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Strategy Elements for a Sustainable Bioenergy Policy Based on Scenarios and Systems Modeling: Germany as Example

Bioenergy is an important renewable energy carrier with uncertainties in future development due to sustainability issues. Its further development requires a robust bioenergy strategy on a national level. To provide these strategy elements, a dedicated approach was developed, which includes a new modeling framework, an impact assessment, and stakeholder involvement. Demonstrating the approach on the example of Germany, four bioenergy utilization scenarios for a period up to 2050 have been assessed using seven indicators that cover aspects from local infrastructure to global food security. The devised strategy elements address the national and international feedstock supply, promising fields of utilization, and appropriate frame conditions. The results coherently focus on a wide range of policy fields, which has not been possible in the past.

Keywords: Bioenergy, Bioenergy policy, Sustainability assessment

Received: April 29, 2016; *accepted:* October 07, 2016

DOI: 10.1002/ceat.201600259

1 Introduction

Bioenergy is made from renewable biomass sources. In recent decades, it has been the most significant renewable energy carrier in Germany, Europe, and the world [1–3]. On a global level, bioenergy counts today for 100 % of the renewable transport fuels, over 90 % of modern renewable heat, and 8 % of renewable power [3], with a significant rise in bioenergy utilization through all sectors, which means a doubling of the use between 2006 and 2014, and significantly contribute to global greenhouse gas (GHG) emission reduction [4]. Advanced renewable energy goals and the availability of a wider spectrum of cost-efficient renewable energy technologies, i.e., wind power, photovoltaics, heat pumps, and e-mobility, mean the role of bioenergy in future energy systems is expected to change [5–7].

However, concerns have also arisen about the availability of feedstock to cover additional energy demands using bio-based energy carriers. Although biomass is a renewable resource, its availability is limited at a certain point in time, especially when environmental impacts on biodiversity, soil quality, natural carbon stocks and sinks, e.g., are taken into account [8–10]. Nevertheless, the rise in the demand for biomass for food production, feed production, and material use is expected to continue in the future [11–14]. It is commonly agreed that bioenergy has to be utilized in line with the goals of sustainable development; in particular, food security ranks higher than using biomass for energetic purposes [15, 16].

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Scenarios for future bioenergy use differ widely in quality and quantity regarding feedstock availability and bioenergy application fields (heat, power, fuels) as well [17]. Hence, policy makers from different fields are faced with very complex decision-making issues. These complexities pose a major hurdle in the successful development of efficient bioenergy technologies when biomass utilization priorities and the related focuses on research are not robust. Because technology development is a stepwise process that takes decades, a stable, long-term bioenergy strategy must be in place before bioenergy conversion concepts, i.e., biogas, gasification, biofuels production, can be developed further.

Germany is affected significantly by those different trends: a considerable rise in bioenergy utilization in the last decade has been noticed throughout all sectors (Fig. 1). With ambitious targets for a sustainable energy supply ("Energiewende"), Germany widely bases its future energy system on renewable energy. In such a system, bioenergy has to fill the gaps that cannot be filled by other sources – a view which has dominated the discussion at the start of the 21st century [18–21]. The utilization of bioenergy has to adjust to these changing needs and bioenergy can only play a substantial role if research and development continue to improve conversion technologies [22–24]. A robust bioenergy strategy, which includes the energy and the sustainability goals comprehensively, is a precondition to perform the transition successfully.

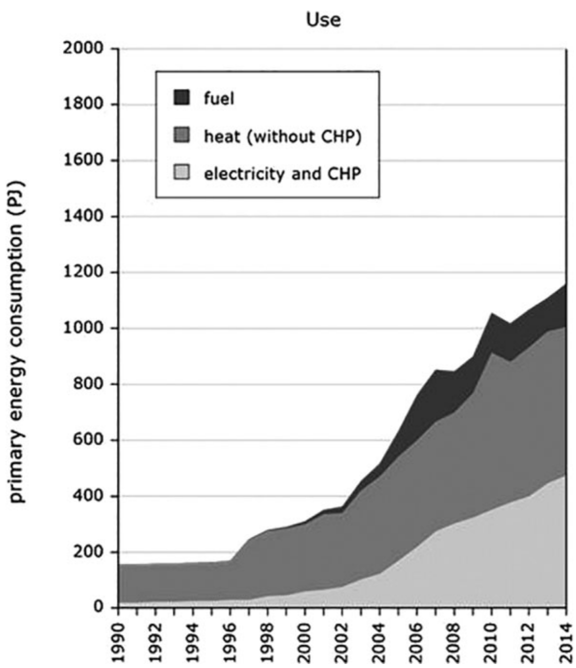

Figure 1. Development of bioenergy provision in Germany (based on [58]).

Currently, the methodologies for translating these goals of having a robust and sustainable bioenergy strategy at the national level are still under development [25]. The development of such a methodology faces two major challenges:

(1) Bioenergy supply chains are complex systems with multiple interactions between agriculture, forestry, food supply, technical development, energy markets, and environmental goods. Therefore, a comprehensive understanding of the structure and the way these systems function is necessary in order to frame robust policies that avoid unintended consequences. One key issue is to include economic, environmental, and social aspects in the assessment.

(2) Policy is implemented on a national level but, due to international markets and the transnational effects of changing demand patterns for bioenergy resources, national bioenergy policies also affect the global situation in terms of the availability of biomass for food, feed, fiber, and other purposes. In contrast, global developments can strongly impact national bioenergy strategies and their implementation.

As a consequence, it is necessary to identify possible options for future bioenergy development and to assess their effects with regard to the different dimensions of sustainable development on different levels. This would provide comprehensive, simplified, and transparent information about the possible impact of future bioenergy policies. It should also consider the feedback between different areas of policy and the robustness of the effects under changing frame conditions and priorities.

In order to grasp the complex interactions between the development of bioenergy technology, energy systems, agricultural commodity markets, and land use changes, Germany was taken as an example and four key research questions were identified: (i) Which future developments of bioenergy utilization are expected in the context of the German Energy Transition? (ii) Which feedstock technology options will become relevant for biomass production? (iii) What are the related environmental, infrastructural, and social consequences? (iv) How can the findings be translated into strategy elements of a sustainable German bioenergy policy?

In this paper, first the method of system modeling and assessment is described (Sect. 2). Then the framework is applied in a stepwise approach (Sect. 3), and finally the results are discussed to develop robust elements for long-term bioenergy strategies for Germany (Sect. 4).

2 Method

To answer identified questions, a research approach was developed that includes five key steps (Fig. 2). The first step is to construct scenarios that illustrate potential future development

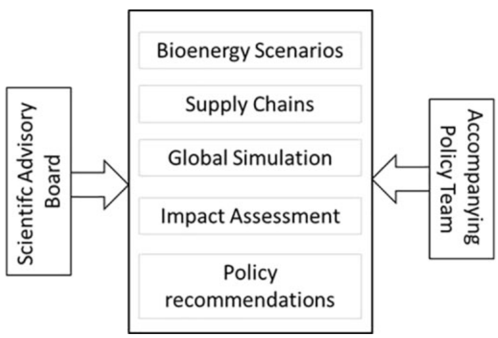

Figure 2. Overview of the method.

pathways of bioenergy use in Germany. The second step is to identify potential bioenergy technology concepts and supply chains. In Step 3, the MILESTONE modeling framework is applied to simulate the resulting global material and energy flows and to deduce promising bioenergy supply chains for Germany. Based on the simulation results, Step 4 assesses the corresponding social and environmental impacts. The objective of the final step is to derive policy recommendations based on the analytical results.

The entire process of developing the research approach and subsequent analysis was conducted in close collaboration with a scientific advisory board and an accompanying policy team, which included experts from five different German ministries. The objective of the coproduction approach was to establish an interface between the scientists and the utilizers of the scientific results to ensure that the results are able to be applied in a policy context.

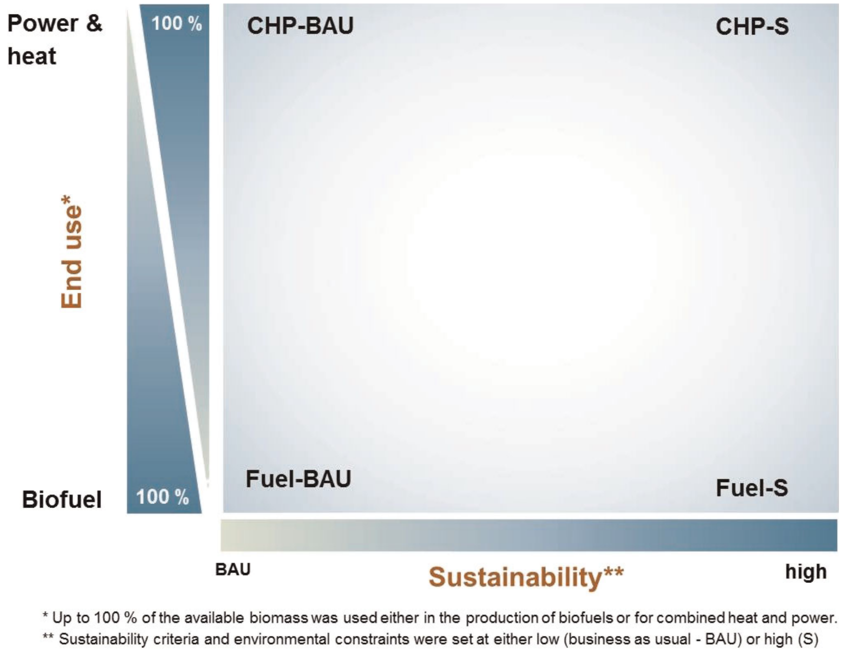

Figure 3. The four scenarios (CHP-BAU, CHP-S, Fuel-BAU, Fuel-S) as part of the "Milestones 2030" project.

2.1 Scenario Setting

Four extreme pathways were simulated in order to cover a wide range of possible outcomes. As heat can also be supplied by other forms of renewable energy, there are strong arguments in favor of using bioenergy as a fuel for road transport and aviation, or as a way to flexibly supply electric power. Assuming there is a limit to bioenergy feedstocks, either fuel or combined heat and power (CHP) are produced in 2050. Additionally, a fundamental prerequisite for the future availability of biomass worldwide is the sustainability of its supply. This normative requirement is endorsed by numerous studies, e.g., [26–29].

Relevant voluntary schemes already exist in the form of the Global Bioenergy Partnership (GBEP) indicators [31] and the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests [32]. Moreover, globally binding standards have already been drawn up for biofuels [33]. Consequently, the scenarios are extended towards encompassing sustainability. In contrast to a business-as-usual (BAU) scenario, the more sustainable scenarios presume that an active land policy is implemented globally which avoids expanding agricultural land into sensitive areas like primary forests or peatlands. A total of four scenarios (Fuel-BAU, Fuel-S, CHP-BAU, and CHP-S) are analyzed which represent extreme developments in terms of both energy supply and sustainability (Fig. 3). Thus, the results have to be primarily discussed relative to one another. They are a necessary tool for drawing conclusions and policy recommendations, but do not represent policy recommendations as such.

These scenarios are embedded in a general context. They take into consideration the expectation that bioenergy is used as part of Germany's energy transition towards a highly efficient energy supply based on renewable sources in 2050 [21, 34]. In terms of the future national bioenergy supply, Nitsch et al. [34] assume that there will be a total primary energy demand of 1550 PJ for biomass used for energetic purposes in 2050. The bioenergy provision of 1100 PJ a^{-1} in 2010 (calculation based on [35]) forms the starting point for the development of an overarching bioenergy strategy for Germany. Further assumptions for the scenario setting are described in [25]. They include assumptions on economic development, population growth, technological development, price projections for fossil fuels CO_2 emission certificates, and the continuous advancement in environmental protection standards in Germany and the EU, e.g., maximum permissible values for emissions, sustainability standards for fuels, and conventions on biodiversity.

2.2 Definition of Bioenergy Supply Chains

Within the bioenergy system, the current investigation considers a selection of bioenergy supply chains that have the potential to make a significant contribution to the German energy system. The relevant conversion technologies are listed in Tab. 1. They include conversion systems for combined CHP systems, biofuels, and heat-only systems. Focus is on biomass-only supply chains. In order to include the increasing demand for more flexible bioenergy provision within an energy system with high proportions of renewables, 5000 full-load hours per year were assumed to be required for power provision.

The supply chains were modeled using the Milestones framework (see Sect. 2.3). The modeling results provide the most competitive supply chains based on future feedstock prices for international commodities (vegetable oil, grains, wood), technical learning, expected revenues for power, GHG certificates, and by-products [36]. The development in wood prices was based on expert opinions and the supposition that

Table 1. Twenty conversion pathways selected within the project "Milestones 2030".

	Combustion	Anaerobic digestion	Fermentation	(Trans-)esterification	Hydrogeneration	Gasification
Electricity / heat (CHP)[a]	CHP (ORC)	Biogas plant				Small gasification (CHP)
	CHP (steam turbine)	Biomethane plant				
	Vegetable oil CHP	Small manure plant				Gasification (CHP, ORC)
		Biowaste				
Biofuels[b]		Biomethane	Ethanol (sugar beet)	FAME (rapeseed)	HVO (rapeseed)	Bio-SNG
			Ethanol (wheat)			BtL (FT-fuels)
			Ethanol (straw)			
Heat	Single room heater (wood logs)					
	Wood pellet boiler					
	Heating plant (wood chips)					

[a] Electricity generation was assumed to be flexible and demand-oriented at 5000 full-load hours per year; [b] Infrastructure costs are considered for liquid and gaseous biofuels. These are higher for gaseous biofuels.

wood prices will develop in line with wheat prices since MAGNET does not include a price for wood dedicated specifically to energy generation. For supply chains based on residues and waste, i.e., for small slurry plants and biowaste fermentation plants, it is assumed that the potential that is available nationally will be unlocked gradually [37].

2.3 Analysis of Biomass-to-Energy Flows and their Geographical Source

The MILESTONE framework models the links between the national bioenergy system and the global land use system. It builds on a set of well-tested models, combining a global economic equilibrium model (MAGNET), a grid-based global land use model (LandSHIFT), and a bioenergy market model (BENSIM). The framework implements the relevant processes following the biomass-to-bioenergy value chain from cradle to grave (Fig. 4). These elements include land use systems that define the resource basis for biomass production from forestry and agriculture, global trade, and biomass markets (economic system), as well as the respective national bioenergy system. Each model focused on different aspects of bioenergy provision. By linking these models, it became possible to incorporate all aspects of bioenergy provision in the analysis and thereby generate consistent results [25]. Biomass-to-energy flows and the related consequences for global land use changes were calculated based on the scenario settings.

2.4 Impact Assessment of the Scenarios

Scenario modeling provides a bioenergy conversion plant pattern for Germany and information on relevant feedstocks and their geographical origin. These biomass-to-bioenergy flows enable us to assess related effects. In terms of bioenergy provision, many different effects are discussed, including those on land use, cumulative environmental effects, and socioeconomic effects (i.e., [38, 39]). In our assessment it was decided to cover them comprehensively and therefore a set of seven indicators was defined as summarized in Tab. 2. These allowed for assessing the development of the different scenarios over time.

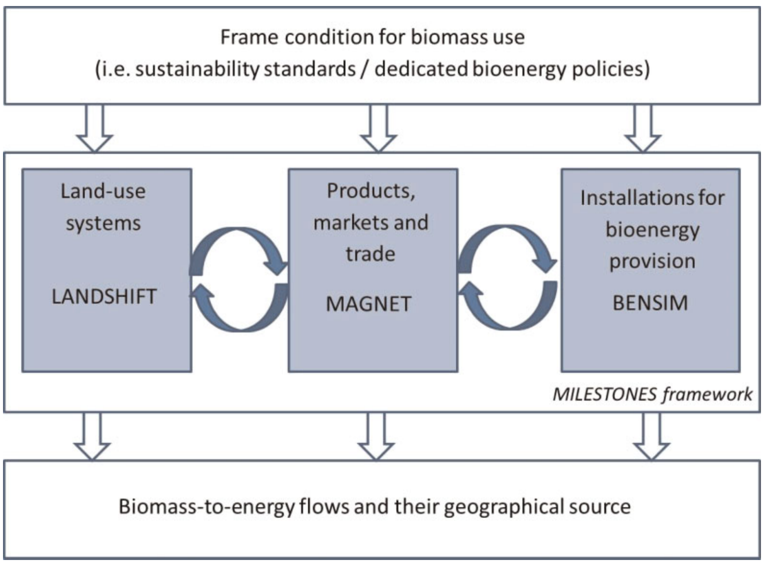

Figure 4. Elements of the Milestones 2030 framework.

Table 2. Impact categories and indicators used to assess the bioenergy scenarios.

Impact category	Indicator	Approach
Effects related to land use from biomass-for-bioenergy provision	(Global and national) biodiversity risks	Cultivation patterns for 2030 and 2050 (LandSHIFT model result) are compared with the cultivation pattern in 2010. The use of areas that were arable land or fallow land in 2010 is classified as being of "low risk" to biodiversity. The use of areas that were primary forest or protected areas is considered to be of "high risk" to biodiversity, and the loss of unused grasslands, wetlands, forests, and peatland is associated with a "medium" to "high risk". The risks associated with the use of already-used grassland are discussed for each country individually.
	Soil quality	Cultivation patterns for 2030 and 2050 (LandSHIFT model result) are compared with the cultivation pattern in 2010. To assess the impact of crop cultivation on soil, the soil suitability map from the International Institute for Applied Systems Analysis (IIASA; soil-constrained-combined (Plate 27)) was used. IIASA categories 1 to 4 are defined as soils that are well-suited for agricultural use. IIASA categories 5 to 6 are defined as being less well-suited, and IIASA categories 7 and 8 are only poorly suited for agricultural use. The assessment assumes that poor suitability is usually accompanied by a high risk to soil quality.
	Emissions from carbon stocks due to land use changes	GHG emissions from land use changes (LUC) result from changes in the carbon inventory of the soil due to the cultivation of energy crops. They are calculated based on the LandSHIFT modeling results. Since the modeling takes into account worldwide soil carbon changes from LUCs, indirect effects are also considered, such as the cultivation of food crops in foreign countries due to land use demands for energy crops in Germany. A worst-case estimate is included for comparison, in which emissions due to indirect land use changes (iLUC) are taken into account based on the iLUC factors in EU Directive 2015/1513 [40]. Carbon emissions depreciate over 20 years.
Cumulative environmental effects due to bioenergy use on a national level	Life-cycle environmental impacts of a defined product basket	Life-cycle assessments are screened for all future bioenergy chains that follow international standards on product life-cycle assessment [54, 55] for selected impact categories. It is assumed that biomass in the energy system only replaces fossil energy carriers, not other renewables. The proportions of bioenergy pathways are taken from BENSIM/MAGNET results. For the comparative system assessment of technologies and scenarios, as well as for the assessment of GHG emissions from land use changes (LUC), a unitary amount of final energy is defined for all scenarios and all points in time, namely the maximum amount of available bioenergy for each year and sector (fuel, electricity, and heat). The amount of bioenergy for each of the sectors in a scenario at a certain point in time is then supplemented with the fossil fuel mix of that year to reach the maximum. This definition is referred to as a "basket of products".
Socioeconomic effects due to bioenergy use on national and regional levels	Risks for food security	Based on the development of a food security model that sets bioenergy use in relation to inadequate nutrition, current and future diets at a national level, and countries at risk for food insecurity were identified. To balance unequal distribution, the model adjusts consumption of bioenergy in countries with a high GDP (gross domestic product) to a defined level that allows biomass to be relocated to countries suffering from scarce food resources.
	Security of energy supply	Energy Diversity is a method used to approximately quantify the aspect of "security of supply" [56]. It uses the so-called Herfindahl Index, which compares the relative weights of energy sources that are used to meet primary energy demands. To do this, data on the biogenic final energy supply were taken from the BENSIM results and from the environmental analysis of the scenarios, and integrated into the overall primary energy balances for Germany. This was used to calculate the Herfindahl Index for the scenarios.
	Impact on regional energy infrastructure	To assess how possible bioenergy use can be integrated from a regional perspective, the development of bioenergy plants up until 2030 and 2050 (BENSIM model results) were compared with the current regional and local infrastructure, such as power grids, district heating systems etc., based on the biomass clusters at the municipal level described by Noll et al. [57].

2.5 Policy Recommendations: Extracting Elements from the Long-Term Bioenergy Strategy

To fulfill the objective of providing recommendations to support and improve policy decision-making, the results of the scenarios were compared with their impact assessments. It was focused on common developments between the scenarios which could be translated into "robust elements". A comparison was made of the output of the different models (BENSIM, MAGNET, LANDSHIFT), the related impact assessment, and the development of their effects between 2010 and 2050. Conclusions from this comparison were translated into potential elements for the stepwise development of a bioenergy policy strategy for Germany, taking both national elements and international needs into consideration. Also, elements that were missing in the bioenergy strategy are discussed.

3 Results

3.1 Biomass and Bioenergy Supply Chains – Modeling Results for the Scenarios

3.1.1 Development of Bioenergy Production Plants in Germany

The simulation from BENSIM illustrates the least-cost developments for biopower and biofuel systems under the different scenario conditions (Fig. 5).

In both BAU scenarios, oilseed-based energy carriers are the least-cost option (see feedstock results for a consideration of the modeled commodity price developments), which dominate the simulated markets. In the CHP-BAU scenario, biogas – and to some extent biomethane – are competitive in the medium term, with some additional wood-based CHP. In the Fuel-BAU scenario, biodiesel dominates to a larger extent in the medium term with some marginal sugar-based bioethanol and biomethane.

In the S scenarios, stronger sustainability criteria lead to a stronger increase in feedstock costs, which, coupled with higher GHG abatement credits and faster cost reductions through R&D (Research & Development) for options not on the market, produce a significantly different result. In the CHP-S scenario, biogas is the least-cost option in the medium term, with oil-based CHP playing a smaller and diminishing role. Wood-based small gasification CHP becomes competitive in the long term. More resource-efficient, methane-based options are preferred in both S scenarios, leading to a higher energetic output from the limited feedstock resource.

In the Fuel-S scenario, the proportion of biomethane continuously increases and out-competes biodiesel in the long run. Bioethanol, which is only present in marginal amounts, experiences two shifts in feedstock. Starch-based feedstocks are more common in the beginning. These are displaced by sugar-based feedstocks and then later by straw. Wood-based synthetic natural gas (SNG) attains a small market share towards the end of the time-span and, notably, biomass-to-liquid (BTL) and hydrogenated vegetable oils (HVO) do not appear on the simulated market. Straw may present a source for biofuels in the long term, although, by definition, this residual resource is limited.

Sensitivity analyses indicate that the results in the Fuel scenarios are relatively insensitive to the availability of low-cost wood feedstocks, learning effects and GHG credits. At the same time, they are sensitive to feedstock cost developments. The CHP scenarios are somewhat less sensitive to feedstock cost developments, but are more sensitive to GHG credits due to differences in heat production. More flexible biopower produc-

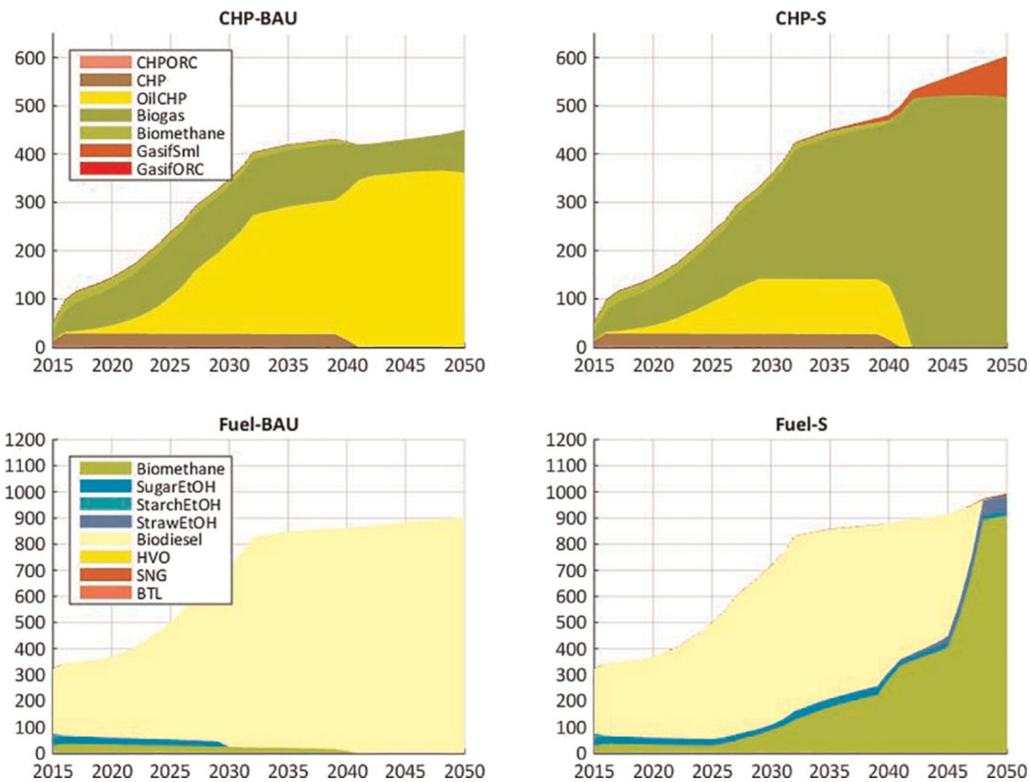

Figure 5. Least-cost developments for the four scenarios, from a simulation in BENSIM. Units on the vertical axes are petajoules (PJ). The two upper graphs show power production under the BAU and S scenarios; the lower graphs illustrate fuel production.

tion leads to an even larger cost advantage for biogas and oil-based CHP compared to wood-based CHP. R&D may play a significant role in wood-based power options.

3.1.2 Development of Global Feedstock Markets and the Influence of Biomass-for-Energy Demand in Germany

Simulations with the MAGNET model show that agricultural markets are and remain dominated by the rising global demand for food and feed in all scenarios. However, bioenergy demands do influence the development to a certain extent as in the case of particular commodities such as oilseeds. German biodiesel demand induces the import of oilseeds and vegetable oils. When this demand decreases, these imports diminish rather than rise. Furthermore, the production of oilseeds in Germany increases much more slowly over time compared to a scenario where there is a high demand for biodiesel. Agricultural prices rise, especially in the sustainability scenarios, as there is less land available for production. Land restrictions and growing prices stimulate technological development, leading to higher yields and an intensification of production on the remaining area.

3.1.3 Development of a Global Land Use Pattern for Biomass Production and the Influence of Biomass-to-Energy Demand in Germany

The simulation results from the LandSHIFT model use a 5-arcmin grid resolution to illustrate global land use changes between 2007 and 2050 under the different scenarios. At the global level, an expansion of arable land in all scenarios is observed. Starting with 1.4 billion ha in 2010, arable land increases to 2.4 billion ha in 2050 in the sustainability scenarios, and to 2.83 billion ha in the BAU scenarios. The main factors behind this are increasing demands for food, feed, and bioenergy. No significant differences in global developments can be found between the fuel and CHP scenarios, as global parameters were kept identical and changes in biomass use (fuel or CHP) were only made for Germany.

In the BAU scenarios, arable land expands most in eastern Brazil (sugar cane and soy bean), southwestern Russia (wheat), and Southeast Asia (oil seeds). In the sustainability scenarios, a lower demand for arable land, in combination with effective mechanisms for protecting natural ecosystems, significantly reduces the loss of natural vegetation. While almost 300 million ha of the 4.3 billion ha of forest in 2010 are cleared by 2050 in the BAU scenarios, deforestation virtually stops in the sustainability scenarios. At the same time, there is a shift in land use change towards other, unprotected areas which reduces the global area of grassland and shrubland ecosystems from 5.5 billion km^2 in 2010 to 4.7 billion ha in the BAU scenarios, and 4.65 billion ha in the sustainability scenarios.

As in the global analysis, in Germany the additional demand for energy crops in all scenarios results in an expansion of arable land. In the fuel scenarios, cropland areas increase from 9.35 million ha in 2010 to 11.46 million ha in the BAU, and to 10.04 million ha in the sustainability scenario in 2050 (Fig. 6). The CHP scenarios see expansions of cropland to 11.72 million ha (BAU) and 11.35 million ha (sustainability). As forests in Germany are assumed to be protected in all scenarios, the expansion of arable land is mainly at the cost of pastureland. Due to legal regulations, no additional pastureland is converted into arable land in the sustainability scenarios after 2020.

3.2 Impact Assessment of the Scenarios

3.2.1 Effects Related to Land Use as a Result of Biomass-for-Bioenergy Provision on a Global Level

3.2.1.1 Global Biodiversity Risks

In the BAU scenarios, approx. 1.35 billion ha of the global arable land area used for commodities can, in principal, be used for bioenergy production in 2030 (LANDSHIFT model results). About 80 % of these areas are of a low risk to biodiversity. Areas that are cultivated by 2030 are mainly unused grassland. Areas that are of medium and high risk to biodiversity are hardly cultivated. By 2050 the global area for the production of the specified commodities increases to 1.85 billion ha. During this period there is a slight increase in the use of areas with a low risk to biodiversity. The use of unused grasslands almost doubles, while that of forested areas, which are of a medium risk to biodiversity, and used grasslands increases at a much

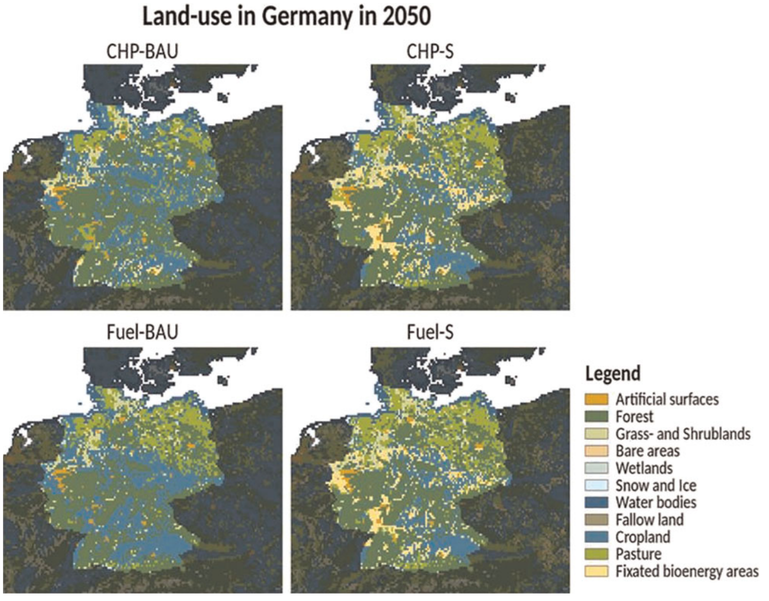

Figure 6. Land use in Germany for all four scenarios in the year 2050.

lower rate. Primary forests, protected areas, and peatland almost never revert to cultivation by 2050.

In the sustainability scenarios, the global arable land used for commodities, which principally can be employed for bioenergy production, is reduced to approx. 1.1 billion ha in 2030 and to approx. 1.65 billion ha in 2050. Due to the strict exclusion of sensitive areas from 2020 onwards, new, cultivated areas are mainly established on previously unused grassland and, to a very small degree, on used grassland. In the sustainability scenarios, cultivation of the remaining arable land intensifies. It is assumed that such intensification impacts biodiversity to a lesser degree than when land that was previously unused is converted. In the Fuel-BAU scenario in the years 2030 and 2050, as well as in the sustainable fuel scenario in the year 2030, feedstock for bioenergy generation is produced in Germany on less than 2 million ha. An additional 10 to 12 million ha are needed outside of Germany. Thus, severe land use changes in foreign countries are expected which will mainly affect unused grassland and, to a slighter extent, used grassland and forestland.

3.2.1.2 National Biodiversity Risks

Biomass for energetic use is mainly cultivated in Germany on areas with a low risk to biodiversity. Nevertheless, there are cases where used grassland is converted into arable land with corresponding risks to biodiversity. In the sustainable fuel scenario, virtually only biomethane from cultivated crops is used in 2050 alongside a small amount of ethanol from cereal straw. Approximately 4 million ha, with a mainly low risk to biodiversity, are used for this, while almost no other sensitive areas are converted into arable land. It should also be noted that using arable land in such a way leads to reduced production of other crops, i.e., the crops are displaced or partly substituted.

3.2.1.3 Soil Quality

About 56 % of the land converted to arable land in order to fulfil the need for additional land for bioenergy production has soils that are well-suited for agricultural use; 27 % of the land is in areas with moderately suitable soils and 17 % of the areas are only poorly suited. This proportion is almost the same for the BAU and the sustainability scenarios, though the overall increase in arable land is lower in the sustainability scenario. This means that a rising demand for area generally results in an increased risk to soil quality.

3.2.1.4 Land Use-Related Effects on Carbon Stocks

The results show that GHG emissions from land use change can sometimes be as high as or even higher than total emissions from cultivation, processing, and use of the bioenergy carrier (see also Fig. 4). The calculated range of results underlines the need for further research in the area of land use change assessment. GHG emissions from land use change are mainly emitted outside the European Union. In the BAU scenarios they are the result of a direct import of biomass, in the sustainable scenarios they are due to the indirect effects of an increased cultivation of energy crops in Germany.

3.2.2 Life-Cycle Environmental Impacts

Based on the product basket approach, i.e., on normalized final energy for all scenarios and years, the results in Fig. 7 indicate that there is a general decline in GHG emissions over the years in all scenarios. However, GHG emissions caused by land use changes (LUC) strongly reduce the savings achieved by increased bioenergy production. This is especially true when there is a high estimate of the indirect effects, i.e., the iLUC factors published in EP & CEU (2015) [40], which are only defined for the fuel scenarios in this study. There may only be a slight decline in GHG emissions by around 2040 and, if conditions are unfavorable, emissions may even remain constant despite the use of bioenergy. Acidification and particulate matter formation also decrease over the years.

The decline in GHG emissions is highest in the sustainable CHP scenario. However, the decline in acidification is higher in the other three scenarios. Also, in some scenarios there is a slight increase in the nutrient input into soils and bodies of water (not displayed) rather than a tendency to decrease. Thus, from a scientific and objective point of view, none of the scenarios can be clearly preferred and no rating can be carried out unless additional subjective criteria are considered. If, for example, a reduction in GHG emissions is the major goal, then the sustainable CHP scenario performs best.

3.2.3 Socioeconomic Impacts from Bioenergy Provision

3.2.3.1 Impact on Food Security

Modeling food security has shown that the number of calories needed in 2010 to meet the minimum requirements for healthy nutrition amount to less than 40 % of the bioenergy demands of the 20 % richest countries. Owing to the generally positive development towards higher per capita income in poorer countries, this percentage is set to drop to 7 % by the year 2050. The results of this theoretical approach are that, in purely arithmetical terms, rich countries would only need to reduce their bioenergy demands by about 7 % over the long term in order to meet the calorie requirements of countries where hunger is prevalent. However, bioenergy demands in these countries are, in fact, expected to increase as a result of one of the policy targets set to combat climate change. The gap can be filled by a change in diet: reducing meat consumption and other animal food products within industrial and emerging countries. This is considered to be a more viable option that would simultaneously provide global food security as well as protect the climate and habitat.

3.2.3.2 Security of Energy Supply

The BAU and sustainability scenarios for both fuels and CHP reveal very different effects on the fossil energy mix and hence

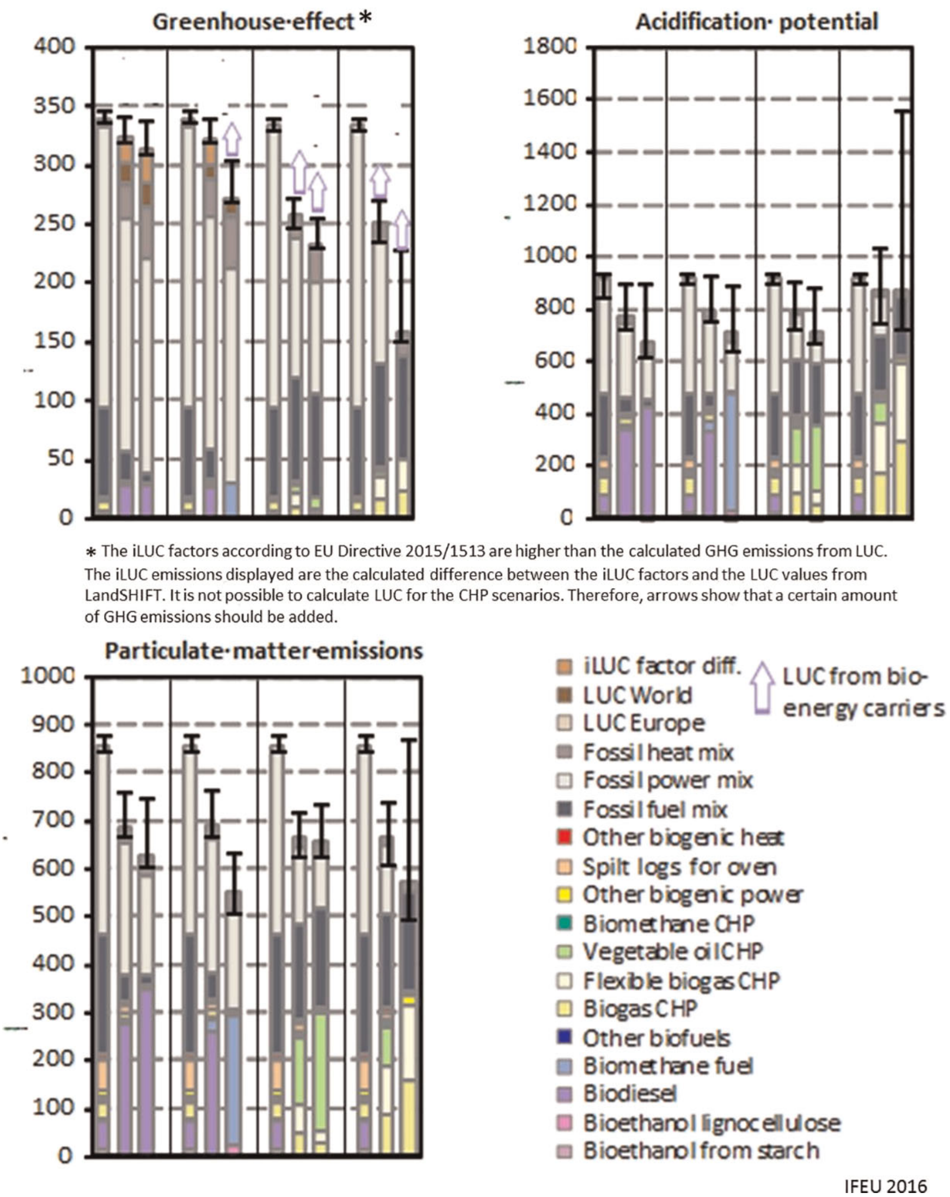

Figure 7. Greenhouse effect including land use changes, acidification, and particulate matter formation for normalized final energy (totals from biogenic and fossil energy identical for every year and scenario), for the four scenarios in 2010, 2030, 2050.

on securing supply. The fuel scenarios require much smaller amounts of mineral oil, but would require biomass imports, whereas, in the CHP scenarios, there is less of a need for coal and natural gas but a greater need for mineral oil. The main differences in energy diversity are between the BAU and the sustainability scenarios (around 3 percentage points in each case), whereas the differences between the sustainability scenarios for fuels and CHP are extremely small. Compared to 2010 figures, the scenarios for 2030 can improve energy diversity by about 7 % (BAU) and 10 % (sustainability scenarios), respectively. Thus, there is a significant potential for bioenergy to improve Germany's security of supply.

3.2.3.3 Impact on the Regional Infrastructure

In regional terms it is possible to adjust the scenario results to the regional situation, particularly because the modeling resulted in small-scale technologies. However, there were clear differences between the scenarios in terms of energy consumption (CHP and fuel scenarios):

- In the CHP scenarios, the large number of small units enables cogeneration options to be well-distributed spatially. In terms of energy demand, the existing CHP plants are able to absorb the amount of energy calculated from a regional point of view. The substrate mix and the biomass supply chain are the only differences between the BAU and the sustainability scenarios in terms of the supply of regional heating in district heating networks.
- In the fuel scenarios, however, there is no cogeneration option. This means that the German government's renew-

able heating targets need to be achieved using low-caloric district heating systems like solar thermal energy, as well as fossil energy sources or electricity-based concepts, e.g., heat pumps or power-to-heat concepts. Local and district heating networks would also face challenges since at present they primarily focus on bioenergy.

Preserving certain proportions of bioenergy in order to provide electrical power and heating is, therefore, regarded as advantageous from the perspective of regional integration.

4 Discussion

4.1 Comparing the Results of the Modeled Bioenergy Supply Chains for CHP or Fuels

Under the assessed scenarios, the least-cost energetic use of biomass was primarily shaped by food crop-based options in both the power and fuel sectors. Bioenergy supply from waste and residues can be expanded, but its quantitative contribution is limited.

In summary, as both the BAU and S scenarios are likely to apply to both the power and fuel sectors simultaneously, four general trends can be seen which have the potential to produce competition between the sectors (the sector preference is outside the scope of this paper):

(i) Under BAU conditions, oil-based feedstocks are relevant for both markets.
(ii) Under S conditions, maize-based biomethane/biogas is relevant for both markets.
(iii) Under S conditions, gaseous fuels become increasingly relevant in both markets.
(iv) Wood-based biofuels (bio-SNG) and power stand a chance of becoming cost-competitive under high sustainability criteria, but this would be in the long run.

In the case of competition between biogas/biomethane and oil-based options, some characteristics may skew the competition. Whole-crop maize is not economically transportable over large distances and is thus unlikely to be traded globally. Thus, the land around biogas plants needs to be set aside for this purpose. In contrast, oil-crops are traded globally. International biogas and biomethane trading, e.g., via the gas network, may rise in importance over the medium term [41].

In the power sector, both biomethane and oil-CHP can provide flexible power using existing technology. In the transport sector, however, liquid fuels have an advantage in that vehicle fleets do not require extensive adjustments. Biomethane is a substitute for natural gas, which is currently not very widely used as a transport fuel.

4.2 Comparing the Results of the Modeled Land Use Aspects

The simulation results indicate that policy measures to prevent land conversion in protected areas and other sensitive environments, as assumed by the sustainability scenarios, are an effective instrument in reducing the negative effects on biological diversity and soil quality. Moreover, it becomes obvious that, if arable land used for energy crops is expanded further, greenhouse gas emissions from direct and indirect land use changes will be on the same scale or even exceed emissions from the cultivation, supply and use of bioenergy sources. This will have a significant impact on the total greenhouse gas balance of the respective biofuels [42].

If the global conversion of carbon-rich ecosystems, such as forests and peatland, can be stopped by 2020, GHG emissions will subsequently decrease but the effects of this would not be visible until after 2040 since the high emissions of the earlier period (discounted after 20 years) would continue to have an impact. These results allow us to conclude that a harmonized international land protection policy is a prerequisite for the successful implementation of a sustainable bioenergy policy in Germany. Conversely, as long as there are no legally binding international land protection standards, new areas should be utilized in a much more moderate way than those modeled in the extreme scenarios.

Since the risk of losing biological diversity and soil quality due to arable land expansion is estimated to be less severe in Germany, we argue that the establishment of bioenergy supply chains based on domestic raw materials available in Germany is preferable to importing feedstock. At the same time, sustainability standards for liquid bioenergy sources, which have been established in recent years, should continue to be tested internationally and extended to other biomass sectors, i.e., for gaseous and solid biofuels but also biomass used as a raw material, food source, and feed source, in order to avoid the negative displacement effects mentioned above [43, 44].

4.3 Effects over Time

The selected modeling approaches generate different trends along the supply chain (see Tab. 3). Thus, in these scenarios it is evident that the technologies and effects that are widespread today will remain important up to 2030, whereas after 2030 the scenarios will increasingly differ. The different trends give rise to different fields of action in the respective time periods.

4.4 Reading the Extreme Scenario Results

It should be noted that the results mentioned above stem from extreme scenario calculations. Due to the high preference for conversion technologies based on agricultural commodities, the calculated demand for land is much higher than the demand in other energy scenarios that were used as a basis. For example, the total amount of directly and indirectly occupied arable land for biofuels in Germany and abroad equals the total national agricultural land in the BAU scenarios. This would lead to a massively larger footprint in terms of the area needed for food, feed, and bioenergy. In the sustainability scenarios, the demand for land is much lower, about 4 million ha, compared to the BAU scenarios due to the higher efficiencies of biogas/biomethane.

On the other hand, the model results demonstrate that, under the assumptions made here, the technologies that use wood as a feedstock in the production of CHP or fuels are

Table 3. Overview of the model results over time.

	2010 – 2030	2030 – 2050
Global demand for biomass	Demand continuously grows, especially for food and animal feed production.	
Land for global biomass production	An increase in biomass production on land not previously used for agriculture, including conversion of pastureland, results in various levels of risk to biodiversity (for all uses).	Land consumption in BAU scenario increasingly encroaches on sensitive regions (for GHG emissions and biodiversity, esp. forests and pastureland); this happens to a lesser extent in the sustainability scenario (and only affects pastureland) with increased intensification on the lands used.
Use of arable land in Germany	Extent of use remains constant but with varying international balance of trade. Conversion of pastureland increases, especially in the BAU scenarios.	
Technological developments in Germany	Bioenergy plants are based on agricultural raw materials (vegetable oil, biogas) in all scenarios; no prospect of new technologies for wood use up to 2030.	Bioenergy production slowly shifts towards biogas/biomethane; wood-based gasification technologies may be ready for the market. The prospects for wood-based fuels remain limited.
GHG from bioenergy used in Germany's energy supply	Generally on the decrease, but with no substantial difference between the different scenarios. Owing to changes in land use there is a risk that greenhouse gas emissions will decrease only slightly or even remain constant despite the use of bioenergy.	
Environmental effects of bioenergy provision in Germany's energy supply	Where the effects on biological diversity and soil quality are concerned, the supply of bioenergy sources from domestic agriculture is considered more manageable and less risky than international supplies of raw materials.	Since installations increasingly operate on the basis of biogas/biomethane, the raw materials are primarily supplied by German agriculture and are more manageable and less risky than international supplies of raw materials. However, in this case there is an increase in nutrient input and sometimes in acidification and particulate air pollution as well.
Food security	Moderate risk to food security due to bioenergy.	Only low risk to food security due to bioenergy.

not competitive at all. This leads to the conclusion that the widely anticipated market entry for wood-based fuels and CHP units is much more difficult than expected. Even if the well-established biomass-to-heat market was not investigated in this study, obviously it might be a robust option for generating bioenergy from biomass in the long term as well. On the other hand, a shift towards increased energy use of wood in the area of electricity/heating (highly recommended in environmental terms) or fuels (still preferable over using biomass for heat) can only be achieved through considerable effort and expense.

Finally, the impact assessment of the four extreme scenarios shows that a bioenergy policy that focuses moderately or strongly on domestic raw materials – in particular one that avoids the need to implement international land use policies – significantly reduces the potential risks for bioenergy. However, if large amounts of biomass for bioenergy lead to increased import of food and feed, indirect effects might only shift.

4.5 Extracting Elements for the Long-Term Bioenergy Strategy

The comparison and discussion of the four extreme scenarios are taken as a basis for establishing the elements of a future national bioenergy strategy. It follows the biomass-to-energy provision chain and includes both national and international policy elements.

The elements and milestones were formulated and reflected on by the Milestones research team as an iterative expert process based on a multitude of results which are filtered with regard to their differences, common features, unexpected results, and anomalies.

4.5.1 Element 1: Consequentially Embedding Bioenergy Policies in the National and International Environmental Policy Framework

Increased demand for bioenergy from energy crops leads to direct and indirect changes in land use which, in turn, results in changes in the carbon stocks from which greenhouse gas emissions are derived. The calculation of these effects is complex and a detailed analysis of them would be beyond the scope of this study. However, it has been possible to show here that – depending on the methods adopted – the overall reduction in greenhouse gas emissions through the use of bioenergy (compared with the use of fossil energy sources) is only slight, or even completely absent, owing to changes in land use. This picture will only change if sustainable land use is implemented globally. As this cannot be expected to happen in the short or medium term, the future bioenergy strategy requires dedicated sustainability standards and a well-adopted monitoring of the potential negative effects such as land use, changes in land use, and the associated carbon balances and greenhouse gas effects – not only for a bioenergy policy but also for the further development of the bioeconomy as a whole. In this way, the development of greenhouse gas emissions resulting from changes in land use and their effects on the desired targets in the energy system can be regularly tested and the strategy can be adjusted.

Hence, a future bioenergy strategy should particularly focus on elements relating to improving quality and less on the question of how to quickly achieve what has been calculated [45] to be the available and sustainable potential of 1550 PJ of primary biomass energy in Germany. By 2030, the contribution of bioenergy to the energy supply should have stabilized to today's levels (see Fig. 1). Later it might increase moderately depending on the type and extent of future land use policies. This conclusion is also derived from the other environmental impacts identified, such as particulate air pollution, acidification and nutrient input, which can rise as a result of bioenergy use. It should also be ensured that the targets for water, soil, and air pollution control are achieved, e.g., EU Water Framework Directive [46] or the National Emissions Ceilings for Certain Atmospheric Pollutants [47] and for the sustainable use of resources, e.g., a circular economy.

Medium-term milestones to enforce this strategy element are: (1) sustainability standards for different biomass are established, (2) ambitious sustainable land use policies have been implemented internationally [48], and (3) monitoring of land use, carbon inventories, and greenhouse gas emissions have been established within the framework of the bioeconomy.

4.5.2 Element 2: Continuing Bioenergy Provision from Domestic Feedstock

Germany should give preference to efficient domestic bioenergy production – whether in terms of biomethane in the fuels sector or in terms of biogas in the electricity/heating sector – over a strategy of importing sometimes less efficient biofuels, since this is associated with a lower level of risk to biodiversity and soil quality at the global level. It has, however, only been possible to roughly estimate the indirect effects of the displacement of other field crops by biogas substrates. This should be taken into account when developing a strategy. In conclusion, this demands future utilization concepts for biogas and biomethane plants and follow-up activities for power production from biomass within the Renewable Energies Act. This will require a detailed analysis of the existing plants in terms of the availability of useful heat sinks for CHP operation, and infrastructure potentials for converting biogas and biomethane plants, e.g., proximity to the existing natural gas network. Parallel to this, the partial shift from existing local biogas electricity conversion units to biomethane processing plants allows for very flexible utilization of the electricity supply with mandatory use in CHP stations or highly efficient gas and steam power stations, and for its use as a fuel. In addition, a sectoral analysis should also be carried out to determine the mobility sectors in which biomethane should be employed in the future, i.e., also in terms of using the fuel in dedicated markets such as the agricultural or forestry sectors.

An additional way to domestically provide bioenergy is to increase the usage of biogenic residues from agriculture, forestry, industry, and municipalities. This was investigated within the study with only rough assumptions. In practice, the domestic potentials are limited and the conversion efficiencies are often low. Requirements are needed for exploitation and best possible use or recycling of local waste, especially biodegradable waste, waste wood, and sewage sludge, through further support and legislative guidance in accordance with the principles of a circular economy as well as adjusted infrastructures so as to enable the sorting and utilization of assorted biomass [49]. One of the huge untapped biomass residues is straw [50]. Lignocellulose decomposition offers a wide range of options for the use of straw and other residual materials. The modeling results indicate that the production of ethanol from (domestically produced) straw may become marketable in the medium term. This needs to be flanked by corresponding R&D activities. From the point of view of environmental protection, however, this type of use is less positive than the possibility of generating electricity and heat from straw [51].

Medium-term milestones to enforce this strategy element are: (1) A development strategy for biogas/biomethane (post-EEG strategy) has been implemented, (2) lignocellulose decomposition of straw has been established on the market and its energy use has been prioritized among the utilization options, and (3) waste recycling legislation and infrastructure have been adjusted.

4.5.3 Element 3: Upgrading the Wood-to-Heat Use

The scenario results indirectly demonstrate that only generating heat, particularly using single room combustion plants and heating networks, but also by industry, will continue to play a significant role. This is due to the very moderate demand for wood for innovative technologies in the shorter term and the well-established regional and local raw material supply structures as well as due to the fact that investment has already been made in district heating systems. At the same time, there is also a need to move towards adaptation to descending heat demands, increased efficiency, and reduced emissions in this area. Gasification technologies and, where relevant, other small-scale systems for combined heat and power generation can bring about the necessary system innovations. The results illustrate that such technologies may become profitable in the medium term, if existing challenges are solved by strong R&D activities.

In addition to the involvement of decision makers at the local government level, the supply of biogenic heat requires support as part of a national heating strategy. The heating strategy should contain an action field for areas (local quarters) with low heat density and for areas with an efficient heat density where it is worth setting up a district heating system (DHS). Due to the larger scale of the installation, the DHS enables the operator to combine highly-efficient CHP units and heating plants supplied with low-quality wood residues. Setting sustainability standards for wood-to-energy provision can prevent undesired environmental impacts especially for small wood combustion facilities, which were not investigated in detail here. This might also be relevant for another potential wood-to-energy application field, which was not the focus of the scenario assessment: The option of co-combusting wood in coal-fired power stations may lead to a short-term increase in (mainly imported) wood consumption if prices for CO_2 emissions certificates increase [52]. Sustainability standards for solid fuels should be implemented to provide a framework for their use when CO_2 prices are high.

Medium-term milestones to enforce this strategy element are: (1) Heat generation from biomass increasingly involves innovative concepts ("upgraded heat recovery") and has been taken into account as part of a national heating strategy, (2) gasification technologies are available, and (3) sustainability standards are set for wood-to-energy provision.

4.5.4 Element 4: Distinguishing between Different Transport Modes within the GHG Emission Reduction Framework

Biodiesel is a low-cost, liquid bioenergy source which exhibits little potential for innovation. The existing production capacities should not be increased further – neither, however, should they be decreased in the near future since the production of fuel results in important co-products (animal feed and glycerol). However, this effect has not been assessed in detail. One point remains open: the targeted development of high-quality liquid bioenergy sources for selected fields of application. This should be developed on the basis of the different developments in the transport modes. Biodiesel and biomethane are promising for some applications, over the long term as well. However, other applications would require long-term support for advanced fuels, e.g., aviation sector, both through R&D measures and through market launch instruments, because in all scenarios such fuels are considerably more expensive than conventional biofuels. The conclusion drawn from the model results is that those energy carriers need to provide dedicated qualities that are necessary for sectors where other alternatives are not at hand, and therefore need to be heavily pushed to the market in the long term.

A medium-term milestone for enforcing this strategy element is that a differentiated biofuels strategy has been implemented.

4.6 Limitation of the Modeling Approach

Due to the comparably new approach, some shortcomings should be noted: The modeling was based on the assumption that bioenergy will supply 1550 PJ of primary energy per year [34]. We did not do a complete energy system modeling but rather focused on the area of bioenergy. The modeling does not elaborate on the general bioenergy potential and not consider the competition between the use of energetic and non-energetic biomass. For the modeling, a variety of parameters were set based on existing studies and expert opinions, each being potentially subject to uncertainties. Additionally, the feedback of the results is assessed to the overall energy system using different indicators, but not using a dynamic approach. These indicators allowed for covering a certain range of aspects, but there are some remaining gaps, i.e., an assessment of soil quality risks was not possible for areas used to cultivate energy crops for biogas production in Germany. A stepwise improvement of the Milestones modeling framework is necessary. In terms of policy recommendation, the shortcomings of the innovative modeling approach were addressed by investigating extreme scenarios and by discussing the approach and the results with different stakeholders.

5 Conclusions

The need for further bioenergy strategies are currently discussed in many countries. Under the different policy fields, namely, agriculture, environment, and energy, as well as scales and stakeholders, the development of strategy elements has been demonstrated successfully for the example of Germany. The analysis has been based on the new Milestones modeling approach. With the chosen analysis of extreme scenario assessment, robust elements for a bioenergy strategy were identified. These are:

- Consequently embedding bioenergy policies in national and international environmental policy framework
- Continuing bioenergy provision from mainly domestic feedstock
- Upgrading the wood-to-heat use
- Distinguishing between different transport modes within the GHG emission reduction framework

These elements address feedstock origin, promising bioenergy carriers, and future application fields, as well as the development of appropriate frame conditions. Additionally, certain pathways have been identified for developing technology which can be expected to become competitive within the bioenergy sector under different frame conditions. Thus, the results coherently address a wide range of policy fields, something which has not been possible in the past.

Additionally, the results of this study not only tackle issues on global and national levels, but also provide information about challenges and opportunities at the regional and local level. For example, the results also indicate that both the operators of existing and the planners of future heating grids should be aware of uncertainties in future biomass pricing due to market competition. Regional supply networks and structures should be installed to overcome these uncertainties. This has not been elaborated upon in this study.

The results from the example of Germany also lead to the more general conclusion that every national bioenergy strategy is strongly connected to different international aspects like land use, and international governance is a relevant element of any sustainable bioenergy policy. With regard to advanced biofuels, the need for expectation management on an international level is obvious: The poos competitiveness of thermo-chemically converted biomass-to-liquid fuels with other biofuels highlights the demand for more competitive technology concepts or dedicated support schemes for a successful market introduction. Finally, expectation on the role of bioenergy in the future energy system is under strong development [53]. From 2030 onwards there are likely to be stronger shifts between the electricity, heating, and fuels sectors as well as in relation to other renewable energies.

Further use of the developed approach should focus on increasing interdependencies between the energy supply in the heat, power, and transportation sectors, i.e., power-to-heat; electro mobility, and flexible bioenergy, as well as the combined material and energy use in a developing bioeconomy.

Acknowledgment

Funding by the Federal Ministry of Economic Affairs and Energy (BMWi) and the Federal Ministry of Food and Agriculture (BMEL) is gratefully acknowledged. The project "Milestones 2030" was conducted by research teams at DBFZ, CESR, IFEU, IINAS, IZES, Öko-Institut, Thünen-Institut, and the Helmholtz Center for Environmental Research UFZ.

The authors have declared no conflict of interest.

Abbreviations

Bio-SNG	biosynthetic natural gas
BtL	biomass-to-liquid
CHP	combined heat and power
DHS	district heating system
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act)
EtOH	ethanol
FAME	biodiesel
FT	Fischer-Tropsch
GasifSml	gasification small
GDP	gross domestic product
GHG	greenhouse gas emissions
HVO	hydrogenated vegetable oils
IIASA	International Institute for Applied Systems Analysis
iLUC	indirect land use changes
LandSHIFT	Land Simulation to Harmonize and Integrate Freshwater Availability and the Terrestrial Environment
LUC	land use changes
ORC	organic rankine cycle
R&D	research and development
SNG	synthetic natural gas

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