

# Socio-economic impacts of future electricity generation scenarios in Europe: Potential costs and benefits of using CO<sub>2</sub> Capture and Storage (CCS)



Barbara Sophia Koelbl<sup>a,\*</sup>, Richard Wood<sup>b</sup>, Machteld A. van den Broek<sup>a</sup>,  
Mark W.J.L. Sanders<sup>c</sup>, André P.C. Faaij<sup>d,f</sup>, Detlef P. van Vuuren<sup>a,e</sup>

<sup>a</sup> Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CD Utrecht, The Netherlands

<sup>b</sup> Norwegian University of Science and Technology, Industrial Ecology Program, Høgskoleringen 5, NO-7491 Trondheim, Norway

<sup>c</sup> Utrecht University School of Economics (USE), Utrecht University, Kriekenpitplein 21-22, 3584 EC Utrecht, The Netherlands

<sup>d</sup> Energy Academy Europe, University of Groningen, Blauwborgje 6, P.O. Box 9700 AE Groningen, The Netherlands

<sup>e</sup> PBL Netherlands Environmental Assessment Agency, P.O. Box 303, 3720 AH Bilthoven, The Netherlands

<sup>f</sup> Energy & Sustainability Research Institute Groningen (ESRIG), University of Groningen, Blauwborgje 6, P.O. Box 9700 AE Groningen, The Netherlands

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## ABSTRACT

Carbon capture and storage (CCS) is a potential key-technology to mitigate greenhouse gas (GHG) emissions as its use can lead to lower mitigation cost. However, research on other economic impacts of using CCS is scarce. In this paper, we look into economic upstream impacts of CCS use in terms of employment, Gross Value Added (GVA) and import dependency on the macro- and sector-level in Western Europe. We determine these impacts by a static comparison of two scenarios of power production with and without CCS (differences in energy efficiency investments between these scenarios were not accounted for). The two scenarios, both representing a stringent climate policy regime, were produced with the energy-system-simulation-model (TIMER) following the same emission profile until 2050. Data from the two scenarios were respectively implemented into a projected version of a global-multiregional IO-Model (EXIOBASE). Macro-level results suggest slightly higher gross employment, but lower Gross Value Added (GVA) (by 25%), and higher import dependency in the CCS-including scenario compared to the CCS-excluding scenario, given that biomass with CCS (BECCS) is available. Sector-level results show disproportionally higher differences between the scenarios in GVA and employment for some sectors compared to other sectors. Particularly, sectors providing fuels (here mostly bio-energy) have significantly higher GVA and employment in the CCS scenario. This study thus reveals interesting upstream economic effects, which can be linked to the technology choice. However, the exact quantitative results depend strongly on model assumptions. Results therefore need to be further explored in other models.

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## 1. Introduction

A range of technology options is available to mitigate climate change. One potential key technology is carbon-capture and storage (CCS) (GEA, 2012; IEA, 2010). In principle, it would be the most efficient strategy to use all mitigation options (Kurosawa, 2004; Riahi et al., 2004; Smekens-Ramirez Morales, 2004) and in most

model results CCS forms part of the mitigation strategy (Koelbl et al., 2014a). A key reason is that costs can be lower when including CCS into the mix of mitigation technologies compared to excluding it (Azar et al., 2006; IEA, 2012, 2010; IPCC, 2005; Okagawa et al., 2012).

Lower costs are important, however, there are other economic indicators that are relevant to analyze when considering mitigation strategies. Employment is one indicator looked at in numerous studies analyzing low carbon technologies (Lehr et al., 2012; Llera Sastresa et al., 2010; Ragwitz et al., 2009; Wei et al., 2010). Furthermore, Gross Domestic Product (GDP) (or Gross Value Added (GVA)) is used to measure economic impacts on the macro-economic and sector level (Markaki et al., 2013; Saveyn et al., 2011). Finally, import dependency is often taken into account, for example, in a study comparing CCS to other technologies by BMU (2008).

\* Corresponding author. Tel.: +31 0 30 253 4994; fax: +31 0 30 253 7601.

E-mail addresses: [B.S.Koelbl@uu.nl](mailto:B.S.Koelbl@uu.nl) (B.S. Koelbl), [richard.wood@ntnu.no](mailto:richard.wood@ntnu.no) (R. Wood), [M.A.vandenBroek@uu.nl](mailto:M.A.vandenBroek@uu.nl) (M.A. van den Broek), [M.W.J.L.Sanders@uu.nl](mailto:M.W.J.L.Sanders@uu.nl) (M.W.J.L. Sanders), [a.p.c.faaij@rug.nl](mailto:a.p.c.faaij@rug.nl) (A.P.C. Faaij), [Detlef.vanVuuren@pbl.nl](mailto:Detlef.vanVuuren@pbl.nl) (D.P. van Vuuren).

The broader economic impacts of including or excluding CCS into the European mitigation portfolio have, however, not been analyzed in detail. Various studies also compare a CCS inclusive strategy to a scenario without CCS on the global or European level (Knopf et al., 2013; Krey et al., 2014; Riahi et al., 2015). However, with respect to economic indicators, these studies mainly focus on mitigation costs<sup>1</sup>, but do not look at all indicators mentioned above. Other previous work has generally focused at the national level, a mix of mitigation measures and/or at the technology in isolation. For instance, the total effect of programs and standards implemented to support energy efficiency, renewables and CCS as part of (among others) the provisions of the American Clean Energy and Security Act of 2009 (ACESA), were investigated by MISI (2010). In different scenarios, they find small positive and negative impacts on employment, but large variations in specific sectors. Wei et al. (2010) estimated the net job creation of a strategy including energy efficiency measures, renewable portfolio standards and CCS, to be about 4.5 million full-time equivalent job years in the US in 2030. A specific CCS project evaluation was made, for example, by Scottish Enterprise (2011). They calculate that specific pilot projects, built in Scotland between 2014 and 2020, can create GVA between 1.17 and 3.28 billion £ and between 1742 and 5054 full-time jobs (Scottish Enterprise, 2011). Finally, AEA (2010) calculates impacts in the UK of future coal and natural gas power with CCS. They find that in 2030 about 27,000 CCS related jobs and roughly 3 billion £<sub>2008</sub> of GVA can result from CCS deployment in the UK (AEA, 2010). However, none of these studies allows for a direct comparison between deploying CCS as a mitigation technology and an alternative strategy without CCS, and thus the net result of using rather than excluding CCS from the technology portfolio has not yet been quantified.

The research objective of this study is to assess the difference between two mitigation scenarios, following the same emission profile up to 2050, but respectively including and excluding CCS in Western European<sup>2</sup> power production. The difference is measured in terms of employment, Gross Value Added (GVA) and import dependency. In our analysis, we look at both overall economy-wide impacts as well as at sector-level results. To calculate the difference in these measures we develop a method by implementing detailed technological information from a bottom-up model into an economic Input-Output Model (IO-Model). This paper thus provides new insights to complement the analysis of different greenhouse gas (GHG) mitigation strategies, while also offering recommendations to deal with methodological issues when using bottom-up data in top-down IO-Models.

The method chosen is a future projection of an IO-Model based on the EXIOBASE database (EXIOPOL<sup>3</sup>) (Tukker et al., 2013; Wood et al., 2014). The advantage of this method is that IO-Models allow for high sectoral detail, while using a future projection of this model alleviates the historic character associated with IO-Model analysis. We generated the scenario data for the CCS and NOCCS scenario with the energy-system-simulation model TIMER<sup>4</sup> (De Vries et al., 2001; PBL, 2014; Van Vuuren et al., 2006), where we impose a stringent GHG-mitigation target of 450 ppmv CO<sub>2</sub>-eq. To make a fair comparison between these scenarios, both scenarios follow the same emission profile. To increase technological detail, we extended the IO-Model using a hybrid IO-Model life cycle approach

(see Wood et al., 2012). Such hybrid approaches are widely used to link life cycle inventories to impacts from the overall economy in the field of environmental sciences (Hertwich et al., 2014; Strømman and Solli, 2008; Wiedmann et al., 2011).

In Section 2, we first discuss the details of our method, including data and underlying assumptions. In Section 3, the results are presented, which are further discussed in Section 4. Finally, the conclusions are presented in Section 5.

## 2. Method

### 2.1. Method overview

To compare the impacts of a mitigation strategy with and without CCS in the Western European power sector in 2050, we create two variants of a global multiregional IO-Model. We choose Western Europe<sup>5</sup> because CCS is considered as a decarbonization option in the EU Energy Roadmap 2050 (European Commission, 2011).

Fig. 1 shows an overview of the method. The starting point was the global multiregional IO-Model database (EXIOPOL) constructed from national supply and use tables as described in Tukker et al. (2013) and Wood et al. (2014). The version we use was modified prior to this research by using information from a mitigation scenario projection (Blue-Map-450 (IEA, 2010)) to 2050 (here referred to as EXIOPOL-2050<sup>6</sup>). Next, the EXIOPOL-2050 version was modified further to create two IO-Model variants based on information from two scenarios generated with the global regional bottom-up energy-system simulation model TIMER<sup>7</sup> (De Vries et al., 2001; PBL, 2014; Van Vuuren et al., 2006). Both scenarios project the future energy system under the emission constraint that global GHG-concentrations remain below 450 ppmv CO<sub>2</sub>-eq., until 2100. The only difference between the two scenarios is the availability of CCS. Thus, one of the resulting IO-Model variants (referred to as EXIOPOL-CCS-2050) is based on information about the power sector assuming that all mitigation options, including CCS, are available. In contrast, the second IO-Model variant is based on information from a scenario where CCS is not available in any region, for any application (EXIOPOL-NOCCS-2050).

The information from TIMER was used to modify the IO-Model as follows: In contrast, the first, we use costing data (LCOE and LCOE cost shares) and projected electricity production per generator from TIMER together with detailed cost share information from EXIOPOL-2050 and NETL (2012, 2010) to construct input vectors for each power production option. These vectors were stacked to the EXIOPOL-2050 version to create the EXIOPOL-2050-CCS/NOCCS variants. Second, we use (scenario specific) trade shares for fossil and biomass fuels projected by TIMER to adjust import shares of these fuels in the IO-Model variants. Next, we calculate the value of total electricity demand in 2050 from technology specific LCOE and power production for both scenarios from TIMER. This then constitutes the final demand vectors for the EXIOPOL-2050-CCS/NOCCS variants, respectively. Based on this, we calculate direct GVA and imports as well as indirect GVA, imports and employment. At the same time, we used employment coefficients from literature and the projected physical amount of electricity from TIMER to calculate direct employment from electricity production. Finally, we calculate the differences in results between the CCS and NOCCS scenario

<sup>1</sup> Measured as GDP or consumption losses or by the area under the Marginal Abatement Cost Curve.

<sup>2</sup> For a precise regional definition please see Supplementary material.

<sup>3</sup> EXIOPOL is an acronym for "Environmental Accounting Framework Using Externality Data and Input-Output Tools for Policy Analysis" (Tukker et al., 2009, p. 1928).

<sup>4</sup> The IMAGE Energy Regional Model (TIMER) is a part of the integrated assessment model IMAGE (Bouwman et al., 2006), which for example has been used for the 4th assessment report of the Intergovernmental Panel on Climate Change (Bouwman et al., 2006; Van Vuuren et al., 2007).

<sup>5</sup> For a precise regional definition please see Supplementary material.

<sup>6</sup> The technical coefficients of key-sectors, and the final demand (volume and structure) were adjusted based on Blue-Map-450 scenario data from IEA (2010) and further sources as explained in Wood et al. (2012) and Supplementary material of this paper.

<sup>7</sup> Assumptions made to match technological dimensions of TIMER and EXIOPOL are listed in Supplementary material.

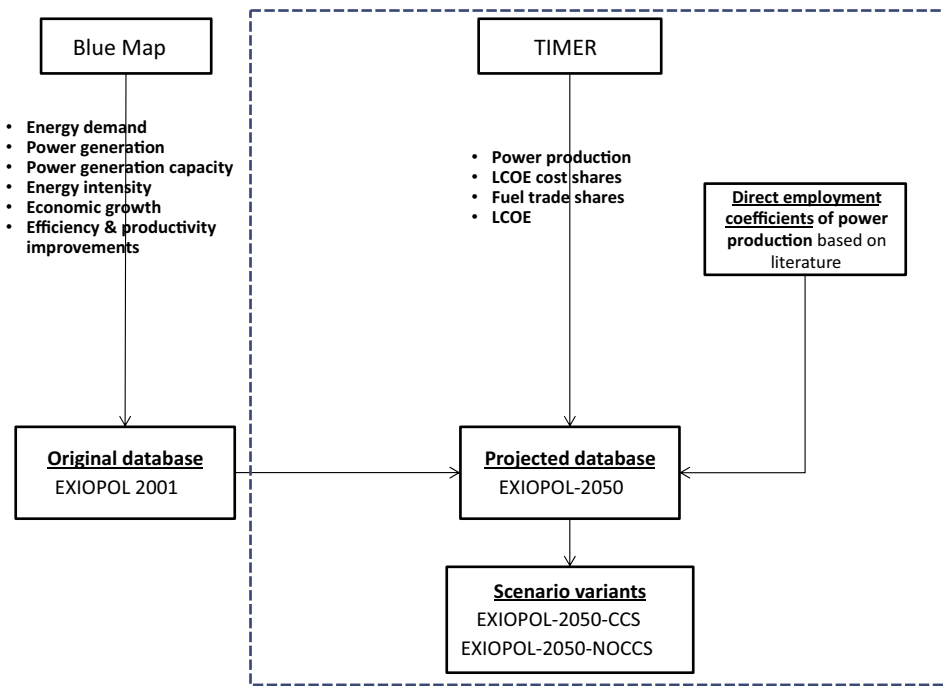


Fig. 1. Method overview.

and compare them. To understand the significance of these differences for each individual sector, we relate them to the total GVA and employment of these sectors. In other words, we express the difference in GVA and employment between the CCS and the NOCCS scenario as a percentage of total GVA and employment calculated for 2050 in the projected EXIOPOL-2050 model.

To concentrate on impacts from power production in Western Europe only, we calculated impacts exclusively from total projected Western European electricity demand. Impacts can occur directly from power production (e.g., labor used at power plants) and indirectly from producing inputs that are used for power production (e.g., labor in coal mining) and all intermediate and primary inputs from higher order production along the supply chain (e.g., labor used to construct drilling machines used in coal mining). The latter is often termed upstream or indirect effect. As this power demand already includes all intermediate demand for electricity (resulting from the production of all consumption goods in this year) and all final demand for electricity (resulting from household electricity consumption), we exclude final demand of all other goods in this year from the final demand vector.

It is important to note that the IO-Model calculations do not capture the investments in sectors associated with energy efficiency (which are included in the TIMER scenarios). Furthermore, this study calculates the difference in effects between two scenarios as opposed to studies that only calculate the total effect of one scenario or technology. In this sense we calculate the result of using CCS net of the result of using an alternative technology mix. However, results are still not pure net effects because a static analysis with an IO-Model excludes macro-economic feedback mechanisms. This makes them “gross effects” (see Blazejczak et al., 2011; Frondel et al., 2010).

The following sections describe the method in more detail. We first describe the scenario set up in TIMER. Second, we discuss relevant outputs from these scenario runs. These outputs serve as a starting point of this study to reveal new insights into economic impacts focusing on upstream effects in the economy. Third, we describe how the information from TIMER was used to adapt the IO-Model. Finally, we briefly describe the collection and projection of data for technology specific employment coefficients.

## 2.2. Energy system scenarios

### 2.2.1. Scenario development

The scenario data from the energy-system model TIMER were generated by imposing a single (idealized) global carbon price in each scenario. This carbon price can be representative of a global carbon tax or seen as the outcome of a global emission trading scheme by imposing an emission cap.

The point of departure is an emission profile that was calculated under TIMER default conditions based on the Baseline of the OECD Environmental Outlook (OECD, 2012) (altered by the transport sector specified in Girod et al. (2012)) to reach a 450 ppmv CO<sub>2</sub>-eq. concentration target until 2100. The emission profile (used earlier by Koelbl et al., 2014b) is calculated by FAIR (Elzen and Lucas, 2006) – a model which calculates the cost minimizing abatement pathway over time, emission sources and GHGs (see also Van Vuuren (2007)). In this emissions profile CO<sub>2</sub> emissions from the energy system become negative after 2050 by making use of BECCS.<sup>8</sup> The same emission profile is used for both runs to ensure comparability.

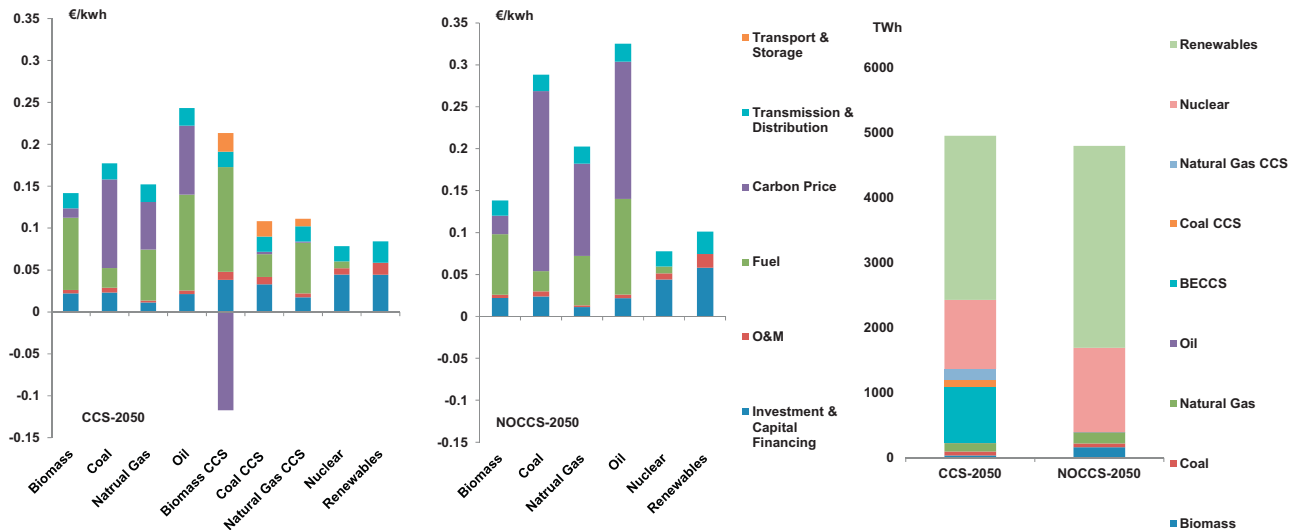
In the first scenario, this emission profile is followed using a carbon price increasing from less than 10 €/2007/tCO<sub>2</sub> in 2015 to 170 €/2007/tCO<sub>2</sub> in 2050 when all options including CCS are available. This scenario uses the same adjustments of CCS relevant variables as in the Base(M) case of Koelbl et al. (2014b). The fossil fuel prices were based on the projections of the World Energy Outlook 2013 (OECD/IEA, 2013) (for details see Supplementary material).

In the second scenario, we follow the same emission profile but CCS is not allowed in any sector and region. The global carbon price in this scenario starts at about 15 €/2007/tCO<sub>2</sub> in 2015 and reaches almost 330 €/2007/tCO<sub>2</sub> in 2050. It should be noted that after 2050, the NOCCS run would not be able to follow the negative emission pathway.

### 2.2.2. Scenario output

The projected power technology portfolio for Western Europe and the LCOE from TIMER are depicted in Fig. 2. Graph (a) and (b)

<sup>8</sup> Resulting implications for this study are discussed in Section 4.



**Fig. 2.** LCOE for different technology groups in 2050 (Graphs (a) and (b)). The LCOE data shows a break down into investment, capital financing, fuel cost, the carbon price, transmission and distribution as well as transport and storage cost. Graph (c) shows the amount of electricity produced per technology group in each scenario in 2050.

show LCOE<sup>9</sup> for technology groups, broken down into its main cost shares. A comparison of cost breakdowns between the two scenarios shows that the carbon price of the NOCCS scenario is higher than in the CCS scenario. This also leads to higher electricity prices in the NOCCS scenario of about 0.01 euro/kWh (10 and 14% for large- and small-scale users respectively).<sup>10</sup> Comparing LCOE shares between technologies shows that the carbon price and fuel cost make up the major share of thermal power production cost without CO<sub>2</sub> capture. Bio-energy fueled thermal plants have significantly higher fuel cost than natural gas or coal fired plants. CCS power options have higher fuel cost as a result of lower efficiency, but have lower carbon emission cost. For bio-energy with CCS (BECCS) the carbon price is important as here the carbon price functions as a subsidy. In contrast to thermal power, the LCOE of non-biomass renewables and nuclear consists mainly of capital costs. Also, operation and maintenance (O&M) and transmission and distribution costs are higher for the renewable options. The reason for the latter is higher system integration costs.

The two electricity production portfolios (Fig. 2(c)) differ strongly by the amount of renewable and nuclear power. These technologies are deployed more in the NOCCS than in the CCS scenario. In contrast, the CCS scenario produces more electricity with thermal plants. Most significantly, biomass (with CCS) is much more used in the CCS scenario. Still, in 2050, CO<sub>2</sub> emitting thermal power with biomass, coal or natural gas also have a higher share in the power portfolio of the NOCCS scenario compared to the CCS scenario. Note that the total amount of electricity produced is also higher in the CCS scenario by about 3% as the higher CO<sub>2</sub> price leads to more investments into efficiency in the NOCCS scenario.

### 2.3. Scenario implementation in EXIOPOL

We appended the IO-Model to increase technological detail in the electricity sector and explicitly represent different specific thermal technologies (such as pulverization or combined cycle). We do this by first constructing input vectors that contain detailed information about individual power production technologies. The information consists of input coefficients defining the share of supplies from different industries of the IO-Model to produce electricity for each individual technology. Next, we stack these vectors to the matrix of input coefficients of the IO-Model without changing the latter. This method is based on the theory of so called hybrid analysis which is applied in different forms in the realm of Life Cycle Assessment (LCA) (see [Suh and Huppes, 2009](#)). Descriptions of hybrid IO-Model combinations with life cycle costing (LCC) or life cycle assessment (LCA) can be found in [Nakamura and Kondo \(2009\)](#), [Settanni et al. \(2011\)](#) and [Suh and Huppes \(2009\)](#). With this method, we can investigate upstream impacts of producing electricity with the technologies we defined (i.e., impacts from producing direct and indirect inputs to the power sector). The method was implemented based on [Wood et al. \(2012\)](#) and [Wood and Hertwich \(2013\)](#) (see also Supplementary material).

#### 2.3.1. Vectors of input coefficients to power production

In total, the EXIOPOL-2050-CCS variant includes 19 distinctly modeled power options and the EXIOPOL-2050-NOCCS variant includes 14 options. These are:

- Renewables (non-biomass): Solar pv, geothermal, hydro and wind power
- Nuclear
- Conventional thermal power: Biomass, oil, natural gas and coal
- Advanced thermal power with and without CO<sub>2</sub> capture:
  - Combined cycle using natural gas
  - Integrated gasification combined cycle using coal or biomass
  - Advanced pulverized biomass or coal plants

For each of these power technologies, input coefficients had to be defined. These input coefficients determine how much each sector has to supply to produce one euro of electricity. This is essentially a break down into cost shares by sector from which the product or service that is needed for the production of electricity occurs.

<sup>9</sup> To adjust technological detail, we derived cost shares for advanced biomass and coal pulverized power plants from the cost structure of the respective combined cycle counterparts. For this we scaled the combined cycle cost shares calculated by TIMER with the ratio of cost shares between the two technology types in [NETL \(2010\)](#). The carbon price share was scaled by the ratio of fuel shares. As wind is not further specified in TIMER, we use the same LCOE cost structure for on and offshore wind.

<sup>10</sup> The reason for this is a supply curve effect in the TIMER model: With less mitigation options, less economical low-carbon options have to be used more in order to reach the same mitigation target. To make them competitive to CO<sub>2</sub> emitting options, a higher carbon price has to be assumed.



To construct the vectors of input coefficients we use the breakdown of LCOE from respective CCS and NOCCS TIMER scenarios. These represent life cycle cost aggregated to a breakdown of 7 items (see first column Table 1). Next, the cost shares are further disaggregated and allocated to regions and sectors according to the sector classification in EXIOPOL-2050. Assumptions made to allocate costs to sectors are listed in Table 1. For the implementation of the advanced thermal plants, we have used a weighting method

to allocate cost components to different industries based on information of similar technologies in EXIOPOL-2050. In formal terms, the input vector of coefficients  $a$  can be derived (separately for intermediate and value added inputs) by:

$$a = \left( (C * \widehat{a_{ref}})^{-1} * (C * \widehat{a_{ref}}) \right)' * Q$$

**Table 1**  
Overview of cost share allocation.

Cost share	Allocation
Transport cost	Split and allocated to sectors according to the input cost structure of the pipeline transportation sector in EXIOPOL-2050. The cost structure of the pipeline transport sector was chosen because inputs to this sector are most similar to CO <sub>2</sub> transport with pipelines.
Storage cost	<b>Step 1:</b> Split into EOR and other storage. <b>Step 2:</b> Split of the fraction of CO <sub>2</sub> stored with enhanced oil recovery (EOR) into <i>gross storage cost</i> and <i>oil-revenues</i> according to assumptions in NETL (2011a) <sup>a</sup> . <b>Step 3:</b> <i>Oil-revenues</i> : Allocated to oil mining sector (with a negative sign as we assume that the oil is sold to this sector). <i>Gross storage cost</i> : Split and allocated to sectors according to the input cost structure of the oil mining sector in EXIOPOL-2050. The cost structure of the oil mining sector was chosen because inputs to this sector are most similar to storage of CO <sub>2</sub> in geological formations.
Transmission and Distribution cost	<b>Step 1:</b> Split according to EIA (2014) into 30% transmission cost and 70% distribution cost. <b>Step 2:</b> System integration cost for renewables were added to transmission costs, which were then allocated to the transmission of electricity services while distribution costs were allocated to the distribution and trade services.
Carbon price/credit	Allocated to other net taxes on production. The carbon credit is treated as a subsidy. (see SNA, 2008, p. 148)
Fuel	<b>Step 1:</b> Split into agricultural and woody biomass based on production shares in TIMER.
Biomass	<b>Step 2:</b> <i>Agricultural biomass</i> : Inputs from Western European production were split into different agricultural crops based on Wit & Faaij (2010). <b>Step 3:</b> <i>Agricultural biomass from W. Europe</i> : further split and allocated based on information of similar technology in EXIOPOL-2050. <i>Agricultural biomass all other regions</i> : allocated to all agricultural sectors based on information of a similar technology in EXIOPOL-2050. <i>Woody biomass</i> : allocated to sectors forestry, wood manufacturing, and pulp and paper production based on shares in EXIOPOL-2050.
Coal	<b>Step 4:</b> Adjustment of regional allocation of biomass trade shares based on trade shares from TIMER (excluding transport margins). <b>Step 1:</b> Allocated to coal mining sector.
Natural gas	<b>Step 2:</b> Adjustment of regional allocation of trade shares based on trade shares derived from TIMER (excluding transport margins). <b>Step 1:</b> Allocated to the sectors natural gas extraction, manufactured gas and the distribution services, based on the distribution between these sectors of a similar technology in EXIOPOL-2050. <b>Step 2:</b> Adjustment of regional allocation of trade shares classified as natural gas extraction products based on trade shares derived from TIMER (excluding transport margins).
Oil	<b>Step 1:</b> Allocated to oil mining sector. <b>Step 2:</b> Adjustment of regional allocation of trade shares classified as oil mining products, based on trade shares derived from TIMER (excluding transport margins).
Uranium	Allocated to uranium mining sector. Regional distribution based on existing information in EXIOPOL-2050.
Investment cost	<b>Step 1:</b> Split of total investment into Total Overnight Cost (TOC) <sup>b</sup> and capital financing cost. The investment cost share in LCOE is annualized (with a 10% discount rate in TIMER) and include interest during construction (IDC). We calculate the capital financing cost as: $\text{Capital financing cost} = \frac{\text{CRF} \times \text{TASC}}{8760 \times \text{Load factor}} - \frac{\text{TASC}}{8760 \times \text{Load factor} \times \frac{\text{Life Time}}{\text{Life Time}}} + \frac{\text{IDC}}{8760 \times \text{Load factor} \times \frac{\text{Life Time}}{\text{Life Time}}}$ (CRF = capital recovery factor, TASC = total as spent cost) Capital financing cost is calculated in this way as this subtracts costs that are not associated directly with the supply of a physical power plant component. <b>Step 2:</b> Financing cost were allocated to remaining operating surplus. <b>Step 3:</b> <i>TOC of Advanced thermal plants</i> : further split into cost shares with engineering studies of NETL (2012, 2010) <sup>c</sup> , and further split and allocated according to the breakdown of capital cost, originally from EU KLEMS (2009) (see Supplementary information 1.2) <sup>d</sup> . <i>TOC of renewable, conventional thermal and nuclear</i> : Allocated according to the breakdown of capital cost, originally from EU KLEMS (2009) (see Supplementary information 1.2) <sup>e</sup> .
O&M	O&M of Advanced thermal plants: <b>Step 1:</b> Split into cost shares with engineering studies of NETL (2012, 2010). <b>Step 2:</b> Split further and allocated based on information of similar technologies in EXIOPOL-2050. O&M of renewable, conventional thermal and nuclear: <b>Step 1:</b> Split and allocated according to breakdown in EXIOPOL-2050, excluding coefficients of fuel cost, production tax, operating surplus, financial services, as well as transmission and distribution cost as these were determined by the other LCOE components.

<sup>a</sup> The assumptions about the oil profit in NETL (2011a) have been compared to the assumptions in Bock et al. (2003), which turn out to be similar to NETL (2011a).

<sup>b</sup> Refers to TOC as defined in NETL (2011b).

<sup>c</sup> No cost data for bio-energy fired IGCC were available. Thus, the same detailed cost structure for these LCOE shares as of coal fired combined cycle plants were used.

<sup>d</sup> Note, by this method, we internalize capital cost for power producing technologies which are normally part of the exogenous value added account "fixed capital formation". We do this in order to account for upstream effects of capital inputs to electricity production. However, we do not internalize capital for any other sector than the power sector. Note further, that capital inputs are only defined by capital type and thus imports are not accounted for on the first production layer, but only from the second production layer onwards.

<sup>e</sup> See previous footnote.

where,  $\hat{\cdot}$  means diagonalization and  $\cdot'$  means transposing,  $\mathbf{a}_{\text{ref}}$  is the input vector of coefficients of a similar (reference) technology,  $\mathbf{Q}$  is the vector of cost items to be allocated to one or multiple sectors of the IO-Model classification, and  $\mathbf{C}$  is a binary concordance matrix between original cost classification and the classification of the IO-Model.

The vectors of input coefficients per technology group (Fig. 3 graph (a) and (b)) show the distribution of cost shares after allocating LCOE cost components to (aggregated) input sectors for each technology group. High fuel costs of thermal power options result in high input coefficients from fuel producing sectors (e.g., mining or agriculture and forestry). System integration costs result in a significant input share of “transmission and distribution of electricity” services for all technologies. These are higher for renewables because of additional system integration costs. Furthermore, the CO<sub>2</sub> price results in large value added shares of thermal power without CCS. Conversely, a large subsidy reduces the value added of BECCS as subsidies are seen as negative value added component from the macro-perspective of an IO-Model. Value added of renewable and nuclear power consists to a large share of operating surplus or wages. This is a result of the higher non-fuel O&M costs and the higher investment cost compared to thermal options.

#### 2.4. Trade of fossil and biofuels

The future fuel import shares are based on the trade module outcomes of the TIMER model, described in detail in [de Vries et al. \(2001, p. 120\)](#). While fossil fuel trade shares are adjusted for all sectors, biomass trade shares are only adjusted for electricity production from bio-energy. Transport cost is excluded from the value of fuels traded between regions.

#### 2.5. Expenditure on electricity as final demand

The third data set from TIMER used in the IO-Model is the total expenditure<sup>11</sup> (final and intermediate demand) for electricity. These are calculated from the LCOE<sup>12</sup> and physical electricity production per technology. This results in the final demand vector consisting only of expenditure on electricity to satisfy final and intermediate power demand of Western Europe. Thus, the impacts calculated in the IO-Model are only induced by the demand of electricity in Western Europe.

Fig. 3(c) shows the breakdown of the final demand per electricity producing technology for the two scenarios in billion €. Unlike physical electricity production, expenditure on electricity is higher in the NOCCS scenario – mainly due to the higher carbon price and higher investment expenses. However, the share of each technology in the portfolio is roughly similar to the physical distribution in Fig. 2(c).

#### 2.6. Direct employment coefficients for power production

Power production from the TIMER scenarios was also used in combination with physical labor requirement factors for which a data set was compiled using information from [BBC \(2009\)](#), [Scottish Enterprise \(2011\)](#), [Rutovitz & Harris \(2012\)](#), [Shell \(2014\)](#) and [Wei et al. \(2010\)](#). These were projected to 2030 and remain the same for

2050. Labor requirement factors for conventional and renewable plants were projected using annual decline rates given in [Rutovitz and Atherton \(2009\)](#). Labor requirements of advanced power plants (with and without CCS) were projected to 2030 given optimistic and pessimistic annual decline rates of investment costs in [Koelbl et al. \(2014b\)](#), based on the suggestion of [Rutovitz and Atherton \(2009\)](#) (Detailed assumptions and original data can be found in Supplementary material). Note that direct employment in this study includes only employment from operation of the plant, while employment from constructing and manufacturing is accounted for in the upstream effects via the IO-Model.

### 3. Results

We present our results beginning with the aggregate level of Western Europe. Then, we zoom in on the sector level.

#### 3.1. Macro-level differences of employment, GVA and trade balance impacts in Western Europe

In Table 2 macro-level impacts are listed for each scenario in 2050. First, overall output generated directly and indirectly by electricity production in Western Europe is slightly lower in the CCS scenario relative to the NOCCS scenario. Furthermore, about 25% less Gross Value Added (GVA) is generated in the CCS scenario than in the NOCCS scenario. Also, import dependency is stronger if the CCS strategy is realized. Yet, total employment in Western Europe is higher by 1% in the CCS scenario.

##### 3.1.1. Gross output

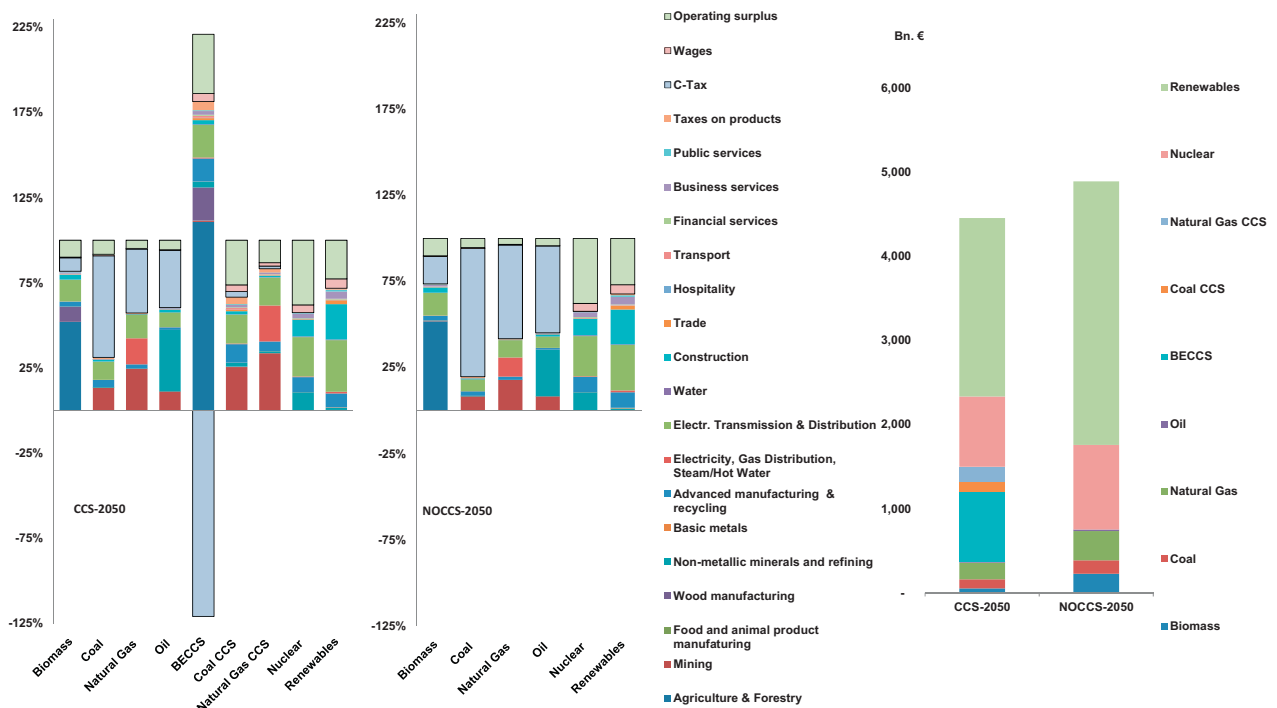
Slightly lower total output in the CCS scenario than in the NOCCS scenario is the net effect of two opposing forces caused by the differences between the electricity portfolios. First, direct gross output of the electricity sector in the CCS scenario is lower by almost 9% (Table 2), reflecting the relative difference in total expenditure. Total expenditure is higher in the NOCCS than in the CCS scenario. As less production options are available in TIMER in the NOCCS scenario, a higher carbon price is necessary to reproduce the same emission pathway than in the CCS scenario. This goes back to the assumption of upward sloping supply curves, which reflect that less cost effective resources have to be used (for instance, wind mills will be built in areas more complicated to reach).<sup>13</sup> Consequently, expenditures on investments, operation and maintenance and taxes are higher. This leads to higher total spending on electricity production in the NOCCS scenario than in the CCS scenario.

Second, higher upstream market expenditure in the CCS scenario cause higher indirect effects. This results in higher indirect gross output of 6%. Upstream market expenditure is higher in the CCS scenario (despite higher total expenditure in the NOCCS scenario), because the power sector pays fewer taxes, and additionally receives large amounts of subsidies for using BECCS. Thus, more money is available to demand inputs for electricity production. This results to a large part in substantially higher spending on fuel (almost 100 billion €) and outweighs the higher spending of the NOCCS scenario on investment, O&M and system integration costs. (As the government is exogenous, upstream effects of additional government consumption from tax revenues and lower government consumption due to subsidy payments are not taken into account). The net result of the lower direct output effects and the higher upstream market effects is the slightly lower gross output in the CCS scenario on the total Western European level.

<sup>11</sup> All costs, if not stated otherwise, were converted to Euro<sub>2007</sub> using the producer price energy index from [OECD.stat \(2013\)](#) and a conversion rate of 1.37 USD<sub>2007</sub>/EUR<sub>2007</sub> ([Eurostat, 2014](#)).

<sup>12</sup> The reason for using this approach is that investment costs are distributed over the lifetime and therefore, it takes into account the differences in lifetime of different power options. This is reasonable as we can assume a steady state because at this level of aggregation and point in time capital expenditure should roughly equal total investment.

<sup>13</sup> Note: this is the case despite the fact that learning by doing is implemented in several parts of TIMER.



**Fig. 3.** Input shares into power production for each scenario per technology group in 2050 (Graphs (a) and (b)). The data for input shares to power production is divided into the shares of input costs for intermediate goods supplied by aggregate sectors. Value added components are framed in black. Graph (c) shows the electricity production portfolio per technology group in 2050 in billion €<sub>2007</sub>.

### 3.1.2. Gross Value Added

The subsidy for BECCS is the dominating factor that makes total European GVA lower by 25% in the CCS scenario. To see this, we can look at the breakdown of GVA into direct and indirect effects (in Table 2), as well as to the individual components of direct GVA in the power sector shown in Fig. 4. First, we can see in Table 2 that – similar as in case of gross output – upstream effects of higher expenditure generate more indirect GVA in the Western European economy (outside of the power sector) of about 19 billion €. However, this positive upstream effect is outweighed by the lower direct GVA within the power sector. The reason for this is that the subsidy reduces GVA as it is an expense from the European macro-level perspective. This can be seen in Fig. 4 from the disaggregated direct GVA into its three main components: gross operating surplus (red bars), wages (green bars), and taxes or subsidies (blue bars). The subsidy (blue bar of BECCS in graph (a)) makes around 100 billion € in the CCS scenario, and thus substantially reduces direct GVA in the

CCS scenario such that the difference of direct GVA to the NOCCS scenario becomes 131 billion € less. This is obviously much higher than the 19 billion € extra indirect GVA in the CCS scenario. Hence, the net effect is that the positive upstream impacts are strongly outweighed to about 112 billion less GVA in the CCS scenario.

### 3.2. Gross employment

Employment is higher in the CCS scenario despite the lower output and GVA, which is counter intuitive. Yet, in contrast to GVA, higher upstream employment impacts in the CCS scenario are large enough to outweigh lower direct employment impacts from power production. Direct employment from power generation adds up to about 130,000 less jobs in the CCS scenario, but this is offset by 154,000 more jobs from the upstream economy if CCS is used. The major difference between the CCS and NOCCS scenario causing this, is the difference in bio-fuel use. Bio-fuel use is much higher

**Table 2**  
Economic impacts of Western European electricity production in 2050.

		Gross output				Gross Value Added			
		Total Europe	Direct	Indirect		Total Europe	Direct	Indirect	
2050	CCS	1,032,840	445,829	587,011	Mio €	334,697	52,399	282,298	Mio €
	NOCCS	1,041,395	489,348	552,046	Mio €	447,162	183,510	263,652	Mio €
	Δ	–8,555	–43,520	34,965	Mio €	–112,466	–131,111	18,645	Mio €
	% Δ	–0.8	–9	6	%	–25	–71	7	%
		Trade Western Europe – ROW				Gross employment			
		Total W. European Imports	Direct	Indirect		Total Europe	Direct	Indirect	
2050	CCS	101,117	76,725	24,393	Mio €	1755	485	1270	1000 person
	NOCCS	33,931	11,603	22,329	Mio €	1731	615	1115	1000 person
	Δ	67,186	65,122	2,064	Mio €	24	–130	154	1000 person
	% Δ	198	561	9	%	1.4	–21	14	%

Note: Δ indicates the difference between the CCS and the NOCCS scenario (CCS–NOCCS).

% Δ indicate the difference between the CCS and the NOCCS scenario relative to the NOCCS scenario. Such that: % Δ = ((V.CCS–V.NOCCS))/V.NOCCS. Where, V.CCS and V.NOCCS indicate the value of the respective indicators for the CCS and NOCCS scenario.

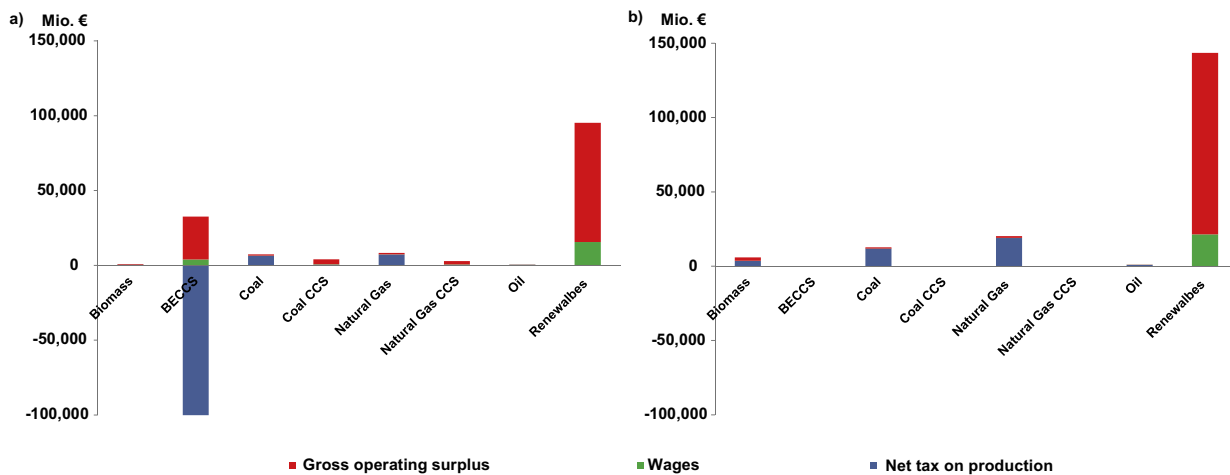


Fig. 4. Gross value added components per generation type in Western Europe of the CCS-2050 (a), NOCCS-2050 (b) scenario.

in the CCS scenario because BECCS is more competitive than other options. The subsidy for negative emissions plays a vital role here. The subsidy is however exogenous to the IO-Model and therefore the net effect of withdrawing this money from other economic activity is not taken into account.

### 3.3. Import dependency

Import dependency in the CCS scenario is higher for two reasons: First, the total value of imports is higher by 67 billion €. Second, imports are less regionally diversified in the CCS scenario.

Total imports are more in the CCS scenario, mostly because higher fuel consumption of the CCS inclusive power portfolio significantly increases direct imports. In particular, bio-energy imports contribute most to the difference, as they are higher by 63 billion €, while fossil fuel imports are higher by around 2.6 billion € in the CCS scenario. Hence, the assumed subsidy for BECCS does not only make fuel expenditures the dominating difference in the domestic upstream market, but could also substantially increase expenditure on foreign markets.

Furthermore, bio-energy imports are also responsible for the lower regional diversification in the CCS scenario. This is because bio-energy imports (as calculated in TIMER) in the CCS scenario are nearly all from Economies in Transition & Non-OECD Europe, OECD North America as well as Africa & the Middle East (Regions are defined in Supplementary material). Fossil fuel imports also come mostly from these regions, but only about 85% of the fossil fuel imports. About 15% are from three other regions. As bio-energy imports widely dominate total direct imports, their regional concentration dominates the overall direct import structure.

Fig. 5 illustrates the regional distribution of imports. In fact, more than 90% of the imports are from three regions in the CCS scenario. These are Economies in Transition, closely followed by OECD North America, and Africa & Middle East, from where respectively 44%, 32% and 18% of all imports are supplied in the CCS scenario. In contrast, import shares in Fig. 5 are more distributed over regions in the NOCCS scenario. Here, Western European imports to power production stem to 39% from Africa and the Middle East, followed by 17% from OECD Pacific and 16% from Economies in Transition and Non-OECD Europe. Together these make about 70% of all imports.

Fig. 5 clearly shows the dominance of the direct imports in the CCS scenario in the three regions. Unsurprisingly, this is dominated by the higher bio-energy imports. Almost the entire amount of woody biomass is imported from Economies in Transition & Non-OECD Europe. This makes more than half (63%) of the direct imports from this region, while agricultural imports contribute

with another 30% to the imports from this region in the CCS scenario. In contrast, fossil fuel imports make only 5% of all imports from this region. Similarly, imports from OECD North America are also mostly higher, because of the bio-energy imports. Bio-energy makes 94% of imports by the Western European power sector from this region. Also here, fossil fuel imports make only 3% of the imports in the CCS scenario.

### 3.4. Sensitivity analysis

In the first sensitivity analysis, biofuel trade shares were kept at the same level as in the original EXIOPOL database. This changes results on the macro-level significantly: Historical import shares of bio-energy are very low (roughly 15%). Therefore, the discrepancy in import dependency between scenarios becomes a lot less (total imports to Europe decrease from 67 billion euro to about 12 billion euro) if we assume no change in import shares of bio-energy crops in the future. Furthermore, the already strong indirect impacts of biofuel consumption in the CCS scenario intensify even more. Thus, the difference in total GVA is roughly halved to about 60 billion € less GVA in the CCS scenario. The upstream output difference increases by a factor of five changing the sign of the difference in total European output to about 140 billion € more output in the CCS scenario. Finally, additional employment in the upstream market rises by a factor of three and thus strongly outweighs the lower direct employment in the NOCCS scenario.

In the second sensitivity analysis, employment coefficients of power production are varied. One major factor in our study is the high employment coefficient of hydro power (0.4 jobs/GWh). Varying this by  $\pm 30\%$  (0.28–0.52 jobs/GWh) makes direct employment in the CCS scenario by 83,000–177,000 jobs less than in the NOCCS scenario. Together with the positive difference in the upstream market of 154,000 jobs, total European employment can be between 71,000 more in the CCS scenario up to –22,000 jobs less. Varying all coefficients by 30% at the same time spans a smaller range, but still changes the sign on the macro level from –15,000 less jobs in the CCS scenario to about 63,000 more jobs.

### 3.5. Sector-level differences

Zooming in on sector level results, (aggregated to 17 sectors<sup>14</sup>) of both scenarios as presented in Fig. 6(a) and (b), reveals three

<sup>14</sup> For aggregation details see Supplementary material.



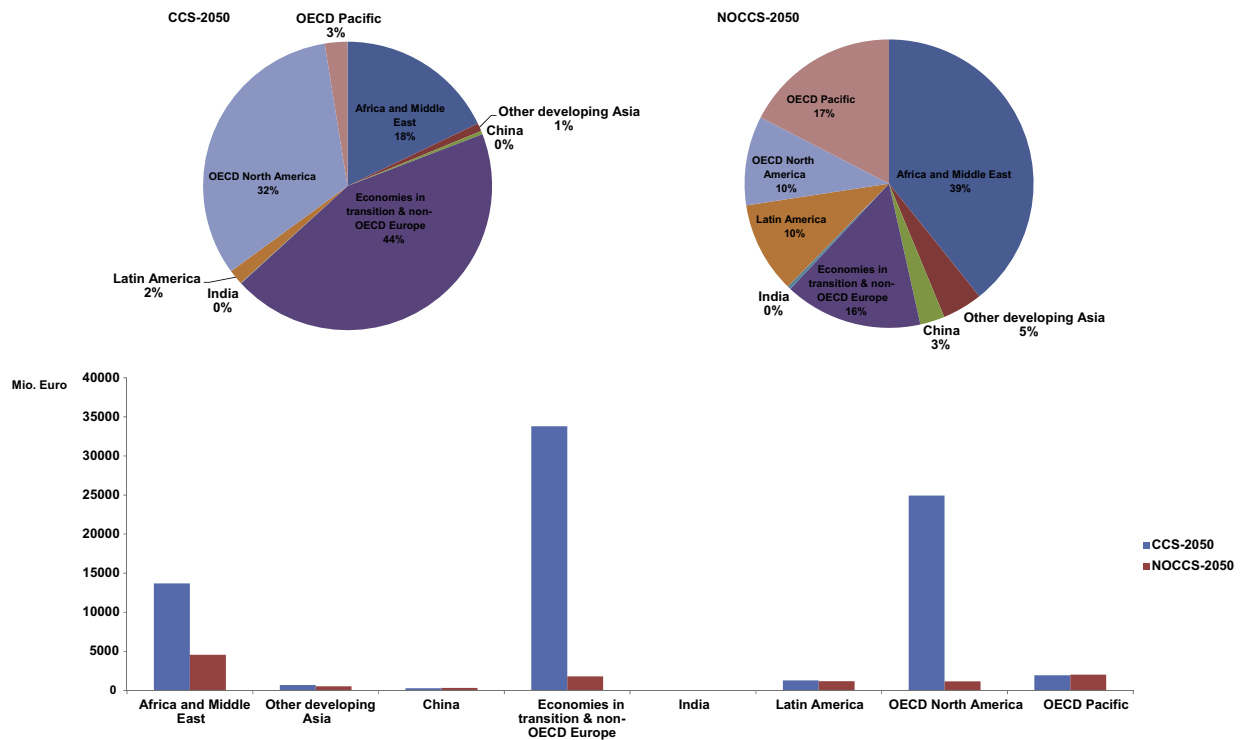


Fig. 5. Direct import shares to power production by region in 2050 and total direct imports to power production per region.

further insights, for 2050. First, for a few sectors the difference matters disproportionately more, than for other sectors. Second, some impacts can make a considerable share of the respective total sector results (i.e., total employment or GVA of this sector in EXIOPOL-2050)<sup>15</sup>. Third, primary and secondary sectors associated with fuel production for thermal power perform better under a CCS strategy, while some tertiary sectors may significantly benefit from the strategy excluding CCS.

The differences of GVA between the CCS and NOCCS scenario (indicated by  $\Delta$  in Fig. 6) span a wide range. For many sectors, the difference stays within a range of  $\pm 2$  billion €, or below  $\pm 10,000$  jobs in 2050. Also, relative to their sector size the scenario difference mostly stays below 0.5% of their projected sector result. However, some sectors show more extreme deviations between the scenarios.

Especially fuel producing sectors have higher GVA and employment when the CCS strategy is used. As shown in the method section, the final demand portfolio consists of more thermal power in the CCS scenario (Fig. 3), and because this leads to higher fuel costs (see LCOE breakdown in Fig. 2), the intermediate demand for fuels produced in primary sectors is higher in this scenario. This is especially reflected in the exceptionally large differences of results (Fig. 6(a) and (b)) for the agricultural sector and the mining sector.

Different upstream effects on agriculture and forestry, as well as manufactured wood demand lead to about 19 and 2 billion euro more GVA and 175,000 and 14,000 more jobs. In agriculture and forestry this difference makes more than 3% of GVA and more than 1% of the projected jobs. Thus, the CCS inclusive strategy is often

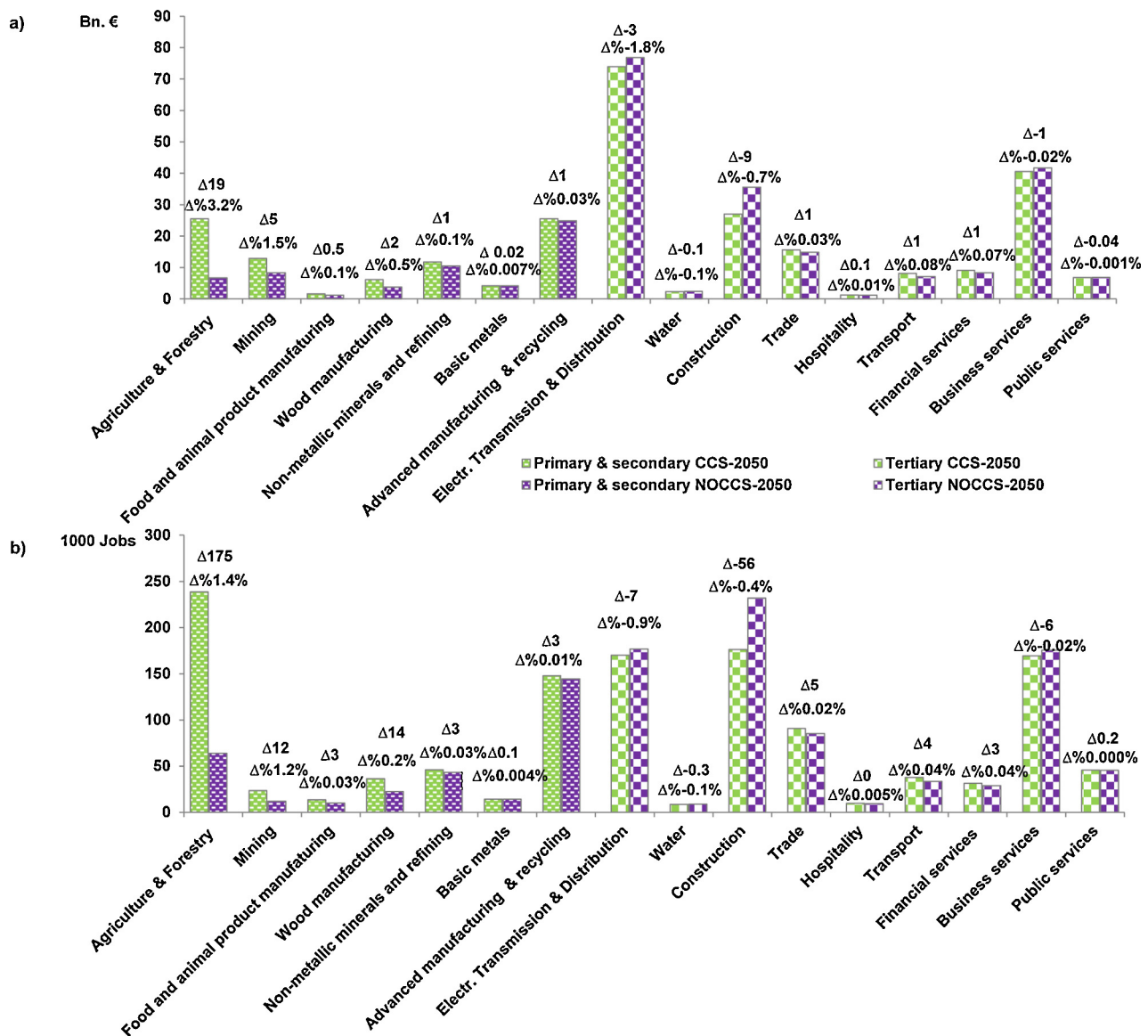
significantly more beneficial for primary and secondary sectors. This can be explained by the larger amount of bio-energy fuel used for BECCS. Similarly, more coal and natural gas could be used if their emissions are captured and stored. Therefore, we see more GVA in the order of 5 billion € and about 12,000 more jobs in the mining sector under the CCS strategy.

In contrast, significantly lower results under the CCS strategy can be found in some tertiary sectors. The portfolio with CCS produces less electricity with nuclear, hydro and wind power. Extra system integration services for wind power are assumed to be provided by the transmission and distribution service sector. Therefore, the results show about 3 billion € less GVA in this sector and 7000 less jobs. The former makes 2% of the projected GVA of this sector in this year and almost 1% of employment. Furthermore, these technologies have higher capital cost, for which we can see in the capital input vector<sup>16</sup> large shares are construction supplies. As a consequence we find higher inputs to electricity production from construction in the NOCCS scenario. This leads to around 9 billion € less GVA and about 56,000 less jobs in this sector in 2050 in the CCS scenario compared to the NOCCS scenario. Both, the transmission and distribution sector as well as the construction sector aggregates are classified as tertiary sectors. This makes around 1% of the mining sector GVA or employment.

Finally, this tendency is also reflected in the total aggregate numbers: the sum of primary and secondary sector result is higher in the CCS scenario than in the NOCCS scenario, while the sum of service sectors is lower when the CCS strategy is used. In primary and secondary sectors GVA is higher by 29 billion € and employment is higher by over 200,000 jobs. In the service sectors there is about 10 billion € less GVA and about 56,000 less jobs in the CCS scenario than in the NOCCS scenario.

<sup>15</sup> To understand the significance of the differences between scenario results for the individual sectors, we calculate how much this difference makes in the total sector result of the projected IO-Model (EXIOPOL-2050). We set the cutoff value to determine significance for the difference between the scenarios to  $\pm 2$  Bn. € GVA or  $\pm 5,000$  jobs, if the difference makes at least 0.5% of the sectors GVA, or employment in the respective sector of the EXIOPOL-2050 model.

<sup>16</sup> See Supplementary material for information and sources of capital input vector data.



**Fig. 6.** Indirect GVA (Graph (a)) and employment (Graph (b)) from W. European electricity generation in W. Europe upstream sectors in 2050 (for sector aggregation details see Supplementary material).

#### 4. Discussion

In this research, we used an IO-Model where we insert scenario data from an energy system model to look into the wider economic impacts of scenarios with and without CCS. This approach benefits from the dynamic representation of the energy system model and the detailed economic representation of the IO-Model. There are, however, still some key limitations of this system. Below we briefly discuss these and compare our results to expectations in the literature.

##### 4.1. Limitation of energy system model

The fact that we focus on CO<sub>2</sub> emission budgets raises the question of impacts of including non-CO<sub>2</sub> emissions from agriculture due to the different levels of biomass production. However, we assume second generation transport fuel or woody bio-energy with small non-CO<sub>2</sub> emissions. We account for them in the bio-energy price. More importantly, indirect bio-energy associated land-use

CO<sub>2</sub> emissions are accounted for by an emission factor (about 20% of the alternative fossil fuel, based on the IMAGE land use model—to which TIMER is normally coupled). We expect therefore that full coverage of non-CO<sub>2</sub> emissions in the budget would not lead to significant changes in the results.

Compared to other model runs, the price difference between the scenarios is not uncommonly large. For example, excluding CCS in a multi-model experiment in Krey et al. (2014) results in a cost increase<sup>17</sup> of up to four times the cost, compared to a full technology availability scenario. However, the price difference could be smaller. Although, the energy system model TIMER includes some dynamic features like learning-by-dong for renewable technologies, it lacks the influence of R&D on costs. Including additional dynamics could decrease prices faster. Especially in the absence of CCS this would lead to more accelerating effects for other low

<sup>17</sup> Measured as consumption loss, or by the area under the MAC curve.

carbon technologies. For this research this would imply a smaller carbon and electricity price difference between the two scenarios.

Moreover, as stated in the method section, the carbon price was calibrated to follow an emission pathway until 2050. After 2050 this emission pathway has to become negative in order to reach the target in 2100. This is only possible with BECCS. Therefore, the NOCCS scenario would require earlier and stronger mitigation action if CCS shall remain to be excluded after 2050. This implies that in this experiment we may even underestimate the difference in the carbon price before 2050 between the CCS and NOCCS scenario.

#### 4.2. Limitations of the IO-Model

Two IO-Model related caveats are especially relevant for this study. First, due to missing price effects, it is, for instance, impossible to anticipate how the larger demand for biomass can affect the consumption of agricultural or wood related products. Therefore, offsetting price effects are excluded from the results. Second, government consumption and spending is exogenous in the IO-Model. Making the government endogenous, could change results because expenditures on taxes and subsidies have a strong impact on direct results, but their indirect impact is cut off.

As we introduce the different electricity sectors of the two scenarios by stacking additional detailed input vectors to the original matrix of input coefficients (A-Matrix), we do not change any of the original IO-Model. This comes at the cost that upstream electricity demands are counted again. (We account for all industrial and household demand of power in the final demand vector). The difference in GVA between scenarios is however only 0.1% of the original size of the sector. Thus the difference does not significantly influence the results and upstream impacts of this “extra”-production can be expected to be negligible.

#### 4.3. Limitations of the study scope

This study focuses exclusively on the power sector. This ignores the impacts of investments in efficiency measures for end-use applications in the NOCCS. As costs are higher in the NOCCS scenario, about 3% less electricity is produced. Spending on R&D or investment and maintenance of more advanced end-use application is not part of the expenditure included in the final demand of the IO-Model. If this was included, employment and GVA would be higher in the NOCCS scenario and thus, the employment gap between the two scenarios would be smaller, while the GVA difference would be even larger.

Another issue neglected in this research is the interaction between CCS deployment and fossil fuel prices. One would expect that with the global availability of CCS fossil fuels are used more and hence fossil fuel prices rise. In this research we disable this mechanism by amending the fossil fuel prices such that they follow the prices in WEO (World Energy Outlook) (OECD/IEA, 2013) (see also Supplementary material). Thus, the impact of changing fuel prices is not taken into account for fossil fuels. With higher fossil fuel prices, the cost of thermal power would increase. Consequently, renewable power generation would replace thermal power generation in the CCS scenario. Therefore, the difference between the two scenarios could be smaller. This implies that results of this research may be less extreme under more dynamic real world conditions.

#### 4.4. Data limitations

Input vectors at the level of detail as in IO-Models are not available from bottom-up data. The refined allocation of the inputs for different technologies was generically derived for the EXIOBASE database. Moreover, we introduce further technologies as described in the method section. This may introduce inaccuracies

in the detailed input structure of the vectors. However, the major cost components are based on detailed bottom-up data and only the finer distribution is based on generic data. The main conclusions can therefore be related to the major assumptions and patterns in the bottom-up data. Thus, main conclusions of this research give reasonable indications about the difference between the portfolios.

Transport cost is a specific example to be discussed explicitly. Reports about power plant cost do not list transport cost of individual components separately. Therefore, we assume for newly introduced thermal plants that these are included in the delivery and are thus purchased further upstream. However, transport costs are listed separately in EXIOBASE. As we use this database as a basis for detailed cost allocations of some plant types, there is a mismatch between assumptions between different plant types. This may bias the impact on the transport sector. However, finding more transport activity in the CCS scenario seems reasonable, because indirect demands are higher and therefore more transport is taking place in this scenario.

Furthermore, we internalize capital cost for the power plants by distributing them as supplies over IO-Model sectors using data from EU KLEMS (2009). Capital goods there are specified by type of good but not by region of production. Therefore, we assume imports induced by capital goods only from the second production layer onwards, but no direct imports of capital goods. However, in order to test the sensitivity of results to this assumption, we use the regional distribution of import shares per good from the A-Matrix to further specify regional origin of the capital goods. This shows that the effect on macro-level results is marginal.

Uncertainty in employment requirements of future power options adds uncertainty to our results. We compared data compilations of Rutovitz and Harris (2012) as used in this study to values derived from Wei et al. (2010). The comparison shows that the range is large and that values derived from the two sources are not consistently higher or lower. A crucial value in this study is the employment coefficient of hydro-power as it contributes strongly to the result in 2050. To test the sensitivity, we vary labor requirements for hydro power by  $\pm 30\%$ . This results in a range of about 71,000 more jobs to around 22,000 less jobs in the CCS scenario. Thus, results can change significantly depending on the choice of labor requirements especially for those technologies where the difference in electricity production is large between the two scenarios. This implies that more intensive research is required to provide firm assumptions for this indicator in the power sector.

Further data uncertainty relevant for the results of this study comes from the uncertainty in system integration costs of non-biomass renewables, which play an important role for the difference between the CCS and NOCCS scenario results. System integration costs are very variable (IPCC, 2011). Values for wind power reported in the literature (as compiled in Brouwer et al. (2014)), can be up to 15.6 USD<sub>2005</sub>/MWh<sup>18</sup>. This would be up to 28% of the LCOE used in this study. The values from TIMER make between 16 and 20% of LCOE (excl. transmission and distribution cost) in our study. If these costs were higher, additional GVA and employment would be the outcome especially in the NOCCS scenario in 2050. Then, all else equal, the difference in aggregate impacts would be larger for GVA (as this is already lower in the CCS scenario) and smaller for employment (as this would partially level off higher employment of the CCS scenario) and vice versa if this cost parameter was smaller.

A comparison of LCOE used for 2050, to values found in the literature (OECD/IEA, 2014; Van den Broek et al., 2009), suggests, that values used in our study are rather conservative in comparison (see Supplementary material). This would, however, have little

<sup>18</sup> This number results from adding up the highest values found for all cost types (i.e., balancing, cycling and transmission investment costs).

impacts on the conclusion of our study, because we are comparing two portfolios, whereof one does not include CCS as an option. In contrast to this, relative cost competitiveness between technologies can matter for the results, because relative competitiveness determines the share of the technologies in the electricity production portfolio. This can impact the comparison, if the share of the technology that makes the major difference between the portfolios changes. Here, there is a considerable difference in thermal plants with biomass, which determines the large difference for the agricultural sector. If, for instance, more natural gas was used with CCS instead of biomass, GVA impacts could become stronger and employment impacts would be less severe, due to changes in GVA and employment intensity. This would, all else equal, decrease the difference between the two scenarios on the macro-level.

Biomass technologies play a key role in the scenarios but their availability is subject to large uncertainties and raises the question of food supply security. To confirm plausibility, we use estimates from the literature as a benchmark. First, global biomass use in 2050 is – as discussed in Koelbl et al. (2014b) – within technically producible ranges as assessed by IPCC SRREN (2011). Second, total modern biomass use in Western Europe is projected to be about 21 EJ/yr in 2050. Roughly 6 EJ/yr are produced domestically and about 4 EJ/yr are imported from Central Europe and Ukraine. The total potential of purposely grown and residue biomass for EU27 plus Ukraine calculated in De Wit and Faaij (2010) for 2030 ranges from 7.8 to 27.7 EJ/yr. This range covers the TIMER projections for 2050 of total use of modern biomass in Western Europe. Potentials in De Wit and Faaij (2010) have been calculated after accounting for land that would be required for food and animal feedstuff, livestock, building areas, and nature protection. This suggests that the calculations for this research are consistent with potentially producible resources. However, as also stressed by the IPCC SRREN (2011) this is subject to large uncertainty. Thus, the results of this paper are also afflicted with large uncertainties. Furthermore, according to the definitions given in IPCC SRREN (IPCC, 2011, p. 220), “technical potentials” “can”, but do not necessarily have to be estimated taking into account environmental protection. Therefore, the range of available biomass may be restricted further.

#### 4.5. Comparison to other studies

The outcomes of this study are hardly comparable with results presented in the literature as experiments comparing alternative strategies with a focus on the inclusion or exclusion of CCS have not been undertaken for Europe. Fankhauser et al. (2008) discuss employment effects arising from climate change mitigation policies. For CCS they expect lower employment effects if CCS is used. This expectation is based on the assumption that on the one hand the cost-performance ratio of high investment cost to employment in CCS “is likely to be low” (Fankhauser et al., 2008, p. 425), and on the other hand, they expect budget effects particularly from subsidies which might be required for CCS. In contrast, results of this study suggest, that employment is higher if CCS is part of the portfolio. We can depict four reasons, why our study does not confirm this expectation: First, labor requirements for power production with CCS in combination with biomass is higher than with fossil fuels or nuclear and high enough to compete with wind (see Supplementary material); Second, the indirect employment effect is larger in our scenarios, than the direct employment effect in all scenarios, thus lower direct employment in the CCS scenario is outweighed by the indirect employment generation. The latter is again majorly influenced by the additional biomass production. Third, as discussed before, budget effects are not taken into account in our study which makes them gross effects. Finally, employment from efficiency measures is not accounted for in this study.

## 5. Conclusion

In this study we made a static comparison of Gross Value Added, employment and imports resulting from power generation portfolios in Western Europe with and without CCS. We did that by integrating detailed technology based projections for power generation options from a bottom-up energy system simulation model into a projected version of an IO-Model. The scenario data was generated under a stringent mitigation target.

We used a hybrid method which allows for the integration of technology costs and scenario specific information into an economic IO-Model. For this we developed practical solutions to convert different types of cost breakdown of technology specific data (measured as levelized cost of electricity) into IO-Model specific classifications. However, as discussed, availability of more detailed technology specific data with a breakdown into IO-Model product or sector disaggregation is desirable for future research, if more detailed answers are to be investigated.

The static comparison for Western Europe indicates that excluding CCS from the electricity production portfolio may not lead to better results for all economic indicators looked at if BECCS is available (gross output, Gross Value Added, gross employment and import dependency). While the strategy excluding CCS leads to higher output, as well as GVA and comes with lower import dependency, a CCS inclusive strategy is associated with more gross employment, given that bio-energy is available and subsidized on a carbon price basis. The scenario that includes CCS comes with about 24,000 more jobs in Western Europe around the year 2050. This is because of higher upstream demands in the CCS scenario. The additional bio-energy demand plays an important role here as the major difference in jobs between the scenarios is from agricultural and forestry supplies. Gross Value Added is lower by about 112 billion € as high subsidies for BECCS outweigh the higher upstream impacts of the CCS scenario. Furthermore, import dependency is higher as more fuels have to be imported largely because of the higher bio-energy use in the CCS scenario. It should be noted that overall the NOCCS scenario uses less energy as a result of increased investments into energy efficiency. The economic impacts of these investments have not been accounted for.

Results are subject to large uncertainty. Results rest upon the use of BECCS and the production of bio-energy. Domestic production shares of this are uncertain. Using historical bio-energy import shares from the EXIOBASE database decreases the difference between the scenarios in import dependency and GVA, and intensifies the difference in gross employment. However, it is unclear whether domestic production potentials of bio-energy in Western Europe are sufficient to cover this level of production while respecting sustainability standards. Also, employment coefficients for future power plants are uncertain. The sensitivity analysis showed that the difference in direct jobs between the scenarios can become so large that the positive upstream effects in the CCS scenario are outweighed on the macro-level in favor of the NOCCS scenario.

The difference in GVA and gross employment between the scenarios is not distributed similarly between sectors. For a few sectors this can be a notable difference. The difference between the CCS and the NOCCS scenario for individual sectors varies from 9 billion € less GVA to 19 billion € more GVA in the CCS scenario in 2050. Gross employment results for aggregated sectors reach from 175,000 more jobs to 56,000 less jobs in the CCS inclusive strategy. Measured against their projected sector size in 2050 these individual sector differences can make more than 0.5% of their sector size in a few cases.

The results suggest that a CCS strategy comes with more employment and GVA for primary and secondary sectors. More fuel consumption in the CCS scenario must be a major reason for



the stronger concentration of economic activity in the primary and secondary sectors, as the difference between the two scenarios is largest for fuel producing sectors. In this particular experiment bio-energy producing sectors are affected the most, due to the major share of BECCS among the CCS technologies.

Outcomes also suggest that the CCS strategy is less beneficial for tertiary sectors like electricity transmission and distribution as well as the construction sector. The electricity and transmission sector shows higher activity in the NOCCS scenario due to more wind. This sector is assumed to supply the higher system integration efforts associated with wind energy. The higher GVA of the construction sector under the NOCCS strategy is a result of higher investment expenditure and larger shares of construction in nuclear and renewable power.

We recommend further research using a model that allows for price and budget effects as well as endogenous government spending. Results of this research are based on a static comparative analysis in an IO-Model. This excludes the influence of price, substitution and budget effects. Thus possible impacts from higher fuel demand in the CCS scenario are not accounted for in the results. Furthermore, government spending is exogenous. As taxes and subsidies play a noticeable role for the results, this presents some limitation to the qualification of these results. Therefore, this research should also be undertaken with a method that can take such effects into account.

Additionally, we recognize the need for more detailed power technology data with respect to inputs and employment. Although there is research on employment coefficients for several power producing options, we found little data about employment coefficients for advanced thermal power, in particular for CCS. As this information is important to assess and compare future power technologies, it is crucial to obtain solid estimates for this indicator. Furthermore, coefficients in existing literature span a wide range, indicating large uncertainty. This should be reduced as well to increase robustness of results. Finally, we find that detail of results could be strengthened with more refined data on the input structure for specific future power technologies. Especially a breakdown similar to IO-Model detail is required for this.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2015.08.010.

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