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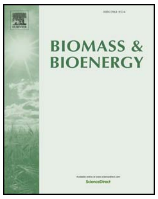

Research paper

On the macro-economic impact of bioenergy and biochemicals – Introducing advanced bioeconomy sectors into an economic modelling framework with a case study for the Netherlands

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ABSTRACT

Advanced uses of biomass for bioenergy and biochemicals are being gradually introduced and are expected to grow considerably in regional economies, thus raising questions on their mid-term macro-economic impacts. To assess these impacts, we use a computable general equilibrium model and a regional energy systems model side-by-side. The former is extended with new sectors of lignocellulosic biofuels, bioelectricity, biochemicals, lignocellulosic biomass supply and tradeable pellets. Next to 1st generation biofuels and other renewable energy supply, the economic impacts of bioeconomy are assessed for technology development and trade openness scenarios. We demonstrate the macro-economic model by assessing developments of the Dutch bioeconomy in 2030. Under rapid technical growth and trade openness, the models consistently show increased biomass consumption and supply of bioenergy and biochemicals from lignocellulose through large-scale deployment of advanced biomass conversion technologies. Traditional fossil-based sectors are replaced by biomass, which brings additional macro-economic benefits on gross domestic product (0.8 bn€ a^{-1}) and value added (0.7 bn€ a^{-1}). Furthermore, it reduces projected decline in trade balance (0.7 bn€ a^{-1}) and employment (2.5–4.5%) compared to low technology development. Extending the temporal scope to beyond 2030 may demonstrate additional macro-economic benefits of bioeconomy. This requires assessing the influence of improvements in the agricultural sector that may lower biomass prices, learning and other developments of promising biomass conversion technologies in the longer term. Uncertain fossil fuel and CO_2 price developments necessitate additional sensitivity analysis.

1. Introduction

The role of biomass in today's economies extends beyond traditional sectors such as food, feed, materials (e.g. plant fibres, lumber, paper and pulp) and traditional uses for energy (inefficient heating and cooking). While more than half of current global biomass use for energy is traditional (48–54 PJ, 76–79% in 2008), advanced and efficient supply of bioelectricity, biomass heat and biofuels is growing rapidly and is expected to continue so in the future [1]. Lignocellulosic biofuels and advanced biomaterials are being gradually introduced in some regions [2–4]. Aviation and shipping rely exclusively on biofuels to partly decarbonise their energy use [5,6]. Biochemicals and biochemical products (e.g. bioplastics) are already produced globally and consume about 4.5% of biomass used for energy and biochemicals [7]. In 2016, global production capacity of bioplastics reached 2 Mt and based on the industry's projections it is expected to quadruple before 2020 [8].

These expectations raise questions on the impacts of bioeconomy developments, possible synergies, and conflicts of biomass supply to different sectors, especially when in competition for biomass from emerging uses such as biochemicals, and on their role in climate change mitigation. Long-term projections of the global energy system simulation model TIMER show that bioenergy can contribute about 20% in emission reduction with carbon taxes above 130 \$ t CO_2^{-1} by 2100 [9]. The largest greenhouse gas (GHG) emission reductions come from

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Abbreviations: BECCS, Bioenergy and Carbon Capture and Storage; CCS, Carbon Capture and Storage; CGE, Computable General Equilibrium; COP, Conference of Parties; EPPA, Emissions Prediction and Policy Analysis; EU, European Union; FT, Fischer-Tropsch; GDP, Gross Domestic Product; GHG, Greenhouse gas; Glob, Global; GTAP, Global Trade Analysis Project; HighTech, High Technology development; IEA, International Energy Agency; LowTech, Low Technology development; MAGNET, Modular Applied GeNeral Equilibrium Tool; O&M, Operation and Maintenance; PE, Polyethylene; PLA, Polylactic Acid; RED, Renewable Energy Directive; Reg, Regional; RJF, Renewable Jet Fuels; WEO, World Energy Outlook

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biofuels in road transport and bioelectricity in combination with carbon capture and storage (BECCS), whilst the emission reduction from biochemicals remains relatively small. Nevertheless, about 18% (19 EJ) of the chemical sector's secondary energy use may come from biomass in 2100 [9]. Such outcomes demonstrate the importance of bioeconomy on a global scale and in the long-term.

However, increase of biomass consumption for bioenergy and biochemicals in the mid-term may already entail large and rapid changes in the structure of regional economies with possible effects on their gross domestic product (GDP), value added and trade balance. Under this perspective, applied economics are uniquely suited to understand the impacts of various policy and technical trajectories [10]. Hoefnagels et al. [11] assessed macro-economic impacts of bioeconomy developments in the Netherlands by combining a computable general equilibrium model (CGE; LEITAP) with a bottom-up Excel tool. Hoefnagels et al. [11] demonstrated that substitution of fossil energy carriers by bioenergy and biochemicals may come with economic benefits and contribute to GHG emission reduction under preconditions of enhanced technology development and imports of sustainable biomass resources. However, as the authors indicate, their approach was faced with limitations. Firstly, LEITAP did not include a detailed representation of lignocellulosic feedstocks such as agricultural residues thereby ignoring cost-efficiency improvements that can be achieved assuming densification and trade of solid biomass (e.g. pelletisation) and the impact of by-products. The availability of low-cost biomass can be pivotal for the competitiveness of biomass conversion technologies and can also have potential impacts on other sectors and land requirements. Secondly, bio-based and fossil-based conversion technologies were aggregated at a high level. The macro-economic model could benefit by improved cost-structures, especially on capital-intensive 2nd generation technologies that utilise low-cost biomass feedstocks [11]. Thirdly, LEITAP did not include other renewable energy sources (e.g. wind, solar). Subsectoral changes, however, were found to have major influence on the macro-economic impacts [11]. Finally, the biochemical sector in LEITAP was modelled implicitly and its biochemical product portfolio was limited. Therefore, the higher level of disaggregation and improved representation of competing resources, technologies and sectors are needed to shed light on underlying elements that can be critical for the bioeconomy.

Conversion of different biomass feedstocks to an array of food, feed, material, energy and biochemicals have created complex dynamics through which biomass participates in different sectors of the economy [12]. The bioeconomy does not only affect farmers, but also material, energy and chemical industries, the well-being of consumers, balance of trade, and governmental budget. Understanding the impacts of the bioeconomy on the overall economy requires an improved modelling framework that accounts for the feedback mechanisms between bioeconomy and other markets, takes direct and indirect effects of biomass use into account and covers the global dimension of supply, trade and sustainability that are inherent to biomass. CGE analysis is considered most suitable [12,13] as partial equilibrium and input-output economic models do not capture the whole economy or include price effects, respectively. For example, CGE models have been used to address implications of biofuel policies on agricultural markets, land-use change and related emissions. This led to improved endogenous modelling of land markets in CGE models [14]. Recent efforts also focused on improving modelling of biofuels by introducing ethanol, biodiesel and their by-products [15,16], and prospective biomass feedstocks for advanced biofuels production such as corn stover, energy crops, palm oil residues [17,18]. To date, the biochemical sector is too small and there is no clear distinction in statistics and databases (e.g. Global Trade Analysis Project (GTAP)), which are used by CGE models. Furthermore, the chemical industry sector is aggregated at a high level, while in reality the sectoral flows of the industry are much more complex. As biomass conversion technologies to biochemicals may offer renewable alternatives at different levels [19], disaggregation of the chemical industry sector in CGE models is required. Choumert et al. [20] have presented a method on how to improve the oil-refining sector in the CGE model Emissions Prediction and Policy Analysis (EPPA), however, chemical products still remain at an aggregate level.

By using a global, multi-region, multi-sector CGE model, this article addresses the key limitations of the study conducted by Hoefnagels et al. [11]. To this purpose, we expanded the Modular Applied GeNeral Equilibrium Tool (MAGNET), the successor of LEITAP. MAGNET is expanded with advanced and emerging bioeconomy sectors and in particular lignocellulosic biofuels, electricity, heat and chemicals from biomass. Furthermore, we improved the representation of biomass supply including agricultural residues, forestry residues and pretreatment of those feedstocks to pellets for international solid biomass trade. We extended the model with regional renewable energy policies that are crucial for the current bioenergy developments. To overcome a key limitation of CGE models on technology representation, we improved technology details in MAGNET by collaborating with a cost-minimisation linear programming energy system model of the Netherlands (MARKAL-NL-UU). Recently, advanced biomass conversion technologies, biochemicals and renewable jet fuels (RJF), have been incorporated in MARKAL-NL-UU [19,22]. The analysis shows that renewable electricity from wind turbines, biofuels, biomass heat and carbon capture and storage (CCS and BECCS) may play a crucial role by 2030 [22]. Biochemicals are expected to become cost-competitive with fossil-based chemicals as they are produced even where no drivers such as a CO_2 emission tax are assumed (5–10% of the sector's supply) [22]. RJF, on the other hand, are produced only under specific assumptions that assume high technology development rates. Factors such as the rate of technical change, the cost-supply of biomass and fossil fuel price projections affect the level of biomass deployment in the energy system. Nonetheless, whether to meet renewable energy targets [19] or to embark on cost-efficient emission mitigation pathways [22], advanced and emerging bioeconomy uses in the Netherlands need to grow substantially, from about 140 PJ in 2015 to up to 760 PJ in 2030 [22]. Model collaboration can take place as alignment and harmonisation of input data, detailed model comparison and model linkage [21]. Following Zilberman [10], we apply a framework where the energy system model MARKAL-NL-UU [19] is used side by side with MAGNET and supplies it with insights on technology trajectories to 2030. We compare results obtained by MAGNET and MARKAL-NL-UU and highlight points of interaction that can lead to improved representation of bioeconomy in CGE models that are required to assess its macro-economic impacts.

2. Materials and methods

To improve technology details of existing sectors and expand MAGNET with new bioeconomy sectors, we develop a modelling framework in which, the cost-minimisation linear programming energy system model, MARKAL-NL-UU is also used. MAGNET is a multi-regional, recursive-dynamic, applied general equilibrium model based on neo-classical microeconomic theory [23]. MAGNET contains a number of advanced features pertinent to modelling the impact of technological and policy developments within the bioeconomy where land-use is a crucial production factor [24,25] (Supplementary material section S1). Biofuel production is included by introducing production and use of ethanol, biodiesel and their by-products [26,27]. Blending targets are included in the model via an end-user tax on road transport fuels that is used to subsidise biofuel production and stimulate production up to the level implied by the blending target. MARKAL-NL-UU is a model of the Dutch energy system that has been recently expanded to assess techno-economic impacts of bioeconomy developments in the Netherlands to 2030 [19,22]. Following a total system cost-minimisation paradigm MARKAL-NL-UU is suitable to highlight key technologies per sector under different scenarios in the mid-term [22]. An overview of MAGNET is presented in the Supplementary material (section S1). An overview of MARKAL-NL-UU is presented in Tsiropoulos et al. [19] and in the Supplementary material (section S2).

2.1. Overview of the modelling framework

We select key fossil and renewable energy conversion technologies (e.g. natural gas and coal, electricity, biomass co-firing in coal plants, onshore and offshore wind turbines), estimate their current and future cost-structures based on the MARKAL-NL-UU input database, and supply them to MAGNET. To select key advanced biomass conversion technologies (advanced biofuels and biochemicals) we define four scenarios that are developed around two axes of uncertainty, namely technology development and openness of market. These scenarios are applied on MARKAL-NL-UU, which is then deployed to assess the cost-optimal technology portfolio in each case, the energy and chemical production mix per sector and technology. From MARKAL-NL-UU outputs we obtain the key biomass conversion technology portfolio of existing and new bioeconomy sectors for the Dutch region, we produce their cost-structures and cost reduction pathways and provide them as data inputs to MAGNET to disaggregate key bioeconomy sectors and provide scenario assumptions for technological change for each scenario. This way, MAGNET is enabled to explicitly assess the macroeconomic impacts of different technology development scenarios. The model is calibrated to version 9 of the GTAP database [28], which contains detailed production, bilateral trade, transport and protection data characterising economic linkages within and among regions. All monetary values of the data are in millions of US dollars (M$) and the base year for version 9 is 2007, which is updated to 2015 using macroeconomic, yield and energy data (see section 2.3 and Supplementary material section S1.1). In MAGNET, 1st generation biofuels were included prior to this study [26,27] and updated with data from the Energy Information Administration [29]. In the present study, the database is extended to explicitly represent additional sources of biomass supply (i.e. residues, plantations and pellets), production of lignocellulosic biofuels based on thermochemical and biochemical pathways, bioelectricity and biochemicals (see section 2.2). A detailed overview of the sectoral and regional aggregation in MAGNET can be found in the Supplementary material (Table S1). IMAGE-TIMER is used as a data source for estimating biomass cost-supply curves and technology details for the rest of the world. For new bioeconomy technologies that are not represented in international statistics and IMAGE-TIMER, the same cost-structures as obtained from MARKAL-NL-UU are assumed for other regions of the world. This does not influence the results of this study as production without a specific stimulating policy package is almost not existent in other world regions. Fig. 1 presents the overview of the modelling framework. Section 2.1.1 describes the policy and scenario assumptions applicable to both models. A methodological description of the MAGNET's extension, technology selection and sectoral aggregation is described in section 2.2. The input data generated by MARKAL-NL-UU are presented in section 2.3.

2.1.1. Policy context and scenario assumptions

2.1.1.1. Policy context. In the mid-term, regional (Renewable Energy Directive of the European Union (EU RED) [30]) and national renewable energy policies (Dutch energy agreement (EA) [31]) are implemented to promote the deployment of renewable energy in efforts to mitigate climate change. These are incorporated as key policy assumptions in both models as they are expected to influence macroeconomic and techno-economic bioeconomy developments in the short-term. Firstly, the renewable energy share of electricity, heat and transport fuels for the Netherlands is 14% in 2020 based on the EU RED [30] and 16% in 2030 based on the Dutch energy agreement [31]. Secondly, the biofuel share in road transport is 10% in 2020 including double-counting of biofuels from waste and residues based on the EU RED [30]. Thirdly, a maximum supply of electricity from biomass co-firing (25 PJ) is assumed [31]. In this study the latter two are continued to 2030. A minimum capacity of onshore and offshore wind turbines is supported by the Dutch government (1.8 GW additional capacity of offshore wind turbines in 2015–2020 and 6 GW total capacity of onshore wind turbines by 2020) [31]. Finally, a tax on CO_2 emissions is applied as an additional instrument to stimulate emission reduction (section 2.3).

2.1.1.2. Scenario assumptions. We define and apply four scenarios, similar to Hoefnagels et al. [11] that are developed around two axes of uncertainty, namely rate of technology development and openness of market. Due to their paradigms, the models incorporate these scenarios in a different manner, as discussed below. However, the models apply the same assumptions, thereby allowing data exchange between and output comparison of MAGNET and MARKAL-NL-UU.

2.1.1.2.1. Technology development. We incorporate two scenarios designed to assess different technology development pathways. The two variants assume low (*LowTech*) and high (*HighTech*) speed of technology development. The technological assumptions in the two scenarios differ in terms of improvement rates in efficiency, year of commercialisation, scales and technology portfolio. These parameters, ultimately affect the cost-competitiveness of biomass conversion technologies compared to the reference fossil-based system and other renewable energy options. The scenarios are developed around 2nd generation biomass conversion technologies to biofuels and biomass conversion technologies to biochemicals. The technology development scenarios are described in detail in Tsiropoulos et al. and van Meijl et al. [19,32].

The two variants are applied in MARKAL-NL-UU, which calculates the cost-optimal technology portfolio for each scenario. In the framework of this study, this acts as a criterion for selecting the key technologies in the road transport and chemical industry sector. As Fig. 1 shows, the cost-structures over time of the selected technologies are supplied to MAGNET. In this manner, MAGNET also incorporates the technology development scenarios. Therefore, the learning rate of advanced biomass conversion technologies to biofuels ad biochemicals is implemented exogenously in MAGNET as cost-efficiency improvements over time. For other biomass conversion technologies such as bioelectricity and other energy technologies such as wind turbines or coal-fired power plants the cost development rates are endogenously determined in MAGNET and therefore remain unaffected by the technology development scenarios (see section 2.2.2). CCS and BECCS technologies are not modelled explicitly in MAGNET.

2.1.1.2.2. Openness of market. The influence of biomass sourcing on technology deployment is assessed using two scenario variants, namely a regional (*Reg*) and a global (*Glob*) trade scenario. The Reg scenario assumes that the EU, and in extension the Netherlands, support bioeconomy developments only if EU resources are used (e.g. if the EU applies strict sustainability criteria). It excludes large traded biomass resources such as primary forestry biomass. In the Reg scenario only EU biomass is taken into account for the potential supply. The Glob scenario assumes that no trade barriers for biomass are imposed as development and standardisation of sustainability criteria guarantee the sustainable origins of biomass. Furthermore, another precondition is that logistics infrastructure and supply of biomass take place to achieve low biomass supply costs and make biomass a tradable commodity. In MAGNET trade openness is implemented directly by allowing or disallowing biomass trade between the EU and the rest of the world.

2.1.1.2.3. Biomass cost-supply. Biomass cost-supply curves within the EU are based on Elbersen et al. [33] and for other regions are based on cost-structures of IMAGE-TIMER [34] (section 2.3). MARKAL-NL-UU uses exogenously determined cost-supply curves from Elbersen et al. [33]. The *Glob* variant as applied in MARKAL-NL-UU assumes ad-hoc a maximum supply potential of traded biomass from global markets available to the Netherlands (450 PJ [19]).

2.1.1.2.4. Counterfactual scenario. A *NoBiobased* scenario is used as

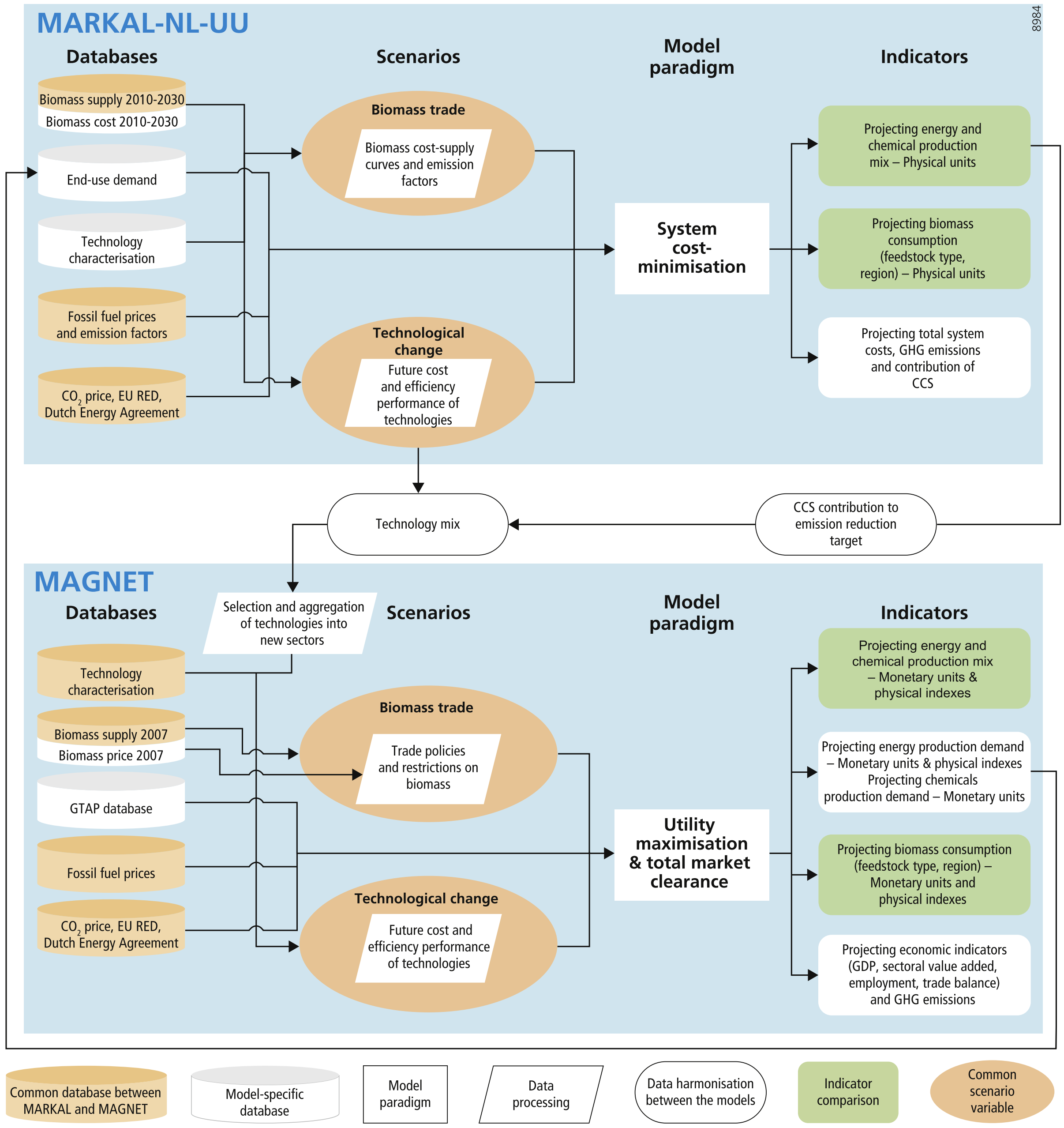

Fig. 1. Model collaboration framework of MAGNET and MARKAL-NL-UU.

a counterfactual within MAGNET. In the NoBiobased scenario new bioeconomy developments in the transport, chemical and energy sectors are reduced to low levels to benchmark the macro-economic contribution of new bioeconomy developments in the other scenarios. In this scenario the renewable energy policies are abolished.

The scenario variables and scenario names used in this study are presented in Table 1.

Table 1
Scenario variables and names used in MAGNET and MARKAL-NL-UU.

Scenario name	Technology development	Openness of market
RegLowTech	Low technology development	EU biomass supply
RegHighTech	High technology development	EU biomass supply
GlobLowTech	Low technology development	Global biomass supply and trade
GlobHighTech	High technology development	Global biomass supply and trade
NoBiobased[a]	No technological development	No new bioeconomy trade

[a] Applicable only in MAGNET.

2.2. *MAGNET extension*

2.2.1. *Biomass supply*

Agricultural and forestry residues are frequently addressed as key biomass feedstocks for energy and non-energy uses (i.e. the feedstock used as raw material that is not used for fuel purposes or transformed to fuels) [9,35]. Energy crops (plantations) on arable land may contribute most to the global total technical potential of biomass, assuming rapid efficiency improvements in agriculture [1]. Solid biomass from residues and plantations may be used directly by conversion sectors or they can be densified to tradable wood pellets leading to increased cost-

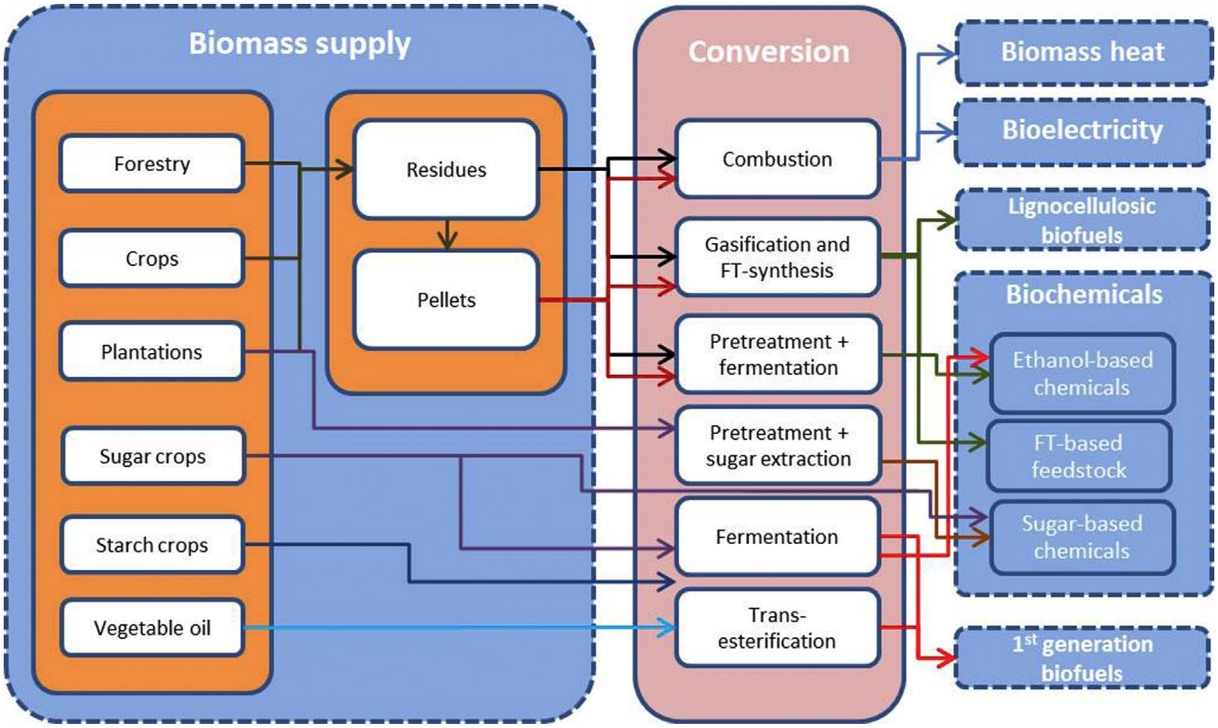

Fig. 2. Overview of bio-based sectors and linkages in MAGNET.

efficiency of the value chain due to reduced storage and logistic costs [36–38]. MAGNET includes 11 primary agricultural, 1 fishery and 1 forestry biomass-producing sector. In the present study, three new sectors are included to capture the developments on the biomass supply side, namely residues, plantations and pellets:

- The residues sector collects and transports various types of forest harvest residues (forest management, logging, wood processing industry) and agricultural residues (harvesting and processing of agricultural crops). Residues can be used directly by conversion technologies or be supplied to the pellets sector.
- The plantations sector produces dedicated woody or grassy crops. Biomass from plantations can be used directly by conversion technologies or be supplied to the pellets sector.
- The pellets sector may use biomass from the residues or plantation sector.

An overview of the biomass supply sectors linked with downstream economic activities is provided in Fig. 2. A detailed overview of the biomass supply sectors and their aggregation in MAGNET can be found in the Supplementary material (Table S1).

2.2.2. Conversion technologies per sector

2.2.2.1. Fuels. 2nd generation technologies have the potential to produce biofuels at lower levelised costs than fossil fuels and lead to higher avoided GHG emissions compared to 1st generation biofuels by 2030 [1,39]. Preconditions for diffusion of lignocellulosic biofuels are the availability of low-cost biomass feedstocks and commercialisation of 2nd generation technologies. In replacing fossil fuels, biochemical, thermochemical and other thermal or catalytic routes (e.g. pyrolysis) may supply lignocellulosic biofuels. Based on MARKAL-NL-UU outcomes (Supplementary material S2.3, Fig. S1), MAGNET is extended to include two production technologies for lignocellulosic biofuels:

- Biochemical, which convert lignocellulosic biomass to ethanol.
- Thermochemical, which involve gasification of solid biomass to syngas and subsequent synthesis to Fischer-Tropsch (FT) fuels.

Other promising biofuel pathways include hydrotreatment of vegetable oils and fats, pyrolysis or other thermochemical routes that produce methanol and hydrogen. These are not included in the analysis as most representative routes are chosen based on the cost-optimal technology portfolio as estimated by MARKAL-NL-UU. The selected pathways may also supply feedstocks required by chemical conversion technologies. The thermochemical pathways may supply naphtha and the biochemical pathways lignocellulosic ethanol and sugar for further conversion. An overview of biomass conversion to lignocellulosic biofuels is provided in Fig. 2. A detailed overview of the biofuel supply sectors and their aggregation in MAGNET can be found in the Supplementary material (Table S1).

2.2.2.2. Electricity. In order to demonstrate substitution effects in electricity supply, the electricity sector in MAGNET needs to be split to several different renewable-based and fossil-based supplying sectors. More renewable options are available at competitive costs and at the same time disaggregation of fossil sectors implies a better representation of available options for GHG emissions mitigation strategies. Therefore, we split the electricity-producing sector in MAGNET into six source sectors for electricity production: from biomass (which includes co-firing of wood pellets in coal-based power plants), wind and solar, hydro and geothermal, coal, natural gas, and nuclear. In addition, an electricity transport and distribution sector is included. An overview of biomass conversion to electricity is provided in Fig. 2. A detailed overview of the electricity sector and its aggregation in MAGNET can be found in the Supplementary material (Table S1).

2.2.2.3. Heat. The contribution of biomass heat to renewable energy demand is expected to be significant and in the EU and globally. For EU27, based on the National Renewable Energy Action Plans biomass heat represents approximately 65% of the final bioenergy demand, and may vary between 62 and 72% depending on scenario conditions [40]. Saygin et al. [41] mention that 13–14 EJ of biomass can be economically deployed at a global level to supply industrial steam by 2030, especially if low-cost biomass residues are used. In MAGNET, heat is not modelled as a separate sector but implicitly as a direct substitute for natural gas [42].

2.2.2.4. Chemicals. In the GTAP database the chemical sector is represented at an aggregate level by a single category that includes basic chemicals and other chemical products and uses only petroleum products as input [43]. However, the flows of the petrochemical industry are more complex. Different crude oil or gas products are used and are converted first to basic chemicals that are further converted to several intermediate chemicals before finally being synthesised and processed to consumer goods such as plastics. Most of the chemical industry's output is consumed for polymers [44], which is also the category we focus on the present study. Along the lines of strategies [45–47] that aim at providing renewable alternatives to the chemical industry those discussed the most are drop-in chemicals and new products. Drop-in chemicals could either be alternative feedstocks for steam crackers or directly chemicals that can be processed further downstream to final products. Drop-in chemicals can use existing infrastructure and compete in established markets as they share exactly the same properties with their fossil counterparts. New biochemicals require new infrastructure and may compete in the same or new markets with conventional chemicals (e.g. polylactic acid (PLA)). By 2100, biomass may provide up to 40% of the primary energy required for non-energy uses by supplying primarily basic chemicals (namely olefins and aromatics), refinery products (namely aromatics) and ammonia [48]. Gerssen-Gondelach et al. [39] demonstrate that fermentation-based chemicals such as PLA are already cost-competitive and that their competitiveness may increase even more compared to their fossil reference products by 2030. In order to capture the emerging sector of biochemicals in MAGNET we account for key strategies and chemicals by splitting the sector and selecting representative pathways based on MARKAL-NL-UU ([19], Supplementary material S2.3, Fig. S2):

- Ethanol to chemicals, which uses 1st generation or lignocellulosic ethanol to produce bioethylene (ethanol-based chemicals; Fig. 3). This sector uses already existing infrastructure and competes in the same markets with fossil-based alternatives. As final product of this route polyethylene (PE) is selected, which is the largest globally produced polymer [49]. Ethanol can be used to produce other drop-in chemicals (e.g. propylene, butadiene) and a variety of other chemicals and could be a potential platform for the future [50].
- Direct sugar to chemicals, which can use 1st generation or lignocellulosic fermentable sugars (white biotechnology [51]; sugar-based chemicals; Fig. 3). Although 1st generation and lignocellulosic ethanol also use fermentable sugars prior to converting it to ethylene, this route produces directly through fermentation products that can replace plastics. Lactic acid and its polymerisation to PLA is chosen as a representative product for using sugar as a platform for biochemicals.

In addition, to assess the option of supplying alternative feedstocks to the industry, we include FT-naphtha as a thermochemical-based feedstock (mixed bio-based and fossil-based chemicals, Fig. 3; Supplementary material S2.3, Fig. S1).

The chemical sector is split in three sectors, namely various conventional fossil-based chemicals, mixed fossil-based and bio-based chemicals, and biochemicals (Fig. 3). The petroleum (Petro, in Fig. 3), conventional sugar and 1st generation ethanol existed in MAGNET prior to this study. The chemical routes and technologies described above are included as four additional new sectors, namely lignocellulosic sugar, ethanol-based chemicals, sugar-based chemicals and a mixed bio-based and fossil-based chemicals sector, next to the remaining fossil-based chemical sector. An overview of biomass conversion to biochemicals is provided in Fig. 2. The MAGNET chemical sector and data aggregation is presented in the Supplementary material (Table S1).

2.3. Input data

Fossil fuel and CO_2 price developments to 2030 are exogenously determined and fixed for both models. These are common between MAGNET and MARKAL-NL-UU based on the International Energy Agency's World Energy Outlook 2014 (IEA-WEO 2014; Table 2), thereby providing consistency in key drivers of both models [52]. Other exogenous data inputs relate only with the macro-economic model. These are GDP and population growth, which are based on the Shared Socioeconomic Pathways 2 scenario of the Intergovernmental Panel on Climate Change Furthermore, as explained in section 2.1.1.2, the two models use different biomass cost-supply curves. These are determined exogenously for MARKAL-NL-UU [19] and endogenously for MAGNET. Both models use the same database for biomass supply potential in Europe based on Elbersen et al. [33]. Finally, for MAGNET, the base years, in terms of value added and production values, for different

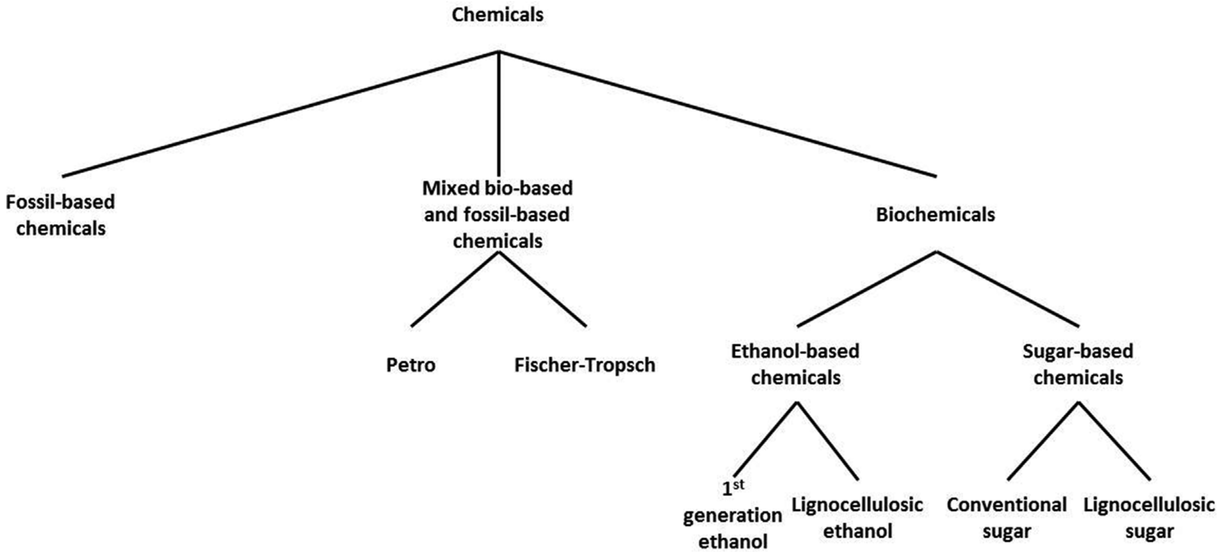

Fig. 3. Interactions between new fossil-based and bio-based chemical products.

Table 2
Exogenous data inputs for MAGNET and MARKAL-NL-UU.

		Base year (2007)	2010	2020	2030	Reference
Oil	€ GJ^{-1}	9.1	9.4	12.6	13.9	[52]
Natural gas	€ GJ^{-1}	5.2	5.0	6.9	7.4	[52]
Coal	€ GJ^{-1}	2.5	3.1	2.9	3.1	[52]
CO_2	€ t^{-1}	0	4.4	14.6	24.1	[52]
Biomass (wood pellets)	€ GJ^{-1}	6.8	*estimated endogenously in MAGNET*			[19]

countries vary according to available statistical economic and technical data.

The database is refined with new bioeconomy sectors as described in section 2.2. Data on production volumes, conversion efficiencies, cost-structures, trade and transport costs are derived from various data sources (Table S2 in Supplementary material S1.1). Input data for the Netherlands in 2007 are shown in Table 3. The production of 1st generation biofuels, which are produced by sugar, starch and oil crops, is split from the “chemicals, rubbers and plastics” industry in the GTAP database. The cost-structure of bioelectricity generation is similar to conventional electricity generation technologies (e.g. co-firing with coal and combined heat and power). It is assumed that all bioelectricity production is purchased entirely by the electricity sector (i.e. non-traded). The price of lignocellulosic biomass (i.e. plantations, residues and pellets, including transport costs), in 2007 is 6.8 € GJ^{-1}, which is the price of imported pellets and is common between MARKAL-NL-UU and MAGNET.

The production volume of the biomass supply sectors is derived from the production of bioelectricity, biochemicals and lignocellulosic biofuels. The production volume of lignocellulosic biofuels and biochemicals in the base year is partially assumed, since in reality production volumes are zero or extremely low. Co-products of biofuels and biochemicals are included as credits that reduce the production costs. The fossil-based and bio-based chemicals sector is the largest sector since it includes the production of plastics from fossil feedstocks.

The production of 1st generation and lignocellulosic biofuels, bioelectricity and biochemicals is not cost-competitive with conventional production technologies in 2007 and is therefore subsidised. The difference in production costs between conventional and bio-based sectors is covered by an input subsidy on biomass, which is paid via an output tax of the bio-based sectors.

Crucial for the cost-competitiveness of the bio-based sectors and for their macro-economic impacts are the development of the efficiency and costs of bio-based conversion technologies. This especially concerns the production of biochemicals and lignocellulosic biofuels. The scenario-specific costs and technical developments for the new technologies are based on MARKAL-NL-UU and shown in Table 4. The latter information is processed to input saving technical progress in MAGNET to implement the HighTech and LowTech scenario variants. The assumed rate of input saving technical change is based on the cost structures presented in Table 4 for 2007 and MARKAL-NL-UU results for 2030. This ensures that the production costs in MAGNET are the same as in MARKAL-NL-UU in 2030. The values show the input per unit output in 2030 compared to input per unit output in 2007 at constant prices. Technical change in the bioelectricity and the 1st generation biofuels sector is partly endogenous in MAGNET and identical between scenarios. In Reg scenarios, trade openness of biomass markets in MAGNET is restricted by applying prohibitive tariffs on biomass between EU and the rest of the world.

3. Results

3.1. Comparison between the bottom-up and the top-down results

In this section, model outputs of MAGNET and MARKAL-NL-UU for the road transport, electricity and chemical sector in 2030 are compared with each other. Despite the methodological differences and the different modelling paradigms and techniques of the two models their outcomes are fairly consistent. The comparison is made on the basis of the monetary flows of MAGNET and the physical flows of MARKAL-NL-UU. For that purpose outcomes are indexed in reference to the RegLowTech scenario results in 2030.

3.1.1. End-use of biomass

Fig. 4 shows that the shares of fossil-based and bio-based fuels in road transport are consistent between MAGNET and MARKAL-NL-UU. The blending target in the LowTech scenarios is the key driver of the biofuel output in both models. This implies that mandates of 10% are met 7% by 1st generation and 1.5% by lignocellulosic biofuels. The latter are counted double in meeting the target but this has no macro-economic implications. Biofuel shares in both models are considerably higher in HighTech scenarios as lignocellulosic biofuels become competitive. In GlobHighTech, the biofuel share is 13% in MAGNET and 12% in MARKAL-NL-UU and is mainly lignocellulosic biofuels (90 < 100%).

Biomass use in electricity production is limited across scenarios (Fig. 5). In MAGNET, biomass use is slightly higher and constant across scenarios while for MARKAL biomass use is higher in HighTech scenarios due to co-produced electricity by biorefineries. The share of fossil-based power production is comparable between scenarios and models. Coal-based power contributes approximately 20% and gas-based power contributes approximately 45% to total power production. Consequently, the renewable energy share is also consistent between the models and equal to about 35%. In both models, wind is the key renewable energy source. In MAGNET, its share in electricity production is 31% and in MARKAL-NL-UU 25.5% in 2030.

Fig. 6 shows the biomass and fossil feedstock use in the chemical sector in the Netherlands in 2030. Both models estimate low to moderate shares of biochemicals over total chemicals. Based on MAGNET ethanol-based and sugar-based chemicals contribute 1% in LowTech and almost 4% in HighTech scenarios. Both models show a higher increase in advanced biochemicals production in HighTech compared to LowTech scenarios. The difference in shares can be explained by the broader statistical definition of the chemical sector used by the GTAP classification in MAGNET. Technological change is key for biochemical developments. The effects of technological change lead to strong increase in biochemicals production, especially in the HighTech scenarios. In MAGNET the output is about 2 bn€ a^{-1} in the HighTech and 0.7 bn€ a^{-1} in the LowTech scenarios. The biochemical output in MARKAL is almost 1.8 Mt in GlobHighTech. This is consistent, assuming a plausible price of 1000 € t^{-1}.

Key products are ethanol-based chemicals from lignocellulosic ethanol (0.6 bn€ a^{-1} in the LowTech and 1.7 bn€ a^{-1} in the HighTech scenarios), sugar-based chemicals from lignocellulosic sugar (0.2 bn€ a^{-1} in the HighTech scenarios) and from conventional sugar (0.06 bn€ a^{-1} in the HighTech scenarios). Openness of market plays a modest role, as biomass for 2nd generation technologies is available within Europe at competitive prices. Openness of market generates additional biochemical output of 0.03 bn€ a^{-1} and 0.08 bn€ a^{-1} in the LowTech and HighTech scenarios, respectively. Without technological change the production and use of biochemicals is limited. A methodological difference is that demand in MARKAL-NL-UU is fixed, and both higher technological change and a more diverse technology portfolio lead to lower use of inputs. In MAGNET, demand is endogenous and technological change leads to an increase in the chemical sector and demand for inputs, explaining the increase in total production output compared

Table 3
Production volume and cost-structures of the new bio-based sectors in the Netherlands.

Production volume[a]	Ethanol (1st generation.; grains)[c]	Ethanol (1st generation.; sugar)[c]	Biodiesel	Plantations	Residues	Pellets	Fischer-Tropsch fuels[d]	Ethanol (lignocellulosic)[d]	Lignocellulosic sugar	Fossil and bio-based chemicals[e]	Sugar-based chemicals[f]	Ethanol-based chemicals[g]	Bioelectricity
	M€	M€	M€	M€	M€	M€	M€	M€	M€	M€	M€	M€	M€
	3	1	48	11	174	9	3	3	0	1783	1	1	245
Production cost shares of endowments and intermediate deliveries (percentage in total costs) ↓ %													
Land	0	0	0	13	0	0	0	0	0	0	0	0	0
Labour	11	11	2	31	8	20	5	8	8	8	11	7	14
Capital	6	8	9	38	45	59	26	10	16	10	31	16	14
Wheat and grains	56	0	0	0	0	0	0	0	0	0	0	0	0
Sugar crops	0	57	0	0	0	0	0	0	0	0	0	0	0
Vegetable oils	0	0	76	0	0	0	0	0	0	0	0	0	0
Plantations	0	0	0	0	0	0	4	4	2	0	0	0	2
Residues	0	0	0	0	20	15	42	47	45	0	0	0	45
Pellets	0	0	0	0	0	0	11	12	8	0	0	0	8
Ethanol (1st gen.)	0	0	0	0	0	0	0	0	0	0	0	48	0
Ethanol (lignocellulosic)	0	0	0	0	0	0	0	0	0	0	0	9	0
Sugar	0	0	0	0	0	0	0	0	0	0	23	0	0
Lignocellulosic sugar	0	0	0	0	0	0	0	0	0	0	4	0	0
Transport	1	2	4	18	26	0	4	6	0	0	0	0	0
O&M[b]	26	22	9	0	0	6	9	14	21	81	31	20	28
Total	100	100	100	100	100	100	100	100	100	100	100	100	100

[a] Production volumes for non-existing sectors in 2007 are assumed as follows: Fischer-Tropsch and lignocellulosic ethanol are same as 1st generation ethanol from grains; for sugar-based chemicals and ethanol-based chemicals 1 M€ production volume is assumed; production of lignocellulosic sugar, pellets, residues and plantations are derived from production of biofuels, biochemicals and bioelectricity.

[b] Operation and Maintenance.

[c] In the calculations the cost-price of ethanol from grains and sugar crops is based on 1st generation ethanol in MARKAL-NL-UU in 2010.

[d] In the calculations the cost-price of Fischer-Tropsch fuel and 2nd generation ethanol is based on 2nd generation ethanol in MARKAL-NL-UU in 2010.

[e] In the calculations cost-price values are used based on weighted cost-price of conventional (fossil-based) polyethylene and bio-based polyethylene assuming a 0.1% share of bio-based polyethylene in total polyethylene production volume. Cost-price of bio-based polyethylene in 2007 is based on the cost-price in MARKAL-NL-UU in 2020.

[f] Cost-price is based on weighted cost-price of polylactic acid production from conventional sugar and polylactic acid production from lignocellulosic sugar assuming a 10% share of the production volume coming from 2nd generation ethanol polyethylene.

[g] Cost-rrice is based on weighted cost-price of polyethylene production from ethanol from grains and sugar crops and from lignocellulosic ethanol assuming a 10% share of the production volume coming from lignocellulosic ethanol polyethylene.

Table 4
Input saving technical change in the biomass conversion sectors in the HighTech and LowTech scenarios (input per unit output in 2030 relative to input per unit output in 2007 at constant prices).

Endowments and intermediate deliveries ↓	Fischer-Tropsch fuel	Ethanol (lignocellulosic)	Lignocellulosic sugar	Fossil and bio-based chemicals	Sugar-based chemicals	Ethanol-based chemicals
	HighTech scenario					
Land	n/a[a]	n/a	n/a	n/a	n/a	n/a
Labour	0.29	0.15	0.47	1.00	0.63	0.83
Capital	0.52	0.36	0.27	1.00	0.70	0.73
Plantations	0.41	0.43	0.56	0.56	n/a	n/a
Residues	0.41	0.43	0.56	0.56	n/a	n/a
Pellets	0.41	0.43	0.56	0.56	n/a	n/a
Ethanol (1st generation)	n/a	n/a	n/a	n/a	n/a	0.76
Ethanol (lignocellulosic)	n/a	n/a	n/a	n/a	n/a	0.76
Sugar	n/a	n/a	n/a	n/a	0.66	n/a
Lignocellulosic sugar	n/a	n/a	n/a	n/a	0.66	n/a
Transport	0.29	0.15	n/a	n/a	n/a	n/a
Other O&M	0.29	0.15	0.47	1.00	0.63	0.83
	LowTech scenario					
Land	n/a	n/a	n/a	n/a	n/a	n/a
Labour	1.00	0.70	0.69	0.69	0.79	0.94
Capital	1.00	0.58	0.70	0.70	0.70	1.00
Plantations	1.00	0.67	0.69	1.00	n/a	n/a
Residues	1.00	0.67	0.69	1.00	n/a	n/a
Pellets	1.00	0.67	0.69	1.00	n/a	n/a
Ethanol (1st generation)	n/a	n/a	n/a	n/a	n/a	0.85
Ethanol (lignocellulosic)	n/a	n/a	n/a	n/a	n/a	0.85
Sugar	n/a	n/a	n/a	n/a	0.66	n/a
Lignocellulosic sugar	n/a	n/a	n/a	n/a	0.66	n/a
Transport	1.00	0.70	n/a	n/a	n/a	n/a
Other O&M	1.00	0.70	0.69	1.00	0.79	0.94

[a] Not applicable.

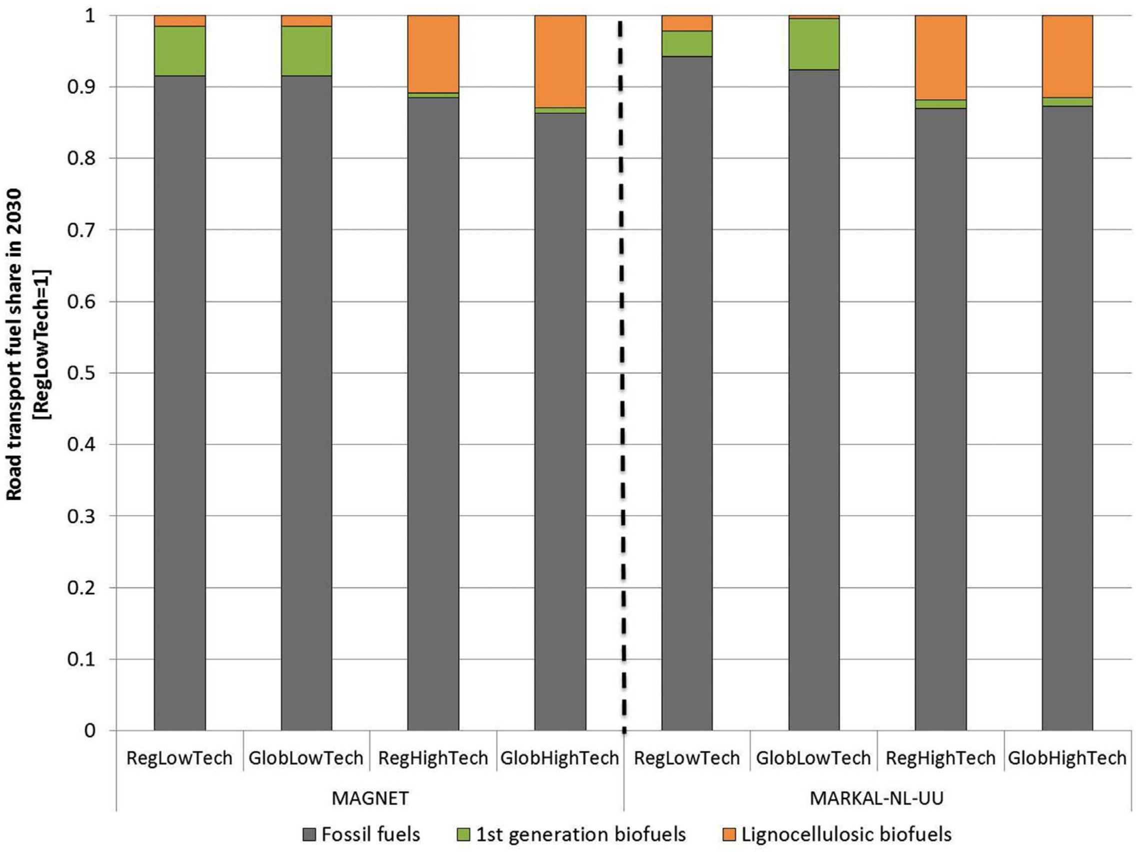

Fig. 4. Comparison of road transport fuel share between MAGNET and MARKAL-NL-UU in the Netherlands in 2030 (index: transport fuel share RegLowTech = 1).

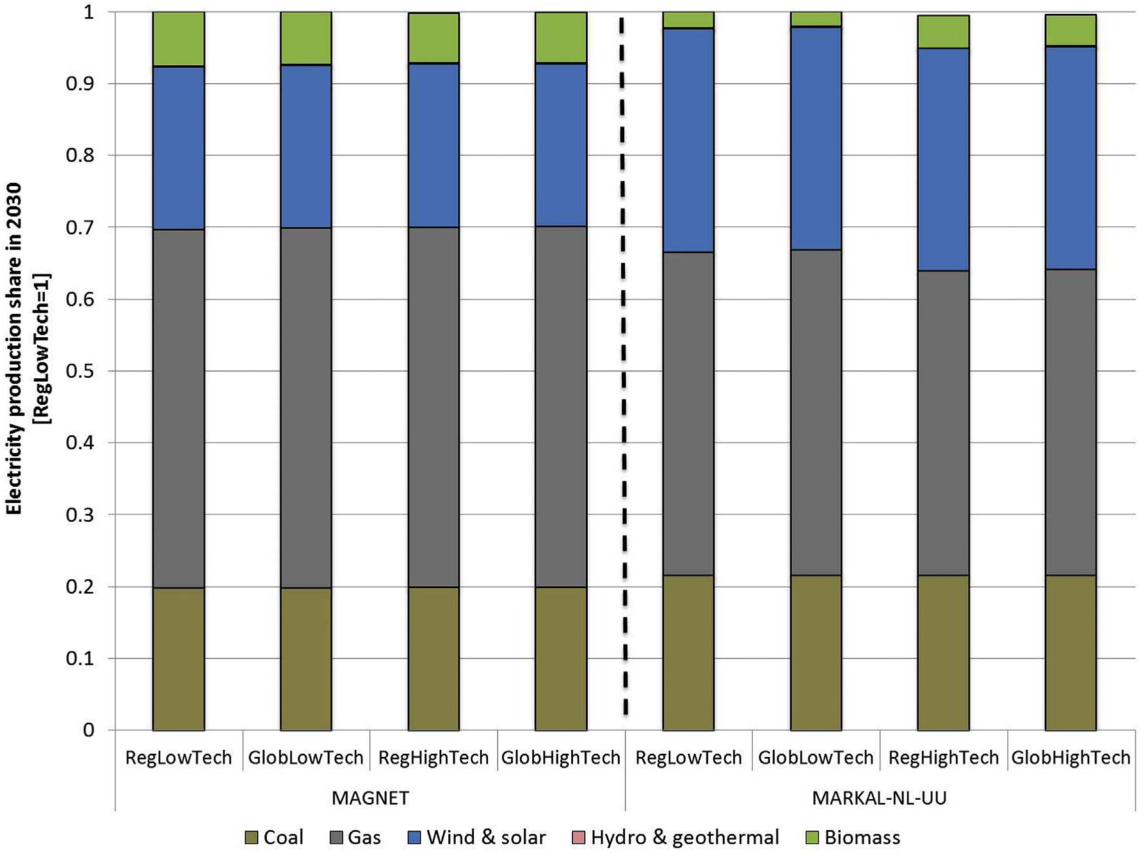

Fig. 5. Comparison of electricity production by source in the Netherlands in 2030 between MAGNET and MARKAL-NL-UU (index: total electricity production RegLowTech = 1).

to MARKAL-NL-UU.

3.2. Biomass consumption

In 2030, total biomass consumption is up to a factor 4 higher relative to no bioeconomy developments (NoBiobased scenario in Fig. 7). Consumption is comparable across the trade openness scenarios, indicating that there will be sufficient biomass available within the Netherlands ("domestic" in Fig. 7) and Europe (not explicitly shown in Fig. 7) at competitive prices to supply bioeconomy developments under the assumed renewable energy targets by 2030. More stringent targets, may lead to imports from extra-EU resources. However, these are not assessed in the present study. Domestic (i.e. the Netherlands) and imported (i.e. intra-EU and extra-EU) lignocellulosic feedstocks, namely biomass residues, play a key role across both technology development scenarios (about 65–75% and slightly above 90% of total biomass consumption in LowTech and HighTech, respectively). In LowTech, 1st generation feedstocks (primary biomass produced by agricultural sectors, i.e. sugar, oilseeds and cereals) are primarily imported and supply about 20–30% of the total consumed biomass (from the EU in the Reg and mostly sugar from North and South America in the Glob scenario variants). As in HighTech scenarios lignocellulosic biomass conversion technologies become cost competitive, 1st generation feedstocks make up only 2–4% of total biomass consumption indicated by the supply of domestic and imported lignocellulosic feedstocks (i.e. biomass residues) which is higher by about 20% compared to LowTech.

3.3. Macro-economic impact

Large-scale deployment of biomass could have a positive impact on the value added of the Dutch economy in the medium term (2030). Across all scenarios only RegLowTech has a negative GDP effect of -0.2 bn€ a^{-1} in 2030 (Fig. 8). Open markets and investments in technology development lead to a positive GDP effect of 0.8 bn€ a^{-1} in 2030 (GlobHighTech). High technology development and global markets add up to 1 bn€ a^{-1} to GDP from 2030 onwards.

In 2015–2020, the main effect that drives the outcomes is the compliance with the EU RED targets, which leads to negative GDP effects in all scenarios compared to a NoBiobased scenario in which the RED targets are not achieved, as bioenergy technologies are not competitive with their fossil substitutes. The negative effect is stronger in the Reg scenarios (-0.8 bn€ a^{-1}) than in the Glob scenarios (-0.2 bn€ a^{-1}) as the EU (and the Netherlands) cannot import (relatively cheap) biofuels from South and North America. The positive effect of technology advances becomes visible in the 2020–2030 period and is larger for HighTech (1 bn€ a^{-1}) than LowTech (0.6 bn€ a^{-1}) scenarios (i.e. it is increase in GDP between 2020 and 2030).

Fig. 9 shows the value added of key bioeconomy sectors in the Netherlands in 2015 and for the scenarios of this study in 2030. The increase in value added of the selected bioeconomy sectors relative to the NoBiobased scenario is higher in HighTech than in LowTech scenarios by about 0.74–0.76 bn€ a^{-1} and 0.56–62 bn€ a^{-1}, respectively. The growth of the bioeconomy has a positive impact on value added of all its sectors. Within the bioeconomy, agriculture is its key sector. In the NoBiobased scenario the value added slightly decreases (by 0.16 bn € a^{-1}) between 2015 and 2030. In all other four scenarios the value added of agriculture in the Netherlands increases. The value added in the biochemical sector due to new biochemicals increases by 0.13 bn€ a^{-1} in LowTech scenarios and by 0.25 bn€ a^{-1} in HighTech scenarios (compared to a NoBiobased scenario in 2030). Value added of biofuels is modest (0.05 bn€ a^{-1}) and similar across the scenarios. In RegLowTech it is slightly higher (0.075 bn€ a^{-1}). Bioelectricity use is largely driven by policies and its value added is fairly constant across the scenarios. Relative to the NoBiobased scenario the value added of

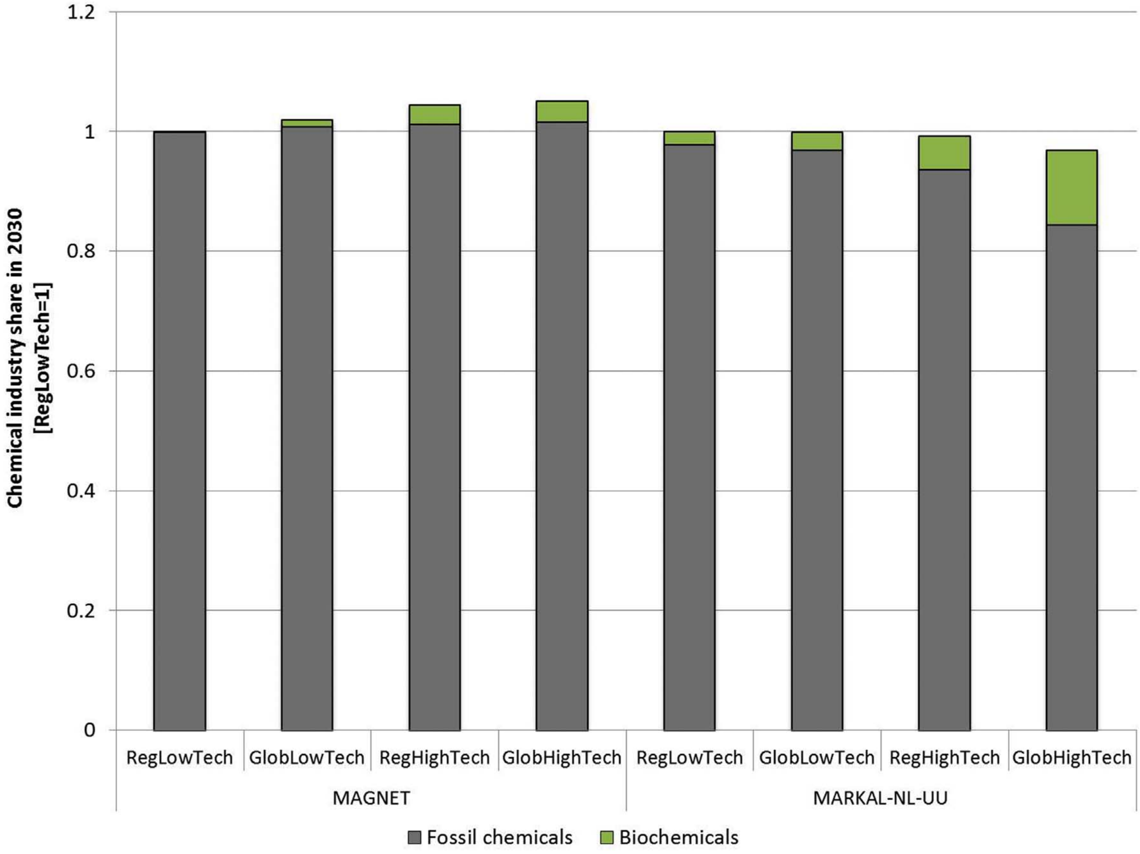

Fig. 6. Comparison of fossil chemical and biochemical share in the chemical sector in the Netherlands in 2030 between MAGNET and MARKAL-NL-UU (index: total chemicals RegLowTech = 1).

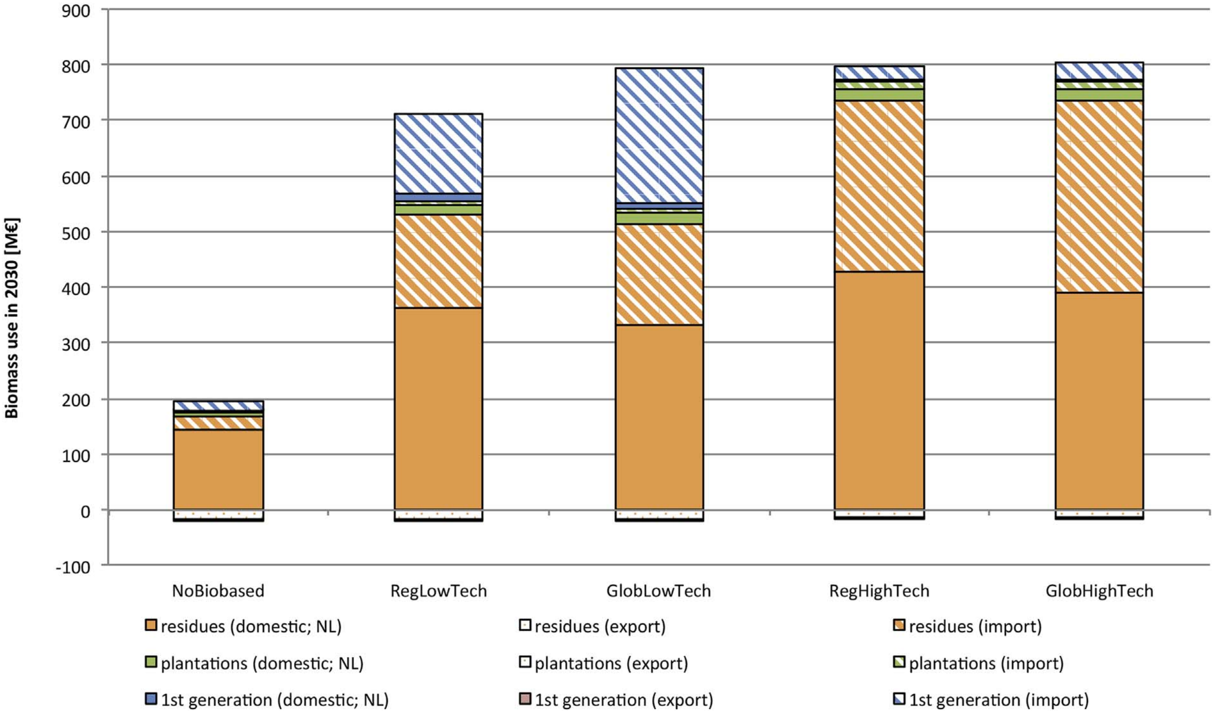

Fig. 7. Biomass consumption per feedstock for bioenergy and biochemicals in the Netherlands in 2030.

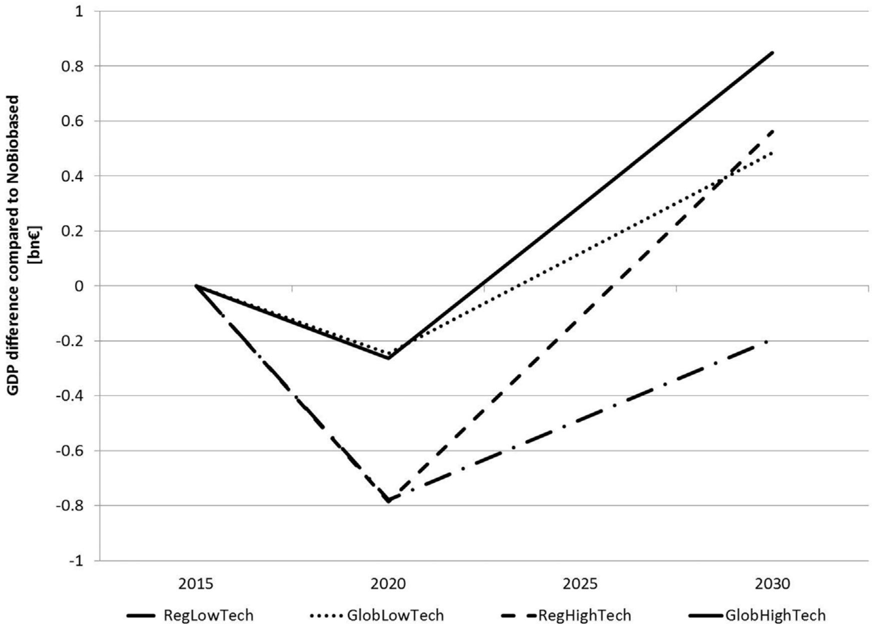

Fig. 8. GDP impact of the different scenarios relative to the NoBiobased scenario in the Netherlands in 2015–2030 (absolute difference, bn€).

bioenergy is about 0.28 bn€ a^{-1} higher in 2030.

In the NoBiobased scenario the employment in agriculture, bioenergy and biochemical sectors is lower in 2030 compared to 2015 as a result of employment decline in agriculture, which is in compliance with the long-term trend (Fig. 10). It is important to realise that we assume full employment in the long run and jobs created in the bioeconomy sectors are drawn from other sectors. Increased employment induced by bioeconomy developments as indicated by the four scenarios in 2030 compared to the NoBiobased scenario in 2030 only partially mitigates the decline in employment. More specifically, without bioeconomy developments employment decreases by 6.5% in 2030 compared to 2015 ("NoBiobased" scenario in Fig. 10). With bioeconomy developments, employment decreases by 5.9–6.1% in 2030 compared to 2015 (all other scenario variants in Fig. 10). The highest impacts in employment come from the production of biochemicals in the case of the HighTech scenarios and to a smaller extent in the GlobLowTech scenario. Employment in the biofuel sector is linked to 1st generation and lignocellulosic biofuels in LowTech and HighTech scenarios, respectively.

Biomass imports and replacement of fossil fuels have several impacts on trade balance (Fig. 11). Relative to the NoBiobased scenario, the trade surplus of the Netherlands decreases by about 1.5 bn€ a^{-1} on average across all scenarios. In the short-term (2020), the total trade balance in the Netherlands is projected to deteriorate relative to a NoBiobased baseline (not shown in Figure). The overall negative impact is caused by the introduction of the EU RED targets, which requires substitution of fossil technologies with more costly biomass conversion technologies, especially in electricity production. The fossil and total energy trade balance improves, but this is more than offset by increased biomass imports and especially the deterioration of the trade balance of other industries and services. However, after 2020 biomass conversion technologies become more cost efficient and Dutch export of lignocellulosic biofuels and especially bio-based chemicals increases. Technical change has a positive impact on the overall trade balance and this reduces the decline of the overall trade balance due to the EU RED. With technology change, the negative impact becomes lower. The reduction of trade surplus is about 1.2 bn€ a^{-1} in the HighTech scenarios and about 2 bn€ a^{-1} in the LowTech scenarios.

The energy trade balance improves in the LowTech scenarios, as fossil energy is substituted by 1st generation biofuels, which are partly

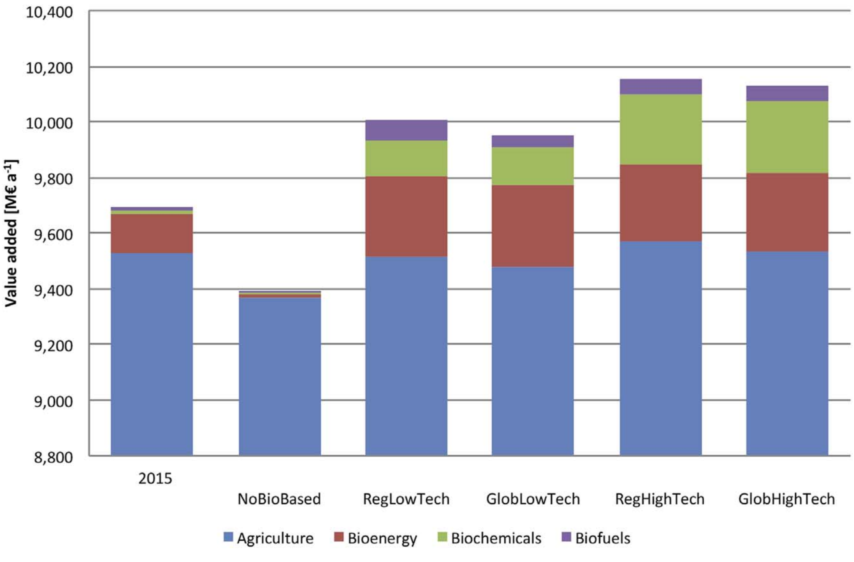

Fig. 9. Value added in different scenarios in the Netherlands in 2030 compared to reference (NoBiobased) and 2015 (excluding food processing, forestry and pulp and papers sectors).

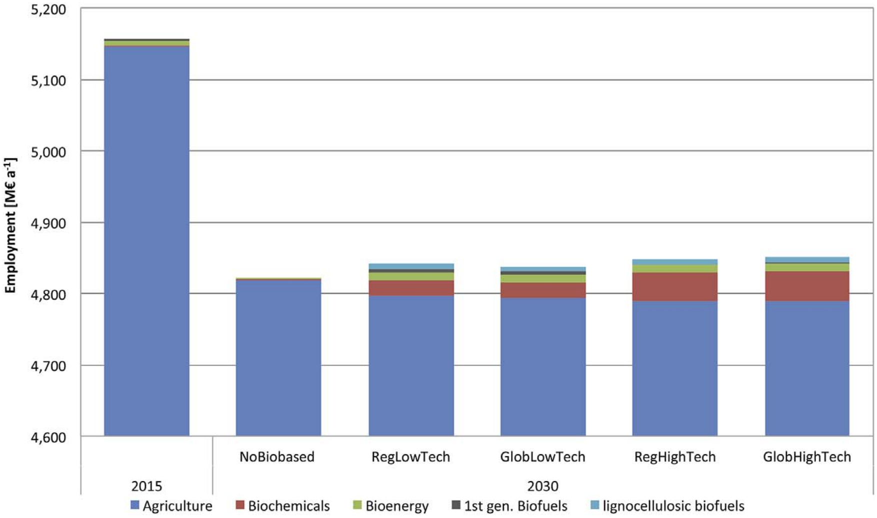

Fig. 10. Employment in agriculture and new bioeconomy sectors across different scenarios in the Netherlands in 2030 compared to NoBiobased in 2030 and the initial situation 2015.

produced domestically. The energy trade balances improves slightly more in the HighTech scenarios as the production of bio-based and conventional fuels and chemicals increases partly due increased export demand. The exports of bio-based products substitute fossil energy use and reduce GHG emissions in other countries.

3.4. Greenhouse gas emissions

Fig. 12 shows the total GHG emissions across all scenarios that occur in the Netherlands in 2030 compared to 2015. The introduction of renewable energy policies and technological change reduce emissions by 4–6%. Relative to 2015, the NoBiobased scenario leads to slightly higher emissions as biomass use in fuels and electricity is suppressed. In the LowTech scenarios, emissions decline by 8 Mt (4% compared to 2015) mainly due to the introduction of the renewable energy directives for biofuels and electricity. In HighTech scenarios, technological change induces the substitution of fossil-based by bio-based technologies and this contributes additionally 1% and 2% in the Reg and Glob scenario, respectively. Fig. 12 also shows that while emissions are reduced by about 15% compared to 1990, there is still significant emission reduction of about 50 Mt CO_{2eq} required to achieve the 40% emission reduction target set by the EU in 2030. The Reg and Glob scenario variants, assume sustainable sourcing of biomass (section 2.1.1.2), with limited GHG emissions in sourcing regions. If, however, sustainable practices are not followed, then GHG emissions from primary production due to land-use change and non-renewable use in supply chains may lead to increase in emissions at a global level, thereby reducing the savings achieved by the Dutch energy system. To harmonise further input data between the models we recommend to use biomass prices from MAGNET and apply them to the biomass cost-structures of MARKAL-NL-UU and iterate the model runs.

4. Discussion

4.1. Modelling framework

The framework and the extension of bioeconomy sectors in MAGNET presented in this article, stand as an improvement of previous efforts that aimed at addressing future impacts of the bioeconomy using CGE models. Firstly, the incorporation of policy targets (EU RED) and the explicit representation of advanced biomass conversion technologies next to other renewable conversion technologies, allowed us to

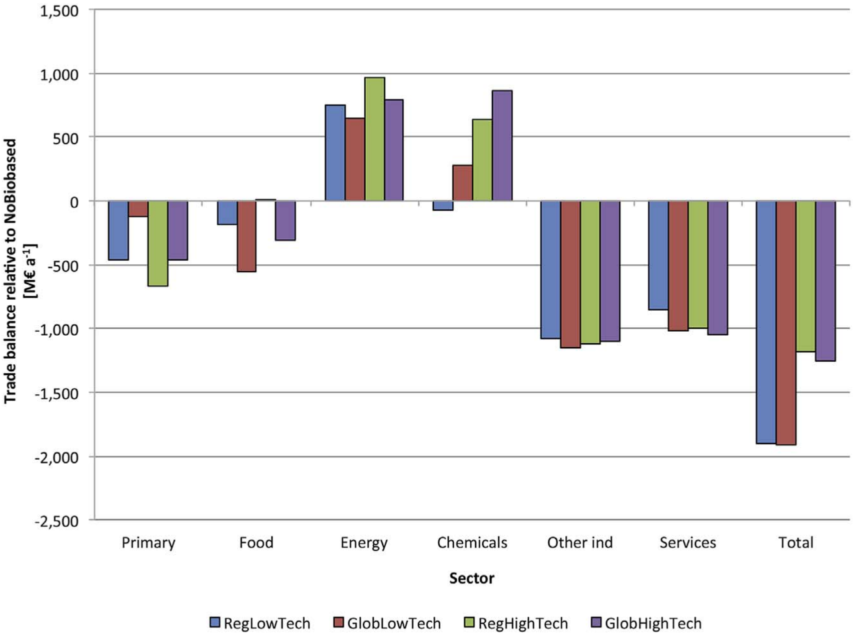

Fig. 11. Trade balance difference relative to NoBiobased scenario in 2030.

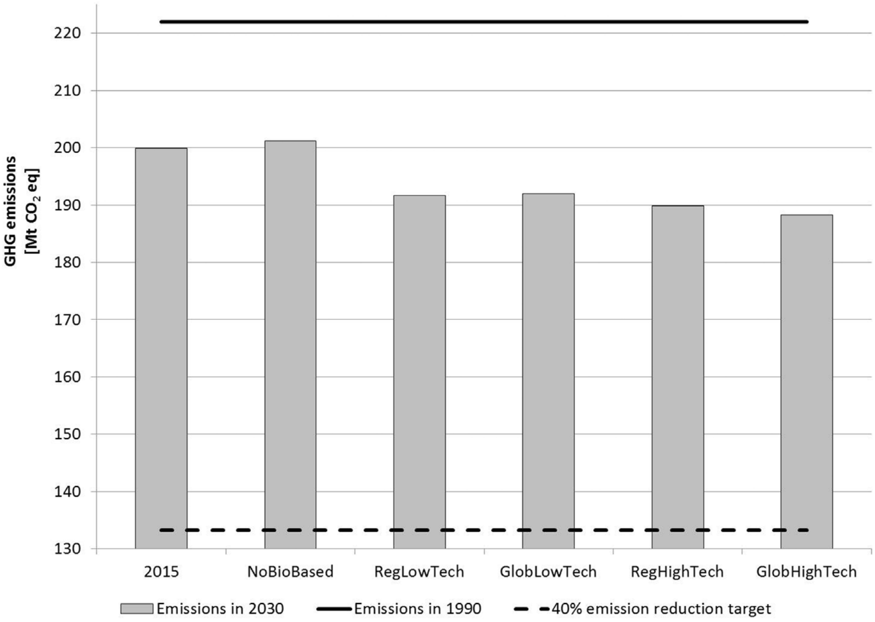

Fig. 12. Total greenhouse gas emissions in the Netherlands in 2030.

assess the sectoral deployment of biomass and other renewable energy as a model output, in contrast to fixed and scenario-dependent deployment levels as assumed in Hoefnagels et al. [11]. Secondly, instead of relying on ad-hoc technology comparison, the cost-competitiveness of technologies within the energy system and the chemical industry was taken into account prior to MAGNET's extension. The selection of technologies, their cost-structures and cost-efficiency improvements over time were based on key technologies projected to be deployed within the energy system of the Netherlands by 2030 as a result of a cost-optimal technology portfolio of biomass conversion technologies next to other renewable resources and fossil fuel conversion technologies. This enabled us to incorporate biochemicals in MAGNET by splitting the chemical industry sector of the GTAP database according to the method applied in the chemical industry module of MARKAL-NL-UU [19]. This is a significant improvement of biochemicals' representation in the CGE family of models, which to date was scarce. MAGNET can now address the macro-economic impact of biochemicals deployment in line with strategies that aim at providing renewable alternatives to the chemical industry. Furthermore, similar to other economic models, we included in MAGNET lignocellulosic biofuels and feedstocks. Additionally, we included the option to densify woody biomass from residues and energy crops to tradeable pellets. MAGNET is one of the few CGE models that can take, next to liquid biofuels, also effects of global solid biomass trade into account. Lastly, this framework harmonises key elements of two very distinct models enabling their soft-linking. For example, MAGNET can also provide data based on macro-economic interactions such as developments of demand and prices to MARKAL-NL-UU (e.g. as in van Meijl et al. and van den Broek et al. [32,53]).

The models' outcomes are consistent based on the strong model collaboration, harmonisation of input parameters and improved sectoral representation in MAGNET from insights received by MARKAL-NL-UU. Both models show that high technology development and open trade stimulate large-scale biomass deployment in the economy. They both indicate that biomass conversion to modern energy and chemicals is larger when compared to low technology development counterparts. Furthermore, both models show that technology development and trade scenarios affect the growth of biochemicals and influence the type of biofuel supply (1st generation in LowTech as opposed to lignocellulosic in HighTech scenarios). Bioelectricity production is fairly constant as wind turbines are the main supplier of renewable electricity.

Linking monetary flows of MAGNET with physical indicators of MARKAL-NL-UU can enable comparison of the models' outputs also on an absolute basis as opposed to the relative basis that was performed in this study. Biomass price levels between the models are different. Global and domestic biomass prices in MAGNET are estimated endogenously based on equilibrium of supply, while MARKAL-NL-UU uses fixed and exogenously defined cost-supply curves. Furthermore, biomass for industrial heat was shown to be an important pathway in the cost-minimisation results. This is expected to remain the largest bioenergy sector to 2030 by other studies [40]. The framework of this study could be used to improve the representation of the heat sector in MAGNET. However, increase in industrial energy efficiency and efficiency improvements in the built environment, may lead to a decline in heat demand. Including this in models requires more sophisticated data on the heat sector regarding technologies, efficiency measures and their development over time.

Finally, the framework and the models presented in this study could benefit by soft-linking the models' input and outputs. For example, in MAGNET, international trade of produced commodities (electricity, fuels, chemicals) is calculated endogenously and it affects the equilibrium prices of commodities and the regional demand, based on supply-demand elasticities, costs and market shares. On the other hand, the demand in MARKAL-NL-UU is fixed, exogenously determined and international trade in produced commodities is not included. By supplying demand projections, for example, of chemicals from MAGNET estimates to MARKAL-NL-UU and iterating the model runs, more insights could be obtained. As shown in Tsiropoulos et al. [22], biochemical output in MARKAL-NL-UU decreases when assuming lower demand for chemicals.

4.2. *Sensitivity*

The macro-economic outcomes, similar to Hoefnagels et al. [11], show that high technology development and open trade come with significant macro-economic benefits for the Netherlands in 2030. Nonetheless, in order to provide robust directions that can support policy making, additional analysis is required. First and foremost, as demonstrated in Tsiropoulos et al. [22] fossil fuel prices are a key determinant of technology competitiveness (range of 183–762 PJ of biomass consumption in 2030). Similarly, variation in fossil fuel prices can affect the macro-economic developments assessed by MAGNET, as they are exogenous parameters. Lower fossil fuel prices are expected to reduce the macro-economic benefits derived from bio-based technologies. Higher fossil fuel prices on the other hand may lead to an increase of their macro-economic benefits. A local sensitivity analysis on fossil fuel prices is therefore recommended.

Secondly, the scenarios were developed around technology development and biomass trade. However, more than 90% of value added lies in the agricultural sector (Fig. 9). Therefore, yield developments may impact the results. Assuming a 10% increase in the Dutch crop and forestry sectors, leads to significant positive effects on GDP (0.3% compared to 0.12% in GlobHighTech) and value added, due to the increase of the market share of Dutch export-oriented agri-food industries. Nonetheless, as shown by MAGNET outcomes (Fig. 7), only a minor part of domestic primary agricultural products are consumed by the Dutch bioenergy and biochemical sectors. An increase of biomass supply to global markets is noticed, as the global agricultural feedstock prices do not decline significantly from the increased supply of the Netherlands. A more detailed local sensitivity analysis on improvements in agriculture is therefore recommended.

Production costs of bioenergy and biochemical and their development over time are a determinant of the size of bioeconomy and its impacts. Literature indicates a wide range of production costs depending on the technology type, their techno-economic parameters (e.g. size, efficiency), and location [39]. The broad coverage of MAGNET, requires simplification of the technology portfolio that is included, thereby ignoring other options that may be available. For the selected technologies, the dependency of production cost on the technology size and efficiency is addressed by different input assumptions in the technology development scenarios. However, for currently non-commercially existing technologies, MAGNET applies the same technological assumptions on cost-structures and development over time for all regions of the world. These could be improved, if region-specific cost-structures are defined for the advanced biomass conversion technologies that were introduced in this study. Robustness of outcomes could be further assessed by conducting a sensitivity analysis on production costs in line with ranges found in literature.

4.3. Emission reduction pathways

The assumed tax on emissions and cost-competitiveness of renewable technologies reduce CO_2 emissions in the Netherlands by about 15% in the mid-term compared to 1990 (Fig. 12). This, however, is not adequate to achieve the EU wide 40% emission reduction target in 2030 compared to 1990 [54]. For the Netherlands, this outcome is also supported by MARKAL-NL-UU results [19,22]. In the present study, renewable energy deployment is primarily driven by the assumed renewable energy targets. Stronger climate policy such as a CO_2 tax of about or above 100 $ t CO_2^{-1} in 2030 (based on IEA-WEO 2014), is required to embark upon least-cost trajectories that achieve the 2 °C climate target that was agreed at the Conference of Parties in Paris in 2015 (COP21 [55]). The modelling framework presented in this article did not assess such ambitious CO_2 mitigation scenarios. To demonstrate their implications on the economy, improvements are required. Firstly, a plethora of models show that the role of CCS and BECCS is critical to achieve emission reduction in the mid-term and long-term [35]. Without CCS, mitigation costs may increase significantly [56]. Large investments would already be required from 2030, which may also induce socio-economic implications. In addition, the contribution of CCS and BECCS in CO_2 mitigation may also influence the levels of bioenergy in modern bioeconomy sectors and of other renewable resources. Similar to many CGE models that include CCS (e.g. EPPA, ReMIND [57,58]), MAGNET could also incorporate in power and liquid fuel sectors CCS technologies endogenously.

Secondly, ambitious emission reduction scenarios entail large biomass production and consumption volumes from regions also outside the Netherlands. At a global level, the overall emission savings of bioeconomy developments eventually depend on factors beyond the changes in the Dutch energy system. Carbon stock changes either due to transformation of existing land-use in regions of primary production or due to land shifts in other regions lead to a variation of emissions and uncertainty associated with feedstock supply that ultimately affect the savings and abatement costs of bioenergy chains [14,59]. This entails that accounting for direct and indirect land-use change emissions may increase the abatement costs achieved by bioeconomy developments either due to lower savings or due to higher costs of land-use management required to avoid negative indirect land-use change. Due to regional and temporal variability of land-use change emissions induced by biofuels there is limited knowledge on which land-use changes are most beneficial for carbon mitigation strategies. The latter require spatially explicit integrated assessment modelling frameworks and metrics that estimate supply levels of biofuels and associate them with different emission factors and payback periods [60]. Other factors such as by-product use and fossil energy use (e.g. for transport, fertilisers) and emissions from fertilisers increase the complexity and uncertainty of emissions from biomass production for bioenergy [61]. To assess such dynamics, a larger regional-scope is more relevant. To some extent, MAGNET being a global multi-region model can address some of the challenges related with land-use and technology development [21], provided that region-specific cost-structures are introduced. However, integrated assessment models are better positioned to address more complex issues related with biophysical interactions. Along these lines, the temporal scope of the assessment presented in this study needs to be extended beyond 2030, as technical progress is limited by the time horizon of the present study, not only on conversion side but also on the supply side (e.g. feedstock supply). Extending the time-horizon may create different dynamics driven by the mitigation efforts and could possibly demonstrate a larger deployment of modern bioenergy and biochemicals in the economy. This also entails that additional technologies may need to be included in the portfolio of the models used in this framework.

5. Conclusions

We presented a harmonised modelling framework comprised of an energy systems model (MARKAL-NL-UU) and a CGE model (MAGNET) that improves macro-economic assessments of the bioeconomy. The results on bioeconomy outputs (i.e. bioenergy and biochemicals) are consistent between the two models, albeit their different modelling paradigms. We found that HighTech development and open trade is a no-regrets option in terms of macro-economic impacts. By 2020 our findings indicate a temporary deterioration of GDP and trade balance due to the support required in order to meet EU RED targets. However, investing early in the time horizon on bioeconomy may come with macro-economic benefits to the Netherlands on GDP (0.8 bn€ a^{-1}), value added (0.7 bn€ a^{-1}), reduce projected decline in trade balance (by about 0.7 bn€ a^{-1} or 36% compared to LowTech) and employment (by about 2.4–4.5% compared to LowTech). The largest difference in value added comes from the biochemical sector, which can increase its absolute and relative contribution if HighTech is supported. Nonetheless, emission reduction to 2030 is modest (i.e. 15% or about 30 Mt CO_2 eq. compared to 1990). To meet climate goals, more ambitious scenarios need to be assessed (e.g. with CO_2 tax of at least 100 $ t CO_2^{-1}). Pursuing ambitious emission mitigation goals may replace additional fossil-based capacity, thereby increasing the significance of bioeconomy.

To provide concrete directions to policy-making, the present study requires thorough sensitivity analysis on factors and uncertainty parameters that can influence bioeconomy developments such as fossil fuel prices, CO_2 prices and agricultural management practices. Furthermore, consistency between the outputs of both models could be improved by an enhanced linkage between the models, for example by supplying outputs of MAGNET to MARKAL-NL-UU, such as biomass price or future energy demand and iterate the model runs. This requires a consistent approach of converting monetary to physical outputs or vice-versa. Finally, by incorporating CCS and BECCS technologies in the power and liquid fuel sectors of MAGNET, and by extending the temporal and regional scope of the assessment more ambitious climate mitigation scenarios can be assessed.

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Appendix A. Supplementary data

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