needs for food and, if possible, for feed, mobility and other purposes (e.g. base chemicals) while preserving nature.
- Science provides the basis for future development, and research should thus seek to overcome the narrowness that exists today by providing visions on how future needs can be sustainably met: e.g. many studies (this one included) focus deeply on aspects related to specific sectors. However, the complexity of supplying overall demands while reducing negative consequences requires holistic approaches and visions.

### 8.6.3. Final remarks

Many of today's challenges arise from a two (so far often) diametric needs: On the one hand, there is a need of society for services and products. These needs change due to a growing world population and changing consumption patterns. On the other hand, there is a need to prevent negative environmental consequences (e.g. pollution, biodiversity loss). To overcome this dichotomy, it should be questioned more often how these needs can be fulfilled in the most sustainable way and if they need to be fulfilled at all. At present, the narrow scope in policy-making (focusing on single sectors and countries) and often science might hinder seeing the bigger picture. For example, there is no inherent need for biofuels. There is only a need for mobility/transportation of people and goods. The need for (bio)fuels only exists because society and policy chose that the needed degree and modality of mobility (also choices) should be partly fulfilled by biofuels. Policy and science are often stuck in the details and lose track of that bigger question on which needs are essential and how these can be fulfilled in the most sustainable way. This results in locked-in situations in the industry, policy instruments and in scientific studies that dig deep but lose sight of the bigger picture. To overcome this, the focus should more often be put on the overarching question on what essential needs are, how they can be supplied and how all this can be accomplished while preserving nature.

Synthesis of results and conclusions

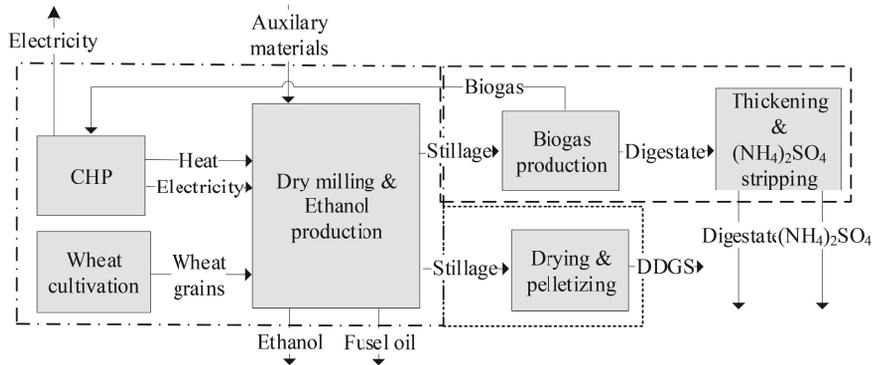


# Appendix Chapter 4

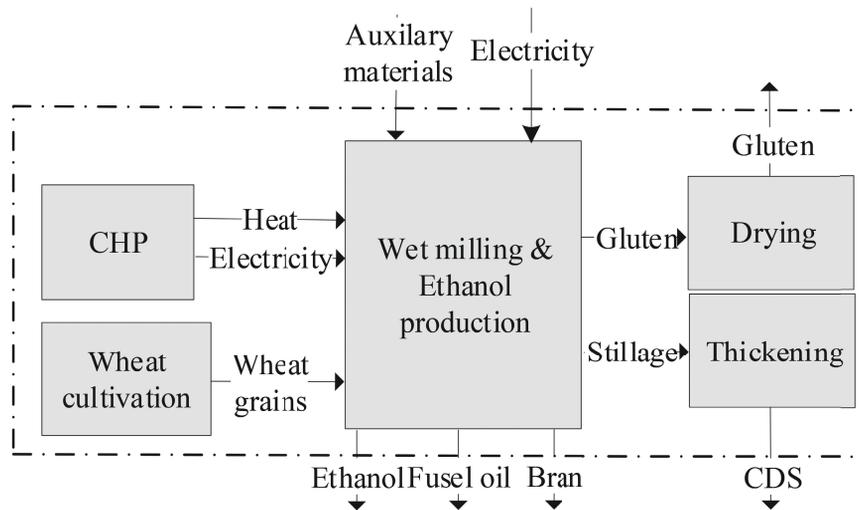
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## Appendices

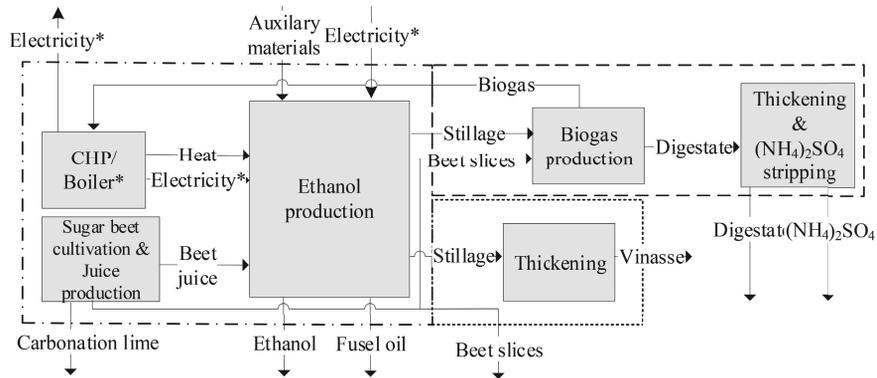
### A.1. Figures



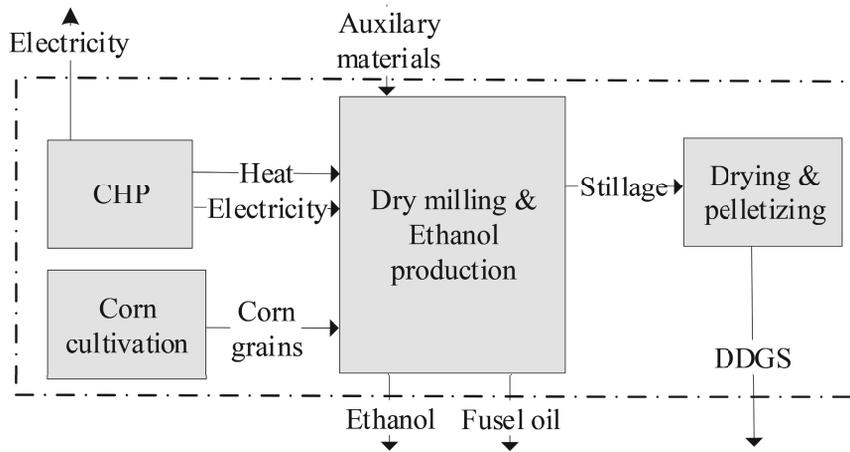
**Figure A - 1** Scheme of ethanol production from wheat by dry milling and subsequent DDGS production (dotted line) or biogas production (dashed line). Abbr.: CHP: Combined heat and power; DDGS: Dried distiller grains with solubles.



**Figure A - 2** Scheme of ethanol production from wheat by wet milling. Abbr.: CDS: Condensed distillers solubles; CHP: Combined heat and power.



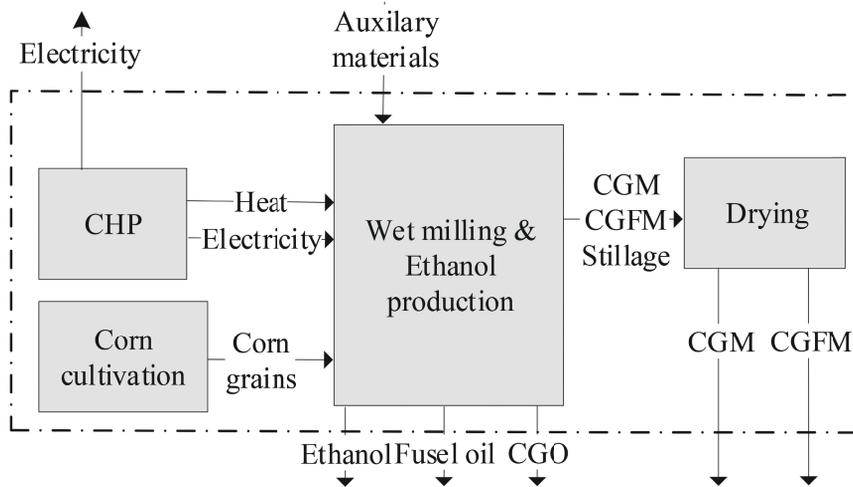
**Figure A - 3** Scheme of ethanol production from sugar beet and subsequent vinasse production (dotted line) or biogas production (dashed line). Electricity generation and export/import is concept-dependent (Table 4-1) Abbr.: CHP: Combined heat and power; (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>: Ammonium sulfate.



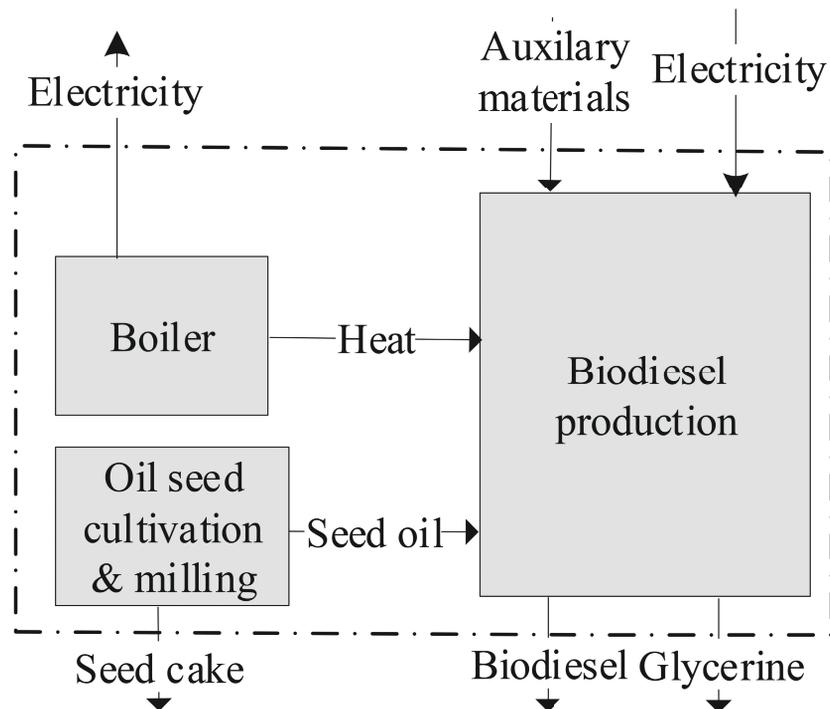
**Figure A - 4** Scheme of ethanol production from corn by dry milling. Abbreviations: CHP: Combined heat and power; DDGS: Dried distiller grains with solubles.

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**Figure A - 5** Scheme of ethanol production from corn by wet milling. Abbr.: CGM: Corn gluten meal; CFGM: Corn gluten feed meal; CGO: Corn germ oil; CHP: Combined heat and power.



**Figure A - 6** Scheme of biodiesel production from oil seeds.

## A.2. Tables

**Table A - 1** GHG intensity of feedstock and substitutes.

	Unit	kg CO <sub>2</sub> -eq.	Data sources used for calculations
<b>Feed &amp; feedstock</b>			
Barley	kg <sup>-1</sup>	0.36	[398, 595]
Oat	kg <sup>-1</sup>	0.37	[398, 596]
Rapeseed meal and oil <sup>a</sup>	(kg meal) <sup>-1</sup>	1.23	[364, 398]
Soymeal and oil	(kg meal) <sup>-1</sup>	0.85	[364, 398]
Maize	kg <sup>-1</sup>	0.30	[398]
Wheat	kg <sup>-1</sup>	0.36	[398]
Palm oil production <sup>a</sup>	(kg palm fruits) <sup>-1</sup>	0.49	[364, 398]
Sunflower meal <sup>a</sup>	kg <sup>-1</sup>	0.26	[364, 398]
Cereal market mix	kg <sup>-1</sup>	0.32	[432–434]
Feed market mix	kg <sup>-1</sup>	0.51	[432–434]
Oil market mix	kg <sup>-1</sup>	0.84	[432–434]
<b>Products &amp; processed materials</b>			
Ammonium sulfate	kg <sup>-1</sup>	2.24	[364]
N-Fertilizer market mix	(kg N) <sup>-1</sup>	6.54	[364, 410, 597]
P-Fertilizer market mix	(kg P <sub>2</sub> O <sub>5</sub> ) <sup>-1</sup>	1.02	[364, 410, 597]
K-Fertilizer market mix	(kg K <sub>2</sub> O) <sup>-1</sup>	1.81	[364, 410, 597]
Glycerin	kg <sup>-1</sup>	2.51	[364]
Isoamylalcohol (3-Methyl-1-butanol)	kg <sup>-1</sup>	1.64	[364]
Petrol provision	kg <sup>-1</sup>	0.29	[364]
Petrol combustion	kg <sup>-1</sup>	3.23	[598]
Diesel provision	kg <sup>-1</sup>	0.30	[364]
Diesel combustion	kg <sup>-1</sup>	3.18	[598]
Wet milling of wheat <sup>a</sup>	(kg starch) <sup>-1</sup>	0.94	[364, 369, 398, 402]
Wet milling of maize <sup>a</sup>	(kg starch) <sup>-1</sup>	0.96	[364, 398, 401, 402, 599]
Electricity, conventional gas power plant	MJ <sup>-1</sup>	0.16	[364]

<sup>a</sup>GHG intensities are not allocated. Factors for meals, wet milling and palm oil production comprise all products, i.e. oils, gluten, meals etc.

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**Table A - 2** Chemical inputs.

Feedstock Process	Bioethanol						Biodiesel				
	W Dry milling	W Dry milling	W Wet milling	W Dry milling +biogas	SB Dry milling	SB CG	SB Biogas	CG Dry milling	CG Wet milling	RS	SF
<b>Chemical inputs</b> (10 <sup>-4</sup> kg MJ <sup>-1</sup> )											
n-hexane								0.75		1.01	0.94
Fuller's earth										2.35	2.35
Phosphoric acid								6.40		6.40	
Hydrochloric acid										7.53	7.53
Sodium carbonate										0.94	0.94
Sodium hydroxide	3.73	3.73	3.73	3.73	3.73	3.73	3.73	3.73	3.73	2.53	2.53
Ammonia	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87		
Sulphuric acid	7.16	7.16	7.16	7.16	7.16	7.16	9.53	7.16	7.16		
Sodium sulfate							1.27				
Sodium phosphate							1.90				
Methanol										818.4	818.4
<b>Data source</b>	RED <sup>e</sup>	IND <sup>d</sup>	IND <sup>d</sup>	IND <sup>d</sup> , LIT <sup>e</sup>	IND <sup>d</sup> , LIT <sup>e</sup>	RED <sup>e</sup>	IND <sup>d,f</sup>	IND <sup>d</sup> , LIT <sup>e</sup>	IND <sup>d</sup> , LIT <sup>e</sup>	RED <sup>d</sup>	RED <sup>d</sup>

<sup>a</sup> A negative sign indicates electricity export to the grid.

<sup>b</sup> Electricity in MJ MJ<sup>-1</sup>; all other products in kg<sub>DM</sub> MJ<sup>-1</sup>.

<sup>c</sup> [398]

<sup>d</sup> [369]

<sup>e</sup> [370, 379–381]

<sup>f</sup> [400]

<sup>g</sup> [401, 402]

Abbr.: CG – Corn grain; IND – Industry data; LIT – Literature data; RED – Renewable Energy Directive (biograce standard data); RS – Rapeseed; SB – Sugar beet; SF – Sunflower seed; W – wheat.

**Table A - 3** Characteristics of feed co-products.

	DM	LHV	ME	nXP	Crude fibre	Oil content	Source
	kg (kg FM) <sup>-1</sup>	MJ (kg DM) <sup>-1</sup>			kg (kg DM) <sup>-1</sup>	kg (kg seed) <sup>-1</sup>	
Barley grain	0.88	18.4	12.4	0.15	0.05		[600, 601]
Beet slices	0.25 <sup>a</sup> /0.30 <sup>b</sup>	17.2	12.5	0.15	0.15		[369, 407, 602]
Beet tailings	0.19	18.4	10.8	0.13	0.10		[603]
CDS	0.27	21.0	13.1	0.22	0.02		[604, 605]
Glycerine	0.82	17	15.6	0.00	0.00		[407]
Maize DDGS	0.76	21.8	12.0	0.21	0.08		[423, 606, 607]
Maize germ meal	0.96	20.0	13.1	0.14	0.10		[402, 608, 609]
Maize gluten feed meal	0.90	21.4	12.5	0.19	0.08		[402, 610]
Maize gluten meal	0.90	23.7	15.3	0.48	0.01		[402, 610]
Maize grain	0.86	18.7	13.4	0.17	0.03		[402]
Maize oil	0.95	28.9	20.3	0.00	0.00	0.43	[611]
Maize silage	0.33	18.8	10.9	0.14	0.20		[612, 613]
Oat grain	0.88	17.8	11.2	0.10	0.15		[614, 615]
Palm kernel meal	0.91	20.1	11.6	0.09	0.20	0.36	[616, 617]
Rapeseed meal	0.81	19.0	12.0	0.22	0.13	0.48	[407, 602]
Soybean meal	0.89	19.0	13.5	0.30	0.09	0.20	[407, 602]
Sunflower seed meal	0.81	19.4	9.1	0.29	0.28	0.41	[407, 618]
Vinasse	0.33	17.0	11.4	0.15	0.00		[369, 602]
Wheat grain	0.88	18.2	11.8	0.15	0.03		[601, 619] [370]
Wheat bran	0.86	18.8	10.2	0.15	0.12		[369, 614, 620]
Wheat DDGS	0.76 <sup>a</sup> /0.90 <sup>b</sup>	21.8	12.2	0.22	0.09		[407, 605, 621]
Wheat gluten	0.95	25.1	12.7	0.15	0.06		[369, 622]

<sup>a</sup>DM content refers to standard values applied in the RED example cases.

<sup>b</sup>DM content refers to industry data or data found in literature that is applied in the respective cases.

Abbr.: CDS – Condensed distillers solubles; DDGS – Dried distillers grains with solubles; DM – Dry mass; FM – Fresh mass; ME – Metabolizable energy; nXP – usable crude protein.

**Table A - 4** Nutrient content of fertilizer co-products.

	DM	N <sub>min</sub>	N <sub>org</sub>	P	K	Mg	Ca	Source
	kg (kg FM) <sup>-1</sup>	kg N (kg DM) <sup>-1</sup>	kg N (kg DM) <sup>-1</sup>	kg P <sub>2</sub> O <sub>5</sub> (kg DM) <sup>-1</sup>	kg K <sub>2</sub> O (kg DM) <sup>-1</sup>	kg MgO (kg DM) <sup>-1</sup>	kg CaO (kg DM) <sup>-1</sup>	
Digestate								
Wheat	0.20	0.0158	0.1871	0.1750	0.2486	0.0411		[370]
Sugar beet	0.20	0.0148	0.0349	0.0386	0.2130	0.0349		[370]
Beet soil	0.60	0.0011	0.0049	0.0022	0.0120	0.0100		[602]
Carbo lime	0.70	0.0011	0.0045	0.0160	0.0004	0.0200	0.4271	[267, 607]

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# Appendix Chapter 5

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## Appendices

### B.1. Methodology

#### B.1.1. Global warming potentials

**Table B - 1** GWP according to the RED [54] and IPCC [453].

Substance	RED	IPCC 2013
Carbon dioxide, fossil	1.0	1.0
Carbon dioxide, from soil or biomass stock	1.0	1.0
Carbon monoxide, biogenic		2.5
Carbon monoxide, fossil		4.1
Carbon monoxide, from soil or biomass stock		4.1
Chloroform		16.4
Dinitrogen monoxide	296.0	264.8
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a		1301.3
Ethane, 1,1,1-trichloro-, HCFC-140		160.1
Ethane, 1,1,1-trifluoro-, HFC-143a		4804.4
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113		5823.7
Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b		782.0
Ethane, 1,1-difluoro-, HFC-152a		137.6
Ethane, 1,1-difluoro-, HFC-152a		137.6
Ethane, 1,2-dichloro-		0.9
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114		8592.2
Ethane, 1-chloro-1,1-difluoro-, HCFC-142b		1982.0
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123		79.4
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124		526.5
Ethane, chloropentafluoro-, CFC-115		7665.4
Ethane, hexafluoro-, HFC-116		11123.5
Ethane, pentafluoro-, HFC-125		3169.3
Methane, biogenic	23.0	28.5
Methane, bromo-, Halon 1001		2.4
Methane, bromochlorodifluoro-, Halon 1211		1746.5
Methane, bromotrifluoro-, Halon 1301		6291.6
Methane, chlorodifluoro-, HCFC-22		1764.6
Methane, chlorotrifluoro-, CFC-13		13893.4
Methane, dichloro-, HCC-30		8.9
Methane, dichlorodifluoro-, CFC-12		10239.2
Methane, dichlorofluoro-, HCFC-21		147.7
Methane, difluoro-, HFC-32		676.8
Methane, fossil	23.0	29.7
Methane, from soil or biomass stock	23.0	29.7
Methane, monochloro-, R-40		12.2
Methane, tetrachloro-, R-10		1728.5
Methane, tetrafluoro-, R-14		6625.8
Methane, trichlorofluoro-, CFC-11		4662.9
Methane, trifluoro-, HFC-23		12397.6
Nitrogen fluoride		16070.0
Pentane, perfluoro-		8546.7
Sulfur hexafluoride		23506.8

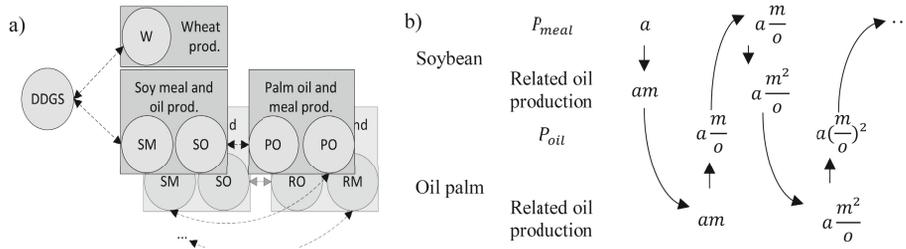
**B.1.2. Feed as a co-product: feed and oil substitution**

DDGS substitutes protein feed and cereals (Eq. 4-7 and Eq. 4-8). The provision of such a protein feed meal is coupled to vegetable oil production. When meal is substituted, oil production is reduced and needs to be supplied from other suppliers. This can be expressed by a converging series (Figure B - 1):

$$P_{meal} = \sum_{i=0}^n a\left(\frac{m}{o}\right)^i \Rightarrow P_{meal} = \lim_{n \rightarrow \infty} \sum_{i=0}^n a\left(\frac{m}{o}\right)^i \Rightarrow P_{meal} = \frac{a}{1 - m/o} \text{ for } m/o < 1 \quad \text{Eq. B - 1}$$

$$P_{oil} = \sum_{i=1}^n a\left(\frac{m}{o}\right)^i \Rightarrow P_{oil} = \lim_{n \rightarrow \infty} \sum_{i=1}^n a\left(\frac{m}{o}\right)^i \Rightarrow P_{oil} = \frac{a \cdot m/o}{1 - m/o} \text{ for } m/o < 1 \quad \text{Eq. B - 2}$$

Where P denotes protein production substituted by the feed co-product ( $P_{meal}$ ) and the production of protein that is coupled to oil production ( $P_{oil}$ ).  $m$  and  $o$  denote the oil content per protein and  $a$  denotes the starting quantity of protein that is substituted.



**Figure B - 1** Depiction of substitution mechanisms (a) and its mathematical representation (b). Abr.: DDGS – dried distiller’s grains with solubles, PM – Palm kernel meal, PO – palm oil, SM – Soybean meal, SO – Soybean oil, W - Wheat. Adapted from [623].

Integrating Eq. B - 1 and Eq. B - 2 and into the linear system of Eq. 4-7 and Eq. 4-8 allows the calculation of the appropriate amount of feed that is substituted while accounting for the metabolizable energy, digestible protein, as well as occurring feedback loops.

**B.2. System description**

**B.2.1. Sustainable straw potential**

According to Weiser et al. [4], the quantity of straw that can be sustainably extracted from an agronomic system is mainly dependent on the consequences on soil humus. Soil humus provides nutrients, stores water, filters drainage water and shows a high biological activity [5,6]. All these factors are of crucial importance for healthy ecosystems and therefore for agricultural production as well. As straw removal affects the soil humus reproduction, the quantity of straw that can be sustainably removed restricts the technical straw potential [4]. Thus, the sustainable amount of straw that can be harvested can be determined by the standard humus balance method developed

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for Germany by the Associations of German Agricultural Analytic and Research Institutes (Eq. B - 3) [5]:

$$\text{Soil humus} = \text{Input of humus} - \text{humus demand} \quad \text{Eq. B - 3}$$

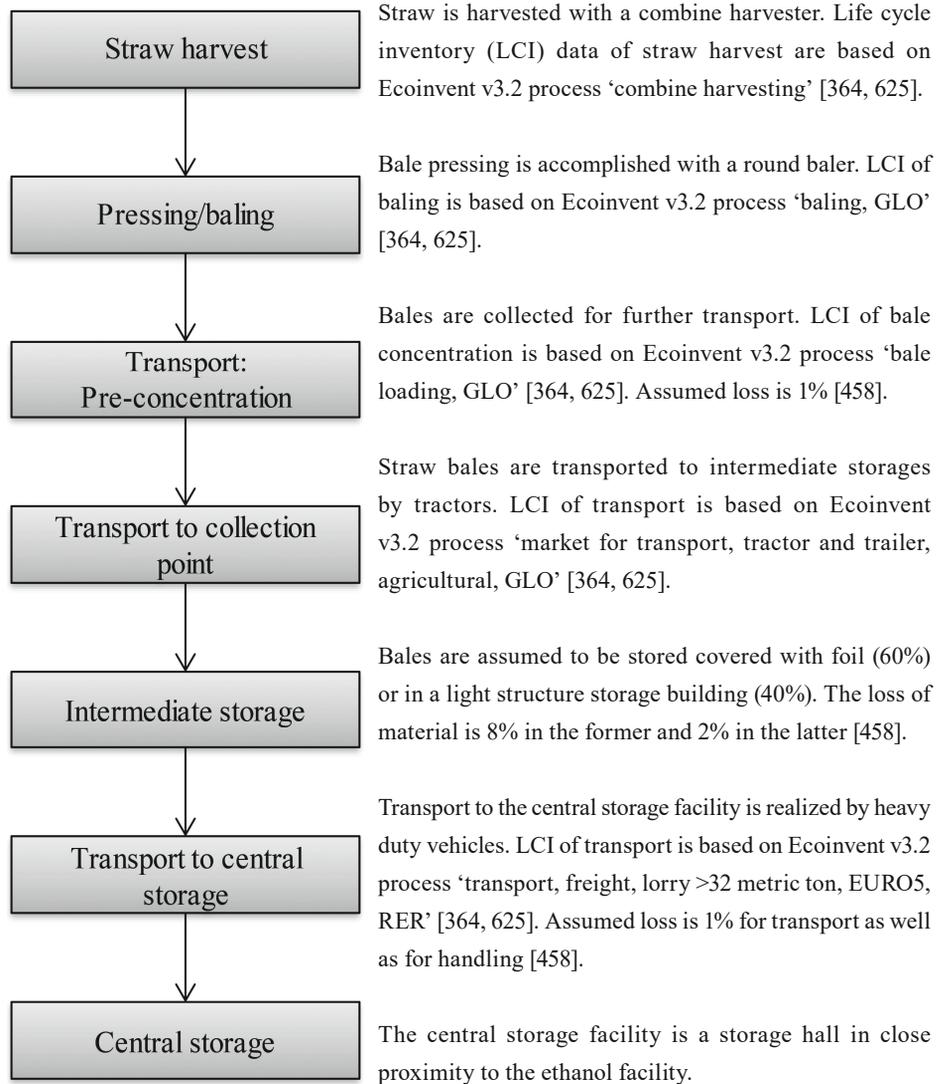
In order to avoid humus loss, the soil humus balance should equal zero [273]. The input of humus and the humus demand depend on endopho-climatic conditions. The factors to be applied in the standard method are based on decades of measurements in Germany (6 sites), Sweden (2), Czech Republic (1), Denmark (1), Poland (1) the UK (1) [624]. At these sites, sand, loamy sand, sandy loam, loam/clay and chernozem soils can be found. The mean temperature at these sites ranges from 5.5 (Sweden) to 10°C (Germany). The average annual precipitation ranges from 484 (Germany) to 790 (Denmark). The humus demand of cereal cultivation ranges from 280 to 400 kg C/(ha a) [461, 624]. The lower value is chosen, as it represents soils with adequate supply of nutrients and soil in good conditions [461]. The reproduction of soil humus from wheat straw is 80 to 100 kg C/(t substrate) [461]. In case of intensive agriculture, the reproduction is 80 kg C/(t substrate) [2]. The assumed grain yield is 7.9 t/(ha a) and the grain to straw ratio is 0.8 [370]. The soil humus balance without straw removal can be calculated based on Eq. B - 3 according to Eq. B - 4:

$$\text{Soil humus}_{\text{no straw removal}} = 80 \frac{\text{kg C}}{\text{t straw}} * 6.32 \frac{\text{t straw}}{\text{ha a}} - 280 \frac{\text{kg C}}{\text{ha a}} = +225.6 \frac{\text{kg C}}{\text{ha a}} \quad \text{Eq. B - 4}$$

The share of straw that can be removed can thus be calculated at 44.7%. This calculation is comparable to other studies (e.g. [273]).

### B.2.2. Straw handling

The handling and transportation of straw after harvest is modelled as follows.



Transport of straw is modelled, assuming a rectangular quadratic area from where feedstock is sourced (Figure B - 2). The total area,  $A_{total}$ , from which straw is collected, is calculated with Eq. B - 5:

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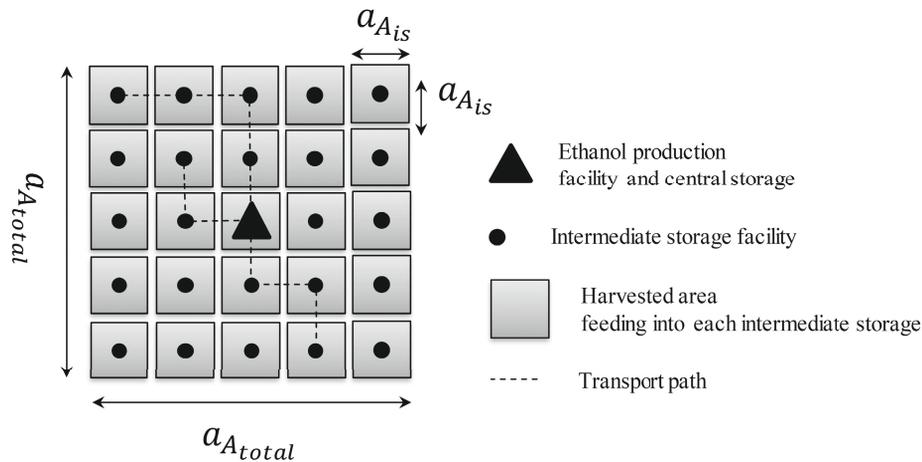
$$A_{total} = \frac{S_d}{\prod(1 - l_i)} S_a \quad \text{Eq. B - 5}$$

Where  $S_d$  describes the straw demand of the ethanol facility,  $l_i$  the losses at each processing step, and  $S_a$  the straw availability (adapted from [8]). Each intermediate storage facility is used to store straw from 9 parcels, measuring 20 ha each. The average availability of straw,  $S_a$ , is 0.27 t<sub>DM</sub>/ha [458]. This value presents an estimation of the straw availability in Germany, based on the sustainable straw potential of 44% and the total surface area.

The area of each intermediate storage,  $A_{is}$ , can be calculated based on Eq. B - 6:

$$A_{is} = \frac{A_{total} 180ha s_p}{S_d \prod(1 - l_i)} \quad \text{Eq. B - 6}$$

$S_p$  is the technical straw potential. The average distance from each parcel to the intermediate storage, realized by tractors, is calculated by the square root of  $A_{is}$ . The average distance from all intermediate storages to the central storage/ the ethanol facility, accomplished by heavy duty vehicles, is calculated by the square root of  $A_{total}$ .



**Figure B - 2** Schematic depiction of modelled straw transport (adapted from [626]).

### B.2.3. Ethanol from wheat straw

**Table B - 2** Composition of solid and liquid phase and recovery rates of steam explosion of wheat straw at 190°C for 10 minutes [465].

<b>Liquid Fraction</b>	<b>g/100g raw material</b>	<b>Solid fraction</b>	<b>% of DM</b>
Glucose	3.1	Glucan	62.80%
Xylose	14	Xylan	13.10%
Galactose	1.4	Galactan	0.20%
Arabinose	2.2	Arabinan+ Mannan	0.80%
Mannose	0.2	Acid insoluble lignin	24.30%
		Ashes	2.80%
<b>Inhibitors</b>			
Furfural	0.09		
5-HMF	0.02		
Acetic acid	0.58		
Formic acid	0.34		
Vanillin	0.02		
Coumaric acid	0.02		
Ferulic acid	0.00		
<b>Recovery rates</b>			
Glucan recovery	97.95%		
Xylan recovery	91.10%		
Solid recovery	50.09%		

### B.2.4. Substitution mechanisms

Yields and planted area of soy production have been stable in the US in recent years, while yields and planted area showed an increase in Brazil (Figure B - 3). Therefore, Brazil is considered the marginal supplier of soybean (meal).

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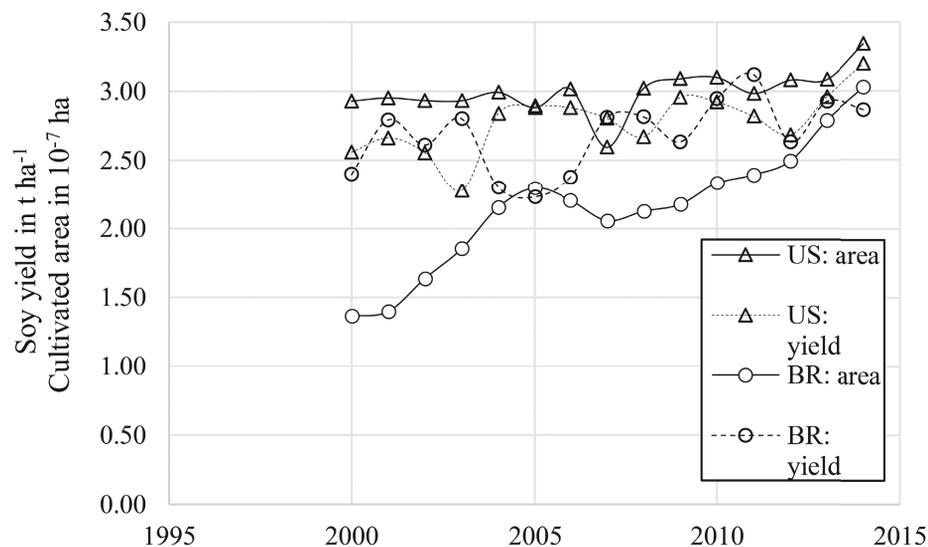


Figure B - 3 Planted area and yield of soy production in Brazil (BR) and the United States (US) [456].

## B.3. Results

### B.3.1. GHG intensities

Table B - 3 GHG intensities.

Substitute	kg CO <sub>2</sub> -eq./		
Petrol	kg	1.25	[364]
Petrol combustion	MJ	0.08	[598]
Rape meal	kg	0.91	[464]
Maize	kg	0.37	[464]
Palm fruits	kg	0.16	[464]
Electricity from coal	MJ	0.29	[364]
Natural gas provision	m <sup>3</sup>	0.41	[364]
Natural gas combustion	MJ	0.06	Own calculation
Additional fertilizer	kg straw removed	0.06	[364]
Soybean meal	kg	0.51	[464]
Wheat	kg	0.25	Own calculation
Ammonium sulfate	kg	2.24	[364]
Compressed CO <sub>2</sub>	kg	0.70	[364]
Enzymes	kg	9.0	[377, 627]
Transport, transoceanic tanker	tkm	0.01	[364]
Transport, transoceanic ship	tkm	0.01	[364]
Transport, lorry >32 ton, EURO5	tkm	0.08	[364]

GHG intensities of other materials, not mentioned in Table B - 2 were obtained from the ecoinvent 3.2 database [364].

### B.3.2. Emissions from LUC

**Table B - 4** Emissions from LUC [89, 370, 400, 464].

Crop	Country	Conversion mechanism		Yield kg/ha	Change in carbon stock t C/ha/a
		from	to		
Wheat	Germany	Set-aside land	Cropland	7900	-1.13
Soybean	Brazil	Scrubland	Cropland	2798	-3.80
Oil palm	Malaysia	Permanent Cropland	Plantation		1.29
		Continental rainforest	Plantation	24978	-6.70
	Indonesia	Insular rainforest	Plantation		-8.50

### B.3.3. Sensitivity analysis

In the following section the effect of changes in several key parameters and the effect of different LUC assumptions is assessed (Table B - 5). Changes in production modalities affect *GHG savings* estimated by RED methodology<sup>26</sup> and thereby alter the quantity of biofuel to be blended with fossil fuel as well as the amount of co-products resulting in a change in substitution mechanisms.

**Table B - 5** Assessed aspects in the sensitivity analysis.

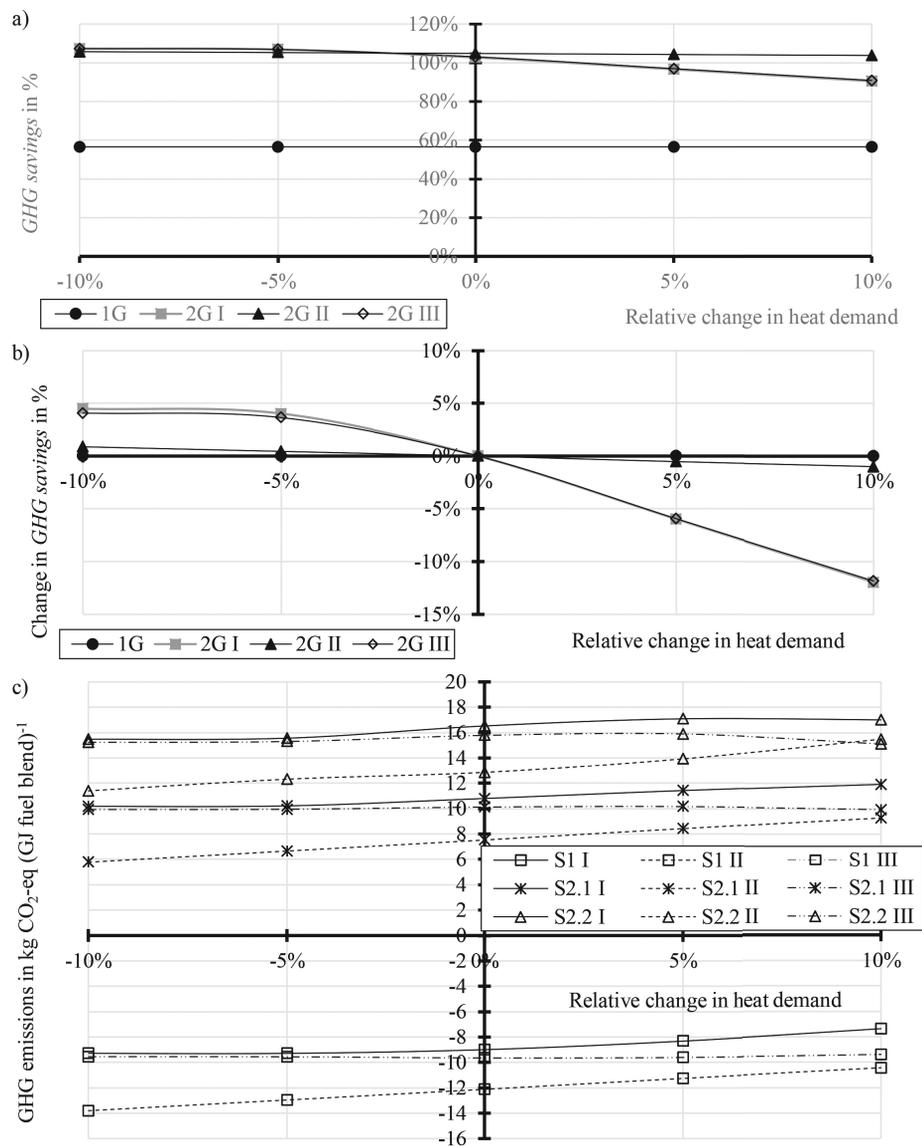
Section	<i>GHG savings</i> according to RED	<i>GHG emissions</i> based on consequential approach
B.3.3.1	Process heat demand	Process heat demand
B.3.3.2	Conversion efficiency	Conversion efficiency
B.3.3.3		<i>GHG savings</i> according to RED methodology
B.3.3.4		LUC emissions: wheat grains
B.3.3.5		Cultivation practice: soybean
		LUC emissions: soybean
B.3.3.6		LUC emissions: oil palm

#### B.3.3.1. Dependency of results on energy demand

The 2G process concepts modelled in this paper are not at full market maturity yet. Thus, process parameters of commercially competitive 2G facilities are largely unknown. Therefore, a change in heat demand is assessed to see its significance to overall results. The sensitivity analysis shows that the effect of a change in energy demand is low. The relative change in *GHG savings* remains below 10% for all concepts if the energy demand changes by 10%. The energy demand effects the consequential model by two aspects: (1) a change in *GHG savings* alters the quantity of fuel to be blended with fossil fuel to achieve legal targets, and (2) by altering the quantity of electricity provided as a co-product. The sensitivity analysis indicates that a change in heat demand does not affect results by a large extent (Figure B - 4).

<sup>26</sup> The terminology „*GHG savings*“, here and hereafter, exclusively refers to the value calculated by RED methodology (Eq. 4-1) and does not present an occurring reduction in GHG emissions. In contrast, terms like “decrease in GHG emission” or “increase in GHG emission” refer to estimations of changes in emissions based on the consequential approach, thus respecting occurring changes in emission due to changes induced by the change in the system (i.e. introduction of 2G ethanol)

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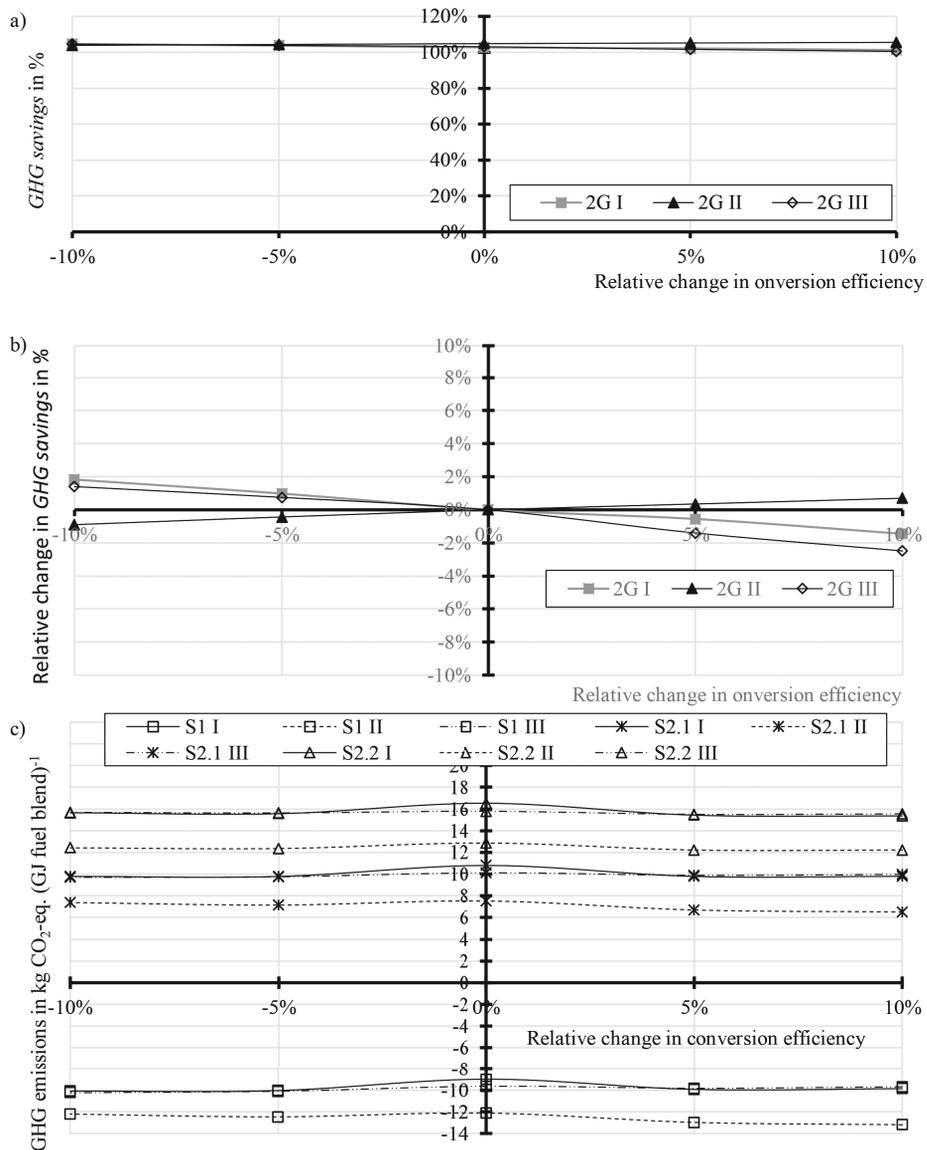


**Figure B - 4** Dependency of *GHG savings* and GHG emissions on a change in process heat demand: (a) absolute and (b) relative change in *GHG savings* according to RED methodology, and (c) change in GHG emissions due to a production of 1G and 2G ethanol and a shift from 1G to 2G ethanol production.

### B.3.3.2. Dependency of results on conversion efficiency

The conversion efficiencies assumed in this paper are based on literature research and are thus subject to uncertainties. Again, a change in quantities affects the system by altering *GHG savings* and by changing the quantity of feed co-product (molasses) and the amount of electricity that is generated from solid residues. The sensitivity analysis shows that a change in conversion

efficiency does not affect results to a large extent. A lower process efficiency results in more feedstock needed but at the same time, increases co-products, which lower the allocation factor of ethanol in the RED methodology and result in additional credits for feed and electricity in the consequential model.

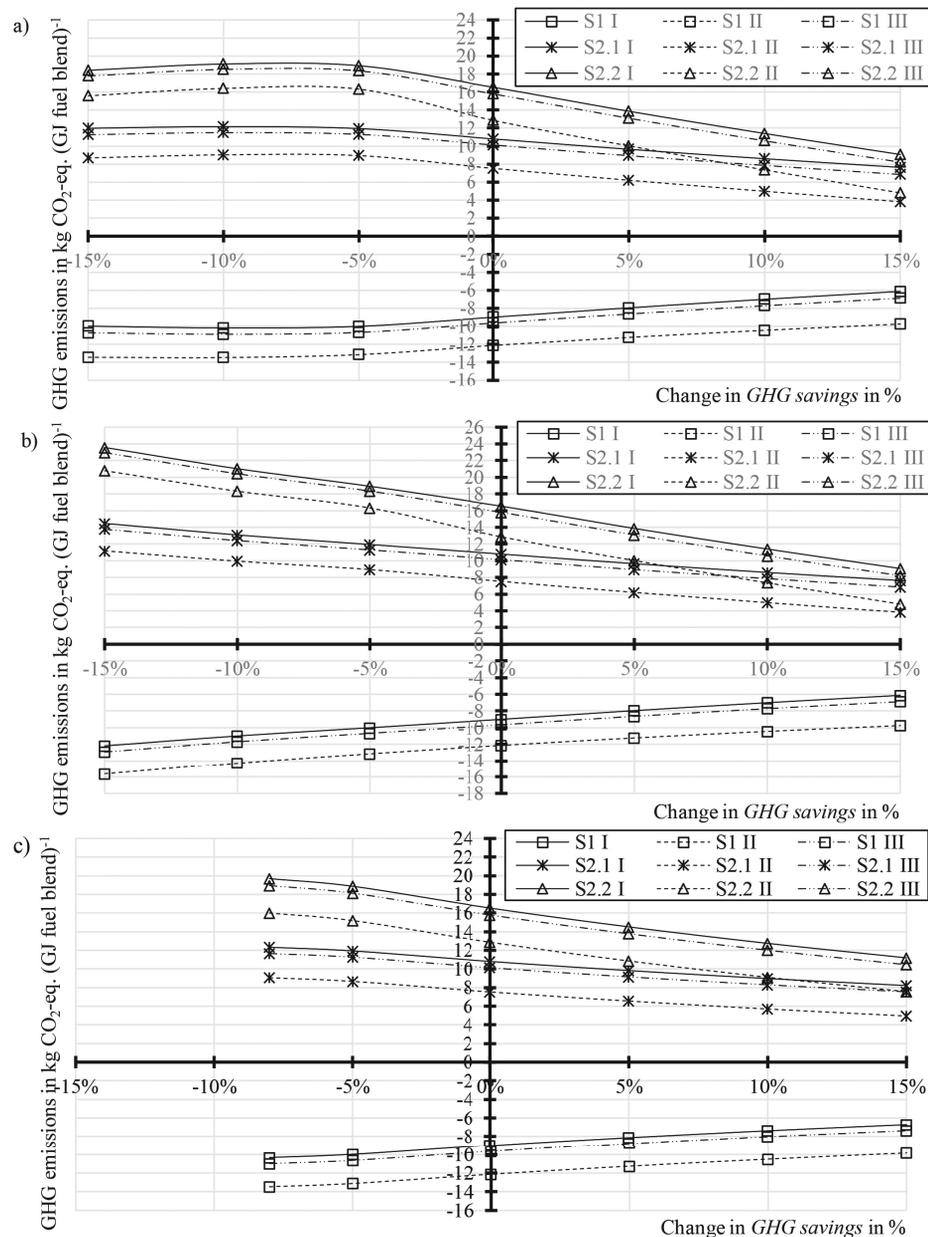


**Figure B - 5** Dependency of *GHG savings* and GHG emissions on a change in conversion efficiency: (a) absolute and (b) relative change in *GHG savings* according to RED methodology, and (c) change in GHG emissions due to a production of 1G and 2G ethanol and a shift from 1G to 2G ethanol production.

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### B.3.3.3. Dependency of results on GHG savings according to RED methodology

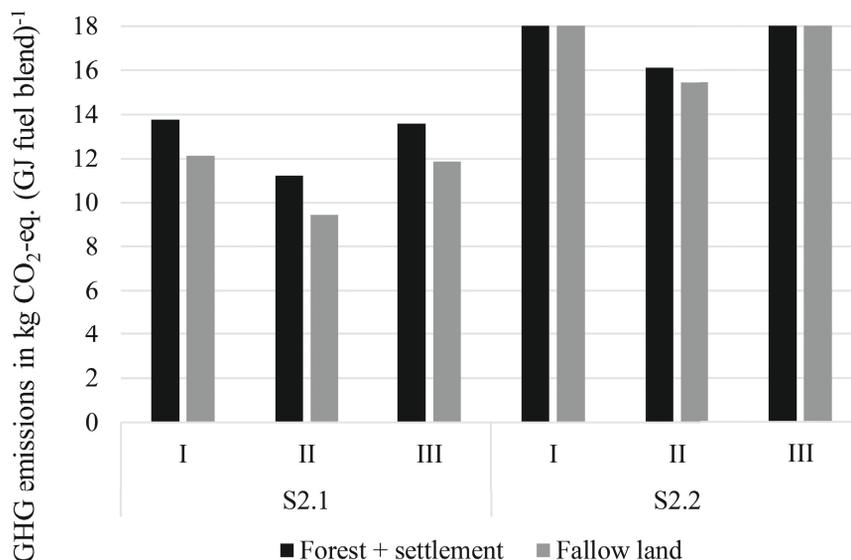


**Figure B - 6** Change in GHG emissions (consequential approach) in dependence of a change in *GHG savings* based in RED methodology (attributional approach): (a) *GHG savings* of 1G and all 2G concepts change, (b) 1G remains 58%, 2G concepts change, and (c) 2G concepts remain unchanged, 1G *GHG savings* change. Note: The minimum *GHG saving* requirement is 50% as of 2020. Hence, 50% is the fixed minimum in case of (a) and (c) in case of 1G ethanol.

The quantity of fuel to be blended with fossil fuel is dependent on *GHG savings* according to the RED methodology. Figure B - 6 shows the change in GHG emissions as a consequence of a change in *GHG savings* without affecting the quantity of co-products, e.g. by a change in emissions from feedstock cultivation. Results are most sensitive to changes in *GHG savings* of 1G ethanol, while *GHG savings* of other concepts remain fixed (case (c)): in scenario 1, the reduction of GHG emissions is reduced, while, in scenario 2.1 and 2.2, the increase in GHG emissions decreases. Thus, as higher the *GHG savings* according to RED methodology of 1G ethanol, and thereby, as closer the *GHG savings* of 1G and 2G concepts, the lower the change in emission. The same effect can be observed in case of a change in *GHG savings* of 2G concepts (case (b)).

#### B.3.3.4. LUC emissions from wheat production

Results presented in Figure 5-6 refer to the change of agricultural land to fallow land as a consequence of wheat grains that become available. In Germany, agricultural land decreased by 0.47 million ha, while forest and settlement area, including infrastructure, increased by 0.28 and 0,32 million ha, respectively, between 2004 and 2014 [15, 17]. As an alternative to the presented LUC variant (conversion to fallow land), the conversion to forest ( $F_{LU} = 0.1$ ,  $F_{MG} = 1$ ,  $C_{veg_{0,T}} = C_{veg_0} = 27 \text{ t/ha}$ ) is assessed [15]. In scenarios S2.1 and S2.2, it is therefore assumed that 46% of unused cropland is converted to forest while 54% are used for construction of buildings and infrastructure. In case land that becomes available eventually becomes a forest, the increase of GHG emissions from a shift from 1G to 2G ethanol will be lower (Figure B - 7): the change ranges from 6 to 9% of total emissions.



**Figure B - 7** GHG emissions due to the shift from 1G to 2G ethanol in dependence of LUC assumptions for wheat grains.

B

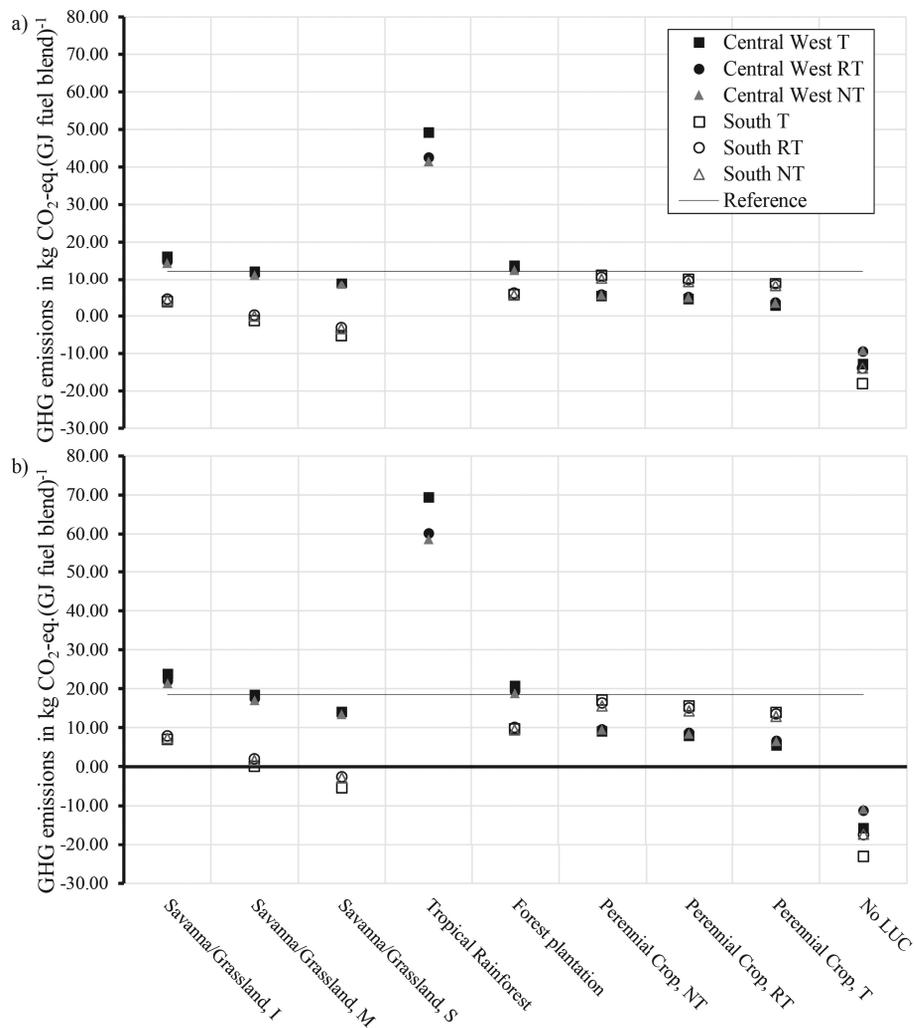
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### B.3.3.5. Soybean cultivation: Cultivation practice, location and related LUC emissions

In addition to the base case, other LUC assumptions were assessed (Table B -6). Soybean cultivation and related LUC are the largest contributor to an increase in emissions due to a shift from 1G to 2G ethanol (scenarios S2.1 and S2.2, Figure 5-7. Figure B - 8 shows emissions per GJ fuel blend for 2G concept I with respect to changes in production modalities and LUC. The soybean yield (2978 kg/ha) has been adapted based on [18]: 3332 and 3428 kg/ha in case of reduced and no tillage, respectively. The sensitivity analysis reveals that for most biomes, emissions changes will remain positive in case of a shift from 1G to 2G ethanol. Only if no LUC occurs or if soy is cultivated on severely degraded savanna, emissions will be reduced by a shift from 1G to 2G ethanol. The effect of cultivation practice is in most cases negligible in comparison to total emissions or effects of changes in biomes in which LUC emissions occur.

**Table B - 6** Parameters for sensitivity analysis of cultivation practice, location of cultivation and LUC as well as different LUC scenarios [15, 18]. Abbr.: BR – Brazil; I – improved management; LAC – low activity clay; M – moderately degraded; NT – no tillage; RT – reduced tillage; S – severely degraded; T – tillage. Parameters as defined in Eq. 5-6 and 5-7. The base case is marked in bold.

Location	Climate	Soil	Land use		SOC, ref [t C]	F,LU	F, MG	F, I	C,veg [t C]	C total [t/ ha/20a]	
BR, Central West	Tropical moist	LAC	Soy plantation	NT	47	0.48	1.22	1	0	28	
				RT	47	0.48	1.15	1	0	26	
				<b>T</b>	<b>47</b>	<b>0.48</b>	<b>1</b>	<b>1</b>	<b>0</b>	<b>23</b>	
BR, South	Warm temperate	LAC		NT	63	0.69	1.15	1	0	50	
				RT	63	0.69	1.08	1	0	47	
				T	63	0.69	1	1	0	43	
BR, Central West	Tropical moist	LAC	Savanna	I	47	1	1.17	1.11	53	114	
				<b>M</b>	<b>47</b>	<b>1</b>	<b>0.97</b>	<b>1</b>	<b>53</b>	<b>99</b>	
				S	47	1	0.7	1	53	86	
				47	1			198	245		
			Forest plantation	47	1	1	1	58	105		
			Perennial crop	NT	47	1	1.22	1	14.4	72	
				RT	47	1	1.15	1	14.4	68	
				T	47	1	1	1	14.4	61	
BR, South	Warm temperate	LAC	Forest plantation	63	1	1	1	31	94		
				Perennial crop	NT	63	1	1.15	1	43.2	116
					RT	63	1	1.08	1	43.2	111
				T	63	1	1	1	43.2	106	
			Grassland	I	63	1	1.14	1.11	6.8	87	
				M	63	1	0.95	1	6.8	67	
	S	63	1	0.7	1	6.8	51				



**Figure B-8** GHG emissions per GJ fuel blend of 2G concept I, scenarios S2.1 (a) and S2.2 (b), in dependence of cultivation practice of soybeans (tillage (T); reduced tillage (RT); no tillage (NT)); cultivation location (Central-West and Southern Brazil) and the biome where LUC occurs. The reference line presents the value without any changes for sensitivity analysis. Abbr.: I – improved management; M – moderately degraded; NT – no tillage; RT – reduced tillage; S – severely degraded; T – tillage.

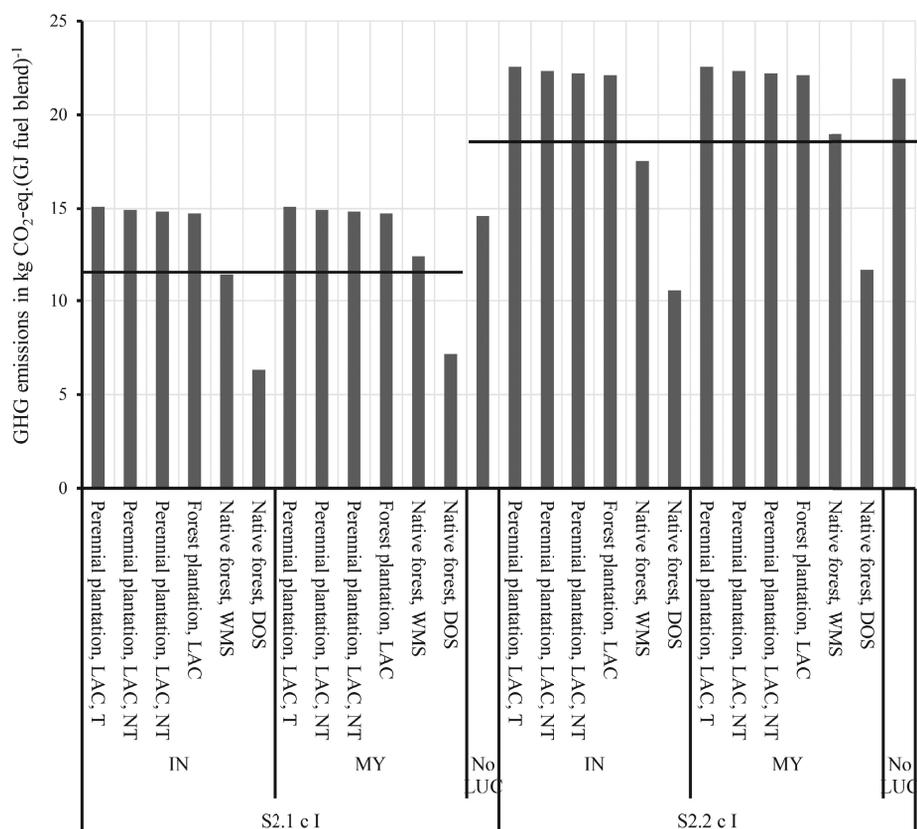
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### B.3.3.6. LUC emissions from oil palm cultivation

As a consequence of the shift from 1G to 2G ethanol, DDGS is not supplied anymore. DDGS is replaced by soybean meal which results in a provision of vegetable oil. This oil reduced demand for other vegetable oil (see chapter B.1.2.). Thus, the shift triggers a reduction in demand for palm oil. The effect of a change in biome where LUC of oil palm cultivation occurs reveals that in most cases, GHG emissions in both scenarios increase when the biome changes (Figure

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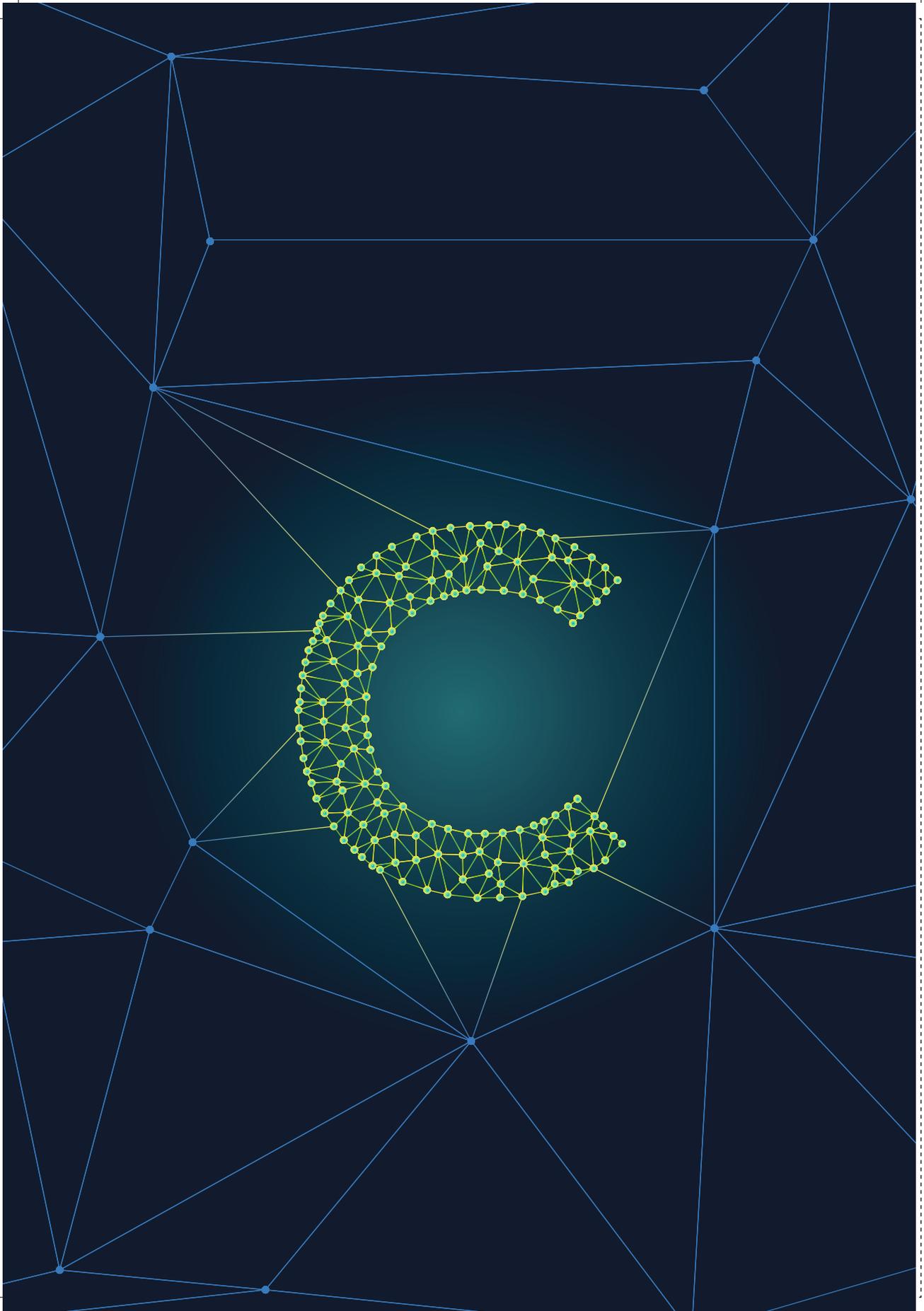
B - 9). This is due to the fact that less carbon is stored in most biomes listed in Table B -7, e.g. perennial plantations, compared to native rainforest (as assumed in the analysis). Likewise, the emission increase that results from a shift from 1G to 2G ethanol (scenario 2) is lower if palm oil is substituted that originates from biomes where formerly large quantities of carbon were stored, e.g. peat. Regardless of the biome, the shift from 1 to 2G ethanol results in an increase in emissions.



**Figure B - 9** GHG emissions per GJ fuel blend of concept I, scenarios 2.1 and 2.2, in dependence of the biome where LUC of palm oil cultivation occurs assuming a 100% provision from the respective biome and location. The reference line presents the value without any changes for sensitivity analysis. Abbr.: DOS – drained organic soil (peat); IN – Indonesia; LAC – low activity clay soil; LUC – land-use change; MY – Malaysia; NT – no tillage; RT – reduced tillage; T – tillage; WMS – Wetland mineral soil.

**Table B - 7** Parameters for sensitivity analysis of location of cultivation and related LUC emissions of oil palm cultivation [15, 19]; DOS – drained organic soil (peat), IN – Indonesia, LAC – low activity clay soil, LUC – land-use change, MY – Malaysia, NT – no tillage, RT – reduced tillage, T – tillage, WMS – Wetland mineral soil

Location	Land use		SOC, ref	F, LU	F, MG	F, I	C, veg	On-site	Off-site	CH <sub>4</sub>	N <sub>2</sub> O	C	
								CO <sub>2</sub>	CO <sub>2</sub>			total	
			[t/ha]				[t/ha]	[t C/ (ha a)]	[t C/ (ha a)]	[t CO <sub>2</sub> - eq./(ha a)]		[t C/ ha]	
IN	LAC	Perennial plantation	T	60	1	1	1	34.3					94
			RT	60	1	1.15	1	34.3					103
			NT	60	1	1.22	1	34.3					108
	WMS	Forest plantation		60	0.8	1	1	64					112
			Oil palm plantation	49	1	1	1	60					109
			Native forest	49	1			230					279
DOS	Oil palm plantation					60	11.0	0.8	1.1	0.6	-210		
MY	LAC	Perennial plantation	T	60	1	1	1	34.3					94
			RT	60	1	1.15	1	34.3					103
			NT	60	1	1.22	1	34.3					108
	WMS	Forest plantation		60	0.8	1	1	64					112
			Oil palm plantation	49	1	1	1	60					109
			Native forest	49	1	0	0	185					234
DOS	Oil palm plantation			1	1	1	60	11.0	0.8	1.1	0.6	-210	



# Appendix Chapter 6

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## Appendices

### C.1. Land use change

**Table C - 1** Parameters used to determine LUC emissions according to [89].

Land use	Parameter	EU South East	EU North	EU South West	EU Central
	<b>Climate</b>	Warm tempered, dry	Cool temperate, moist	Warm tempered, dry - except France (moist)	Cool temperate moist
	<b>Soil type</b>	High Activity Clay Soils	High Activity Clay Soils - except Finland and Sweden (Spodic Soils)	High Activity Clay Soils	High Activity Clay Soils
<b>Grassland/set aside land</b>	<b>C, veg</b>	3.1	6.8	3.1	6.8
	<b>F,LU</b>	1	1	1	1
	<b>F,MG</b>	0.95	0.95	0.95	0.95
	<b>F,I</b>	1	1	1	1
<b>Cropland</b>	<b>C, veg</b>	0	0	0	0
	<b>F,LU</b>	0.8	0.69	0.8	0.69
	<b>F,MG</b>	1	1	1	1
	<b>F,I</b>	1	1	1	1

**Table C - 2** Carbon content of topsoil and GHG emissions resulting from LUC. Topsoil carbon content was taken from [628]. Carbon content per ha and per crop output was determined applying the methodology provided in [89] (applying parameters reported in Table C - 1) combined with data on land use and yields [509, 629]. Average yields (2012-2016) were applied.

Country	C content t C ha <sup>-1</sup> in topsoil	Delta t C ha <sup>-1</sup>	Delta kg CO <sub>2</sub> -eq. (kg wheat grain) <sup>-1</sup>	Delta kg CO <sub>2</sub> -eq. (kg corn) <sup>-1</sup>
AT	94.11	-31.27	-1.04	-0.58
BE	58.69	-22.06	-0.47	-0.48
BG	48.65	-4.20	-0.17	-0.13
HR	N.D. <sup>a</sup>	-6.66	-0.24	-0.18
CZ	63.39	-23.28	-0.72	-0.55
DK	76.46	-13.08	-0.32	-0.37 <sup>d</sup>
EE	110.26	-35.47	-1.61	-1.04
FI	156.13	-33.79	-1.49	-0.93 <sup>e</sup>
FR	69.39	-11.24	-0.29	-0.24
DE	75.91	-26.54	-0.61	-0.50
GR	49.28	-4.29	-0.26	-0.07
HU	53.76	-20.78	-0.80	-0.59
IE	154.39	-33.34	-0.68	-1.07 <sup>f</sup>
IT	65.05	-6.66	-0.22	-0.13
LV	90.05	-30.21	-1.23	-0.88 <sup>d</sup>
LT	N.D. <sup>b</sup>	-35.47	-1.30	-1.04 <sup>d</sup>
LU	N.D. <sup>c</sup>	-26.54	-0.81	-0.78
NL	71.38	-25.36	-0.52	-0.59
PL	70.10	-25.03	-1.00	-0.73
PT	63.03	-6.35	-0.61	-0.14
RO	56.89	-5.43	-0.29	-0.26
SK	65.27	-23.77	-0.87	-0.69
SI	83.84	-9.48	-0.34	-0.22
ES	59.38	-5.81	-0.32	-0.10
SE	145.37	-31.00	-0.82	-0.85
UK	140.46	-29.72	-0.70	-0.96

<sup>a</sup> Carbon content per ha of Italy applied.

<sup>b</sup> Carbon content per ha of Estonia applied.

<sup>c</sup> Carbon content per ha of Germany applied.

<sup>d</sup> No data on corn yield was available in the applied dataset. Yield of Lithuania was applied.

<sup>e</sup> No data on corn yield was available in the applied dataset. Yield of Sweden was applied.

<sup>f</sup> No data on corn yield was available in the applied dataset. Yield of United Kingdom was applied.

## Appendices

### C.2. Detailed process descriptions and life cycle inventory

#### C.2.1. Feedstock composition, conversion efficiencies, and probability

##### distributions applied to Monte Carlo simulation

Table C - 3 Evaluated parameters of feedstock composition and production Monte Carlo Simulation.

Analyzed parameter	Parameters	Parameters		Significance of K-S Test <sup>1</sup>	Comment and data sources
		Mean	CV		
Grain	Starch	6.82 10 <sup>-1</sup> kg (kg DM) <sup>-1</sup>	0.9 %	0.855	
	Gluten	1.34 10 <sup>-1</sup> kg (kg DM) <sup>-1</sup>	15.6 %	0.241	[630]
	Bran	1.50 10 <sup>-1</sup> kg (kg DM) <sup>-1</sup>	6.7 %		No suitable data for statistical analysis was found on bran content of whole grains. Therefore, a mean of 0.15 kg (kg DM) <sup>-1</sup> and a CV of 6.7 % were assumed according to the range of 14 to 16 % reported in [630].
	Nitrogen	1.96 10 <sup>-2</sup> kg (kg DM) <sup>-1</sup>	18.4 %	0.231	
	Phosphorus	3.44 10 <sup>-3</sup> kg (kg DM) <sup>-1</sup>	22.9 %	0.510	
	Potassium	9.08 10 <sup>-3</sup> kg (kg DM) <sup>-1</sup>	124.6 %	0.057	
Straw	Cellulose	3.72 10 <sup>-1</sup> kg (kg DM) <sup>-1</sup>	15.7 %	0.827	
	Hemicellulose	2.69 10 <sup>-1</sup> kg (kg DM) <sup>-1</sup>	16.9 %	0.570	
	Lignin	1.91 10 <sup>-1</sup> kg (kg DM) <sup>-1</sup>	25.0 %	0.142	
	Glucan	3.54 10 <sup>-1</sup> kg (kg DM) <sup>-1</sup>	10.4 %	0.420	
	Galactan	1.78 10 <sup>-1</sup> kg (kg DM) <sup>-2</sup>	98.6 %	0.056	
	Xylan	2.15 10 <sup>-1</sup> kg (kg DM) <sup>-1</sup>	14.8 %	0.463	
	Mannan	3.13 10 <sup>-1</sup> kg (kg DM) <sup>-1</sup>	67.2 %	0.157	
	Nitrogen	5.96 10 <sup>-3</sup> kg (kg DM) <sup>-1</sup>	37.3 %	0.059	
	Phosphorus	8.04 10 <sup>-4</sup> kg (kg DM) <sup>-1</sup>	56.2 %	0.097	
	Potassium	6.97 10 <sup>-3</sup> kg (kg DM) <sup>-1</sup>	50.4 %	0.637	
Grain yield	7.53 t/ha	12.5 %	0.099	[629]	
Grain to straw ratio	1.06 kg straw DM (kg grain DM) <sup>-1</sup>	16.5 %	0.237		

<sup>1</sup> The null hypothesis is rejected at  $\alpha < 0.05$ .

**Table C - 4** Statistical parameters of conversion efficiencies used in Monte Carlo simulation. Distributions (D): LN – lognormal, ND – normal, TD – triangular.

Variable	D	Parameters (Concept: Mean, CV)	Comment
<b>Pretreatment</b>			
Glucan →Glucose	ND	SE: 0.07 [465], 5.1% [465] OS: 0.04 [516], 5.1% [520]	Normal distribution assumed based on [520]. No data or study was found on organosolv pre-treatment. Thus, the same CV was applied.
Glucan recovery	ND	SE: 0.91 [465], 5.1% [465] OS: 0.91 [516], 5.1% [465]	Normal distribution assumed. No data or study was found on OS pre-treatment. Thus, the same CV was applied as for SE.
Xylan → Xylose	ND	2G SE: 0.28 [465], 3.0% [520] 2G OS: 0.30 [516], 3.0% [520]	A normal distribution and a CV of 3% are applied according to [520]. No data or study was found on OS pre-treatment. Thus, the same CV was applied as for SE.
Xylan recovery	ND	SE: 0.20 [465], 8.8% [465] OS: 0.05 [516], 8.8% [465]	Normal distribution assumed based on [520]. No data or study was found on OS pre-treatment. Thus, the same CV was applied as for SE.
Arabinan → Arabinose	ND	SE: 1.0 [465], 8.4% [520] OS: 0.74 [515], 8.4% [520]	Normal distribution assumed based on [520]. No data or study was found on OS pre-treatment. Thus, the same CV was applied as for SE.
Galactan → Galactose		SE: 0.6 [465], 8.4% [520] OS: 0.9 [515], 8.4% [520]	Normal distribution assumed based on [520]. No data or study was found on the CV of galactan conversion. Therefore, the same CV as for arabinan conversion was assumed.
Acetyl groups → acetic acid	ND	2G OS: 0.79 [515], 5%	Normal distribution and CV assumed.
Xylan → furfural	ND	2G OS: 0.3 [515], 5%	Normal distribution and CV assumed.
<b>Enzymatic hydrolysis</b>			
Glucan → Glucose	ND	1G: 0.91 [369], 5.8% [520] 2G SE: 0.82 [465], 5.8% [520] 2G OS: 0.89 [516], 5.8% [520]	Normal distribution assumed based on [520]. No data or study was found on OS pre-treatment and CV of 1G, 2G SE and 2G OS. Thus, the same CV was applied as for glucan conversion
Xylan → Xylose	ND	2G SE: 0.63 [465], 5.8% [520] 2G OS: 0.92 [515], 5.8% [520]	Normal distribution assumed based on [520]. No data or study was found on OS pre-treatment and CV of SE and OS. Thus, the same CV was applied as for glucan conversion.
<b>Fermentation</b>			
Glucose → Ethanol	ND	1G: 0.95, 3.2% [520] 2G: 0.95 [520], 3.2% [520]	Normal distribution assumed based on [520]. CV for all concepts derived from [520].

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Table C - 4 Continued

Variable	D	Parameters (Concept: Mean, CV)	Comment
Xylose → Ethanol	ND	2G COF: 0.93 [468], 3.5% [520]	[520]
Xylose → xylitol	ND	Mean: 0.92 [518], 5.8%	CV assumed as for xylose to ethanol fermentation reported in [520].
<b>Other</b>			
Biogas potential	ND	1G DM BG: $1.1 \cdot 10^{-1} \text{ m}^3 \text{ (kg stillage)}^{-1}$ 1G WM BG: $8.5 \cdot 10^{-2} \text{ m}^3 \text{ (kg stillage)}^{-1}$ 2G SE: $5.2 \cdot 10^{-2} \text{ m}^3 \text{ (kg molasses)}^{-1}$ , 2G OS: $4.4 \cdot 10^{-2} \text{ m}^3 \text{ (kg molasses)}^{-1}$ CV (all): 3.2% [631]	Rath et al. [631] report a normal distribution of biogas yield for corn. Due to the lack of primary data, the CV reported by Rath et al. [631] is assumed.
N <sub>2</sub> O emissions	LN	Geometric mean: 0.01 Geometric SD: 2.57	The uncertainty range provided by [230] was converted by the methodology provided to a lognormal distribution.
N availability	TD	Modus: 0.3 Min: 0.25 Max: 0.75	The mean was derived from [632]. This value is in accordance with values reported for other organic materials [547]. Due to the lack of statistical data, the range presented by Cherubini et al. [633] was applied. A triangular distribution was assumed as lower values are considered more realistic than the higher end of the range according to values reported in [634].

### C.2.2. Energy

These assumptions were made to evaluate the marginal supply of energy provision:

- Manufactured gases, e.g. coke oven gas is an inflexible supplier (by-product of other processes). Thus, the supply of electricity from these gases is considered unaffected by an increase or decrease in electricity demand.
- Marginal hydropower supply is assumed to be reservoir installations. In mountainous countries, alpine reservoirs are assumed.
- No data was found on the annual production of nuclear power by power plant type for each country. Therefore, it was assumed that 50% originate from pressure water reactors and 50% from boiling water reactors.

### C.2.3. Biorefinery concepts

The following process description provides additional information and data in addition to the description in the main text. Additional information not contained in chapter 6 is underlined.

### C.2.3.1. Ethanol production

The compositions of grains (starch, gluten and bran content) and straw (lignin, cellulose and hemicellulose sugars) were determined by statistical analysis of available literature (Table C - 3). The conversion efficiencies are presented in Table C - 4. Energy is provided by a natural gas boiler with a steam turbine. An overall efficiency of 0.85 and 0.8 is assumed in case of natural gas and biomass combustion, respectively [511]. The power to heat ratio is dependent on the respective energy requirements of each process setup. Two concepts of ethanol production of ethanol from wheat grains (1G) are assessed

- **Standard concept (1G DM DDGS and 1G DM BG)** Wheat grains are milled in a dry-milling process. Subsequently, the contained starch is hydrolyzed and transformed to sugars by the aid of enzymes. Afterwards the resulting sugars are fermented to yield ethanol. The efficiency of enzymatic hydrolysis is 91.4 % of the theoretical maximum [369]. The fermentation efficiency of glucose is 95 % of the theoretical maximum [520]. Stillage that remains after the distillation step is either dried to yield dried DDGS (**1G DM DDGS**), or used as feedstock for biogas production (**1G WM BG**).
- **Elaborated concept (1G WM CDS and 1G WM BG)** Before milling, bran is separated from grain. After milling, gluten is extracted by washing and dried. A gluten recovery of 54 % is achieved (determined by industry data [369] and wheat grain composition (Table C - 3). Gluten drying requires 2.32 MJ heat and 0.58 MJ electricity per kg gluten (95 % DM) [369]. The efficiency of enzymatic hydrolysis is 81.0 % of the theoretical maximum [369]. The same fermentation efficiency as in case of 1G DM concepts is assumed. The arising stillage is either thickened to produce CDS (**1G WM CDS**) or sent to a biogas facility (**1G WM BG**).

Likewise, two concepts of ethanol from wheat straw (2G) are assessed:

- **Standard concept (2G SE)** The wheat straw is pre-treated by steam explosion, yielding a liquid phase rich in C5-sugars, e.g. xylose, arabinose and a solid stream rich in lignin and C6-sugars, e.g. glucan, glucose and minor quantities of other C6 sugars. Steam explosion is conducted (210 °C, 5 minutes). Conversion coefficients are taken from laboratory experiments conducted by Alvira et al. [465]. The retention of glucan, xylan, galactan, arabinan, mannan and lignin are 91.2, 19.6, 0.0, 0.0, 0.0 and 99.2 %, respectively, of material contained in raw material [465]. The severe pre-treatment conditions result in the formation of inhibitors, such as furfural, 5-hydroxymethylfurfural (HMF), acetic acid and formic acid that inhibit subsequent process steps [512]. The streams are detoxified by and resin-wafer electro-deionization and washing, in case of the liquid and the solid stream, respectively [513, 514]. The removal efficiencies of RW-EDI of acetic acid, furfural and HMF are 95, 40 and 25%, respectively [513]. The washing of the solid fraction using six volume of water

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per volume of solid matter and removes acetic acid, formic acid, furfural and HMF with efficiencies of 64, 87, 86 and 87%, respectively [580]. The solid stream is sent to hydrolysis which requires 20 g enzymes per kg of cellulose [466]. The efficiency of enzymatic hydrolysis is 81.8 and 63.3 % in case of glucon and xylan, respectively [465]. Glucose, xylose and arabinose are fermented with efficiencies of 95, 93 and 54 %, respectively [468]. The overall process yields a solid stream, mainly consists of lignin that is combusted to provide process energy. GHG emissions arising of its combustion are taken from the probas data base [469]. The process furthermore generates a liquid stream that is composed of the liquid fraction after pre-treatment and the liquid phase separated after ethanol distillation. This stream, mainly consisting of xylose and minor quantities of other pentose sugars is either thickened to be sold as molasses (2G SE MOL), used as a feedstock for biogas production (2G SE BG) or for xylitol production (2G SE XYL) or fermented together with the solid stream (2G SE COF). In case of molasses production, it is assumed that 50 % of the process water can be recycled. All concepts are described below.

- **Elaborated concept (2G OS)** The organosolv pretreatment conditions need account for the aim of optimizing lignin output for use as a substitute for phenol-formaldehyde resin and the output of ethanol. Therefore, the pretreatment needs to fulfill the following criteria: (1) high lignin output, (2) high lignin purity, (3) high reactive H-OH group content, (4) low molecular mass, and (5) high enzymatic hydrolysis yields. Huijgen et al [635] and Wildschut et al. [516] analyzed 11 and 14 different organosolv-derived lignins, respectively. Of all analyzed pretreatment conditions, the auto-catalyzed ethanol pretreatment with an ethanol concentration of 60 % w./w., catalyst dose of  $30 \cdot 10^{-3} \text{ Mol H}_2\text{SO}_4 \text{ L}^{-1}$ , a temperature of 190°C and a duration of 60 minutes is considered the most suitable results based on the defined criteria. The process scheme is based on the modelling study presented by [515] and experimental data published by Wildschut et al. [516]. After ethanol organosolv pretreatment, pulp containing mainly hexose sugars is washed twice (once with ethanol and once with water). The pulp contains 91.0, 4.7 and 24.2 % of the glucon, xylan and lignin, respectively, contained in the raw material [516]. To increase lignin yields, the stream is washed with ethanol. A subsequent water washer removes all ethanol and other inhibitors. After washing, hexose sugars that are contained in the delignified and detoxified pulp are hydrolyzed and subsequently fermented. The hydrolysis converts 89 and 68 % of glucon and xylan, respectively [465, 516]. The post-pretreatment liquid stream contains mainly dissolved lignin, xylose and furfural. The latter is extracted at the ethanol recovery stage and subsequently concentrated. The hydrolysis of acetyl groups can lead to the formation of acetic acid [517], which are extracted in the subsequent step. Analogously to 2G SE concepts, the liquid stream is either used to produce molasses (2G OS MOL), biogas (2G OS BG), xylitol (2G OS XYL) or ethanol through co-fermentation of hexose and pentose sugars (2G OS COF). After distillation/rectification of ethanol, the remaining suspended solids

are combusted to provide process energy while the liquid stream is processed treated in a waste-water treatment plant (2G OS COF) or is processed with the pentose sugar stream (all other concepts).

In all case, glucose is fermented with an efficiency of 95.0, 93.0 and 54.0 % of the theoretical maximum [520]. The latter two are only applied in case of co-fermentation (COF, see below). Fermentation requires 3 g enzymes per t ethanol [369]. In all concepts, the purification of ethanol is accomplished by distillation/rectification and sieves (purity of 99.7 %). Emissions of volatile organic compounds are estimated based on measurements [40]. Wastewater is treated in a waste-water treatment facility. Ethanol is assumed to delivered 150 km to the filling station [464]. If mass balances reported in literature regarding pretreatment conversion efficiencies are incomplete (sum of products is below 100 % of inputs). It is assumed that only those fractions can be used for further processing that were recovered in the cited laboratory studies. The remaining degradation products are assumed to be treated with the wastewater.

#### C.2.3.2. *Unfermented sugar utilization*

All concepts yield a side stream consisting of unfermented sugars (e.g. pentose sugars in all 2G non co-fermentation concepts) and other components (concept-dependent). Several processes are considered that are combined with the aforementioned ethanol concepts:

- **Feed production (1G DM DDGS, 1G WM CDS, 2G SE MOL and 2G OS MOL)** The side stream can be dried or thickened to generate a feed product. Thickening and drying of products requires, 5.83, 0.33, 1.18 and 0.67 MJ per kg of DDGS (90% DM), CDS (27 % DM), molasses from SE (60 % DM) and molasses from OS (DM 60 % DM), respectively (own calculations based on data from [369, 515]).
- **Biogas production** The production of biogas from side streams arising from each bioethanol production concept, i.e. stillage as well as pentose sugars and unfermented hexose sugars, in case of 1G and 2G production concepts, respectively, was analyzed. The composition of biogas and the biogas potential were derived from laboratory experiments [379] in case of 1G concepts and from experimental data published in literature [470] combined with calculations of the theoretical methane potential in case of 2G concepts [636, 637]. The biogas potentials are 0.70, 0.74, 0.75 and 0.75 m<sup>3</sup> biogas per kg organic dry substance, in case of 1G DM, 1G WM, 2G SE and 2G OS, respectively, with a DM degradation of 65% [379]. The methane contents of biogas are 55 % and 49% in case of 1G concepts [379] and 2 G concepts, respectively. The electricity demand of biogas production is 1.6 % of the energetic output [638]. No additional heat is required due to the latent heat of stillage. Digestate contains extractable nutrients that can replace mineral fertilizers. To this end, ammonium sulfate is stripped from the digestate (nutrient content according to [470]) with a stripping

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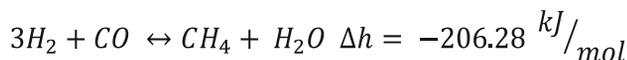
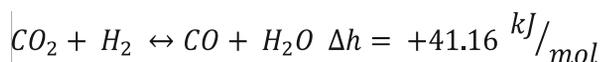
efficiency is 80% [379]. Afterwards the digestate is dewatered through centrifugation and thermal drying (20% DM). The resulting thickened digestate still contains nutrients and can thus be used as a fertilizer. Thickening requires 0.69 kWh electricity per t digestate treated in a decanter and 1.16 MJ heat per kg of water that is evaporated in a two-step evaporation column [476]. The upgrading (1G DM BG, 1G WM BG, 2G SE BG and 2G OS BG) and methanation of CO<sub>2</sub> (1G DM BG CH<sub>4</sub>, etc.) as well as the synthesis of methanol from biogas (1G DM BG MeOH, etc.) are assessed (see below). Measurements of diffuse methane emissions revealed emissions from below 1% of produced methane (excluding open digestate storage tanks, gas engines and upgrading; a close digestate storage system is assumed in this study) [639–641]. Conservatively, gas leakage of 1 % of produced gas is assumed.

- **Xylitol production** Xylitol can either be produced catalytically or biologically. The fermentation of xylose by yeast (*Candida tropicalis*) is chosen, as this allows the use of a diluted solution of xylose [518]. The unfermented glucose benefits the cell biomass growth and the xylitol yield. First, the liquor is de-toxified using activated charcoal, ionic resins and chromatographic separation [518, 519]. Subsequently, xylose is fermented yielding 0.73 kg crystallized xylitol per kg xylose [518]. The process requires 15.3 g ammonia and 0.38 kg yeast per kg xylitol. It is assumed that unfermented sugars from ethanol production are sufficient to sustain biomass growth and respiration. In addition, 190.5 g CO<sub>2</sub> are produced per kg of crystallized xylitol which is further processed as the CO<sub>2</sub> arising from ethanol fermentation. Xylitol is purified using ion exchange membranes and activated carbon to remove contaminants. Finally, after the removal of precipitates and subsequent vacuum distillation to increase xylitol concentration, xylitol crystallization is accomplished by adding ethanol and cooling to -20°C. The crystals are washed out and dried. A purification loss of 9.51 % was assumed based on the theoretical maximum production reported by Mountraki et al. [518] of 86 mol xylitol per 100 mol xylose, the output of 0.73 kg crystallized xylitol per kg xylose and the fermentation efficiency of 92 %.. Process integration and water recycling allows the full integration of used in the evaporator (25.90 MJ per kg xylitol) [518]. The overall process requires 84.33 L water per kg xylitol (part of which is contained in the pentose stream). The electricity demand of the process is estimated to be 10 % of the heat demand [642].
- **Ethanol production** In case of 2G ethanol production, the co-fermentation of pentose sugars is considered (2G SE COF and 2G OS COF). Xylose and arabinose are fermented with an efficiency of 93.0 and 54.0 %, respectively [468, 520]. Unfermented sugars are thickened to yield feed (i.e. molasses).CO<sub>2</sub> and biogas utilization: Power-to-X and other concepts

### C.2.3.3. CO<sub>2</sub> and biogas utilization: Liquefaction, methanation and methanol synthesis

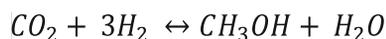
The CO<sub>2</sub> produced in the fermentation (all concepts) and anaerobic digestion (BG concepts) is a potential feedstock for additional products. In total, three concepts are assessed in combination with the aforementioned ethanol production concepts:

- **Standard concept (no suffix)** CO<sub>2</sub> from ethanol fermentation is captured and liquefied. The product can be used in the chemical, beverage and food industry. This intercooled 5-stage compression process requires 0.43 MJ electricity per kg CO<sub>2</sub> [463].
- **Standard BG concept (no suffix)** Biogas is cleaned and upgraded to biomethane and CO<sub>2</sub>: At first, biogas is de-sulfurized by activated carbon before being purified by pressure swing adsorption (PSA); this cleaning process requires 2.1 10<sup>-4</sup> kg activated carbon and 1.5 10<sup>-4</sup> kg lubricant oil per m<sup>3</sup> purified gas [385]. The methane slip (unburnt methane) that leaves the waste gas flare is 0.2% of the waste gas stream [474]. Biomethane is compressed and the energy content is adjusted to meet grid requirements by adding propane (0.013 m<sup>3</sup>/ m<sup>3</sup> CH<sub>4</sub>) [475].
- **Methanation (+CH<sub>4</sub>)** The generation of methane from CO<sub>2</sub> is based on experimental data and process modelling Witte et al. [521, 522]. Based on their works, a setup is developed for methanation of CO<sub>2</sub> from fermentation and of biogas. The latter process setup is capable of handling biogas feeds ranging from 40 to 50 % biomethane and requires biogas cleaning (H<sub>2</sub>S removal) by activated carbon prior further processing. The process consists of biogas cleaning, compressing, mixing of biogas with hydrogen, gas heating, methanation in a bubbling fluidized bed reactor and, finally, methane upgrading. In the reactor, the reverse water gas shift reaction and the methanation reaction are realized:

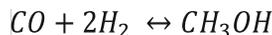


The required hydrogen is supplied by alkaline electrolysis (see below). The methane yield is 98.70 %. The process requires 0.625 MJ electricity per kg CH<sub>4</sub> generated. The process requires steam to prevent catalyst deactivation. Steam requirement is 0.5 m<sup>3</sup> steam per m<sup>3</sup> CO<sub>2</sub> that is fed to the reactor. The side stream of membrane upgrading is recycled and fed to the compressor unit.

- **Methanol synthesis (+MeOH)** The production of methanol from fermentative CO<sub>2</sub> is based on the modelling results of Hoppe et al. [524]. The overall reaction is a combination of the reverse water gas shift reaction and the methanol synthesis from synthesis gas [523]:

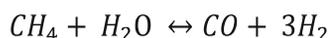
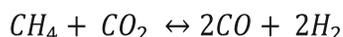


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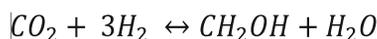
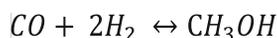


The reactor works with a molar H<sub>2</sub> to CO<sub>2</sub> ratio of 3 to 1 [523]. The reaction delivers 0.73 kg methanol and requires 0.14 kg H<sub>2</sub> and 0.24 kg water per kg of CO<sub>2</sub> feed. The overall reaction is exothermic.

In BG concepts, methanol is directly synthesized from biogas. The data inventory is based on modelling results of Hernández and colleagues [525]. In these cases, H<sub>2</sub>S is first removed. Subsequently methane is reformed (steam and dry reforming):



After refining, methanol is synthesized:



A part of the biogas (16.3 %-vol.) is used for energy provision of the reforming step. After the reforming, syngas is cleaned (water removal and a PSA to remove traces of hydrocarbons and nitrogen). Subsequently, a by-pass, a water gas shift reactor and a hybrid membrane-PSA are used to adjust the H<sub>2</sub> to CO ratio. It is assumed that the output of methanol can be increased by addition of hydrogen derived from electrolysis. The overall process yields 1.26 and 1.14 kg methanol per m<sup>3</sup> biogas in case of 1G BG and 2G BG concepts, respectively. The process requires 0.56 kg water and 1.38 MJ electricity, emits 0.15 kg CO<sub>2</sub> per kg of methanol [525].

- **Electrolysis** Hydrogen is supplied by alkaline electrolysis. The efficiency of alkaline electrolysis is 68.6% (Table C - 5). The used KOH solution needs to be replaced after 10 years. GHG emissions related to materials needed for electrolysis amount to 0.6 g CO<sub>2</sub>-eq. per MJ H<sub>2</sub> [643]. The influence regarding overall results is considered negligible, cf. [644].

**Table C - 5** Key parameters of alkaline electrolysis [521, 522].

		kg	MJ
<b>In</b>	Water	8.97232563	
	Electricity		174.93121
<b>Out</b>	Hydrogen	1	119.972
	Oxygen	7.97232563	
<b>Efficiency</b>			0.68582387

Table C - 6 LCI of base concepts.

	IG DM			IG WM			2G SE			2G OS				
	DDGS	BG	CDS	BG	MOL	BG	MOL	BG	XYL	COF	MOL	BG	XYL	COF
<b>Inputs</b>														
Feedstock	3.39	3.39	3.85	3.85	7.65	3.85	7.65	7.65	7.65	5.19	6.26	6.26	6.26	4.69
Water	4.85	4.46	3.69	3.69	50.63	3.69	56.56	100.77	100.77	35.98	33.60	33.60	55.23	25.17
Enzymes	3.00	3.00	3.00	3.00	54.76	3.00	54.76	54.76	54.76	37.80	54.76	54.76	54.76	37.80
Corn steep liquor					0.10		0.10	0.1	0.1	0.06	0.06	0.06	0.06	0.04
Diammonium phosphate	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Natural gas	14.25	11.72	15.60	13.33			11.62	9.94	9.94		59.97	81.00	74.52	45.19
Electricity from grid	0.00	0.52	0.43	0.97	3.17	0.97	2.08	1.47	1.47	2.67	0.73	0.00	0.00	0.44
<b>Outputs</b>														
Ethanol	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Liquefied CO <sub>2</sub>	0.81	0.94	0.81	0.88	0.81	0.88	0.96	1.24	1.24	0.81	0.81	0.90	1.16	0.81
Feed	1.08	1.08	0.75	0.75	2.85	0.75				0.95	1.74			0.43
Gluten			0.29	0.29										
Bran			0.58	0.58										
Biomethane							14.75					8.70		
Digestate		1.55		0.98										
Ammonium sulfate		6.44		4.13			19.80					13.68		
Xylitol								0.50					0.40	
OS lignin											1.02	1.02	1.02	0.76
Acetic Acid											0.65	0.65	0.65	0.49
Furfural											0.43	0.43	0.43	0.32
Methanol														
Oxygen														
Wastewater	4.82	3.64	2.8	3.12	50.17	3.12	48.52	101.93	101.93	36.61	34.58	32.30	56.82	26.30

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**Table C - 7** LCI of concepts with additional methanation (+CH<sub>4</sub>). Values present calculated means of 5000 Monte-Carlo Simulations. If values differ by less than 2%, values are not explicitly stated again. Instead, the reader is referred to Table C - 6.

		1G DM			1G WM			2G SE			2G OS		
		DDGS	BG	CDS	BG	MOL	BG	MOL	COF	XYL	BG	MOL	COF
<b>Input</b>													
Feedstock	kg FM												
Water	kg	8.17	20.09	7.01	15.48	53.95	75.38	109.30	39.30	63.78	47.96	28.56	
Enzymes	10 <sup>-3</sup> kg							Table C - 6					
Corn steep liquor	kg							Table C - 6					
Diammonium phosphate	kg												
Natural gas	MJ	14.70	11.71	15.62	13.35	0.00	12.02	10.19	0.00	75.44	82.97	45.02	
Electricity from grid	MJ	14.15	22.94	14.98	19.46	17.69	29.39	17.44	17.26	15.23	20.82	15.25	
<b>Outputs</b>													
Ethanol	kg							Table C - 6					
Liquefied CO <sub>2</sub>	kg							Table C - 6					
Feed	kg												
Gluten	kg												
Bran	kg												
Biomethane	MJ	17.37	17.38	39.21	28.36	17.38	48.19	19.10	17.36	35.87	19.14	17.74	
Digestate	kg							Table C - 6					
Ammonium sulfate	10 <sup>-3</sup> kg N												
Xylitol	kg												
OS lignin	kg												
Acetic Acid	kg												
Furfural	kg												
Methanol	MJ												
Oxygen	kg	1.39	2.16	1.39	1.79	1.39	2.63	1.53	1.39	1.42	2.14	1.419	
Wastewater	kg	4.82	3.64	2.8	3.12	50.17	48.52	101.93	36.61	34.58	32.30	26.30	

**Table C - 8** LCI of concepts with additional methanol synthesis (+MeOH). Values present calculated means of 5000 Monte-Carlo Simulations. If values differ by less than 2%, values are not explicitly stated again. Instead, the reader is referred to Table C - 6.

	IG DM			IG WM			2G SE			2G OS				
	DDGS	BG		CDS	BG		MOL	BG		COF	MOL	BG	XYL	COF
Input														
Feedstock														
Water	6.38	5.22	6.54	5.50	5.50	52.16	58.76	102.30	37.51	35.13	35.53	56.76	26.70	
Enzymes								Table C - 6						
10 <sup>-3</sup> kg								Table C - 6						
kg														
Corn steep liquor														
kg														
Diammonium phosphate														
kg	14.69	11.73	15.63	13.35	0.00	12.06	10.14	0.00	59.04	83.16	76.60	44.93		
Natural gas	13.65	5.62	14.43	3.89	17.18	9.05	16.88	16.74	15.04	2.87	14.65	14.74		
Electricity from grid														
MJ														
Outputs														
Ethanol								Table C - 6						
kg														
Liquefied CO <sub>2</sub>														
kg														
Feed								Table C - 6						
kg														
Gluten														
kg														
Bran														
kg														
Biomethane														
MJ														
Digestate														
kg								Table C - 6						
Ammonium sulfate														
10 <sup>-3</sup> kg N														
Xylitol														
kg														
OS Lignin														
kg														
Acetic Acid														
kg														
Furfural														
kg														
Methanol	13.84	27.91	13.84	21.96	13.84	33.61	15.23	13.84	25.63	13.84	15.52	13.84		
MJ														
Oxygen	1.05	0.38	1.05	0.20	1.05	0.53	1.16	1.05	1.07	0.31	1.16	1.07		
kg														
Wastewater	4.82	3.64	2.8	3.12	50.17	48.52	101.93	36.61	34.58	32.30	56.82	26.30		
kg														

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### C.2.4. Life cycle inventories (LCI)

## C.3. Detailed description of substitution mechanisms and LUC

### C.3.1. Substitution mechanisms

Table C - 9 Substitution mechanisms for all products.

Product Concepts	Substitution mechanism
<b>Acetic acid</b> OS concepts	Acetic acid supplied by organosolv concepts replaces acetic acid produced by methanol carbonylation. As the number of companies planning to supply acetic acid is expected to decrease within the EU [645], it is assumed that European production is substituted. A transport distance of 300 km is assumed.
<b>Biomethane</b> BG concepts +CH <sub>4</sub> concepts	The change in gas supply between 2012 and 2016 was assessed using Eurostat statistics [505]. It is assumed that in the medium term, supply of methane will eventually contribute to ongoing supply trends. The GHG intensities of natural gas supply used in European countries supplied by different countries was derived from [507]. GHG intensities for a marginal increase and a marginal decrease are determined for each country.
<b>Bran</b> 1G WM CDS CDS 1G WM CDS	Bran is assumed to substitute a combination of domestically produced barley and oat. <i>See DDGS.</i>
<b>CO<sub>2</sub></b> All concepts except +CH <sub>4</sub> and +MeOH	Captured CO <sub>2</sub> is assumed to replace fossil derived CO <sub>2</sub> from ammonia production. The substituted CO <sub>2</sub> stems from steam reforming of natural gas.
<b>DDGS</b> 1G DM DDGS	DDGS substitutes a combination of protein feed and cereals. Vegetable oil completes the substitution mechanism (chapter 6.2.1.2). Worldwide, soybeans presents to most important and fastest growing market for meal extracted from oil seeds [646]. In 2018, the U.S. became the most important provider of soybeans. At the same time, the share of soy imported from Brazil decreased [647]. Consequently, it is assumed that DDGS supply substitutes soybean (meal) imports from Brazil. Wheat grains complement the nutrient and energy balance. It is therefore assumed that DDGS, if supplied to the feed market, displaces soy imports from Brazil. The majority of Brazilian soybean (meal) is exported from Paranaguá (36%), Santos (25%), Vitória (8%) and Rio Grande (1%) [483]. It is assumed that all soybean is shipped to Rotterdam by bulk cargo ships from these ports. Palm oil presents the most used vegetable oil world-wide and the price of palm oil has been lower than that of rapeseed and soybean oil in the past years [429, 431, 481]. Therefore it is assumed that palm oil is the oil that complements the feed substitution mechanism. The major exporters of palm oil are Indonesia and Malaysia, providing 56 % and 34 % of global palm oil exports in 2018, respectively [648]. Indonesian palm oil originates mainly from Sumatra (75%) and Kalimantan (21%) [484]. It is assumed that palm oil is shipped from Port Klang, Jakarta and Pontianak in case of production in Malaysia, Sumatra and Kalimantan, respectively. GHG emissions for shipping to Europe are included. Transportation of grain and protein feeds within the EU from bulk terminals is mainly conducted via inland waterways (70% of transported mass). The inland waterway transportation is omitted. With regards to overall emissions, the omission of these is considered justifiable. Subsequently road transport via trucks for another 300 km is assumed for soybean meal and palm oil.

Table C - 9 Continued

Product Concepts	Substitution mechanism
<b>Electricity</b> 2G SE MOL <sup>a</sup>	Electricity generation and the change in generation between 2012 and 2016 was assessed based on Eurostat data. The GHG intensity of marginal electricity supply is determined by combining the weighted change in electricity supply and the GHG intensity of the respective electricity supply from [502]. GHG intensities for a marginal increase and a marginal decrease are determined which are applied for an increase in electricity demand originating from the operation of the facility and that is displaced through a supply of surplus electricity.
<b>Ethanol</b> All concepts	Among presently exploited oil resources, shale oil is considered highly sensitive to changes in demand [649]. It is therefore assumed that ethanol substitutes gasoline from shale oil. The GHG intensity of shale oil was derived from [589].
<b>Fertilizer</b> BG concepts +CH <sub>4</sub> concepts	Thickened digestate and ammonium sulfate replace mineral fertilizer according to their nutrient content. A transport distance of 300 km is assumed.
<b>Furfural</b> OS concepts	According to Jong and Marcotullio [650] most furfural is presently produced in highly inefficient plants in China. Furthermore, the number of companies that supply furfural is expected to increase in the EU [645]. It is therefore assumed that furfural production in China is substituted. A shipping to Europe plus an additional road transport of 500 km is considered. No inventory data on commercial furfural production was found. The modelling results presented by Le Nhien et al. [651] were used as an approximation of GHG emissions related to the production of furfural. If inefficient plants are disappearing from the market as a consequence of newer concepts entering the market, GHG credits can be expected to be higher.
<b>Gluten</b> IG WM concepts	It is assumed that gluten substitutes gluten production from wheat grains. Gluten production is coupled with the production of starch, which needs to be supplied to the market if wheat gluten production ceased. Thus, it is assumed that potato starch complements the substitution mechanism.
<b>Molasses</b> 2G SE MOL <sup>a</sup> 2G OS MOL <sup>a</sup>	Molasses, is assumed to substitute maize based on the metabolizable energy [471]. Maize is assumed to be cultivated in Germany as 85 % of domestic maize consumption is provided by domestic production [485]. Maize is assumed to be transported 300 km by truck.
<b>Methanol</b> +MeOH concepts	At present more 90 % of methanol is produced from natural gas. The production involves steam gas reforming, hydrogenation of CO and subsequent distillation [652]. It is assumed that biomethanol substitutes the aforementioned production (assuming that there is a market for “green” methanol [653]) and eventually occurring oxidation of carbon contained in methanol (or any other product derived from methanol).
<b>OS Lignin</b> OS concepts	Lignin derived from organosolv pretreatment shows a high purity and is thus suitable for a broader spectrum of applications than lignin derived from other pretreatment methods, e.g. steam explosion [635]. Due to its high purity and high number of reactive groups, organosolv-derived lignin can be used in phenolic resins as a substitute for phenol-formaldehyde resin [654, 655]. It is assumed that OS lignin substitutes phenol-formaldehyde that is produced from natural gas via catalytic oxidation [656].
<b>Oxygen</b> +CH <sub>4</sub> and +MeOH	It is assumed that oxygen provided by electrolysis substitutes oxygen production from air separation.

## Appendices

**Table C - 9** Continued

Product Concepts	Substitution mechanism
<b>Xylitol</b> 2G SE XYL <sup>a</sup> 2G OS XYL <sup>a</sup>	Xylitol is assumed to replace catalytic xylitol production from corn-cobs produced in China [657]. A shipping distance of 20,322 km from Nanjing to Hamburg plus an additional road transport of 500 km is considered. Xylitol could be used as a substitute for sucrose. The use of xylitol instead of sucrose is however rather demand driven than stimulated by an increased production of xylitol. It is therefore unlikely that the supply of xylitol displaces sucrose.

<sup>a</sup>Only base case concepts are mentioned. The respective advanced concept (+CH<sub>4</sub>) provide

### C.3.2. GHG intensity of substitutes

**Table C - 10** GHG intensity of displaced products.

Product	kg CO <sub>2</sub> -eq.	Data sources for modelling
Acetic acid	kg <sup>-1</sup> 1.50	[502]
Ammonium sulfate	kg <sup>-1</sup> 1.45	[502]
Bran	kg <sup>-1</sup> 0.69	Own feedstock modelling based on [502], incl. LUC
CDS (soybean, wheat and oil palm)	kg <sup>-1</sup> 1.19	Own feedstock modelling based on [502], incl. LUC
Corn	0.13	Own feedstock modelling based on [502], incl. LUC
DDGS (soybean, wheat and oil palm)	kg <sup>-1</sup> 4.66	Own feedstock modelling based on [502], incl. LUC
Furfural	kg <sup>-1</sup> 0.61	[651]
Gasoline	MJ <sup>-1</sup> 0.13	[589]
Gluten	kg <sup>-1</sup> 1.79	Own feedstock modelling based on [502], incl. LUC
Liquefied CO <sub>2</sub>	kg <sup>-1</sup> 0.69	[502]
Methane	MJ <sup>-1</sup>	Country specific, see main text
Methanol	MJ <sup>-1</sup> 0.11	[502]
Molasses (soybean, wheat and oil palm)	kg <sup>-1</sup> 0.13	Own feedstock modelling based on [502], incl. LUC
Organic fertilizer from digestate (1G)	kg <sup>-1</sup> 0.14	Nutrient composition calculated. Fertilizer displacement according to [502]
Organic fertilizer from digestate (2G)	kg <sup>-1</sup> 0.10	Nutrient composition calculated. Fertilizer displacement according to [502]
Oxygen	kg <sup>-1</sup> 0.70	[502]
Phenol-formaldehyde resin	kg <sup>-1</sup> 2.79	[656]
Xylitol	kg <sup>-1</sup> 0.04	[658]

**Table C - 11** SOC changes from LUC of soybean and palm oil cultivation [504].

Affected system	Location	Resulting change in SOC and carbon stored in vegetation in t C per ha	Converted land or mechanism
Soybean cultivation	Brazil	76.0	Savanna → Soy plantation
Oil Palm cultivation	Indonesia	170	Native forest → Plantation
	Malaysia	90.0	Native forest → Plantation

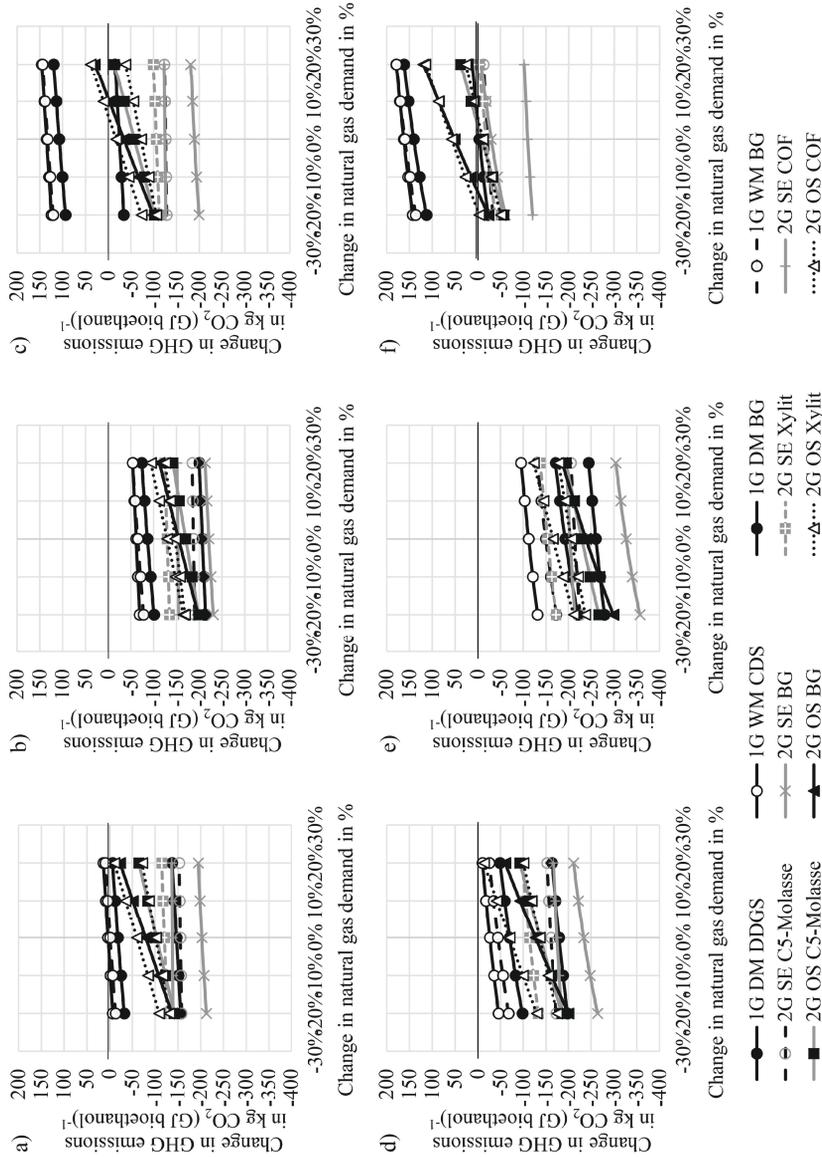
### C.4. Sensitivity analysis: Results of Monte Carlos simulations

**Table C - 12** Results of Monte Carlos Simulations (5000 runs). The simulation was conducted for all concepts located in Germany. Abbr.: Pre-treatment: DM – dry milling, OS – organosolv, SE – steam explosion, WM – wet milling; Sugar stream processing: BG – biogas production, COF – co-fermentation (molasses production from unfermented sugars), MOL – molasses production from pentose and unfermented hexose, XYL – xylitol production; CO<sub>2</sub> stream usage: +CH<sub>4</sub> – methanation, +MeOH – methanol synthesis, no suffix – liquefaction.

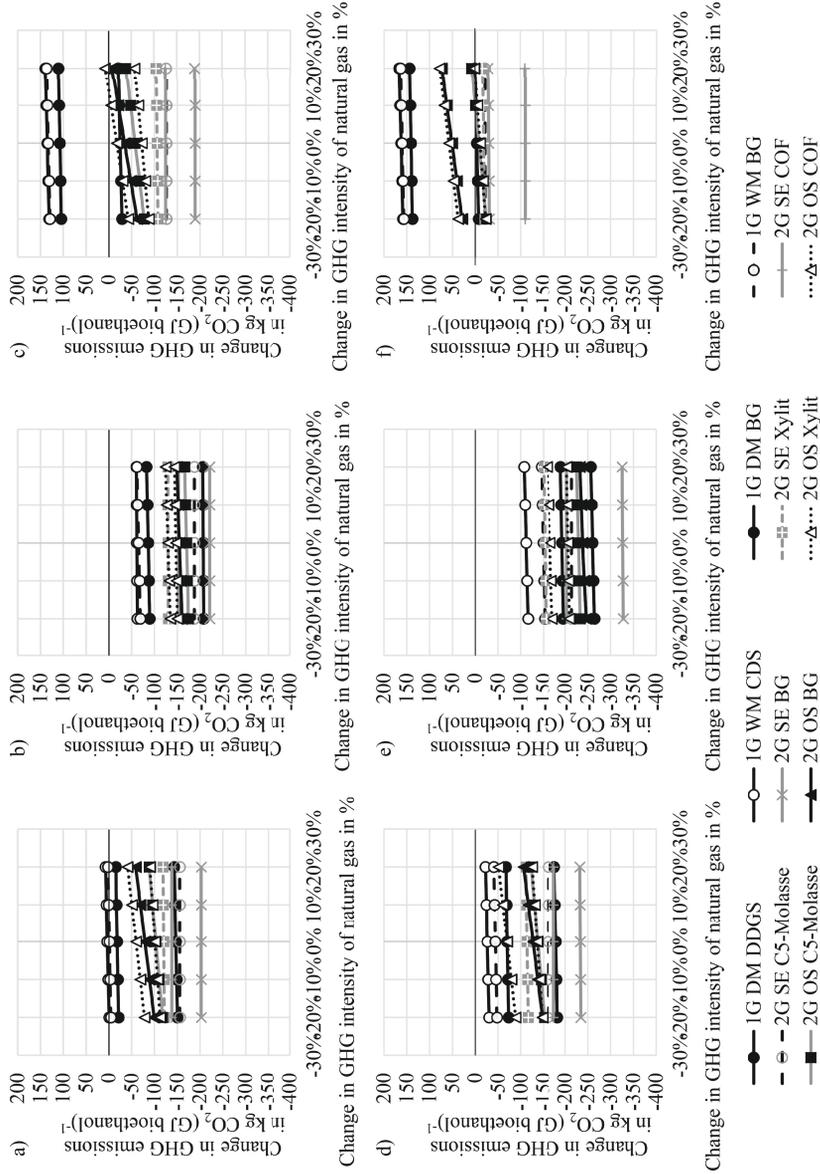
Concept	Mean	Median	Minimum	Maximum	5% Percentile	95% Percentile	Probability to increase GHG emissions
1G DM DDGS	-158.27	-155.81	-312.60	-51.09	-211.98	-111.60	0%
1G WM CDS	-9.53	-10.54	-42.12	104.89	-25.83	9.75	17%
1G DM BG	-24.57	-25.54	-51.44	31.54	-38.33	-7.36	2%
1G WM BG	-11.02	-12.24	-41.04	58.06	-25.95	8.40	13%
2G SE MOL	-155.34	-154.30	-239.74	-105.28	-183.37	-129.97	0%
2G SE BG	-190.99	-190.62	-283.21	-110.14	-225.06	-159.32	0%
2G SE XYL	-123.28	-123.66	-171.59	-45.94	-149.88	-94.70	0%
2G SE COF	-134.16	-133.44	-193.57	-104.21	-151.82	-118.79	0%
2G OS MOL	-100.31	-100.64	-187.43	10.50	-142.80	-55.62	0%
2G OS BG	-64.26	-65.48	-159.42	90.02	-109.03	-15.29	2%
2G OS XYL	-53.84	-55.12	-159.75	60.02	-96.72	-7.21	3%
2G OS COF	-97.12	-97.16	-164.43	-3.91	-129.55	-64.20	0%
1G DM DDGS +CH <sub>4</sub>	-171.24	-168.96	-293.93	-76.49	-227.60	-123.63	0%
1G WM CDS +CH <sub>4</sub>	-19.73	-21.10	-49.02	73.33	-35.58	-0.54	5%
1G DM BG +CH <sub>4</sub>	-46.31	-47.08	-78.52	27.84	-61.44	-28.91	0%
1G WM BG +CH <sub>4</sub>	-28.51	-29.66	-60.07	55.88	-45.24	-8.58	2%
2G SE MOL+CH <sub>4</sub>	-146.64	-145.52	-219.40	-78.62	-175.82	-121.24	0%
2G SE BG +CH <sub>4</sub>	-187.51	-187.50	-266.64	-95.84	-221.75	-152.61	0%
2G SE XYL+CH <sub>4</sub>	-97.99	-98.70	-141.02	-4.93	-127.70	-63.84	0%
2G SE COF +CH <sub>4</sub>	-161.11	-160.63	-204.56	-122.76	-177.34	-146.18	0%
2G OS MOL+CH <sub>4</sub>	-114.39	-114.73	-206.16	-10.97	-157.46	-71.71	0%
2G OS BG +CH <sub>4</sub>	-87.13	-88.67	-176.38	26.79	-132.07	-36.54	0%
2G OS XYL +CH <sub>4</sub>	-38.68	-40.17	-129.97	92.68	-83.84	13.53	9%
2G OS COF +CH <sub>4</sub>	-111.83	-112.29	-184.37	-4.30	-143.73	-77.57	0%
1G DM DDGS +MeOH	-173.15	-173.08	-275.59	-84.25	-218.53	-129.26	0%
1G WM CDS +MeOH	-28.72	-30.04	-56.00	50.39	-44.31	-8.94	2%
1G DM BG +MeOH	-75.63	-76.54	-106.62	-6.54	-90.48	-57.84	0%
1G WM BG +MeOH	-55.48	-56.56	-84.62	30.73	-71.12	-36.04	0%
2G SE MOL+MeOH	-173.48	-172.99	-258.49	-116.87	-200.30	-148.58	0%
2G SE BG +MeOH	-252.34	-251.82	-387.89	-157.02	-297.46	-208.93	0%
2G SE XYL +MeOH	-108.18	-108.71	-152.92	0.34	-137.33	-75.93	0%
2G SE COF +MeOH	-153.33	-152.86	-195.98	-117.66	-169.20	-139.07	0%
2G OS MOL+MeOH	-123.99	-124.56	-215.13	35.62	-166.91	-79.14	0%
2G OS BG +MeOH	-116.21	-117.84	-201.53	11.89	-161.11	-65.97	0%
2G OS XYL +MeOH	-49.46	-51.18	-149.71	116.63	-93.54	0.18	5%
2G OS COF +MeOH	-120.44	-121.28	-184.31	-34.59	-151.11	-87.56	0%

C

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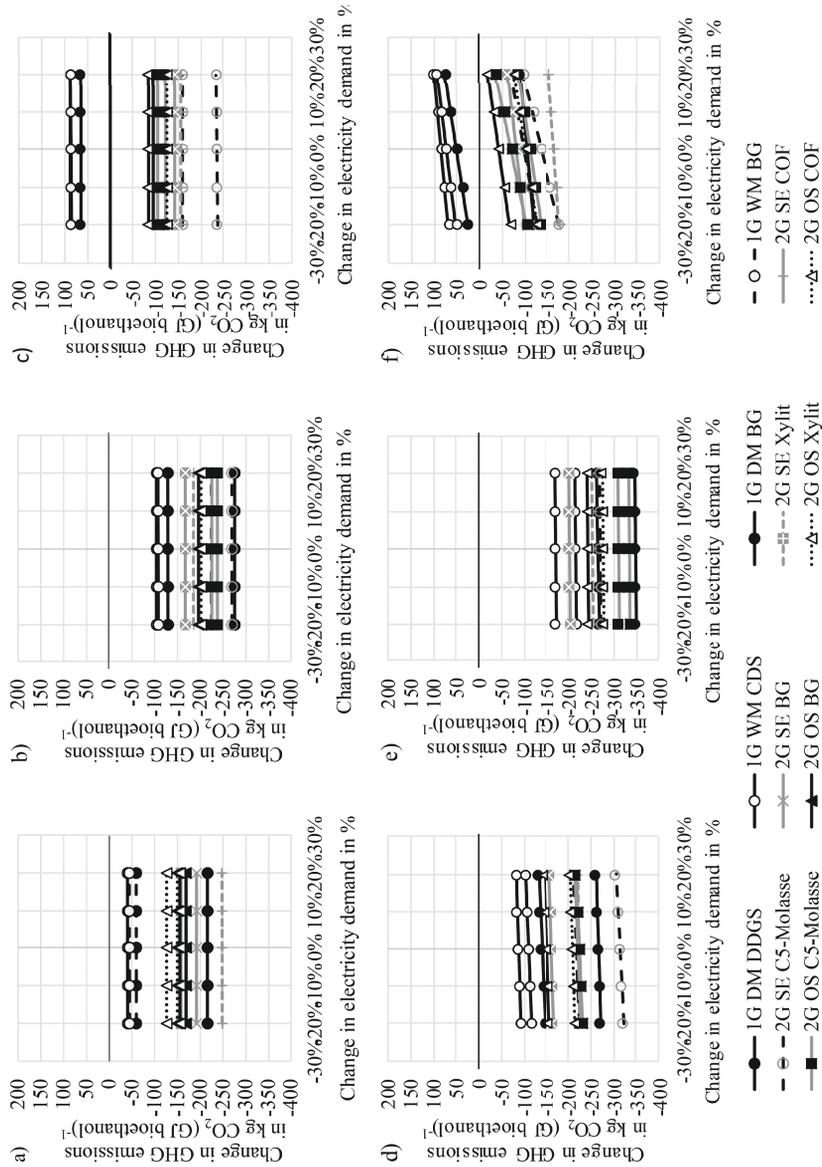
**Figure C - 1** Sensitivity of results to a change in natural gas demand. Parts a), b) and c) depict the average result of all 26 locations, the highest net reduction in GHG emissions and the lowest net reduction in GHG emissions for each concept, respectively, for the base case (CO<sub>2</sub> liquefaction). Parts d), e) and f) present similar cases for all concepts with additional methanation from captured biogenic CO<sub>2</sub>.



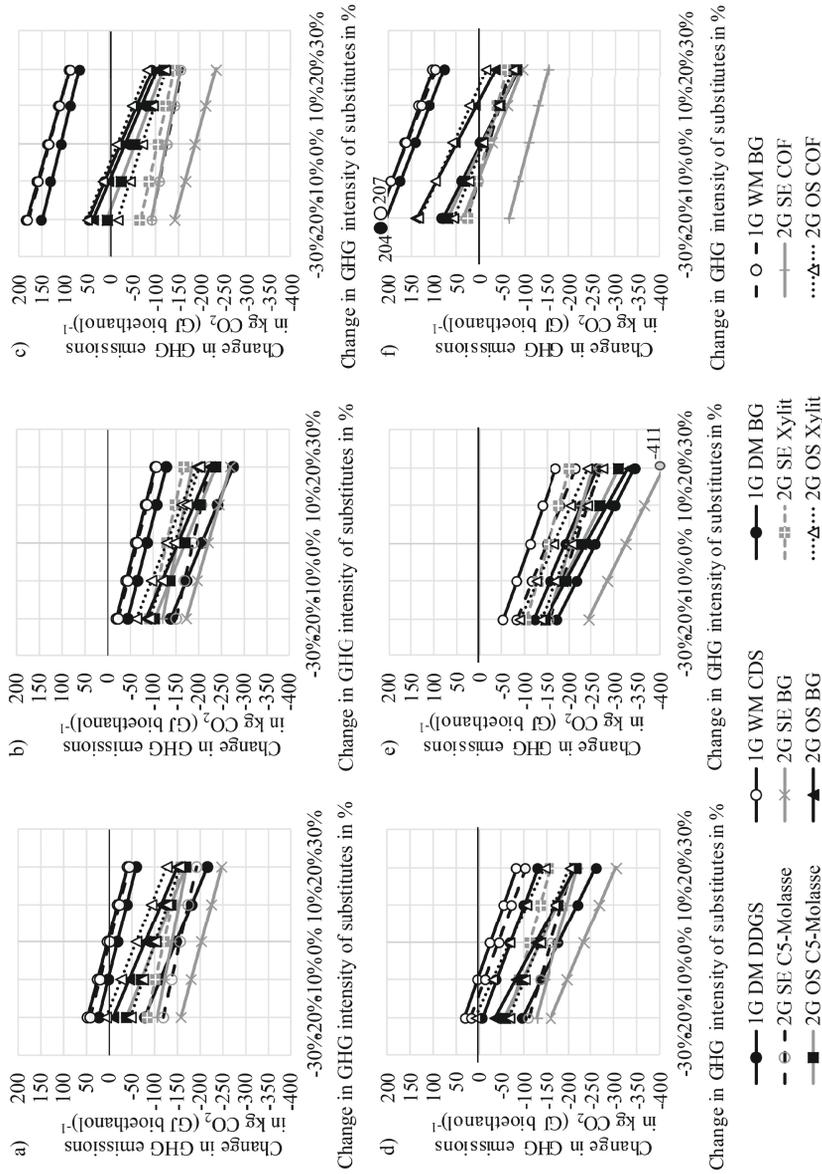
**Figure C - 2** Sensitivity of results to a change in GHG intensity of marginal gas supply. Parts a), b) and c) depict the average result of all 26 locations, the highest net reduction in GHG emissions and the lowest net reduction in GHG emissions for each concept, respectively, for the base case (CO<sub>2</sub> liquefaction). Parts d), e) and f) present similar cases for all concepts with additional methanation from captured biogenic CO<sub>2</sub>.



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**Figure C - 3** Sensitivity of results to a change in electricity demand (or the GHG intensity of marginal electricity supply) Parts a), b) and c) depict the average result of all 26 locations, the highest net reduction in GHG emissions and the lowest net reduction in GHG emissions for each concept, respectively, for the base case (CO<sub>2</sub> liquefaction). Parts d), e) and f) present similar cases for all concepts with additional methanation from captured biogenic CO<sub>2</sub>.



**Figure C - 4** Sensitivity of results to the GHG intensity of marginal supply of displaced products (Parts a), b) and c) depict the average result of all 26 locations, the highest net reduction in GHG emissions and the lowest net reduction in GHG emissions for each concept, respectively, for the base case (CO<sub>2</sub> liquefaction). Parts d), e) and f) present similar cases for all concepts with additional methanation from captured biogenic CO<sub>2</sub>.





# Appendix Chapter 7

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## Appendices

### D.1. Selection of parameters for the minimum and maximum reduction scenarios

**Table D - 1** Combinations of production parameters, emission factors (EF) and decomposition curves to derive the minimum and maximum scenarios of biomethane production.

	Minimum GHG reduction			Maximum GHG reduction		
	Straw	Org. fertilizer	Min. fertilizer	Straw	Org. fertilizer	Min. fertilizer
organic matter mineralization	Minimum decay	Maximum decay		Maximum decay	Minimum decay	
EF	Lowest EF	Highest EF	Highest EF	Highest EF	Lowest EF	Lowest EF
	<b>Biogas production</b>			<b>Biogas production</b>		
Technical parameters	Highest values			Lowest values		
	<b>Substitution</b>			<b>Substitution</b>		
GHG intensities	Lowest GHG intensity		Highest GHG intensity	Highest GHG intensity		Highest GHG intensity

**Table D - 2** Combinations of production parameters, EF and decomposition curves to derive the minimum and maximum scenarios of bioethanol production.

	Minimum GHG reduction			Maximum GHG reduction		
	Straw	Animal feces	Min. fertilizer	Straw	Animal feces	Min. fertilizer
organic matter mineralization	Minimum decay	Maximum decay		Maximum decay	Minimum decay	
EF	Lowest EF		Highest EF	Highest EF		Lowest EF
	<b>Bioethanol production</b>			<b>Bioethanol production</b>		
Technical parameters	Lowest values			Highest values		
	<b>Substitution</b>			<b>Substitution</b>		
GHG intensities	Lowest GHG intensity		Highest GHG intensity	Highest GHG intensity		Lowest GHG intensity

### D.2. Marginal supply

#### D.2.1. Biomethane provision

The marginal suppliers are determined for electricity (increased demand), for natural gas and mineral fertilizer (decreasing demand). The marginal suppliers are identified based on observed market trends between 20014 and 2018, except for mineral fertilizer. In case of fertilizer, the change is assessed between 2013 and 2017: the severe drought that took place in Germany in 2018 is considered an anomaly that exceptionally influenced the demand of specific fertilizer types, cf. [659]. The identification of marginal suppliers and the related GHG intensities are presented in Table D - 3. The marginal electricity supply comprises all electricity sources that increased production. No single electricity source was selected because some sources, e.g. wind and solar,

supply electricity intermittently. As the assessed facility runs constantly, other sources that are able to supply electricity constantly are considered as well, i.e. biomass and natural gas. In 2018, 69 and 31% if the newly installed wind power capacity were onshore and offshore installations, respectively [660, 661]. The capacity increase of electricity from biomass is driven by the capacity increase of biogas plants [662].

Furthermore, small amounts of additional N fertilizer are required as the higher availability of N in digestate results in higher N losses. These are compensated by mineral N fertilizer. According to fertilizer statistics, urea is considered the marginal fertilizer product that is used in case of an increasing demand. There was no data found on the availability of P and K of digestate. It was thus assumed that the shift from straw incorporation does not result in a change in available P and K.

Arising CO<sub>2</sub> can be liquefied and sold. This is considered an optional processing step. It is assumed that liquefied CO<sub>2</sub> replaces CO<sub>2</sub> captured from ammonia production (steam reforming of methane). The mean, low and high GHG intensities are 0.80, 0.60 and 1.1 kg CO<sub>2</sub>-eq. per kg CO<sub>2</sub> for the base case, low and high value, respectively.

**Table D - 3** Identification of marginal suppliers and related GHG intensity of products provided by the biomethane concept. The identified marginal suppliers are market in bold.

Electricity [663]			Natural gas [664–668]			Mineral N fertilizer [669]		
Electricity source	Change 2014- 2018	Share of increase	Supplier <sup>b</sup>	Change 2014- 2018	Share of decrease <sup>a</sup>	Type <sup>c</sup>	Change 2013- 2017	Share of increase <sup>a</sup>
Hydro	-0.1%		NL	-13%	43%	<b>Urea</b>	+13%	55%
Nuclear	-21.2%		<b>NO</b>	-11%	57%	CAN	-8%	
Lignite	-6.4%		Other EU	+600%		UAN	0%	
Bituminous coal	-32.9%		RU	44%		NP- Fert.	-11%	
<b>Natural gas</b>	+42.7%	17.0%				NPK- Fert.	-21%	
<b>Wind</b>	+90.5%	67.9%				Other	+12%	45%
<b>Solar</b>	+26.9%	12.4%						
<b>Biomass</b>	4.9%	2.7%						
GHG intensity <sup>d</sup> in g CO <sub>2</sub> -eq./MJ [502]			GHG intensity in g CO <sub>2</sub> -eq./MJ [507]			GHG intensity <sup>d</sup> in g CO <sub>2</sub> -eq./kg N [502]		
Mean	Lowest	Highest	Mean	Lowest	Highest	Mean	Lowest	Highest
27.00	25.72	29.06	12.60	9.30	17.30	4.37	3.84	5.00

<sup>a</sup>The share of increases and decreases was determined based on absolute changes in demand reported in the respective literature sources. Thus, the share presents the share of the overall increase or decrease of absolute values, respectively.

<sup>b</sup>EU – European Union; NL – Netherlands; NO – Norway; RU – Russian Federation

<sup>c</sup>CAN – calcium ammonium nitrate; UAN – urea ammonium nitrate

<sup>d</sup>The min and max GHG intensity present the 5 and 95% percentile of 5000 Monte-Carlos-Simulation runs with uncertainties provided by the Ecoinvent database [502].

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### D.2.2. Bioethanol provision

To determine the displaced petrol supplier as a consequence of ethanol supply, global production statistics were analyzed. These statistics reveal that between 2014 and 2018, Venezuelan crude oil exports decreased the most (20% of all decreases in supply) [664–668]. It is therefore assumed that the supply of bioethanol replaces the production and refining of crude oil from Venezuela. The substitution of crude oil and its refining is assumed as it is presumed that producers can easily shift the crack spread of refineries, shifting towards other products. The sensitivity of results regarding this substitution mechanism is assessed in the sensitivity analysis. The mean, minimum and maximum up- and mid-stream emissions of Venezuelan crude oil amount to 8.9, 8.4 and 9.4 g CO<sub>2</sub>-eq. per MJ, respectively [507]. The GHG intensity of refining in Germany is 5.5 g CO<sub>2</sub>-eq. per MJ. The minimum and maximum refinery GHG intensity of refining were estimated by multiplying the mean GHG intensity by the weighted average percental difference between minimum and average and maximum and average GHG intensity of all refining GHG intensities reported in [507]. This yields 3.4 and 7.8 g CO<sub>2</sub>-eq. per MJ refined crude oil. The GHG intensity of gasoline combustion is 75.9 g CO<sub>2</sub>-eq. per MJ [598].

Molasses is assumed to substitute maize based on the metabolizable energy [471]. The substitution ratio is 0.39 kg maize per kg C5-molasse. Maize is assumed to be cultivated in Germany as 85% of domestic maize consumption is provided by domestic production [51]. Maize is assumed to be transported 300 km by truck. The GHG intensity of maize production is 349.6 g CO<sub>2</sub>-eq. per kg [464]. Additionally, LUC emissions of 422.3 g CO<sub>2</sub>-eq. per kg are added. This value was determined based on the methodology presented in [89] and assuming a maize yield of 9.84 t per ha [485]. A detailed description of applied parameters of the conversion of set-aside land to cropland in Germany can be found in our previous publication [504]. It is furthermore assumed that the use of molasses instead of maize does not alter emissions arising from enteric fermentation and manure application.

A share of nutrients contained in wheat straw is contained in molasses while the remainder is lost through combustion of solid residues for energy provision and subsequent waste treatment of incineration ash. It is assumed that nutrient availability of nutrients in (digested) molasses and maize are similar. Therefore the feed subsystem is excluded (Figure 7-1 ). Thus, the displacement of maize does not affect availability of nutrients. In contrast, the share of nutrients that is contained in combusted solid residues needs to be compensated by mineral fertilizer. The identification of marginal P and K fertilizer suppliers is presented in Table D - 4.

**Table D - 4** Identification of marginal suppliers and related GHG intensity of mineral fertilizers required to compensate nutrient losses arising from bioethanol provision. The identified marginal suppliers is market in bold. Mineral N fertilizer production and electricity supply is presented in Table D - 3.

Type <sup>c</sup>	Mineral P fertilizer		Type <sup>c</sup>	Mineral K fertilizer	
	Change 2013- 2017	Share of increase <sup>a</sup>		Change 2013- 2017	Share of increase <sup>a</sup>
<b>Super-phosphate</b>	+22%	100%	Kalinite	-15%	
PK-Fert.	-12%		<b>Potassium chloride</b>	+9%	92%
NP- & PK- Fert.	-29%		Potassium sulfate	+10%	8%
Other	-34%		PK- Fert.	-13%	
			NPK- Fert.	-24%	
GHG intensity <sup>d</sup> in g CO <sub>2</sub> -eq./kg P [502]			GHG intensity in g CO <sub>2</sub> -eq./kg K [502]		
Mean	Lowest	Highest	Mean	Lowest	Highest
0.90	0.73	1.20	0.21	0.17	0.31

<sup>a</sup> The share of increases and decreases was determined based on absolute values reported in the respective literature sources. Thus, the share presents the share of the overall increase or decrease in absolute values, respectively.

<sup>b</sup> EU – European Union; NL – Netherlands; NO – Norway; RU – Russian Federation

<sup>c</sup> CAN – calcium ammonium nitrate; UAN – urea ammonium nitrate

<sup>d</sup> The min and max GHG intensity present the 5 and 95% percentile of 5000 Monte-Carlos-Simulation runs with uncertainties provided by the Ecoinvent database [502].

### D.3. Life Cycle Inventory

GHG intensities of products and services from background processes, were modelled with data from the ecoinvent database [502], except for enzymes and corn steep liquor. The GHG intensity of enzymes was taken from [627] and corn steep liquor production was modelled with data from [402] and [502].

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### D.3.1. Emission factors

**Table D - 5** EF of organic fertilizer processing and field application. Values presented in parentheses are lowest and highest values reported in literature or, if not available, 90% and 110% in case of low and high EF, respectively.

	Field application of organic material (straw and digestate) and mineral fertilizer	Digestate separation	Digestate storage
<i>Direct emissions</i>			
N <sub>2</sub> O kg N <sub>2</sub> O-N/kg N	0.01 [91] (0.003, 0.03)		
NH <sub>3</sub> kg NH <sub>3</sub> -N/kg N org.	0.2 [91] (0.05, 0.5)	0.0012 [670] (0.0007, 0.0020)	0.0150 [670] (0.0086, 0.0263)
% of NH <sub>4</sub> -N in digestate emitted as NH <sub>3</sub>	45.8* [385]		
kg NH <sub>3</sub> -N/kg N in mineral fertilizer	0.1 [91] (0.03, 0.3)		
NO kg NO-N/kg N	0.001 [671] (0.0009, 0.0011)		
NO <sub>3</sub> kg NO <sub>3</sub> -N/kg N	0.3 [91] (0.1, 0.8)		
CH <sub>4</sub> % of production			1.0 [385]
<i>Indirect emissions</i>			
N <sub>2</sub> O kg N <sub>2</sub> O-N/ kg NO <sub>3</sub> -N	0.0075 [91] (0.0005, 0.025)		
kg N <sub>2</sub> O-N/ kg N volatilized	0.01 [91] (0.002, 0.05)		

\*The EF for ammonia volatilization is applied to mineral N (NH<sub>4</sub><sup>+</sup>) in the organic fertilizer.

### D.3.2. Composition of straw, organic fertilizer and molasses

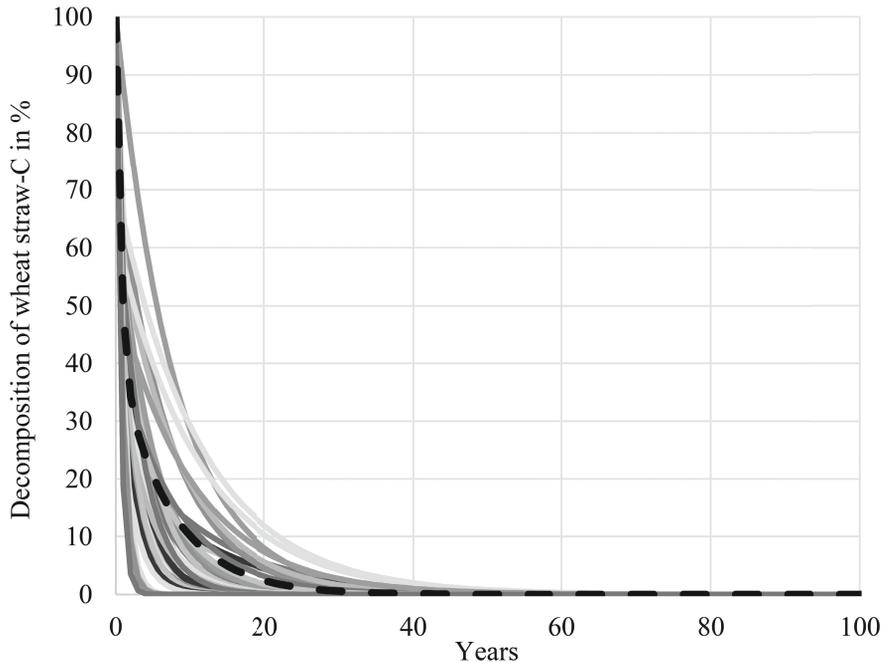
**Table D - 6** Composition of wheat straw and organic fertilizer obtained from digestate in% of DM (average of values reported in [26] in case of straw and values reported in [27] in case of molasses). Nutrient composition of organic fertilizer and carbon content of molasses calculated based on nutrient composition of straw and values reported in [28].

	DM	N	P	K	C
Straw	90.0	0.62	0.08	0.7	45.50
Organic fertilizer	22.2	1.26	0.17	1.46	47.22
Molasses	60.0	0.65	0.13	3.2	40.00

The share of mineral N (NH<sub>4</sub>-N) contained in the organic fertilizer is 32.7% [672].

### D.3.3. Current straw use: incorporation into soil

Figure D - 1 shows straw decomposition curves derived from literature.



**Figure D - 1** Decomposition of wheat straw added at  $t=0$  years. The solid dashed black line presents the average decomposition [30–36]. All other grayscale lines present the decomposition curves derived from literature [ibid.].

### D.3.4. Biomethane production

At first straw is harvested (besides grain) with a combine harvester. Subsequently straw is taken up from the ground and baled. Subsequently, bales are transported by tractors to a storage facility where it is covered in foil and stored. Later on, straw is transported by high duty vehicles to the central storage located nearby the biomethane facility. The material loss of baling, intermediate and final transport are assumed to be 8, 2% and 1%, respectively [458]. The transport distances are calculated based on the aforementioned assumption that 56% of straw remain on the field while the remainder is harvested and the methodology and parameters presented in [504]. Transportation amounts to  $7.6 \cdot 10^{-3}$  tkm per kg DM of straw by tractor and 5.8, 6.0 and  $5.6 \cdot 10^{-2}$  tkm per kg of straw by truck, in case of the base case, minimum and maximum GHG reduction. Process parameters of comminution, anaerobic digestion, biogas upgrading, digestate processing and (optional)  $\text{CO}_2$  liquefaction are presented in Table D - 7.

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Table D - 7 Base case, low and high values of important process parameters.

Process step	Parameter	Unit	Base case	Low value	High value	Source and comment
<b>Comminution Anaerobic digestion</b>	Electricity demand	MJ ( $t_{DM}$ comminuted) <sup>-1</sup>	12.67	12.67	12.67	[673]
	Methane yield	MJ (kg DM) <sup>-1</sup>	9.1	7.6	10.8	Average, lowest and highest of values reported in [567–578]
	Methane content	%	60	50	70	Average, lowest and highest of values reported in [567–578]
	Biomass degradation	%	52	52	52	Average of values reported in [567–578]
	Heat demand fermenter	% of production	9	6	12.6	An electric efficiency of 35% was assumed to convert values reported in [674].
<b>Biogas upgrading: Desulfurization</b>	Electricity demand	% of production	1.6	1.6	1.6	[638]
	Activated carbon	10 <sup>-4</sup> kg (m <sup>3</sup> raw gas) <sup>-1</sup>	2.1	2.1	2.1	[35]
	Lubricant oil	10 <sup>-4</sup> kg (m <sup>3</sup> raw gas) <sup>-1</sup>	1.5	1.5	1.5	[35]
<b>Biogas upgrading: MEA washing</b>	Methane loss	% of production	0.1	0.0	0.2	Lowest and highest value assumed
	Heat demand	MJ (m <sup>3</sup> raw gas) <sup>-1</sup>	2.2	1.9	2.4	Mean derived from [475]. Lowest and highest value estimated as 90 and 110% of mean, respectively.
<b>Biogas upgrading: Compression</b>	Electricity demand	MJ (m <sup>3</sup> raw gas) <sup>-1</sup>	0.32	0.32	0.32	[475]
	MEA	kg (t CO <sub>2</sub> removed) <sup>-1</sup>	1.5	1.5	1.5	[675]
	Electricity demand	% of production	3	3	3	[676]
<b>Digestate dewatering Digestate storage Optional: CO<sub>2</sub> liquefaction</b>	Dewatering	MJ (t processed) <sup>-1</sup>	0.87	0.87	0.87	[677]
	CH <sub>4</sub> emissions	% of production	1	0.5	2	Low and high value assumed
	Efficiency	kg CO <sub>2</sub> liquefied (kg CO <sub>2</sub> influx) <sup>-1</sup>	0.85	0.85	0.85	[504]
Electricity demand	Water demand & wastewater	MJ (kg CO <sub>2</sub> liquefied) <sup>-1</sup>	0.72	0.72	0.72	[504]
		L (kg CO <sub>2</sub> liquefied) <sup>-1</sup>	1.5	1.5	1.5	[504]

### D.3.5. Decomposition of organic fertilizer

The decomposition curve (Eq. 7-1) was determined by experimental data. The laboratory experiment was conducted according to EN ISO 16072:2011 [678]. Based on these data [679], the decay function was determined with  $\alpha=58.64$ ,  $k_1=2.03 \cdot 10^{-6}$ ,  $k_2=2.58$ . The incubation experiment was conducted for duration of 170 days (140 days correspond to an open-field experiment duration of one year [680]). As the parameters were determined under laboratory conditions and due to the lack of literature data, no decay function based on (field) condition could be obtained. Therefore, minimum and maximum decomposition curves were derived by multiplying the decay rates and the factor determining the share of quickly and slowly degrading material ( $\alpha$ ) by 50 and 150%, respectively. Due to the uncertainty related to this procedure and the usage of laboratory data, the effect of excluding SOC changes is assessed in the sensitivity analysis.

### D.3.6. Bioethanol production

Alternatively, straw can be used to produce bioethanol. The assessed concept is comprised of a straw harvest and transportation (as described above), pretreatment, ethanol production and distillation. After harvest. In total, straw is transported ( $7.6 \cdot 10^{-3}$  tkm per kg DM of straw by tractor and 7.4, 7.8 and  $7.0 \cdot 10^{-2}$  tkm per kg of straw by truck, in case of the base case, minimum and maximum GHG reduction. A detailed description on the harvesting process and the determination of transport distances can be found in our previous work [504]. The process parameters of all subsequent processing steps are listed in Table D - 8 and Table D - 9. GHG emissions of lignin combustion are taken from the [469].

**Table D - 8** Conversion efficiencies of bioethanol production. The minimum and maximum values of sugar retention, enzymatic hydrolysis and fermentation efficiencies are estimated as 90% and 110% of the base case value.

Process step	Parameter	Base case	Low value	High value	Source
<b>Steam explosion</b>	Glucan to glucose	0.067	0.060	0.074	[465]
	Glucan recovery	0.912	0.820	1.000	[465]
	Xylan to xylose	0.276	0.248	0.303	[465]
	Xylan recovery	0.196	0.176	0.215	[465]
	Lignin recovery	0.992	0.992	0.992	[465]
<b>Enzymatic hydrolysis</b>	Glucan to glucose	0.818	0.736	0.900	[465]
	Xylan to xylose	0.633	0.570	0.696	[465]
<b>Fermentation</b>	Glucose to ethanol	0.950	0.855	1.000	[520]
	Xylose to ethanol	0.930	0.837	1.000	[468]

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Table D - 9 Process parameters of bioethanol production.

Process step	Parameter	Unit	Base case value	Low value	High value	Primary data sources used in calculation and comment
<b>Pre-treatment</b>	Heat demand	MJ (kg <sub>DM</sub> straw) <sup>-1</sup>	2.26	2.02	2.50	[477]. Calculated based on heat capacities and solid loading
	Electricity demand	MJ (kg <sub>DM</sub> straw) <sup>-1</sup>	0.08	0.07	0.09	[477]
<b>Detoxification: resin-water electro-deionization</b>	Water demand	L (kg <sub>DM</sub> straw) <sup>-1</sup>	1.5	1.5	1.5	Calculated based on solid loading
	Acetic acid removal	%	95	95	95	[513]
	Furfural removal	%	40	40	40	[513]
	5-hydroxymethylfurfural removal	%	25	25	25	[513]
	Electricity demand	MJ (t <sub>DM</sub> straw) <sup>-1</sup>	0.04	0.04	0.04	[681]
<b>Detoxification: washing</b>	Water demand	L (kg <sub>DM</sub> straw) <sup>-1</sup>	5.4	5.4	5.4	Calculated based on solid loading
	Acetic acid removal	%	64	64	64	[580]
	Furfural removal	%	86	86	86	[580]
	Formic acid removal	%	87	87	87	[580]
	5-hydroxymethylfurfural removal	%	87	87	87	[580]
<b>Enzymatic hydrolysis &amp; fermentation</b>	Electricity demand	MJ (kg <sub>DM</sub> straw) <sup>-1</sup>	0.5	0.5	0.5	[477]
	Enzymes	g (kg <sub>DM</sub> straw) <sup>-1</sup>	9.9	8.8	10.9	[466, 504]
	Corn steep liquor	g (kg <sub>DM</sub> straw) <sup>-1</sup>	13.0	11.6	14.3	[466, 504]
	Ammonia	g (kg <sub>DM</sub> straw) <sup>-1</sup>	5.6	5.0	6.1	[466, 504]
	Heat demand	MJ (kg <sub>DM</sub> straw) <sup>-1</sup>	0.9	0.8	1.0	[504]. 53% of heat demand can be used in previous steps [515]
<b>Molasses dewatering</b>	Heat demand	MJ (kg <sub>FM</sub> molasses) <sup>-1</sup>	4.1	4.1	4.1	[515]
<b>Optional: CO<sub>2</sub> liquefaction</b>						See Table D - 7.

### D.3.7. Fate and decomposition of carbon contained in molasses

Assuming that molasses consists of unfermented C5 and C6 sugars, 48.1, 76.0 and 21.3 kg C is contained in molasses in the base case, minimum and maximum reduction scenarios, respectively, per  $t_{DM}$  of straw converted to bioethanol. According to literature, less than 30% of carbon contained in animal feed is excreted [682]. Conservatively, a share of 30% is considered in this study. Excreted carbon is assumed to be applied to agricultural land. The decomposition curve of animal dung was estimated by values reported in [683] ( $\alpha=1$ ,  $k_1=3.37 \cdot 10^{-1}$ ,  $k_2=1500$ ). The minimum and maximum decomposition curves were derived by multiplying the decay rates and the factor determining the share of quickly and slowly degrading material ( $\alpha$ ) by 50 and 150%, respectively.

### D.4. Sensitivity analysis

The sensitivity of results regarding certain aspects is assessed:

- In literature a range of fugitive biomethane emissions are reported [639–641]. Most of the assessed concepts comprise a fabric membrane cover of the biogas reactor. In the presented case, a closed steel reactor is assumed, as currently used in the only commercially running straw-to-biomethane facility in Germany. If fugitive emissions occur, the GHG emissions of the base case scenario increases by 53.0 kg CO<sub>2</sub>-eq. per 1%-p methane loss.
- The decomposition of organic matter presents a crucial aspect of the present analysis. A first limitation arises from the application of the two-component decay function: the model neglects several aspects, such as the formation and decomposition of microbial biomass, the production of stable organic matter and other effects promoting or inhibiting microbial decay (cf. [684–686] in [687]). It could thus neglect certain effects occurring in the real world. Additional, data availability is a limiting factor: only recently, commercial production of straw-based biomethane production has started. Therefore long-term field studies of organic fertilizer or digestate decomposition of straw-derived digestate are missing. Data of laboratory experiments was applied in that case. Thus, decomposition of organic matter is likely to be different in the real world. Given the fact that microorganisms digest easily degradable fractions of straw preferably, whereas the stable fractions remain and that SOC formation occurs first through biochemical degradation of easily degradable straw components (cf. [688]), it could also be assumed that the contribution to SOC is similar in case of wheat straw and digestate. In this case no changes in organic matter decomposition-related GHG emissions occur from the shift to biomethane production. If, organic matter mineralization is excluded from the analysis, the shift from straw incorporation to biomethane production results in emission reduction of 521, 217 and 937 kg CO<sub>2</sub>-eq. with consideration of the atmospheric load of GHG in the base case, minimum change and maximum change scenario, respectively. To get a better understanding of SOC formation and carbon turnover, long-term field studies are needed.

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- The incorporation of organic fertilizer can substantially decrease NH<sub>3</sub> volatilization [689, 690]. The absolute reduction in GHG emissions of the biomethane base case scenario decreases by 1.26 kg CO<sub>2</sub>-eq. per 10% reduction in NH<sub>3</sub> volatilization.
- It is assumed that biofuel provision substitutes the equal amount (on energy basis) of the respective fossil counterpart. Several studies address rebound effects and indicate a less pronounced substitution of fossil fuels (cf. [492]). Even if no substitution of natural gas occurs at all (meaning that other consumers will fully compensate the increased supply of methane), there will be still a reduction in GHG emissions of 411 and 895 kg CO<sub>2</sub>-eq. (incl. atmospheric load of emissions) in the base case and best case scenarios, respectively. In the worst case scenario, there is a net increase of 53 kg CO<sub>2</sub>-eq. if no fossil natural gas is substituted at all. In this case, at least 13% of the supplied biomethane need to displace fossil natural gas to achieve a net reduction in GHG emissions. In case of ethanol provision, at least 16 and 75% of ethanol must substitute fossil gasoline to result in a net decrease in GHG emission in the base case and the minimum reduction scenario. The maximum reduction scenario results in a decrease in GHG emissions of 69 kg CO<sub>2</sub>-eq. even without substitution of gasoline. The negative GHG emissions arise from avoided N-induced GHG emissions.

Appendix D

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# References

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## About the author

# About the author

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Benedikt Buchspies was born on February 13 1987 in Darmstadt. From 2008 to 2011, he conducted his Bachelor studies in Environmental Engineering at Technical University of Darmstadt. During his Bachelor studies, he spent one semester at Norwegian University of Science and Technology Trondheim. From 2011 to 2014, he obtained a triple Master of Science degree from the Autonomous University of Barcelona, University of Aveiro and Hamburg University of Technology in the Erasmus Mundus Master Programme “Joint European Master in Environmental Studies”. During his studies, he already extensively focused on LCA: he did an internship related to LCA and took several lectures and seminars on LCA. He wrote his bachelor and master theses on topics related to carbon footprinting and LCA. After finishing his master degree, he started working as a research assistant at the Institute of Environmental Technology and Energy Economics at Hamburg University of Technology. The focus of his work was LCA and carbon footprinting of biofuels. Additionally he worked on a joint research project with the University of Johannesburg focusing on LCA and criticality assessment of platinum group metals and their application in fuel cell vehicles. The project involved several research stays at the University of Johannesburg. Since 2018, Benedikt Buchspies worked with Martin Junginger from the Copernicus Institute of Sustainable Development in order to complete his PhD thesis at the Utrecht University.

About the author

# List of publications

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## **Publications contained in this thesis (in order of appearance):**

1. Buchspies B, Kaltschmitt M (2018) Sustainability Aspects of Biokerosene. In: Kaltschmitt M, Neuling U (eds) Biokerosene: Status and Prospects. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 325–373
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4. Buchspies B, Kaltschmitt M (2018) A consequential assessment of changes in greenhouse gas emissions due to the introduction of wheat straw ethanol in the context of European legislation. *Applied Energy* 211: 368–381. doi: 10.1016/j.apenergy.2017.10.105
5. Buchspies B, Kaltschmitt M, Neuling U (2020) Potential changes in GHG emissions arising from the introduction of biorefineries combining biofuel and electrofuel production within the European Union – A location specific assessment. (article submitted)
6. Buchspies B, Kaltschmitt M, Junginger HM (2019) Straw utilization for biofuel production: A consequential GHG assessment of bioethanol and biomethane provision with a focus on the time-dependency of emissions. Article submitted to *GCB Bioenergy* (currently under review)

## **Other peer-reviewed publications:**

1. Thormann L, Buchspies B, Mbohwa C et al. (2017) PGE Production in Southern Africa, Part I. Production and Market Trends. *Minerals* 7(11): 224. doi: 10.3390/min7110224
2. Buchspies B, Thormann L, Mbohwa C et al. (2017) PGE Production in Southern Africa, Part II. Environmental Aspects. *Minerals* 7(11): 225. doi: 10.3390/min7110225

## **Conference posters and presentations**

1. Thormann L, Buchspies B, Kaltschmitt M Life cycle assessment of transportation fuels based on lignocellulosic biomass – Comparison of selected fast pyrolysis conversion technologies. Poster presentation at the 7th International Conference on Life Cycle Management (LCM 2015), August 30 - September 02 2015, Bordeaux (France)

## List of publications

2. Buchspies B, Kaltschmitt M, Lieberei J (2016) Life Cycle Assessment of Biogas Production: Methodological Framework and Case Study comparing Biogas Production in Germany and Costa Rica. Oral presentation at the International workshop on Sustainable Rural Energy Supply Solutions – Agro-Waste as an Energy Source for Biogas Production, EARTH University, March 21 - 23 2016, San José (Costa Rica)
3. Buchspies B, Kaltschmitt M, Junginger HM (2020) Straw utilization for biofuel production: A consequential GHG assessment of bioethanol and biomethane provision with a focus on the time-dependency of emissions. Oral presentation at the 28<sup>th</sup> European Biomass Conference & Exhibition, April 27 – 30 2020, Marseille (France)

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## List of abbreviations

# List of abbreviations

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1G	first generation
2G	second generation
ABE	acetone-butanol-ethanol
AFR	Sub-Saharan Africa
AIC	aircraft induced clouds
AL	algae
aLCA	attributional LCA
ASEAN	Southeast Asian Nations
ASTM	American Society for Testing and Materials
AtJ	Alcohol-to-Jet
BAU	business as usual
BG	biogas
BioD	biodiesel
BKR	broeikasgassen
BR	Brazil
BtL	biomass-to-liquid
C5	pentose
C6	hexose
CAN	calcium ammonium nitrate
CBR	closed bioreactor
CDS	condensed distiller's solubles
CED <sub>fossil</sub>	cumulative fossil energy demand
CG	corn grain
CGFM	corn gluten feed meal
CGM	corn gluten meal
CGO	corn germ oil
CHP	compined heat and power
cLCA	consequential LCA
CN	China
CNo	carbon number
COF	co-fermentation
COG	coarse grains
CS	corn stover
DB	double bonds
DDGS	dried distiller's grain with solubles
DE	Germany
dLUC	direct LUC
DM	dry milling (abbreviation of concepts in certain figures), otherwise dry mass
DOS	drained organic soil
DSHC-SIP	direct-sugar-to-hydrocarbons synthetic iso-paraffin
EAP	East Asia and Pacific
ECA	Eastern and Central Europe
ECN	equivalent carbon number
Eel	electric energy

## List of abbreviations

Eth	thermal energy
EtOH	ethanol
EU	European Union
FAME	fatty acid methyl ester
FAO	Food and Agricultural Organization
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FEP	freshwater eutrophication potential
FM	fresh mass
FQD	Fuel Quality Directive
FT	Fischer-Tropsch
GHG	greenhouse gas
GWP	global warming potential
HDCJ	hydrotreated depolymerized cellulosic jet fuel
HEFA	hydroprocessed esters and fatty acids
HILD	high intensity low diversity
HTG	hydrothermal gasification
HTL	hydrothermal liquefaction
HVO	Hydrotreated vegetable oils
I	improved management
IATA	International Air Transport Association
ID	Indonesia
iLUC	indirect LUC
IND	industry data
IPCC	Intergovernmental Panel on Climate Change
IR	irigated
ISO	International Organization for Standardization
JA	jatropha
LAC	low activity clay soil
LAT	Latin America
LCA	life cycle assessment
LHV	lower heating value
LIG	lignite
LIHD	low intensity high diversity
LIT	literature data
LN	lognormal distribution
LUC	land use change
M	moderately degraded
MA	maize
MeOH	methanol
MEP	marine eutrophication potential
MFSP	minimum fuel selling prices
MI	miscanthus
MNA	Middle East and North Africa
MOL	molasses
MSA	mean species abundance
MY	Malaysia
ND	normal distribution
NG	natural gas
NGb	natural gas boiler

## List of abbreviations

NGchp	natural gas CHP
NGO	non-governmental organization
NL	Netherlands
NMVOC	non-methane volatile organic compound
NO	Norway
NT	no-tillage
nXP	usable crude protein
OP	oil palm
OS	organosolv
PCL	protective concentration level
PO	poplar
POFP	photochemical oxidant formation
PtX	Power-to-X
Q	research question
RED (II)	Renewable Energy Directive (II)
RF	rained
RFS	Renewable Fuel Standard
RM	rapeseed meal
RO	rapeseed oil
RS	rapeseed
RT	reduced tillage
RU	Russian Federation
S	severely degraded
SI.1	concepts using sugar beet (chapter 3)
SA	salicornia
SB	sugar beet
SC	sugarcane
SD	standard deviation
SE	steam explosion
SF	sunflower seed
SG	switchgrass
SKA	synthetic paraffinic kerosene with aromatics
SM	soybean meal
SO	soybean oil
SOC	soil organic carbon
SPK	HEFA-synthetic paraffin kerosene
SQ	soil quality
T	tillage
TAP	terrestrial acidification potential
TD	triangular distribution
TPEC	low total purchased equipment costs
UAN	urea ammonium nitrate
UCO	unused cooking oil
UEA	Australia
UN	United Nations
US	United States
USDA	US Department of Agriculture
VO	vegetable oil
VOC	volatile organic compound

## List of abbreviations

W	wheat (in figures), scenario denomination of concepts using wheat (e.g. W1.1), otherwise Watt
W1.1	concepts using wheat grain (chapter 3)
WF	water footprint
WM	wet milling
WMS	wetland mineral soil
WO	wood
XYL	xylitol
POME	palm oil mill effluent

