Analysing the water and land system impacts of Germany’s future energy system

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ABSTRACT

While it is generally accepted that our fossil fuel-dominated energy systems must undergo a sustainable transition, researchers have often neglected the potential impacts of this on water and land systems. However, if unintended environmental impacts from this process are to be avoided, understanding its implications for land use and water demand is of crucial importance. Moreover, developed countries may induce environmental stress beyond their own borders, for instance through extensive imports of bioenergy. In this paper, Germany serves as an example of a developed country with ambitious energy transformation targets. Results show that in particular, the politically-driven aspiration for more organic farming in Germany results in a higher import quota of biomass, especially biofuels. These imports translate into land demand, which will exceed the area available in Germany for bioenergy by a factor of 3-6.5 by 2050. As this will likely bring about land stress in the respective exporting countries, this effect of the German energy transformation ought to be limited as much as possible. In contrast, domestic water demand for the German energy system is expected to decrease by over 80% through 2050 due to declining numbers of fossil-fuelled power plants. However, possible future irrigation needs for bioenergy may reduce or even counterbalance this decreasing effect. In addition, energy policy targets specific to the transport sector show a high sensitivity to biomass imports. In particular, the sector-specific target for greenhouse gas reductions will seemingly promote biomass imports, leading to the above-described challenges in the pursuit of sustainability.

Keywords: energy system, land demand, water demand, nexus, Germany

Word Count: 9040

List of abbreviations including units and nomenclature

BG	Bulgaria
CCS	Carbon Capture and Storage
EEG	Erneuerbaren Energiegesetz (renewable energy law)

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EU	European Union
GDP	Gross Domestic Production
GT	Guatemala
HN	Honduras
HU	Hungary
IKARUS	Energy systems model
PV	Photovoltaic
SDG	Sustainable Development Goals
UA	Ukraine
UK	United Kingdom
US	United States of America

1 Introduction

Germany's energy system is undergoing significant transformation, primarily in order to reduce greenhouse gas emissions and thereby mitigate climate change. Ultimately, this transformation aims to achieve a generally sustainable energy system. In this context, much emphasis is given to the energy system itself, mostly centring on climate change mitigation and with numerous political targets set. Yet, as recent studies in other countries have shown, the impacts of the energy transformation on land and water systems, for instance in relation to land and water use, should be of equal importance in policymaking [1, 2]. Such effects can arise within and beyond national boundaries, such as through the import of biomass.

These water and land system impacts are of utmost importance, as sustainability is not limited to climate change mitigation, but encompasses further ecological goals, such as reducing surplus nitrogen or increasing the share of organic agriculture [3]. Hence, an integrated approach is needed to analyse the impacts of Germany's future energy system on land and water systems to avoid unintended side-effects, which may in turn lead to negative outcomes in the pursuit of a sustainable energy supply.

Previous studies on the water and land system impacts of future energy systems have mostly focused on local implications [4-8] or a global perspective, with the latter not assigning impacts to specific regions or policies [9, 10]. Moreover, several studies have utilised exogenous energy scenarios or demand assumptions [11-14]. Such assumptions hinder investigations into variants or bi-directional interactions of the energy system with the land and water system. Moreover, no research has been conducted to date on endogenously-derived scenarios exists that intensively analyses both the locally-induced demand for land and water within Germany related to the energy transformation, as well as land and water use elsewhere that is associated with imported bioenergy. Further details on the current status of analyses of the water and land system impacts of the future energy systems of Germany and other countries can be found in the Appendix A.

Here, the aim is to provide an integrated analysis for decision-makers with different options for water and land system impact evaluations of energy system pathways in Germany. To the authors' knowledge no study like this exist for Germany until now. Hence, this paper examines the potential water and land system impacts of Germany's sustainable future energy system as a case study of a developed country that has set ambitious clean energy targets and therefore faces the emerging challenges linked to their fulfilment. Herein, the locally-induced demand is analysed for both land and water in Germany in relation to the energy transformation. For this, an energy system model is applied that enables us to examine various permutations of the energy system's interactions with land and water resources, such as available land for bioenergy, the share of organic farming or the chosen types of power plant cooling systems. This enables creating tailored energy scenarios endogenously and to test variations in pathways and interactions, which would not have been possible if exogenous scenarios would have been utilized as some studies in literature has done. As the political framework defining the eligibility of land types for ground-mounted photovoltaic arrays still gives preference to non-agricultural land, the focus lays on land that can be used for bioenergy projects. In addition, land overseas is evaluated whose use is associated with imported bioenergy, which is a novel approach revealing otherwise invisible impacts abroad, and also critically discuss the domestic and 'imported' water used for bioenergy with respect to national water stress. In this context, the effect of a ban of palm oil and a stagnation in soybean oil imports is investigated for bioenergy applications.

In the following, the relevant aspects of the German energy system is briefly described within the context of this paper, as well as current land and water energy connections in Germany (more details on related policies are listed in the Appendix B). Then, this study's main contributions are outlined and the applied methodology described in more detail. The results of the analysis are subsequently presented and the paper concludes with a discussion.

Table 1. Overview of the objectives of the German energy transformation [15-17].

Objectives	**Base year and target years**					
	Base year	**2016**	**2020**	**2030**	**2040**	**2050**
Greenhouse gas emissions	1990	-27.2%	-40%	-55%	-70%	-80 to -95%
Primary energy consumption	2008	-6.5%	→			-50%
Gross electricity consumption	2008	-3.5%	-10%	→		-25%
Renewable share of gross electricity consumption		31.6%	35%	50%	65%	80%
Renewable share of final energy demand		15.2%	18%	30%	45%	60%
Primary energy demand building stock	2008	-18.2%	→			-80%
Final energy demand transport	2005	4.3%	→			-40%
Greenhouse gas emissions transport	1990	-2.0%	→	-40%	further reduction	

2 Background

2.1 The German energy system: Targets and relevant developments

Germany's targets for its energy system include a reduction of greenhouse gases by at least 80% by 2050 against 1990 levels, in tandem with specific sectoral targets, such as a reduction in the total final energy demand for transportation. While those two targets are within the focus of this study, the other goals are highly interlinked with them. A whole set of the targets aims at triggering an increase of renewable energies in different parts of the energy system like in gross electricity consumption or in final energy demand. Also the goal for the primary energy consumption promotes renewable energies as the respective policy neglects renewable energies in primary energy consumption. Another set of policy goals focus primarily at increasing energy efficiency for example by aiming for a reduction in gross electricity consumption, in primary energy demand for the building stock or in final energy demand in the transport sector. Finally, the aim to reduce greenhouse gas emissions specifically in the transport sector can only be achieved by higher efficiencies and fuels produced based on renewable energies. In this regard, biomass is one option to produce such renewable based fuels. An overview of the main targets is provided in Table 1 and further details on implemented energy policies can be found in the Appendix B and in Heinrichs & Markewitz, Heinrichs et al. and Hake et al. [16, 18, 19].

Driven by a variety of interests, including, for example, a reduction in current dependency on oil and gas imports, as well as in greenhouse gas emissions [20], bioenergy – comprised mainly of biomass, biogas, organic waste and residues – is often considered a significant, though controversial [e.g., 21, 22], source of sustainable energy. Much of the controversy is linked to its significant effects on land use patterns and land competition [23]. This has resulted in a new regulation by the European Commission [24], supplementing Directive (EU) 2018/2001, which imposes demanding sustainability rules for bioenergy and practically bans palm oil from contributing to renewable energy targets within the EU. In parallel, the planned phase-out of nuclear power and the scale-back of fossil-based electricity generation in Germany – the primary current link between the energy and water systems – will affect general water demand due to associated changes in water use for cooling. Currently, the cooling of thermal power plants is dominated by comparably expensive but water-efficient cooling towers. However, the extent to which current water use will actually decline along the transformation pathways of the energy system remains unknown. Moreover, the impact of a possible increase in bioenergy for electricity generation (with typically smaller-sized power plants and hence less water-efficient types of cooling) and thus also of water demand is yet to be quantified.

2.2 Land and water connections to the German energy system's

2.2.1 Land-energy connections

With the increasing role of bioenergy, the direct link between energy provision and (agricultural) land use will likely intensify [25]. In Germany, more than half (51.1%) of the surface area is currently used for agriculture, making this sector the largest land user [26]. In 2017, bioenergy crops made up 14% of those cultivated (i.e., 2,650 thousand ha) across areas currently used for agriculture [27]. However, between 1995 and 2015, the agricultural area decreased at an average yearly rate of change of 0.1% [28]. Almost all of this reduction occurred in areas of urban agglomeration and can thus be directly attributed to the effects of increasing urbanization [28]. The level of urbanization increased from 73.3% in 1995 to 75.3% in 2015; a trend that is expected to continue in the future [29]. Of the current agriculturally-used area (18.460 million ha in 2015), roughly 71% is used as arable land, 28% is permanent grasslands and 1.2% is used for permanent crops [30]. In 2015, 6.1% of the total agriculturally-used area was cultivated according to organic standards [31], while energy crops were produced on 13.4% of the total available agricultural land area [32]. Between 2005 and 2015, the share of organically-cultivated agricultural area in Germany increased by an average of 2.8% per year [33].

In the past, significant yield gains have been achieved through changes in production methods, including improved cropping techniques, fertilization and irrigation [34]. While actual yearly yields vary significantly relative to, for example, meteorological variations such as rainfall or temperatures, no or only marginal increases in average yield have occurred in Germany in recent years (i.e., 0.0% per year for wheat and 0.5% per year for sugar between 2000 and

2010). During this period, only the hectare yield of oily crops has developed more rapidly (by an average of 4.9% per year) [34].

A further link between energy provision and (agricultural) land use is the installation of solar PV farms. Between 2015 and 2017, the installation of new solar PV farms was regulated by EEG 2014 and had an associated land use of 939 ha, 232 ha of which are classified as arable farm land and 21 ha as meadows and pastures [35]. It can therefore be expected that the impact of solar PV farms on overall land use will remain comparatively small compared to the roughly 2400 million ha for biomass (cf. Section 3.3). Given Germany's heavy reliance on coal power, there has traditionally been a strong link between land use and energy. Until 2016, a total of 177,000 hectares of land had been claimed for lignite mining, of which 70% have been reconverted into areas for agriculture (28%), forestry (43%), water (19%) and other uses (10%) [36].

2.2.2 Water-energy connections

The energy and water systems in Germany are predominantly linked via electricity and heat generation, which account for nearly 68% of the country's total water demand [37]. In addition, water demand for mining and quarrying contributes roughly 3% to Germany's yearly water demand [37]. While hard coal mining as well as gas production will likely drastically decline over the next few years in Germany due to exhausted domestic reserves, lignite mining will most likely – although at a much lower level – remain a part of the German energy system for another one or two decades [18, 38, 39]. The specifics will mainly depend on the final political design of the German coal phase-out by 2038, which is currently under discussion [40]. Nonetheless, the impact of mining and quarrying on water demand will substantially decrease in the future and its effect can thus be neglected in future energy systems. Other typical links between the energy and water systems, such as agriculture or refining, account for roughly 1.5% and below 1% of German water demand [37]. One reason for this is that agriculture in Germany is mostly rain-fed and major parts of crop irrigation is utilized to grow vegetables [37]. However, .as Germany already has a comparably high water stress of above 40 [41] in accordance with the indicator of Sustainable Development Goal (SDG) 6.4.2 [42], this stress may increase further if the need for crop irrigation grows due to climate change or the current shift in energy supply towards more bioenergy. The SDG 6.4.2 indicator is also known as water withdrawal intensity and shows the ratio between freshwater withdrawal and available freshwater resources [42].

Hence, water demand relating to electricity and heat generation currently represents the only important link between the water and energy systems in Germany. Water demand in the energy sector almost entirely derives from the cooling operations of power plants [37]. In accordance with Koch and Vögele [43], water demand for cooling purposes is mostly determined by the type of cooling and fuel used in power plants. Typically, four different cooling types are distinguished: (a) once through cooling; (b) closed-circuit cooling; (c) hybrid cooling; and (d) air cooling [44]. The overall shares of these cooling types within the current German power plant portfolio are roughly 56% for closed-circuit, 14% once-through, 2% hybrid, 1% air and 27% unknown based on [45, 46] and own investigations. A closer analysis of power plants with unknown cooling types reveals that these are small in capacity, and typically located at industrial production sites, and so are often integrated into the local heat and steam system. Therefore, there is typically no substantial need for cooling in these cases as most of the heat is directly reused. The other shares of cooling types vary between the different power plant types and are independent of their fuel. While lignite and oil power plants are almost entirely cooled by closed-circuit cooling, other fossil and nuclear power plants also demonstrate a share of once-through cooling of 13-50%. Hybrid cooling is mainly conducted in nuclear power plants (12.9%), while air-cooling mostly takes place in small heating plants fuelled by solid waste.

3 Methodology

To analyse the impacts of Germany's future energy system on the country's and indirectly imported water and land resources, the development of the three systems including their linkages has to be derived. The chosen method is similar with the Foreseer™ tool [47], developed by the University of Cambridge, which project the pathways of the three systems (water, land, energy) and their connections into the future. Here, we go even beyond this approach by replacing the projection of the energy system by the full German energy system model, IKARUS [48-50], which is explained in more detail in Section 3.1 together with the required scenario framework. The usage of such an energy system models allows to calculate specifically for this analysis purpose tailored energy scenarios endogenously instead of using an exogenous scenario, which is in most cases identified in literature not created for this specific purpose and hence might bear some limitations for such an analysis. Furthermore, some variations for the projections of the land and water system are added in order to identify the effects of the selected parameters on possible future pathways. The projections of the land system (see Section 3.2) are used as a model input for IKARUS to constrain the use of bioenergy to the available land area, while the projections related to the water system (see Section 3.3) are combined with the IKARUS results to derive the energy system's prospective water demand. Based on the calculated bioenergy imports from the IKARUS model the imported land use is derived. The latter allows considering impacts on the land systems of biomass exporting countries, which would be invisible otherwise. Finally, a sensitivity analysis is added for the most challenging land use and water demand pathways by excluding single and all policy targets for the German transport sector within the energy system (see Section 3.1.3). By this, to evaluate how and to what extent a future German energy system might influence land and water use is enabled.

3.1 Modelling of the energy systems pathways in Germany

In this subsection first the utilized energy system model IKARUS is described followed by showing the scenario framework assumed for this analysis.

3.1.1 The energy system model IKARUS

On the basis of the subsequently described scenario framework, the established IKARUS energy system model is used for the actual investigation. In sum, IKARUS is a bottom-up, technology-rich linear optimization model that covers the entire German energy system. It minimises the total energy system costs in a myopic way, in that it separately optimizes each of the five-year time periods represented by a characteristic year from 2015 to 2050 and utilizes the results as the starting point for the next period. It has to be noted that 2015 serves as a calibrated base year covering the period from 2013 to 2017. As a base year 2020 would cover the period of 2018 to 2022 the base year 2015 represents the newest base year for which official statistics are already available. Hence, all results will be compared to this initial starting point. This myopic optimisation is complemented by constraints on the deployment rates of energy technologies based on historic values, which open up in later years to cover potential market and production adjustments. Thus, the model deviates from classical perfect foresight models and allows for a more realistic projection of future energy system pathways.

The energy system modelled by the IKARUS includes the complete energy conversion chain, from primary energy supply through energy conversion to final energy demand (see Figure 1). The final energy demand arises from the exogenously assumed sector specific demand drivers given in Figure 3. Along this chain, the model includes over 2000 energy technologies, not only energy conversion and transport technologies but also energy saving technologies. An increase in the living space to be heated can be countered, for example, either by thermal insulation or additional energy supply. Each of the technologies is represented by technical, economic and ecological parameters, including efficiencies, investment costs or CO_2 emissions (to only name a few examples). As CO_2 emissions constitute most of the greenhouse gases released within the energy system, the other greenhouse gases are not taken into account by the IKARUS. Political frameworks, goals and technical constraints are added in the form of model constraints. One exemplary constraint forces the model to include enough flexible load to counter intermittent renewable energies by assigning each power plant type a base load factor [51, 52]. The key outputs of the IKARUS model include capacity expansions of power plants, their utilisation, investments in efficiency measures across all sectors, primary energy supply, as well as final energy demand elements, such as information about fuels and applied energy chains. A further detailed model description of IKARUS is given in Martinsen et al. and Stein at al. [48, 53]. Because of this level of detail and the broad system boundary, the IKARUS is suitable for analysing effects arising from synergies or ‘sector coupling’ [16, 18, 38, 50, 54, 55]. Hence, it can support the identification of the impacts of different land pathways in the form of bioenergy potentials, as well as water pathways in accordance with different developments in the electricity mix.

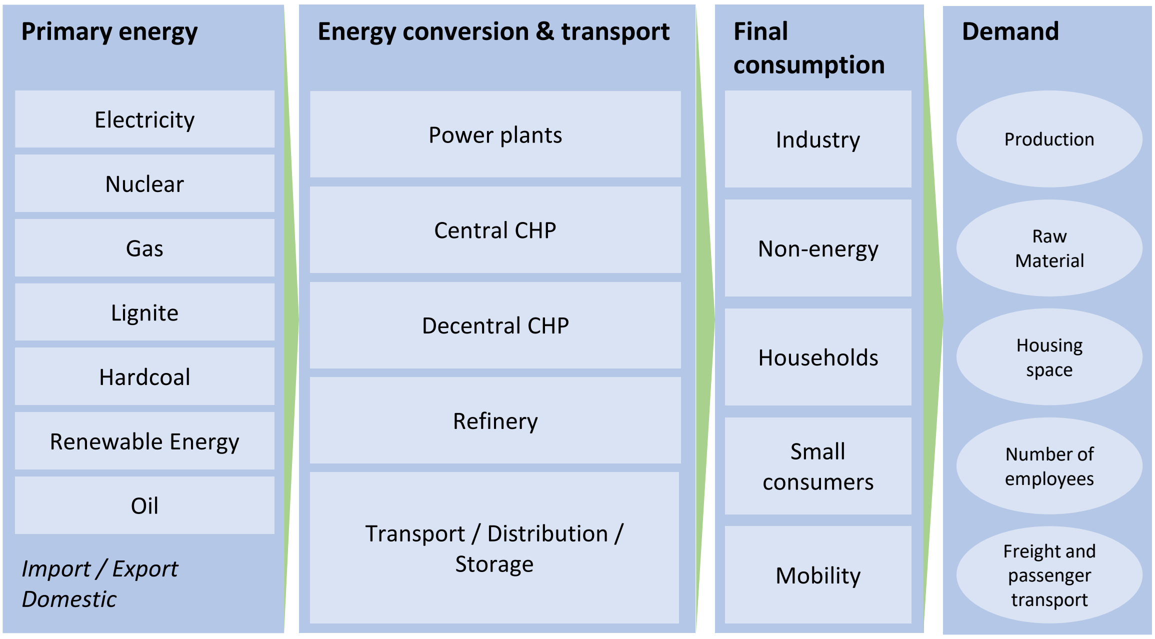


Figure 1. Schematic of the IKARUS energy system model.

3.1.2 Scenario framework for the energy system model IKARUS

To analyse the possible impacts of the future energy system on water and land, a scenario framework is defined as a starting point. This framework assumes that all of the current energy policies, as described above and in the Appendix B.1, will remain in force. Hence, carbon capture and storage (CCS) and the exploitation of unconventional fuels such as shale gas are not part of the scenario, as these are limited by legal restrictions. In addition, new policies for achieving the current energy policy goals are taken into account. This means that all of the energy targets set out in relevant policies, such reducing greenhouse gas emissions by at least 80% by 2050, would be achieved (see Table 1 and Figure 2). More precisely, this means that each row in Table 1 is implemented as a separate model constraint in the energy system model IKARUS, described in Section 3.2. Finally, the underlying optimization method determines with which measures these targets will be met. Figure 2 highlights the remaining challenge to achieve the political goals against the background of the historical development. This scenario is chosen due to it being likely to have a very significant impact on the land system. In addition, Germany’s electricity exports is exogenously assumed through 2050 [56] in order to achieve a scenario that is consistent at the European scale.

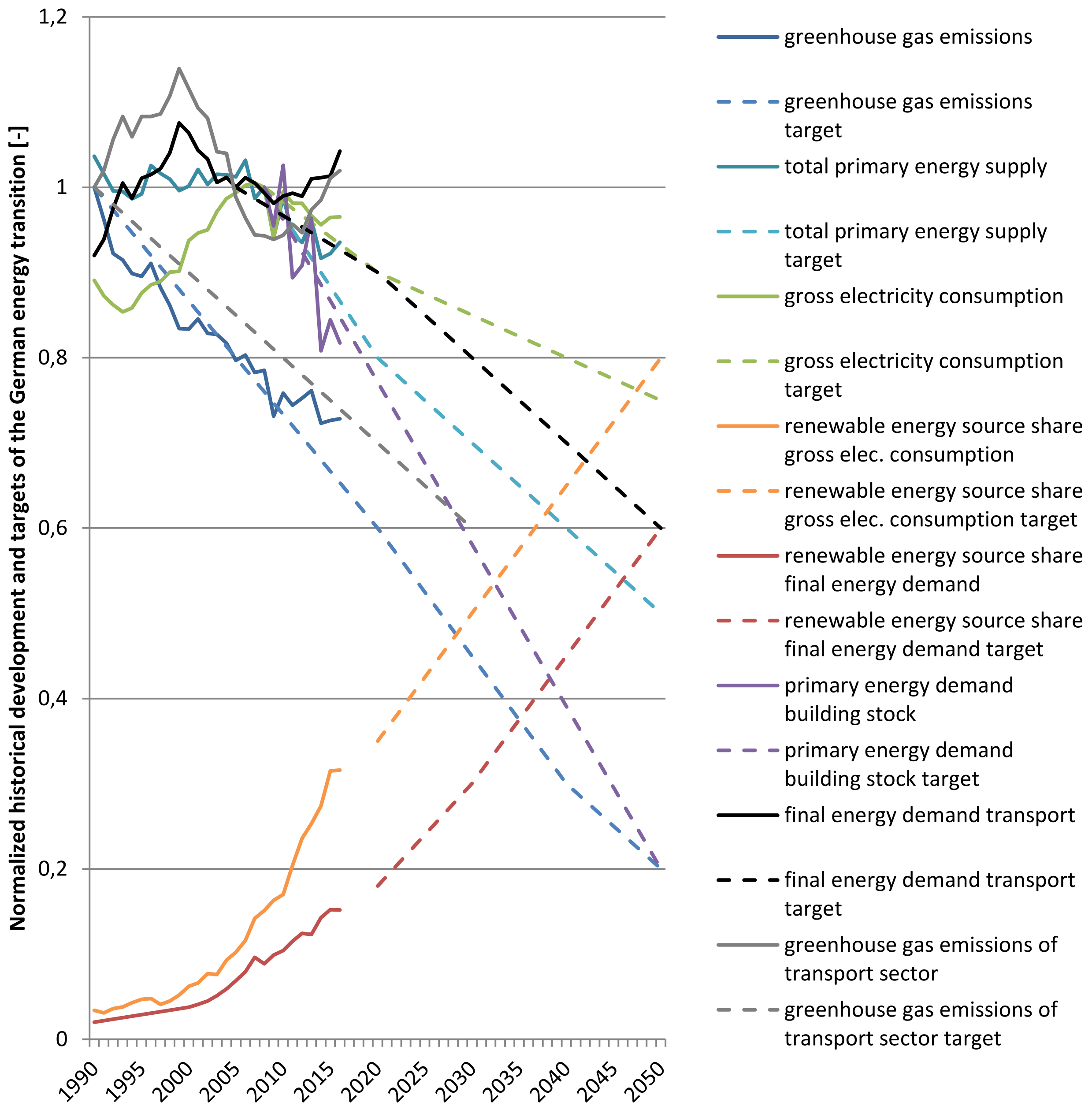


Figure 2. Targets of the German energy transformation and their current fulfilment (own representation based on [17, 57]).

The interactions of the energy and water systems in Germany are fundamentally linked to the operation of fossil-fuelled power plants. As current energy scenarios show a trend towards the phasing out of fossil-generated electricity in Germany [58, 59], the energy-land link is the main driver of the scenario and sensitivity selection.

The necessary socio-economic scenario framework for the energy system model IKARUS is taken from and described in detail in Gillessen [60]. The scenario assumes fuel and CO_2 certificate prices in accordance with the 450 ppm scenario of IEA's World Energy Outlook [61]. The exogenous demand drivers for the model's endogenous determination of the final energy demand of households, industry or mobility correlate predominantly with German population development. For the population variable, the scenario uses the G1-L2-W2 variant of the 13th official population projection of the Federal Statistical Office [62], which assumes only a moderate decline in Germany's total population from 82.2 million in 2015 to 77.4 million in

2050. The main influencing factors are a constant birth rate per woman of 1.4, an increase in the life expectancy of women to 90.4 years and of men to 86.7 years by 2060, and net immigration of 200,000 people per year. Based on historical trends, the gross domestic product (GDP) per employed person, the living space per person, the passenger transport per person and freight transport per GDP are projected. Combined with the assumed population development, these result in the exogenous demand drivers for energy services shown in Figure 3.

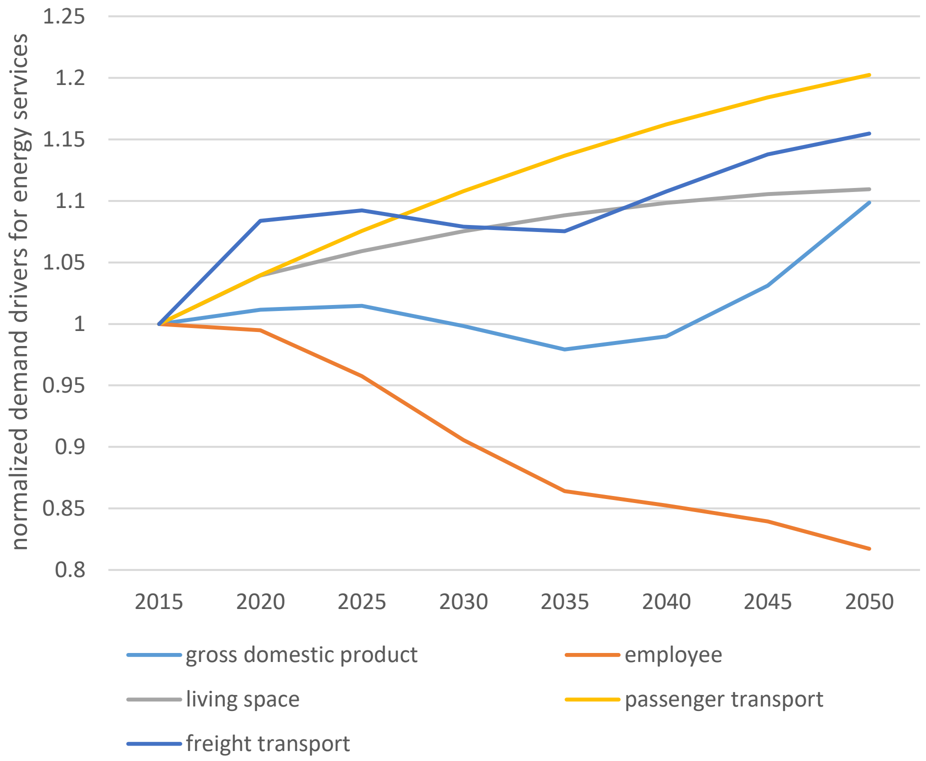


Figure 3. Exogenously-assumed, normalised development of demand drivers for energy services in accordance with assumed population development in Germany.

The trend for more living space per person to continue until 2050, is justified in more single households and an ongoing remanence effect. The employee number decreases significantly through an ageing society. With respect to the gross domestic product, a constant increase of gross domestic product per employee is expected. Due to sinking employee numbers, this leads to a minimum national gross domestic product in 2035. Afterwards the decoupling of the annual growth of the gross domestic product from numbers of employee leads to an increasing gross domestic product after 2035. This can be explained by a further increase in the division of labour and digitalization. The passenger transport increases continuously and, finally, the freight transport rises with a dip due to the temporarily weak gross domestic product development.

3.1.3 Sensitivity analysis regarding transport-specific targets

By excluding one or all targets for the German transport sector, the sensitivity of the results is investigated. The transport-specific targets include greenhouse gas reduction and final energy demand within the German transport sector, as well as the target for biofuel shares (see Table 1). Hence, four model runs (see Table 2) are calculated based on the most challenging land use variant (DALY).

Table 2. Sensitivity cases of targets for the German transport sector and base case for comparison.

Name	Description
DALY	All transport-specific goals (base case)
NON	No transport-specific goals
CO2	Only CO_2 reduction targets of the transport sector
DEM	Only final energy demand target of the transport sector
BIOFUEL	Only minimum share of biofuels

3.2 Deriving pathways of land requirements for bioenergy

In this subsection the derived pathway for the land system regarding its interlinkage to the energy system is explained. This pathway serves as an input for the energy system model IKARUS.

The most important aspects for determining the link between the energy system and land is the land available for bioenergy and achievable yields. As these aspects significantly affect the results, four variations are defined (see Table 3). The first variation assumes constant agricultural land (CAL) between 2014 and 2050 combined with constant yields, which represents a moderately optimistic development. In contrast, in DAL (decline in agricultural land), an ongoing constant decrease of 0.1% in the available agricultural area is assumed in the model calculations, in accordance with historical projections.

Table 3. Variants of the pathways for available land for bioenergy and the development of yields.

Name	Description
CAL	Constant agricultural land: the total agricultural land remains constant, while the land available for bioenergy increases due to a decline in the German population
DAL	Decline in agricultural land: the total agricultural land declines in accordance with historical trends
DY	Decline in yield: while the total agricultural land remains constant, yields decline due to an increase in ecological agriculture
DALY	Decline in agricultural land and yield: combination of DAL and DY

In both variants, the area currently used for agricultural production without bioenergy, which contains a major part for direct or indirect food production, is subtracted from the total area used for agriculture in order to estimate the area available for energy crop production. The land required for agricultural production other than bioenergy depends on the evolution of the national population, as no change in good imports and exports is assumed to avoid mixing the national and international effects of good production. Moreover, the land for agricultural production without bioenergy is differentiated in conventional and organic agriculture, both types of agriculture are related to the total German population and those shares are projected based on their historical development through 2050. This is finally combined with the population decline described above and the results in the agricultural land development in Figure 4.

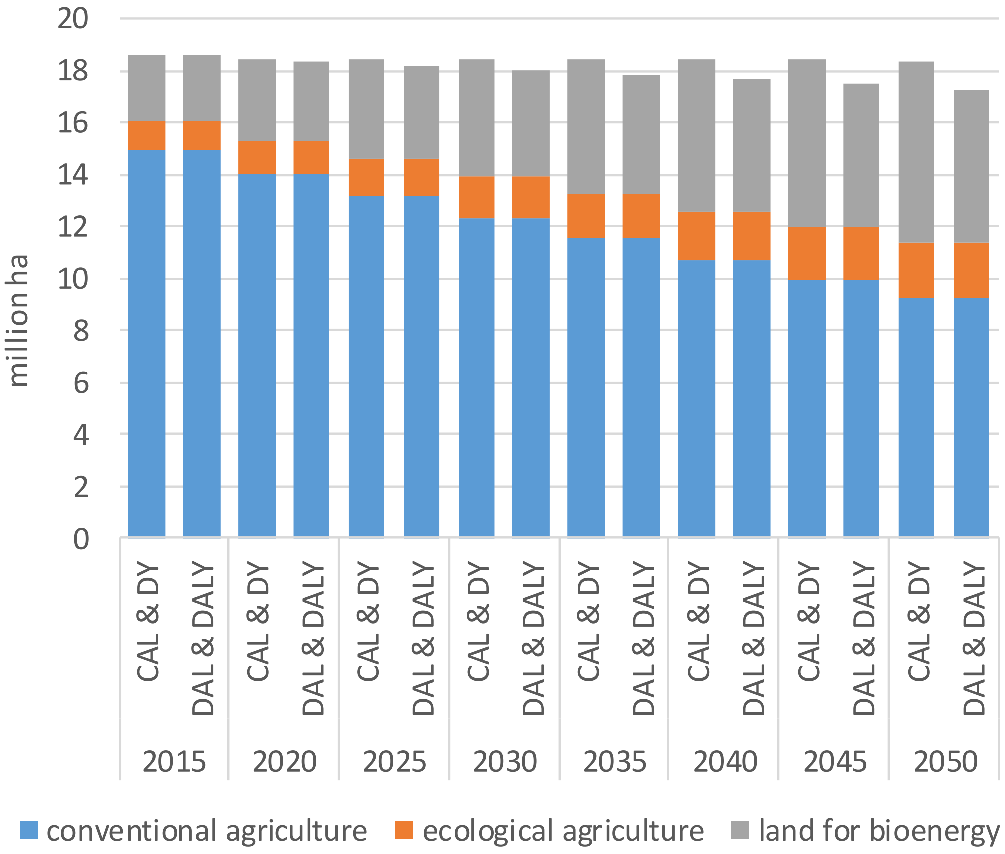


Figure 4. Development of agricultural land and land available for bioenergy.

In order to estimate the future potential of bioenergy, in addition to land use changes, considerations of yield development were also included in the analysis. Assuming the general trend in conventional farming practice will not change and that average hectare yields will remain largely constant, the share of organic farming in total agricultural production will be the main influence on hectare yields. As part of its contribution to the German sustainability strategy and the implementation of the Sustainable Development Goals (SDGs), the German Ministry of Food and Agriculture (BMEL) recently restated its objective to expand the share of organic farming from the current level of ~6% to ~20% by 2030 [31]. As this target refers only to agricultural land in total, it is assumed that levels in organic farming will apply to all agricultural land as a conservative approach. Although the specific temporal target for achieving this objective remains unspecified, a medium-term implementation will require the rapid expansion of organic farming. To reach the goal of 20% by 2025, the annual rate of change will have to jump rapidly, to 12%, in the coming years, as is assumed in our calculations in the DY variant. The DALY variant combines the decline in agricultural land of the DAL and that in the yields of the DY, making it the most challenging variant.

The above-described approach to projecting the future potential of bioenergy only applies to bioenergy crops raised on agricultural land. For biomass types such as (residual) wood, organic waste and residual straw, which have no direct need for agricultural land, an alternative approach is opted for. For all residual bioenergy types, an increasing exploitation of the existing potential is assumed. For non-residual wood, full exploitation would negatively affect the nutrient balance of forests, and so the bioenergy potential of wood is limited to a share that sustains this nutrient balance [63]. In addition, a correlation to the population development is assumed for all organic waste types such as urban waste, the excrement of animals and waste from trade and industry, as well as sewage gas, landfill gas and crop residues from food production. Moreover, land use for open-field PV is incorporated through an upper limit, as its expansion depends more on regulations than land availability.

In all variants, the imports of bioethanol and oily crops are permitted as German agriculture relies heavily and increasingly on international trade, with significant effects on the global land footprint. This holds especially true for low-processed (often land-intensive) goods, which are imported and then further domestically processed or used as fodder with the objective of re-exporting them [26]. These imports are used to identify potentially imported land use, which may cause conflicts relating to the land system in other regions of the world, possibly leading to competition with food production.

To identify such countries, which are burdened with providing this ‘imported’ land used for bioenergy elsewhere, the main producing countries must be identified. In this study, the focus lays on the cheapest oily crops, which include soy oil (HS4 number 1507), palm oil (HS4 number 1511), sunflower oil (HS4 number 1512) and rapeseed oil (HS4 number 1514) [64, 65]. In order to avoid the impacts due to yearly changes in weather conditions, average imports between 2010 and 2017 are utilized. As the listed exporters are not necessarily the producing countries but can be transit countries, the trade chains have been traced back to the producing countries. For these biomass trade pathways, the biomass trade balances of Germany’s neighbouring countries for each of the four oily crops listed above are further traced until the biomass-producing countries are identified. In this way, the possible effect of additional induced needs for biomass imports in neighbouring countries due to exports to Germany is avoided.

In total, over 75 countries were identified as exporters of oily crops to Germany. Currently, countries exporting biomass to Germany with a trade volume of above 1 million tonnes across the four oily crops are Indonesia (3.76 million t), Malaysia (2.50 million t), Papua New Guinea (1.32 million t) and Hungary (1.03 million t). The energy content of these imports is scaled with a factor in accordance with the calculated biomass imports in 2050 from the IKARUS model. These imports form the basis for calculating remote land use within the exporting countries by applying the most recent country-specific yields for the four oily crops [66]. Today’s trading pattern is assumed to remain unchanged for a first approach (A), while in a second approach (B) palm oil is excluded from the biomass imports and soybean imports are fixed to their current level. The second approach is based on the new regulation of the European Commission [24] that practically bans palm oil in the pursuit of the targets of the European Renewable Energy Act [67].This naturally increases the effect on rapeseed- and sunflower-exporting countries, which must be scaled to meet Germany’s import demand.

3.3 Deriving pathways of cooling water use for German electricity generation

This subsection explains how the pathways for the water system are derived. The main focus lays on the cooling water use as the main interlinkage between the water and energy system in Germany. The pathway for cooling water use is combined with the IKARUS results to derive the water demand of the future energy system in Germany.

Starting from today’s situation, the shares of cooling system types of power plants must be projected into the future in order to evaluate the water demand of future energy systems. For the existing power plant mix, no replacement of cooling facilities is assumed. For all newlyinstalled power plants, a few different possible pathways are considered, and are listed in Table 4.

Table 4. Variants of pathways for the shares of cooling types.

Name	Description
PAU	Business-as-usual: overall shares of cooling types remain constant for new power plants
DG	Decentralised generation: increase in closed-circuit cooling due to more decentralised power plant locations that are often too far away from available water for once-through cooling
NCT	No cooling towers: due to a lack in public acceptance, no new cooling towers are allowed to be installed, resulting in almost 100% once-through cooling systems for new power plants

Furthermore, the water demand and consumption factors for each combination of cooling and power plant type are also necessary for determining the overall water used for cooling. The approach described in Koch and Vögele [68] is applied for once-through and closed-circuit cooling to adjust water needs to the German case. For hybrid cooling, the water needs of closed-circuit cooling in summer and of once-through cooling for the other seasons are assumed in accordance with Koch and Vögele [68]. Finally, for air cooling the values used by Konadu et al. [69] are applied.

In combination with the electricity generation derived from the IKARUS results, the pathways of the total national water demand were calculated. Moreover, in order to calculate agricultural water withdrawal for bioenergy exported to Germany as percentage of total water withdrawal of each exporting country, the share of cultivated land needed for bioenergy exported to Germany is derived based on ‘imported’ land used without crop rotation (for approach A and B for imported land resources) and the corresponding total cultivated land in each country drawn from AQUASTAT [41]. This share is then multiplied with the agricultural water withdrawal as a percentage of the total water withdrawal [41], assuming an equal distribution of irrigation for agriculture.

4 Results

The obtained results are centred on the three systems (energy, land and water) considered in this study and focus mostly on the interdependencies between them. Of those, biomass and the consequences of its usage play a key role. Moreover, most results are compared to the model year 2015, which represents the calibrated base year of our approach covering the period from 2013 to 2017, in order to focus on the overall trends and the findings therein.

4.1 Development of the German energy system

4.1.1 Biomass utilization

In all of the variants of land availability for bioenergy, the use of domestic biomass is at a lower level in 2050 compared to 2015 (ca. -13% in CAL to -23% in DALY). Over the same period, the use of biomass peaks at 1432-1455 PJ in 2025, which immediately follows Germany’s final nuclear phase-out and declines thereafter to the 2050 level. This is mainly induced by the prominent role of wind and solar energy in the power sector and restrictions in crop rotation for rape seed oil and available land for bioenergy as biomass is primarily utilized for biofuels in the hard to decarbonize transportation sector. In addition, scenarios with decreasing yield (DY and DALY) show a lower domestic biomass utilisation compared to the cases without a yield decline (CAL and DAL) (see Figure 5a).

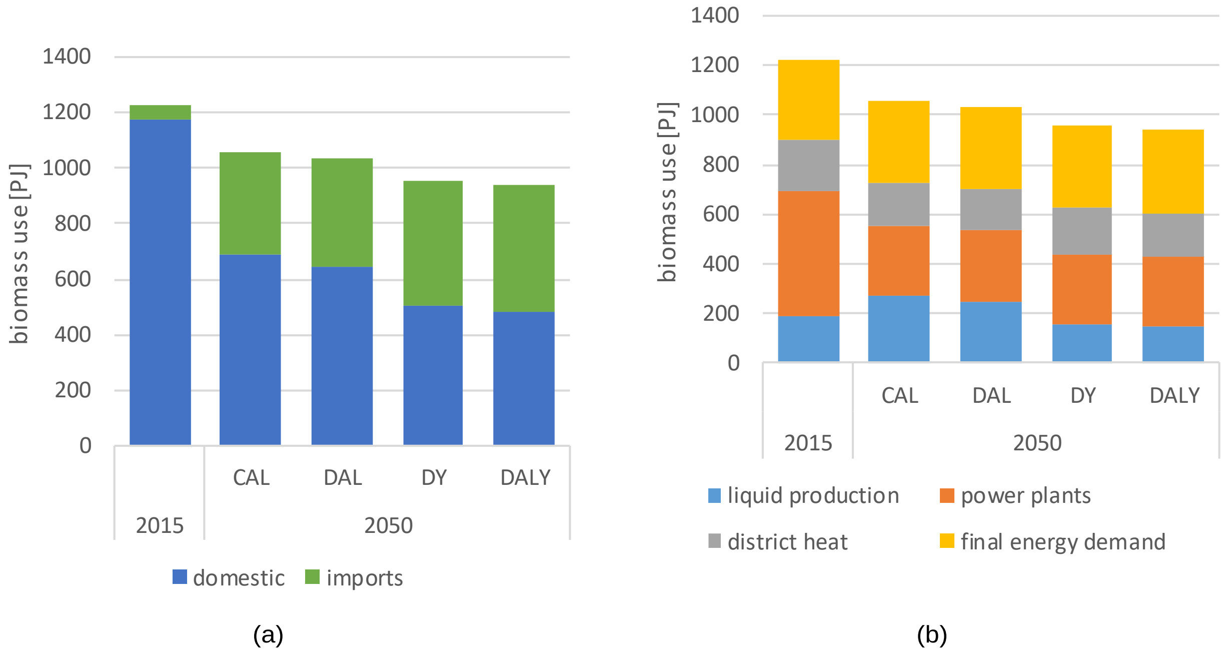


Figure 5. (a) Origins of biomass use in Germany [PJ], (b) Biomass use per sector in Germany [PJ].

At the sectoral level, some further differences in domestic biomass use occur (see Figure 5b). While the domestic biomass processed for liquid fuel production decreases in cases with declining yields (DAL and DALY) by more than 20% in 2050 compared to 2015, cases with constant yields (CAL and DY) result in an increase of 30-40% through 2050. As these biomass-based fuels are primarily used in the transport sector, lower yields translate into less biomass-based fuels from domestic sources. However, as imports of biomass, primarily consisting of oily crops, increase from nearly 4% in 2015 to 26-33% in 2050, the decline of biomass-based fuels from domestic sources is substantially overcompensated for. This results in an overall increase in biomass-based fuels through all land variants from roughly 7% (without renewable electricity) in 2015 to 32% in 2050.

In addition, the use of biomass for final energy demand and in power plants exhibits almost no deviation between the analysed cases, and only small differences for the use of biomass for district heating. For final energy demand, biomass is only used in buildings for heating purposes.

4.1.2 Net electricity generation

Looking at the net electricity generation in more detail reveals which technologies replace parts of the biomass in the German electricity mix through 2050 (see Figure 6). Most notably, wind energy vastly expands due to the comparably high potential, including the availability of offshore wind locations in Germany. An increasing share of photovoltaics whose feed-in curve complements that of wind energy accompanies this expansion. Moreover, a general decrease in electricity generation due to efficiency measures taken in the final energy demand sectors results in lower demand for electricity. These developments occur in all four of the analysed land variants, while net electricity generation shows insignificant differences between these cases. The same also holds true for the total final energy demand and its shares of energy carriers.

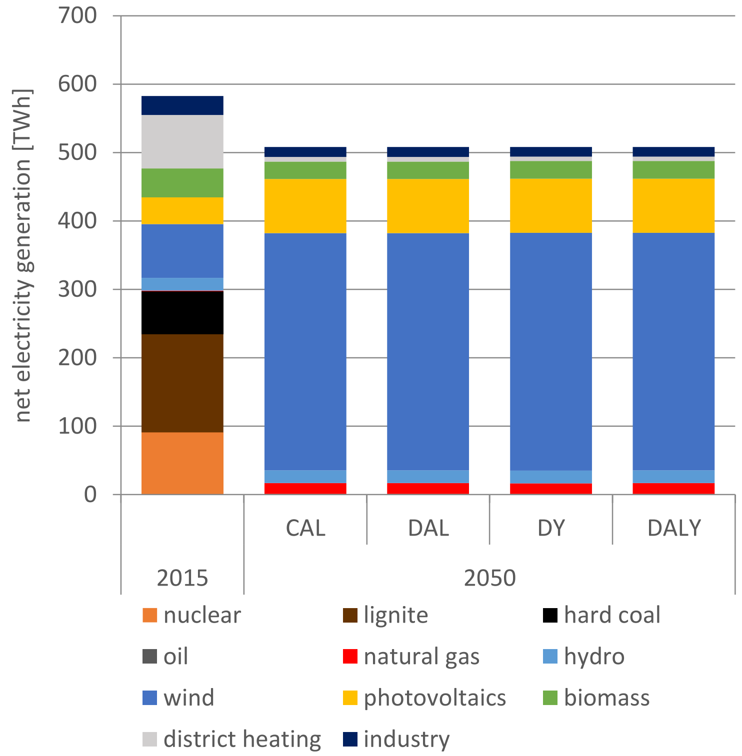


Figure 6. Net electricity generation in Germany [TWh].

4.1.3 CO_2 emissions

The trend towards high shares of renewable energy use leads to a fundamental drop in CO_2 emissions – by 98% in 2050 compared to 2015 in the German electricity sector. In contrast, CO_2 emissions from final energy demand only decrease by ~60% by 2050. As a result, the CO_2 emissions from final energy demand represent the largest segment (~90%) of Germany's remaining CO_2 emissions in 2050 (~60% in 2015). However, the differences between the four land variants are mostly negligible, due in part from CO_2 emissions from the production and transport of imported biomass within this modelling approach.

4.1.4 Final energy demand in transport

No change could be observed amongst the four land variants in the development of final energy demand in the transport sector (see Figure 7), as the sector-specific political targets for final energy demand and CO_2 emissions dominate the development. Overall, the transport sector is one of the main drivers for biomass demand, with an overall share of 32% of biomass use by 2050.

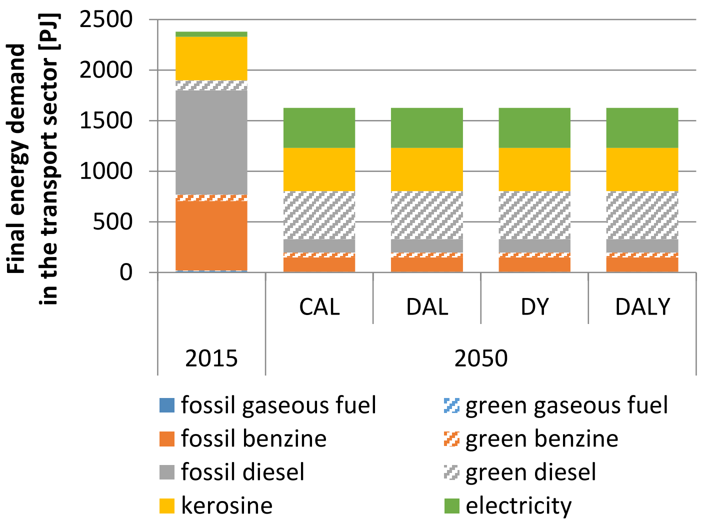


Figure 7. Final energy demand in the transport sector [PJ].

4.2 Land use for bioenergy production in the German energy system

4.2.1 Domestic land use for bioenergy

In all land variants, the total available land for bioenergy production seems not to have been fully exploited compared to the absolute available land. This is even the case in the variants with organic agriculture where the required land is higher due to lower yields (see Figure 8). However, as constraints on crop rotation are included in the model, crops with a high rotation requirement, for example rapeseed, can cover only part of the overall available land for bioenergy each year [63]. Hence, a detailed analysis of the results reveals that land is especially used for oily crops to its allowed maximum in accordance to crop rotation. These oily crops are mainly used for biodiesel for the hard to decarbonize freight transport.

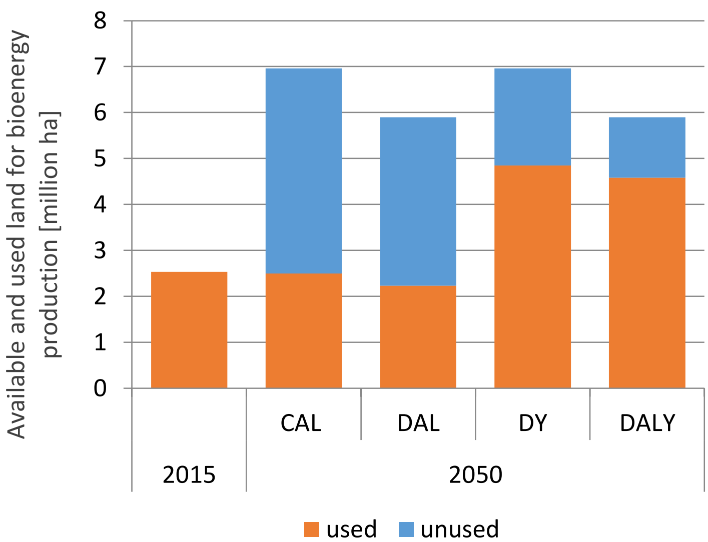
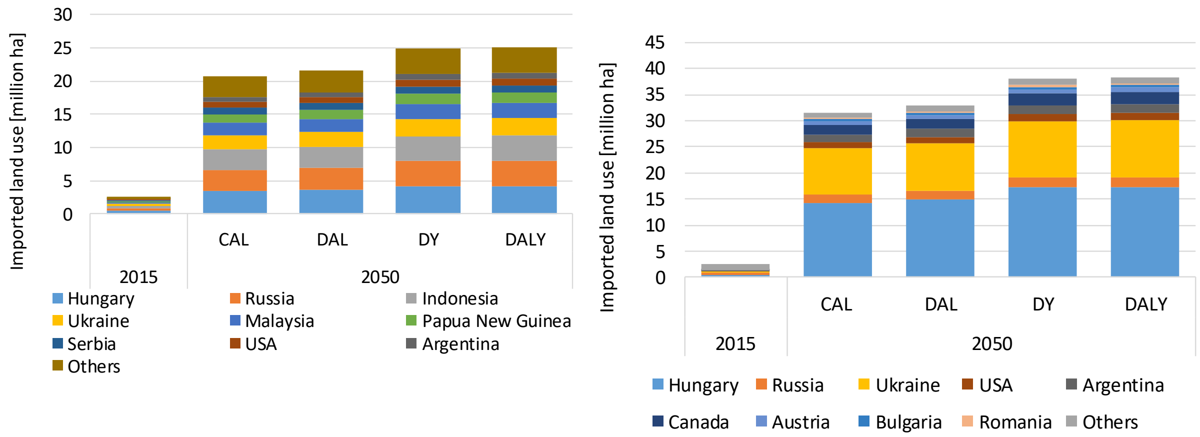


Figure 8. Available and used land for bioenergy production in Germany [million ha].

4.2.2 ‘Imported’ land use for bioenergy

As is shown in Figure 5, the import of biomass increases in all land use variants and especially in those with a high share of organic agriculture. The observed biomass import consists predominantly of oily crops. Such oily crops must be produced elsewhere in the world, requiring land in other countries.

The first approach (A) assuming that there will be no future changes in the biomass trading pattern results in scaling factors for current biomass exporters of 7.8 (CAL) up to roughly 9.5 (DALY) based on the overall import of biomass to Germany of 93.54 million t (CAL) to 113.50 million t (DALY) in 2050 (see Figure 5). This would add seven additional countries (Brazil, Colombia, Guatemala, Honduras, Russia, Thailand and Ukraine) to the list of countries with a trade volume of above 1 million tonnes across the four oily crops for Germany in all of the land-use variants, with Canada and Ecuador also in the DY and DALY variants. The total sum of land use for imports across all countries beyond Germany results in an area of land that is estimated to be ~20.7 to 25.1 million ha by 2050 (see Figure 9a). This is above the current total available land area for bioenergy in Germany (2.53 million ha), represents some 58-70% of Germany’s total area and exceeds the available land for bioenergy in Germany by a factor of 3 to 4.3.



(a) (b)

Figure 9. (a) Imported land use due to imports of bioenergy to Germany [million ha], (b) Imported land use due to imports of bioenergy to Germany without palm oil and a fixed level of soybean imports [million ha].

In terms of the required share of cultivated land in specific countries, in particular in Papua New Guinea, demand for the projected amount of oily crops would not be fulfilled, as the associated land use is above 100% of its cultivated land. This is for sure a theoretical result showing that current biomass supply countries might not be able to provide the required bioenergy to Germany. This picture further worsens if crop rotations are considered. Assuming in a second step the same high standards for crop rotation for all countries in accordance with the German case results in five additional countries (Honduras, Hungary, Malaysia, Solomon Islands and Serbia) exceeding their total cultivated areas to provide oily crops for Germany.

The latter two countries mainly face this land stress due to their smaller sizes and, hence, their comparably small amount of exported oily crops could be shifted to another country.

For the second approach (B) banning palm oil and limiting soybean imports to todays' level, the list of countries with a trade volume of above 1 million tonnes in 2050 changes to the Argentina, Austria, Bulgaria, Canada, Hungary, Russia, Ukraine and the USA. Hence, the exporting countries are more often located in North America and Europe in this case. Overall, an increase in the total imported land use by 10.9 (CAL) to 13.2 (DALY) million ha in 2050 compared to approach A can be observed due to lower yields of rapeseed and sunflowers compared to palm oil (see Figure 9b). This represents 88-107% of Germany's total area and exceeds the available land for bioenergy in Germany by a factor of 4.5 to 6.5.

For these imports, the required share of cultivated land exceeds 100% in Hungary, even without considering crop rotation and, also in Austria and Ukraine, when crop rotation is considered. Those imports would need to be shifted to other countries, further increasing their burden.

4.3 Demand for water for the German energy system

4.3.1 Domestic water use for the cooling of power plants

Due to the major decrease in electricity generation from fossil-fuelled power plants, current (2016) water demand decreases drastically to ~17% of 2016's value by 2050, in accordance with the model calculations. Furthermore, as the four land variants show minor differences in electricity generation (see Figure 6), the derived water demands are very similar to one another, too.

Due to this similarity, the three water demand variants are only presented for the CAL land use variant (see Figure 10). While the major trend of reduced water demand persists, the extent of this reduction varies between the three water demand variants from approximately 9% to 30% of the current value by 2050. Amongst the three water demand variants, NCT, the variant that excludes further cooling towers and hence entails an increase in once-through cooling, shows the highest water demand, while DG with an increase in closed-circuit cooling shows the lowest (%).

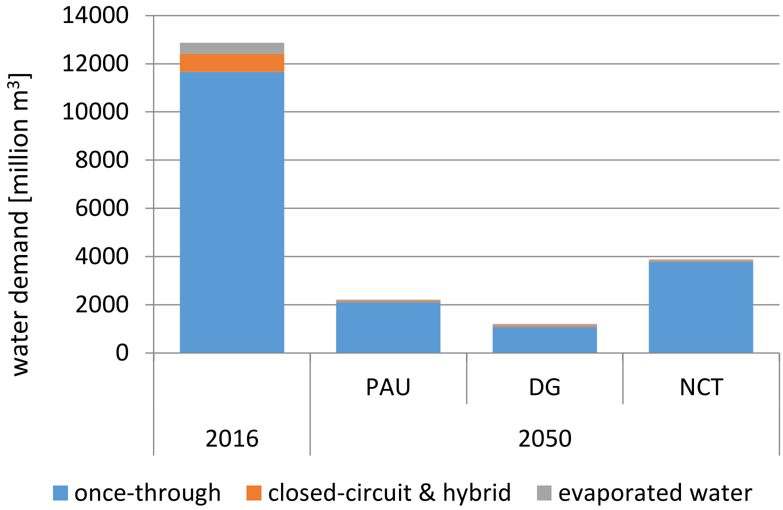


Figure 10. Water demand per cooling type for the CAL land use variant [million m^3] (2016 from [37], 2050: own calculations).

4.3.2 Domestic and ‘imported’ water use for bioenergy

The obtained results for approach A (imported land resources without a palm oil ban) reveal that countries with high shares of cultivated land for exported bioenergy to Germany (>10%) show, in most cases, a low share of agricultural water withdrawal (<10%) and comparably low water stress levels (<10). The only exceptions are Malaysia, Honduras and Guatemala, which have higher shares of cultivated land due to bioenergy exports to Germany (up to 30%, 40% and 20%, respectively) in combination with higher shares of agricultural water withdrawal (roughly 22%, 73% and 56%, respectively), but again comparably low water stress levels of ~3, 2.5 and 4, respectively. In approach B, including a palm oil ban, this pictures changes insofar that Ukraine and Bulgaria face higher shares of cultivated land used for bioenergy exports to Germany (~30% and ~15%) combined with higher shares of agricultural water withdrawal (~30% and ~13%) and higher water stress levels of roughly 14 and 42, respectively. Hence, those countries would most likely be burdened with increasing water stress induced by the needs of the German energy system.

The highest water stress amongst the countries exporting biomass to Germany of above 40 mainly occurs in Europe [41]. Hence, within the top 10 countries in terms of imported land use in both approaches (with and without a palm oil ban), the USA, Ukraine and Bulgaria show a current water stress level of above 10 (USA ~23, Ukraine ~14, Bulgaria ~42). Furthermore, the share of total water withdrawal due to agricultural water withdrawal for exported bioenergy to Germany only remains relatively low in the USA (<1%), while the other two countries face higher shares in at least one approach (Ukraine up to ~10%; Bulgaria up to ~2%). The hotspots in terms of higher shares of total water withdrawal due to exported bioenergy to Germany are Honduras, at nearly 30%, and Guatemala with up to 12% for approach A and Hungary (~24%) and Ukraine (~10%) for approach B. These show a current water stress level of 2.5 (Honduras), 3.8 (Guatemala), 8.2 (Hungary) and 13.9 (Ukraine). All of the other countries remain below 10% of the total water withdrawal for bioenergy exports to Germany, and mostly below 1% in countries with water stress levels above 10 for both approaches (with the exception of Ukraine with ~2% in approach A).

4.3.3 Relevance of transport-specific targets

The results reveal the high sensitivity of the targets specific to the transport sector on biomass imports (see Figure 11). In particular, the sector-specific target for greenhouse gas reductions seems to trigger biomass imports. However, the combination of all three targets exceeds the sum of biomass imports across all sensitivity model runs. Furthermore, those targets also affect the total used biomass and its sectoral use. While the DEM sensitivity shows a similar total amount of biomass compared to the DALY variant, in DEM, no biomass import occurs that is combined with the most biomass use in power plants across the investigated sensitivities. The total amount of biomass in all other sensitivities lays above the DALY and DEM amount without exceeding the biomass imports of DALY. Two other prominent changes are the high amount of biomass for fuel production in CO_2, mainly due to bioethanol production, and the larger amount of biomass for district heating in NON and BIOFUEL. Overall, it can be stated that the differences between NON and BIOFUEL are comparably low, reflecting the lower impact of this transport-specific target.

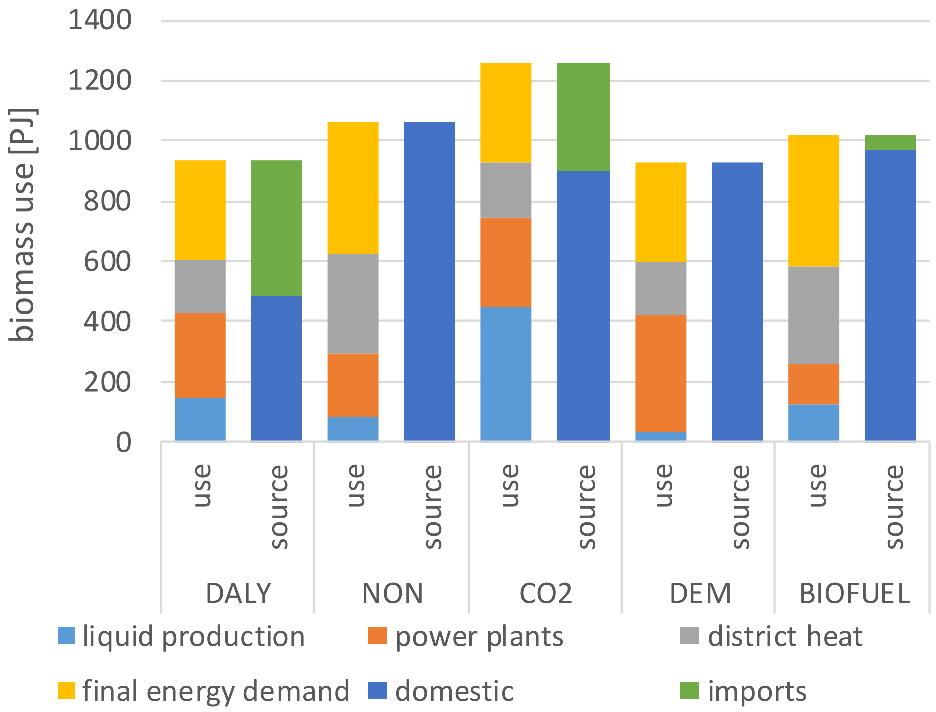


Figure 11. Biomass use for sensitivities based on DALY for 2050.

In order to explain the observed sensitivity in biomass imports, a closer look at the final energy demand in the transport sector reveals big differences in fuel shares. An interesting result is that electric vehicles are part of the cost minimum if the transport sector must meet the final energy demand target for the transport sector (DEM). As Germany's electricity exchange is the same for all sensitivities, this means that the country has enough renewable energy potential to meet the additional supply need for electric vehicles. Additionally, a close connection between the share of green diesel and biomass imports becomes apparent, as DALY and CO2 both feature high biomass import and a high share of green diesel.

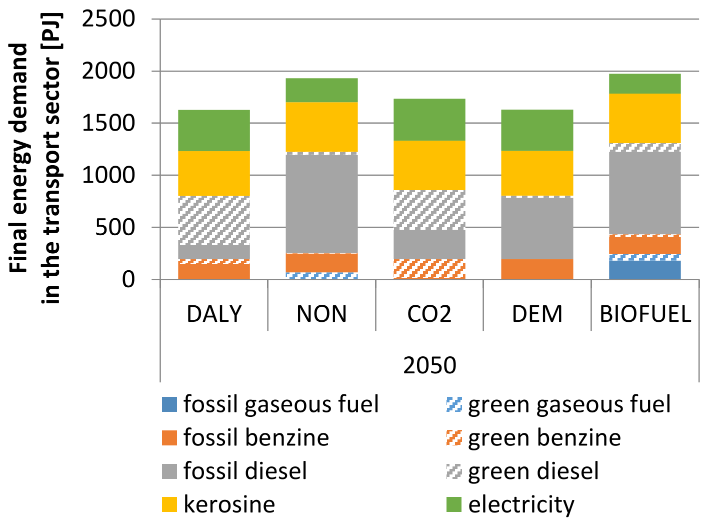


Figure 12. Final energy demand in the transport sector [PJ].

5 Discussions

Based on the results described before, the following general trends and statements can be derived. This is complemented by embedding the findings in relevant frameworks like regulations or political goals.

In regard of biomass utilization, in all of the land-use variants analysed, a decline in the use of biomass in power plants is the most prominent trend observed, while biomass used for district heating or final energy demand only show limited changes through 2050. Hence, it can be stated that biomass use in the analysed cases is most sensitive to changes in yield, while the overall land availability only has a limited impact on the use of biomass. Reflecting the fact that a decrease in yield is closely linked with an increase in organic farming, which is pursued by policy as well, the need for bioenergy in the energy system should be critically questioned and alternatives should be explored in order to reduce the potential conflict with organic farming.

Oily crops in Germany predominantly comprise rapeseed and, to a lesser extent, sunflowers [41]. These oily crops are mainly processed into biofuels (biodiesel) used in the transport sector, which is subject to an additional sectoral CO_2 target in addition to the overall emissions reduction target for the German energy system (see Table 1). Biofuels represent a suitable option for contributing to this CO_2 reduction target. The obtained results show that Germany's transport sector would rely heavily on the harvesting of oily crops, which might cause supply vulnerabilities due to hydro-climatic effects such as the droughts that hit parts of Germany in 2018 and affected the planting season of various crops, especially as the trend of global warming with warmer air temperatures has already led to changes in the duration of the growing season and earlier harvest dates for cereal crops throughout Europe [70]. Whereas in northern Europe, given the longer growing season potentially coming with climate change, agricultural productivity is expected to increase, creating the potential for new crops to be cultivated, extreme heat periods as well as lower precipitation and water availability or the spread of invasive new species may have detrimental effects on crop productivity [70]. In addition, this could result in the need to irrigate all or parts of the fields leading to an increase in water demand and potential water stress. Such circumstances could increase the need for biomass imports even further. Moreover, these effects do not only apply for Germany but also for biomass exporting countries as water stress levels might change in future due to climate change and a growing world population in need of food, which would possibly result in constraints on the bioenergy supply to Germany.

Options to reduce the need for domestic and imported biomass while still meeting the German energy transformation's targets could be, for example, exploiting possible land use synergies between food and bioenergy crop rotation in Germany or increasing the share of organic waste, residues and third generation biomass as intended by the proposal for the amendment of the European Renewable Energy Directive [71]. Another possibility could be the adjustment of some of the sector-specific energy transformation targets in Germany. While the current European Renewable Energy Directive, for example, already considers the greenhouse gas reduction potential of imported bioenergy, it might be worth including competition with food and water demand as well, which may help avoid exporting environmental stress to other regions. Furthermore, replacing bioenergy use, particularly in the transport sector, with other sustainable fuels (i.e., natural gas, renewable electricity, green hydrogen) or by changes in transport practices (i.e., car sharing, modal shifts towards public transport, bicycles or walking) might offer a promising option to avoid unintended side effects from Germany's energy transformation.

The governmental targets for the German energy transition do not explicitly cover emissions from imported bioenergy. However, on the European level, Renewable Energy Directive II [72] has established rules for upper limits on CO_2 emissions for imported biomass to be eligible for the renewable share targets. However, the underling mechanisms of calculating these emissions cannot be covered by the applied methodology. Hence, the impact of this directive on biomass imports was not directly integrated in this analysis. However, by the second approach (B), which excluded palm oil and fixed soybean imports as the two most critically discussed biomass imports, the potential effect of this directive was emulated. The related requirements for land exceeding in some cases even the total amount of cultivated areas in the exporting countries show that this might lead to an unrealistic or at least unreliable supply situation. However, this potential supply thread is not limited to approach B, but occurs in approach A, too, where todays' import pattern is scaled to future imports. Given the fact that over one third of the gross domestic product (GDP) of the exporting countries in approach A, specifically Papua New Guinea, depends on agriculture [41], priority may be given to more valuable crops in order to maximise GDP. For approach B, this GDP consideration applies especially to the Ukraine, which shows the highest value of roughly 14% amongst the biomass exporting countries. This may limit the potential of Germany to increase imports of oily crops even further and may hold true for other countries as well. Hence, a higher diversification or reduction in biomass imports could support reliable energy supply in Germany.

The goal of reducing final energy demand in transport triggers higher shares of electricity, as battery-electric vehicles have higher rates of efficiency compared to fossil-fuelled ones and the energy loss in power plants does not count towards the transport sector. However, the CO_2 reduction target for the transport sector has the largest impact on final energy demand in transport, as CO_2 from electricity is not counted for the transport sector in accordance to the political goal. This constitutes a shift in emissions towards the electricity sector and results in an increase in the burden of reducing emissions there. Furthermore, by this emissions are not only shifted into another sector but into the European Emission Trading System, too, leading potentially to higher CO_2 certificate cost. In addition, emissions from biofuels are not accounted for in the transport sector (emitted CO_2 was drawn from the atmosphere during plant growth) and emissions from the processing or transport of biomass are accounted for in other sectors (e.g., the primary energy sector or the conversion and processing sector). These do not have explicit CO_2 reduction targets, but contribute to the overall national emissions reduction target to differing degrees. Besides the increase in battery-electric vehicles, especially rapeseed as Germany's major oily crop is used to produce green diesel to its upper limit. Its maximum is defined by the available land for bioenergy in Germany combined with the required crop rotation for rapeseed. The reason for using green diesel to reduce greenhouse gas emissions in the transport sector arises from the lack of reliable options for long-distance heavy freight transport. The use of biofuels in aviation is not considered in the scenarios, but can be a future option for the extended use of biomass in transportation. However, the greenhouse gas emissions of the transport sector cannot affect the overall emissions of the energy system in Germany due to the constraint on national greenhouse gas emissions in accordance to the political goals (see the set of targets in Table 1).

As with any methodology the derived findings only hold true within the ranges of applicability and based on the chosen assumptions. In this case, the underlying optimization framework cannot account for full behaviour of all the decision makers within and beyond the energy system. Hence, the derived pathway for the energy system has to be perceived more as a benchmark representing one of the best possible pathways. Moreover, the assumption that the political goals will be reached can be discussed critically as some of those might require more effort as might be politically possible. However, the shown pathway in this study can be used to indicate what might be needed to achieve the political targets and hence, could serve as a discussion basis to find realizable pathways of transformation. Besides, the limitation associated to the utilized energy system model the assumed pathways for the water and land system describe only a set of possible developments without indicating probabilities of their occurrence in the future. For this also some extreme developments are chosen to show the potential ranges of the interplay between the three systems. Hence, a more in between development might be more likely and the results might not be as pronounced as shown in this study. However, the general findings and trends would still remain valid and could serve as policy support in order to aim for system integrating policy making.

6 Conclusions

This study has highlighted the importance of addressing energy system impacts on water and land in order to avoid negative outcomes in the pursuit of a sustainable energy future. While variations in the availability of land for bioenergy have an effect on overall energy system design, they affect the use and import of biomass within the energy system. In addition, lower yields in Germany due to organic farming may increase the quantity of biomass imports. This, in turn, would further increase competition for arable land in bioenergy-exporting countries and could potentially endanger food supply and contribute to deforestation and environmental problems in exporting countries. Hence, it is recommended that other options should be explored for reducing reliance on bioenergy imports in countries such as Germany in order to achieve a secure energy system that is environmentally-friendly, both globally and locally. One recent step in this direction was the European Commission regulation from March 2019 [24] that virtually banned the import of palm oil for biofuels. While this regulation focuses on excluding unsustainable biomass imports, it does not provide alternative options in the pursuit of sustainable energy systems.

Findings of the sensitivity analysis highlighting the lack of sustainable and reliable options for long-distance heavy freight transport as the main driver of biomass imports. Hence, as long as no technologies for sustainable long-distance heavy freight transport (e.g., trolley trucks with full grid infrastructure, fuel cell-electric trucks including sufficient hydrogen fuelling stations or power-to-liquid production with sustainable sources of CO_2) are fully available, the transport sector should not be forced to fulfil a sector-specific greenhouse gas emission target. Furthermore, as changes in biomass exports can have a severe negative influence on the economies of countries relying on these exports, such aspects and their social implications should be taken into account when aiming to reduce or regulate biomass imports.

In accordance with the analysis presented in this paper, the water demand of the entire energy system is the most sensitive to the development of the electricity sector. As fossil fuels and biomass use within the electricity sector declines, no further water stress is expected to arise from the electricity sector and hence for the overall energy system in Germany. However, the extent to which local water scarcity in Germany due to climate change will impact the placement of future (gas or biomass) power plants remains an open question and cannot be answered with the underlying approach.

In addition, the issue of the rising need for water to irrigate crops for bioenergy due to climate change in Germany may promote a further source of water demand to satisfy the energy system needs and add to Germany's current, already relatively high water stress level. The extent to which this will add to the derived water demand for power plant cooling purposes is beyond the scope of this study. Moreover, water demand associated with imported bioenergy for Germany mostly occurs today in countries with comparably low water stress levels (the most important exception being Bulgaria). However, this does not allow conclusions on future perspectives, as climate change or global population growth may add to future water stress in these countries.

In conclusion, this paper has presented an integrated analysis that is aimed in particular at decision-makers and provides a critical evaluation of the water and land system impacts of the German energy transformation's aspirations. Moreover, it provides a fundamental basis for further analyses that discuss alternative options in the pursuit of sustainable energy systems in order to avoid unintended side effects affecting land and water systems.

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Author's contributions

H.U.H. and Z.S.M. conceived the research topic. H.U.H. and B.G. performed the IKARUS model runs. J.L. provided the data for the transport sector. Sa.V. and D.K. provided the method and data for the land use variants. St.V. and D.K. provided the method and data for the water demand calculations. All of the authors contributed ideas, analysis tools and to the writing of the manuscript.

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Appendix

A Status quo of analyses of the water and land system impacts of Germany's and other future energy systems

Most analyses of the water and land system impacts of future energy systems focus on local implications. To list only a few examples, Steinhäußer et al. [4] analyse land use conflicts in Germany from a stakeholder perspective, while Palmer-Wilson et al. [5] constrain the national land use of the electricity system in Alberta, leading to a higher reliance on CCS. In addition, Algunaibet et al. [6] scale planetary boundaries to a regional level in order to explore the impact on land-system change due to developments in the power sector in the United States. Meanwhile, Price et al. [7] apply a model-based approach to evaluate the energy-land-water perspective for Great Britain. Moreover, Clarke et al. [8] assess bioenergy-driven land use changes in Ireland. The imports of energy carriers such as bioenergy or electricity in these studies are often not mentioned, as these are considered to be outside of their scope or are listed without exploring the origin or environmental impacts of such imports in more detail.

Furthermore, some studies have a global focus, such as that of Powell and Lenton [9], who analyse land use due to food production and dedicate the excess land to bioenergy production, or Daioglou et al. [10], who analyse land use in accordance with climate change mitigation scenarios. However, these studies rarely allow for the allocation of impacts to specific regions.

While Laurent and Espinosa [11] focus on the historical trends of the environmental impacts of electricity generation, other authors base their analyses on exogenously-given energy scenarios. For example, Konadu et al. [12] consider the UK's 2050 Carbon Plan, while Cai et al. [13] use the GTAP land change scenarios for the US. Again, other authors, like Weng et al. for China [14], build on exogenously projected bioenergy demand. However, exogenous scenarios or demand limit the capability of these analyses to test the variants or bi-directional interactions of the energy system against the surrounding land or water systems.

The impacts on land use from energy system pathways are more frequently addressed than analyses that deal with impacts on water use. The latter predominantly centre on the role of CCS in the development of water demand [5], the security of supply due to climate change-induced water scarcity [73, 74] or the nitrate contamination of ground water due to increases in bioenergy utilization and related increases in energy demand for water treatment [75]. Analyses that address impacts on land and water systems due to energy system developments (e.g., Price et al., who analysed the entire energy system of the UK [7], or Bukhary et al., who focused on solar energy in the south-western United States [76]) are the least frequent amongst analyses of the water and land system impacts of energy systems.

While bioenergy-induced environmental implications seem to dominate the literature, some studies [77, 78] also address land use for solar energy, such as ground-mounted photovoltaic or concentrated solar power plants.

B Policy frameworks in Germany

B1. Energy System

The most prominent German energy policies are the Renewable Energy Source Act (EEG) [79], the Renewable Energy Heat Act (EEWärmeG) [80], the German Energy Saving Ordinance (EnEV) [81], the Biofuel Sustainability Ordinance (Biokraft-NachV) [82], the laws regulating the phasing out of nuclear power plants [83] and the use of carbon capture and storage (CCS) [84]. While CCS has not been entirely forbidden, the current law constrains the yearly storage of CO_2 to such a degree that an industrial-scale application cannot be pursued.

While the government directly sets several targets for the energy system, Germany also made a commitment to implement the 2030 Agenda for sustainable development and thus the fulfilment of the Sustainable Development Goals (SDGs) in 2015. In 2016, the German Federal Government launched its new Sustainability Strategy, which proposes a management system based on a set of 63 mostly quantified indicators, as well as a time-frame for the attainment of the respective SDGs [3]. Of the 63 key indicators, over 20 directly relate to the water and land system impacts of the German energy system with specific consideration of the interdependencies between energy, land and water. These links most prominently show in the case of bioenergy. With the growing share of bioenergy in the German energy system, the interdependencies between agricultural land, water and energy become increasingly important. Between 2000 and 2015, the total installed power of biomass production facilities in Germany increased from 0.7 to 7.6 GW [85]. In 2018, about 45.7 TWh of electricity were generated from biomass [86], accounting for 7.0% of gross electricity consumption in the country [25]. This rapid increase in bioenergy use in the energy system has mainly been driven by substantial government subsidies, in combination with investment incentives for private investors and favourable technical conditions of agricultural production, and nearly reach stagnation due to adjustments in subsidy schemes [e.g., 87].

B.2 Land System

In the context of bioenergy, the link between energy crop production and its effects on fertilizer and pesticide use – and thus water quality – has been intensively discussed. Despite significant efforts in Germany to reduce the nitrate pollution of groundwater, the massive use of fertilizers and pesticides in agriculture has led to significant challenges with respect to water quality. Especially in areas that are characterized by high livestock density, the nitrate level frequently exceeds the threshold limit of 50 milligrams per litre; for both the period from 2008 to 2011 and from 2012 to 2014, about 18% of all measuring sites in Germany have exceeded this value [26]. Furthermore, the emission of the nitrogen compound ammonia into the air increased from 678 thousand tonnes in 2005 to 759 thousand tonnes in 2015. Of the latter, 95% was due to agricultural activity [26].

With respect to mitigating the negative impacts of agriculture on water resources, the Common Agricultural Policy (CAP) of the EU is currently the most important policy framework. The CAP pursues three main long-term objectives: (a) viable food production; (b) sustainable management of natural resources; and (c) climate action and balanced territorial development [88]. Its core measure is the objective of ‘cross-compliance’, directing payments for farmers to compliance with rules on farming practices that account for the environment, food safety, animal and plant health and animal welfare while maintaining ‘agricultural land in good agricultural and environmental condition’ (GAEC)’ [89]. However, an analysis of the European Court of Auditors recently revealed that the integration of EU water policy objectives with the CAP can, to date, only be considered a ‘partial success’, with several major challenges remaining, often relating to weaknesses in the definition of standards or inconsistencies amongst the member states [89].

As a key funding instrument, the BMEL is currently working to increase the budget for the Federal Organic Farming Scheme and other forms of sustainable agriculture to EUR 30 million annually while ensuring the continuation of the Protein Crop Strategy at the current amount of EUR 6 million [90].

B.3 Water System

Water policy in Germany aims to maintain the quality of water bodies and ensure appropriate water supply, as well as ensure the use of water with respect to leisure and recreation, shipping and energy provision. German water policies are strongly influenced by the European Water Framework Directive, which focuses on the ecological and chemical status of water bodies (including rivers, lakes and groundwater) and serves as a basis for other directives (e.g., the groundwater directive) as well as for regulations at the national level (see e.g., [91, 92]). On the national level, the Federal Water Act (WHG) transposes the European Water Framework Directive into federal framework legislation, forming the framework for water protections and management. The WHG aims to achieve a good status for all water bodies by 2027. Ordinances like the Waste Water Ordinance (Abwasserverordnung, AbwV) [93], the Surface Waters Ordinance (Oberflächengewässerverordnung, OGewV) [94] and the Groundwater Ordinance (Grundwasserverordnung, GrwV) [95] were implemented to concretise elements of the Federal Water Act. Regulations on regional levels supplement those federal laws. In some federal states within Germany, levy charges for the discharge of wastewater and for groundwater abstraction were introduced with the aim of providing an economic incentive for reducing the pollution of the water or water use itself. The German Working Group on the water issues of the federal states and federal government co-ordinates the water management policies of the federal states and federal government.

In recent decades water extraction as well as the pollution of rivers and lakes has been considerably reduced. In particular, the ratio of annual water withdrawals to annual runoff sunk from nearly 25% in the year 1991 to 13% in 2013 [91]. It is expected that, due to technological progress in the coming years, the water demand of the industrial sector, as well as the demand of private households, will continue to decrease. With respect to the availability of fresh water, it is expected that climate change will result in longer periods of water scarcity during summers, whereas in winter, precipitation will increase [96].