Renewable and Sustainable Energy Reviews 68 (2017) 1222–1233

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Interpreting long-term energy scenarios and the role of bioenergy in Germany

Nora Szarka [a,*], Marcus Eichhorn [b], Ronny Kittler [a], Alberto Bezama [b], Daniela Thrän [a,b]

[a] Deutsches Biomasseforschungszentrum, Leipzig, Germany
[b] Helmholtz Centre for Environmental Research, Leipzig, Germany

ARTICLE INFO

Available online 19 March 2016

Keywords:
Bioenergy
Energy scenarios
Policy making
Decision support

ABSTRACT

Defining the long-term development of Germany's energy sector, has been the subject of a series of studies carried out by governmental, industrial and independent interest groups. These studies play a significant role in energy political debate for understanding the long-term role of bioenergy in the national energy system. However, a deep insight and critical assessment of these studies is necessary to increase their transparency and traceability for policy and research. This article aims to provide with information for better understanding energy scenarios and to interpret the expectations of the role that bioenergy can play in 2050.

Firstly, 18 long-term energy scenarios were selected based on defined criteria, and analyzed in details in terms of their goals, methods, data used and obtained results. Furthermore, four specific bioenergy-related indicators were selected to carry out a quantitative analysis and interpretation across the selected studies. The results for the four indicators show a high uncertainty and a wide range of potential bioenergy development futures in Germany by 2050 – e.g. the sustainable domestic biomass potential ranges from 350 to 1700 PJ, the share of biomass in final energy consumption lies between 5 and 28% – principally due to the different key questions and methods and heterogeneous driving forces.

The study provides with recommendations for energy scenario users for quality measures (e.g. traceability and transparency of methods and data) and contextualization of the results

1. Introduction

Germany is aiming to develop and implement an efficient and environmentally sound energy system that is characterized by competitive energy prices. At the same time it strives to maintain high living standards and economic prosperity [1–8]. The proportion of renewables in Germany's energy balance is rapidly growing: renewable power generation grew from 16.4% in 2010 to 26.2% in 2014 [9], resulting in 157 Mt of avoided CO_2 emissions in 2014 [10].

In the aftermath of the Fukushima accident in 2011, the German government changed its stance on nuclear energy and approved an amendment to the nuclear power law [7,8] and the German parliament enacted a nuclear power phase-out by 2022 [11]. In 2011, a set of laws was passed that supported the implementation of the Energy Concept and an envisioned transition of the German energy system (known as “Energiewende”) by providing the necessary instruments and measures.

The German energy system is thereby undergoing a significant transformation in the short and medium term [12] with potential of achieving up to 100% renewable electricity by 2050 [13,14]. Although there is a political will to achieve the goals mentioned above, opinions are divided particularly with regard to the following aspects: firstly, in the way in which the energy system of the future should be constituted and secondly, in terms of the extent to which the various renewable energies will contribute to the energy mix. Finally, opinions are divided when it comes to identify the set of technologies that need to be promoted in order to achieve the forecasted goals.

In order to shed light on these questions and to explore a wide range of development options, a series of energy scenario studies have been independently commissioned by the German government, environmental groups and various energy sector stakeholders. In general, scenarios describe potential future developments of the system under investigation [15–17]. In particular, energy scenarios can be useful tools in (i) assessing energy sectors or system developments under certain assumptions, (ii) discussing various energy futures, (iii) integrating knowledge of different

* Corresponding author.
E-mail addresses: nora.szarka@dbfz.de (N. Szarka), marcus.eichhorn@ufz.de (M. Eichhorn), ronny.kittler@dbfz.de (R. Kittler), alberto.bezama@ufz.de (A. Bezama), daniela.thraen@dbfz.de, daniela.thraen@ufz.de (D. Thrän).

http://dx.doi.org/10.1016/j.rser.2016.02.016
1364-0321/

disciplines and stakeholders, and (iv) guiding and monitoring political decision making [18].

Energy scenarios can support the development of policy goals by evaluating a broad range of future options, as in the case of explorative scenarios. Another type of scenario, the target scenario, is implemented in political decision-making processes to analyze how a set of goals can be attained and their rate of achievement at a specific point in time. Any given scenario can therefore be characterized in terms of its main issues and goals, as well as in terms of the methods used and the degree of detail needed for the aspects under investigation.

Among renewables, bioenergy – i.e. energy derived from the conversion of biomass- has played a key role in Germany, making up to two-thirds of the supplied renewable energy. Biomass can be converted into all final forms of energy – power, heat and biofuel. This also implies that there is a broad range of possible biomass resources, conversion technologies and pathways. Bioenergy is characterized by a diverse and shifting policy related to it, as well as by a decision framework and stakeholders.

In recent years, cascading use of biomass has become an important asset of national biomass usage policies, aiming to a hierarchical valorization and use of biomass [19]. In this context, another important factor in these scenarios is the amount, quality and distribution of the available biomass potential. The promotion of this biomass use is reflected in the implementation of national bioeconomy strategies and roadmaps in Germany [20–22]. Such a shift in the role of bioenergy as a means of biomass valorization may have an important, and yet unknown, impact on its strategic, infrastructural and technological developments, and should be incorporated into long-term energy planning scenarios.

Thus it is difficult to deeply understand and directly interpret results derived from existing scenarios that determine the role and relevance of bioenergy. The executive committee of the International Energy Agency Renewable Energy Technology Deployment (IEA-RETD) has acknowledged the fact that a certain guidance framework is needed for scenario interpretation. It recently published a guide on energy scenarios for decision makers in order to improve their capacity to understand, evaluate and interpret models, including the drivers and values behind them, as well as the results of each scenario [23].

For this reason, our paper reviews a total of eight studies carried out in Germany, which describe, analyze, compare and explain the role of bioenergy within the national energy system. Our goal is to better understand and increase the transparency of energy scenarios and to interpret the expectations of the role that bioenergy will play in 2050.

2. Methodology

2.1. Scenario selection

A literature review was conducted to identify all energy scenario studies focusing on Germany's Energy Transition and the related Energy Concept targets (reduction in CO_2 emissions and increase in renewables). In addition, relevant international literature was reviewed to identify adequate global energy scenario studies which could be compared with the national scenario studies. These screened studies were published between 2007 and 2012. As part of a second screening process, studies were assessed based on their timeframe – up until the year 2050 (i.e. "long-term") –, their scientific credibility considering the applied analytical tools and assumptions, and the comparable information about the bioenergy sector. In order to account for different background motivations, we included studies made by public bodies, research institutions, non-governmental institutions and the energy sector itself. As a result, we selected a total of 18 normative and explorative energy scenarios from eight studies [13,14,24-29]:

- "Signals & Signposts Shell Energy Scenarios to 2050" – Shell 2011 [24] was selected in order to assess global energy system scenarios from an energy sector perspective. Shell has pioneered the development of plausibility-based scenarios, dealing with complexity and uncertainty over the past 40 years. It has developed scenarios as decision support tool for strategic enterprise development, considering long-term trends, based on plausible assumptions and quantifications. Most of the parameters in this study are available for Germany.
- "Energy Technology Perspectives – Scenarios and Strategies to 2050 – IEA 2008" [25], published by the International Energy Agency, was chosen as a second international reference, especially because it contains detailed and differentiated data on bioenergy technology and its usage, also including specific data for Germany.
- To represent the dedicated electricity sector, two scenarios included in the review study were: "Energy target 2050: 100% renewable electricity supply" – UBA 2010 [13] conducted by the German Federal Environment Agency (UBA) and "Pathways towards a 100% renewable electricity system" – SRU 2011 [14], a special report issued by the German Advisory Council on the Environment (SRU). These two studies enabled us to analyze scenarios prepared by national institutions with different motivational backgrounds.
- Four studies were included in the present research that represented the complete energy system. "Long-term scenarios and strategies for the deployment of renewable energies in Germany in view of European and global developments – Lead Study 2011" – prepared by DLR in 2012 [26] and "Scenarios for an Energy Policy Concept of the German Government" – by the Federal Ministry of Economics and Technology (BMWi) [27] were conducted by public and private research institutions on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the BMWi. Both studies aim to explore different ways of achieving the climate and energy goals set by the German government and outlined in the Energy Concept [3].
- In addition, alternative studies submitted by two of the most influential environmental groups, WWF and Greenpeace, were reviewed. Whereas government-related studies focus on scenarios for achieving already defined goals, WWF and Greenpeace aim to bring to the table a more ambitious blueprint for the transition of the energy system. "Blueprint Germany – A strategy for a climate safe 2050" – WWF 2009 [28] was commissioned by the WWF to examine Germany's energy policy concept with regard to further energy savings and GHG mitigation potential.
- Furthermore, because of the heated political and social discussions in Germany on carbon capture and storage (CCS), the study examines scenarios with and without CCS technology. Greenpeace released the most ambitious energy system study called "Climate protection: Plan B – A national energy concept to 2050" – Greenpeace 2009 [29]. Based on the Energy Policy Concept and other official studies, Greenpeace presents a scenario that allows for an early phase-out of nuclear energy and an additional phase-out of coal-fired plants.

Table 1 summarizes the analyzed scenarios, including their geographical scale, scope, scenario types (explorative or target) and model applied, as well as their main goal.

Table 1
Characterisation of the reviewed scenarios.

Scale and scope	Study	Scenario names	Abbreviations	Scenario type	Main goals	Applied models
World Entire Energy System	Shell 2011 [24]	(1) Scramble (2) Blueprint	Shell_Scramble Shell_Blueprint	Explorative	• Support of understanding of global developments and the world's energy supply, use and needs.	
	IEA 2008 [25]	(1) Baseline Scenario (2) ACT Scenarios (3) BLUE Map Scenarios	IEA_Base IEA_ACT IEA_BLUE	BAU Target* Target**	Most cost-effective technologies: • to stabilise global CO_2 emissions (ACT) • reduce CO_2 emission by 50% (BLUE)	• WEM - World Energy Model [a] • MARKAL and TIMES models for individual countries
Germany Electricity Generation	UBA 2010 [13]	(1) Regions Network (2) International-Großtechnik (3) Lokal-Autark	UBA_Energy_Target	Target	Technically and ecologically feasible electricity system integration options to reach 100% RE in the German electricity generation sector.	• Energy System Model SimEE [b]
	SRU 2011 [14]	(1) Self-supply (2.1) Net self-supply and exchange (2.2) Max. 15% import EU (3) Max. 15% import EU & North Africa	SRU_1a; SRU_1b SRU_2.1a; SRU_2.1b SRU_2.2a; SRU_2.2b SRU_3.a; SRU_3.b	Target Target Target Target	Technical and ecological feasibility to reach 100% RE in the German electricity generation sector with a demand of: a=500 TWh target/b=700 TWh target	• Energy System Model REMix [c]
Germany Entire Energy System	DLR 2012 [26]	(1) Scenario 2011 A (2) Scenario 2011 B (3) Scenario 2011 C (4) Scenario 2011 THG95	DLR_Leadstudy_A DLR_Leadstudy_B DLR_Leadstudy_C DLR_Leadstudy_THG95	Target Target Target Target	• Options to reach the German Energy Concept Goals explicitly focussing on the transport sector & e-mobility	• VECTOR21-Vehicle Technologies Scenario [c] • Energy System Model REMix [c] • Energy System Model SimEE [b]
	BMWi 2010 [27]	(1) Reference Scenario (2) IA-IVA (3) IB-IVB *(I-IV variation in nuclear phase-out)* *(A/B variation in retrofit cost)*	BWWI_Ref BMWI_IA-IVA BMWI_IB-IVB	BAU Target Target	• Reduction of GHG emissions of 40% by 2020 and 85% by 2050 • Increase the share of RE in the gross final energy consumption: 18% by 2020 and 50% by 2050 • Influence of the life time of the German nuclear plants	• European Electricity Market Model DIME [d] • PANTA RHEI environmental-economic modelling [e]
	WWF 2009 [28]	(1) Reference Scenario with CCS (2) Reference Scenario without CCS (3) Innovation Scenario with CCS (4) Innovation Scenario without CCS (5) Modell Deutschland	WWF_Ref_CCS WWF_Ref_NoCCS WWF_Inno_CCS WWF_Inno_NoCCS	Explorative* Explorative** Target Target	• Technical and economic feasibility to reduce CO_2 emissions by 95% • Influence of CCS technology	
	Greenpeace 2009 [29]	(1) Reference Scenario (2) Greenpeace Scenario	Greenpeace_Ref Greenpeace_Tar	BAU Target	Technical and economic feasibility to: • reduce CO_2 emissions by 90% • reach 90% RE in final energy consumption • reach 100% RE in electricity generation	• Based on data from the German Federal Environment Agency (UBA) and Lead Study 2008

Abbreviations: CCS – Carbon Sequestration and Storage; BAU – Business as usual. **Note:** The marks * and ** are used to qualitatively classify scenarios in "low" and "high" regarding sustainable and renewable future energy systems. Low denotes pessimistic Scenarios whereas high denotes the optimistic scenarios.

Sources:

[a] International Energy Agency.
[b] Fraunhofer IWES.
[c] DLR- German Aerospace Centre.
[d] EWI-Institute of Energy Economics.
[e] GWS- Gesellschaft für Wirtschaftliche Strukturforschung mbH.

2.2. Scenario analysis with indicators

A comparative analysis of the scenarios was performed by selecting, defining, quantifying and explaining four bioenergy-related indicators and five indicators that characterize the energy system as a whole, taking into consideration the availability of high-quality data.

In order to focus the discussion of this paper on the bioenergy system, results of the comparative analysis, with the selected indicators for the energy system, are presented in Appendix A.

One of the key aspects for the development of the bioenergy sector is the availability of biomass resources that will supply future energy demands. Furthermore, since Germany is aiming to become non-dependent on biomass import, the potential from domestic sources should be taken into account. For this reason the indicator *Domestic biomass potential* was chosen to differentiate between the amounts of available national biomass within the studied scenarios.

Moreover, since a main objective of this study is to show and analyze the role of biomass within various final energy sectors (i.e. power, heat, transport), the indicator *Share of biomass in the final energy consumption* was selected. Due to an insufficient amount of data available in other sectors, only the transport sector could be highlighted and was represented by the indicator *Biofuels in the transport sector*. Finally, the indicator *Allocation of biomass among final energy sectors* was selected to depict the options for using biomass in the power, heat and transport sectors in the future.

The resulting indicators, along with their assumptions and the study framework, were analyzed and a discussion is provided for scenario users.

3. Results

3.1. Status quo and development of the bioenergy system as part of long-term energy scenarios

3.1.1. General analysis

Currently, the potential that bioenergy systems have in contributing to the reduction in greenhouse gases (GHG) and to demand-driven supply plays a significant role in the bioenergy and bioeconomy debate in Germany and Europe. Until the early 1990s, Germany's energy system was almost exclusively based on fossil fuels and nuclear energy. Since then, several legislative acts have come into force e.g. a 1991 feed-in law, the Renewable Energy Act (EEG) and its amendments. This has contributed to an increase in the use of biomass for energy purposes, among other things. In 2010, bioenergy made up 7.7% of the overall final energy consumption, and approximately 70% of the renewable-based final energy supply in Germany [30]. Fig. 1 illustrates the development of bioenergy usage in Germany since 1990.

As a result of the many resources that can potentially be used as feedstock (e.g. energy crops, waste and by-products), as well as the numerous thermo-chemical, biochemical and physical-chemical conversion methods to generate/produce it, bioenergy has the potential to support the generation of energy for all end-use applications (electricity, heat and transport) [30]. Bioenergy's major potential strength in the electricity sector is system stabilization. Bioenergy can be used flexibly, compensating for fluctuations in systems composed mainly of volatile sources such as wind power and photovoltaics [31]. Furthermore, bioenergy conversion usually generates heat and power simultaneously by using combined heat and power plants (CHP). Increased use of cogenerated heat results in high efficiency gains, especially in the up-and-coming field of micro CHP plants used for individual households. In the transport sector, alternative renewable-based fuels

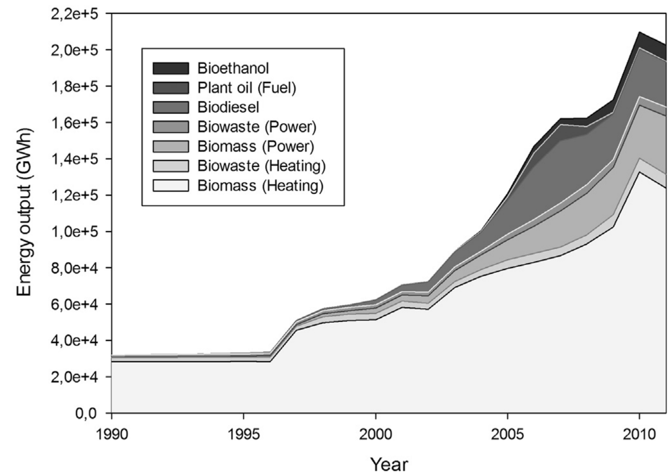

Fig. 1. Development of bioenergy use in Germany 1990–2010 (adapted from [10]).

will likely play an important role in the aviation sector [32]. International ambitions and regulatory mechanisms are principally the key drivers for this development. For example, the International Air Transport Association (IATA) has set the goal of halving international aviation emissions by 2050, compared to 2005 levels. And in this regard biofuels can play a significant role, since bio-jet-fuels are considered to have zero-emissions under the EU ETS system. In addition, the EU Fuel Quality Directive has set a target of reducing GHG emissions by 6% by 2020 (compared to 2010 levels) for all energy used in the transport sector [33]. Germany, on the other hand, has set a goal that, by 2025, 10% of its jet fuel will be bio-jet-fuel [34].

With the National Research Strategy BioEconomy 2030 [35], and the National Policy Strategy on Bioeconomy [22] the German government has outlined an additional future field of application for biomass from various biogenic sources. Using biomass for bio-based industrial products, such as platform chemicals and fertilizers, is considered to be particularly forward-looking.

3.1.2. Specific analysis of the study "Signals & Signposts Shell Energy Scenarios to 2050" [24]

Shell's "Signals & Signposts" study makes no statements concerning global biomass potentials, however it does set out expectations for the primary energy demand of biomass: In its scramble scenario, the proportion of primer energy will be 131,000 PJ (14.6 GJ per capita) biomass and in the blueprint scenario it will be 57,000 PJ (6.3 GJ per capita) by 2050. It makes no detailed differentiations concerning the type of biomass used, but the scramble scenario provides assumptions about the role of biomass, and a "huge push for biofuels" [24] is assumed, especially when it comes to providing liquid fuels for transportation. In particular, first-generation biofuels (produced primarily from food crops such as grains, sugar beet and oil seeds) compete with food production, leading to increased food prices. Furthermore, increased import to the EU as a result of domestic shortfalls leads to deforestation and degradation in the exporting nations. In reaction to this, second-generation biofuel (biofuels produced from non-food biomass such as lingo-cellulosic materials or purpose-grown energy crops) technology is promoted, improving the situation after 2020, especially in OECD countries. At the same time, increased use of waste and agricultural residues means newer certification systems for crop-based biomass are also on the horizon.

3.1.3. Specific analysis of the study "Energy Technology Perspectives – Scenarios and Strategies to 2050" [25]

The IEA study "Energy Technology Perspectives 2008" estimates a biomass potential of between 90 EJ and 150 EJ. In the ACT Map scenario, the demand for biomass is projected to reach 120 EJ per year, in the BLUE Map scenario 150 EJ, whereas 90 EJ is projected annually in the baseline scenario. In the BLUE Map scenario, biomass becomes the most important renewable energy source with its use nearly quadrupling and accounting for approximately 23% of total primary energy world-wide (3604 Mtoe/a) in 2050. Half of the biomass demand will be covered by cropping and forest residues and the remaining amount from purpose-grown energy crops. In order to supply the biomass demand expected in the BLUE Map scenario, between 375 Mha and 750 Mha of land are required (assumption: average biomass yield of 5–10 t of dry matter/ha), which is approximately 3–4% of the six billion hectares of agricultural land in use today. Of this, approximately 160 Mha would be needed for biofuel (BLUE Map scenario). Biofuels will mainly be used in commercial road transport, shipping and the aviation sector because the choice of alternative fuels in these sectors is limited. The IEA assumes a 27% share, or 6.5 EJ [25], per year provided by bio-based jet fuels in 2050 (BLUE Map). The aviation industry is expected to develop and pilot the use of bio-jet-fuel blends which will also be included in the European Union's Emission Trading System.

In terms of individual transport, the BLUE Map scenario estimates that there will be a strong market penetration of alternative systems. By the year 2050, around one billion fuel cell or e-mobility cars will be on the road. Another 700 Mtoe/a will be converted into 2450 TWh electricity annually. Of the used biomass, 21% will be co-fired and the remainder used along other conversion pathways. In total, this means biomass will make up 5–6% of global electricity production in both scenarios in 2050. A significantly higher proportion (approximately 10%) is only expected if CCS technology is not applied around the globe. The remaining 2200 Mtoe per year will be used in producing biochemicals (i.e. bio-lubricants), heating (also process heat in the industrial sector) and cooking.

The cost of biomass-based electricity and transport fuel is expected to drop, but heat generation is expected to remain at today's levels. Advanced combustion technologies, such as circulating fluidized bed (CFB) boilers and co-firing (biomass with coal) steam turbines of up to 100 MW that use access heat via CHP, will compete with other technologies in terms of cost. Biomass gasification technologies are expected to play a significant role because costs are likely to decline by up to 50%. It will not be possible to meet the projected 2050 demand for biomass for both Fischer-Tropsch synthetic diesel and bioenergy power plants unless gasification of biomass becomes a mature and cost-effective technology.

3.1.4. Specific analysis of the study "Energy target 2050: 100% renewable electricity supply"

In the "Energy target 2050" study, the term "potential" relates to the techno-ecological potential which is defined by the best-available conversion technology when ecological restrictions are taken into account. Therefore, only residues and waste are used as sources of biomass for energetic purposes in 2050, excluding biomass import. Within this scenario, only biogas is used for flexible generation to balance the fluctuations of intermittent renewables such as wind and PV, mostly in CHP plants, with the possible use as heat. It is assumed that biogas plants with an installed capacity of 23.3 GW will supply peak loads with a maximum generation of 11 TWh (0.5 GJ per capita).

3.1.5. Specific analysis of the study "Pathways towards a 100% renewable electricity system" [14]

In the "Pathways towards a 100% renewable electricity system" scenarios, only residues and waste are used to produce energy; their potential with solid biomass in CHP is 42 TWh/a, and with biogas in CHP the value is 27 TWh/a. Biomass for power has the highest system use if CHP technologies are applied. The scenarios with 500 TWh annual power demand allow for energy exchange with other countries; only half of the available biomass (solid and biogas) is used to generate electricity and only in combination with CHP technologies. In scenarios 1a and 1b (full self-supply), all of the biomass is used without CHP, mostly to cover peak loads. The demand for electricity uses a third of the biomass potential, and two-thirds is used for heat and biofuels. Biogas will be decentrally produced in agricultural plants, using energy crops, manure, materials from landscape conservation and other biogenic residues and waste.

3.1.6. Specific analysis of the study "Long-term scenarios and strategies for the deployment of renewable energies in Germany in view of European and global developments – Lead Study 2011" [26]

In the "Lead Study" the generation and use of biomass does not vary among the scenarios: imported biomass is not considered (even though the Energy Concept includes 500 PJ import annually). Also, the available national biomass potential is 1550 PJ/year, from which 800 PJ are derived from residues is 100% used. Biomass is primarily converted for heating purposes and used in CHP (1100 PJ/year) because of its higher energy efficiency and GHG reduction potential. Bio-methane and bio SNG (such as wood gasification and injection into the grid) play an important role alongside biogas in conversion technologies for CHP. Moreover, 60 TWh of power is to be generated from biomass by 2050, and flexible generation will play a key role.

The amount of biomass used in district heating goes down to 100 TWh. Solid biomass plays a reduced role in CHP generation and a very limited increase in the heating sector is expected. Gasification for injection and use in CHP will be market-ready. In the transport sector, a maximum of 300 PJ of bio-based resources is used for all scenarios, requiring 2.3 Mha of agricultural land for energy crops. Only second generation biofuels with biogas, bio-methane and biomass to liquid (BtL) are expected, and the anaerobic digestion of the residues for biodiesel and ethanol production is considered to be a further option. However, this study does not include any details on such technology applications.

3.1.7. Specific analysis of the study "Scenarios for an Energy Policy Concept of the German Government" [27]

The study "Scenarios for an Energy Policy Concept of the German Government" assumes a sustainable overall potential for biomass used for energy purposes that amounts to 2200 PJ or 29.8 GJ per capita. Biomass, whether solid, liquid or gaseous, will also be the most important renewable energy source in 2050. The use of biomass in electricity generation is limited because a certain proportion is meant to substitute fossil fuels in the transportation sector. The potential is limited to 2127 kW/h per capita (7.7 GJ per capita). Electricity generated from biomass will be approximately 40 TW/h per year. In 2050, approximately 20% of the biomass will be imported (469–489 PJ). The price of biomass for energetic uses is expected to rise to 43 €/MW/h in 2020 and 50 €/MW/h in 2050.

3.1.8. Specific analysis of the study "Blueprint Germany – A strategy for a climate safe 2050" [28]

The "Blueprint Germany" study limits the potential amount of biomass for energetic uses to domestic and sustainable biomass resources. This "safety rail" is established to ensure that no food/energy crop competition or leakage will arise. In terms of the

German biomass potential, the study refers to previous studies carried out by prominent institutions such as Öko-Institut [36], German Aerospace Centre (DLR) [37] and the German Advisory Council on Global Change (WBGU) [38]. The total amount of available biomass is calculated to be 1200 PJ per year in 2050 assuming there is 4 Mha of land available for energy crop cultivation with primary energy production ranging from 415 to 522 PJ per year and an annual 700 PJ from various residues. A moderate 41.3 TWh is estimated to be the maximum potential of electricity generated from biomass.

Even though the energetic efficiency of biomass used in electricity generation is the most favorable, Blueprint Germany expects biomass to play a major role in second-generation biofuels in the transport sector since the sector is lacking alternative substitutes. In the innovation scenario, 987 PJ of biomass is converted into biofuels and another 7 PJ to biogas, which predominantly substitute natural gas in fulfilling residential energy demands. The innovation scenario estimates an "electrification" of the individual transport sector and a complete market penetration of alternative technologies such as fuel cells, hybrids, e-mobility and (liquid) gas. In the reference scenario, biofuel production reaches only 340 PJ by 2050 because of the continuing dominance of conventional fuels. In turn, biogas production increases to 60 PJ per annum, of which two-thirds are used for residential consumption. In both scenarios, electricity generation from biomass ranges between 41.3 and 44.7 TW/h in 2050. Final energy consumption based on biomass in residential heating drops to 1242 PJ (reference) and 315 PJ (innovation), with wood being a major player, 342 PJ (reference) and 90 PJ (innovation). Biomass demand in the reference scenario will be slightly below the German domestic potential of 1200 PJ (1090 PJ), whereas in the innovation scenario, demand is 120% higher. Even the implementation of further efficiency measures and transport reductions cannot bridge this gap and approximately 80% of excess demand needs to be satisfied through biomass imports.

3.1.9. Specific analysis of the study "Climate protection: Plan B – A national energy concept to 2050" – Greenpeace 2009 [29]

The study "Climate Protection: Plan B" assumes that the biomass potential in energetic usage is already being significantly exploited today and that there is a relatively limited amount left over for further energy production. The study only includes the German domestic biomass potential to limit leakages and food/energy competition that could occur because of biomass imports. Available land for energy crop cultivation is limited to 4.1 Mha in 2050. In order to sustainably increase the use of bioenergy, the study assumes in the target scenario that there is comprehensive use of various residues, such as manure, and that areas with low utilization rivalry are cultivated. These quite strict safety railings lead to moderate growth in available biomass by 2030. By 2050, biomass availability will almost double with an increase in sustainable arable land for energy crop production. The limited potential for energy crop cultivation restricts the use of biomass in CHP electricity generation to 45 TW/h, a share of 33% in CHP energy generation and approximately 10% of the final electricity demand.

3.1.10. Summary

In summary, the analysis of the existing scenarios shows that there is no consensus on the future development of biomass potential in Germany, particularly in terms of its availability to supply the bioenergy system. Moreover, with the exception of the IEA study, none of the analyzed scenarios take into consideration the strategic hierarchy determined by the novel bioeconomy strategies (i.e. the preferential use of higher value-added applications and products prior to the energy generation alternative), which will go up a notch in the future competition over the biomass available for purposes other than to supply food and animal feed. A further analysis is therefore needed that incorporates the suggested cascade use of the available biomass resources in order to capture the effect of the novel bioeconomy strategies on resources available for the bioenergy system.

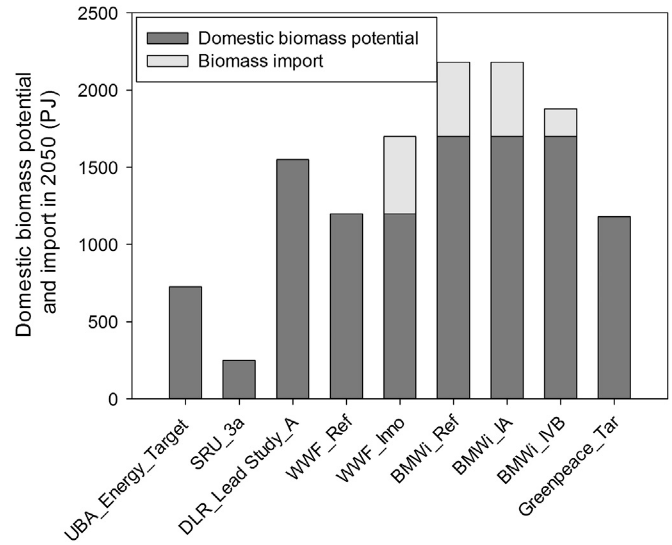

Fig. 2. Domestic biomass potential and import in PJ in 2050.

3.2. Analysis of bioenergy-related indicators

3.2.1. Domestic biomass potential

Fig. 2 summarizes the results for the indicator *Domestic biomass potential*. To avoid the transfer of unsustainable effects to other regions, some scenarios do not allow for an import of biomass (e.g. those of Greenpeace [29]). In contrast, the BMWi [27] and WWF [28] scenarios consider biomass imports because they assume that its sustainable production and trade within Europe will have been resolved. As observed, the amount of domestic biomass potential in 2050 is projected to range from 250 PJ (SRU [14]) to 1.760 PJ (BMWi [27]). In order to understand this range of results, the following sub-sections present specific insights of the analyzed studies.

3.2.1.1. Specific aspects of study "Pathways towards a 100% renewable electricity system" [14]. The SRU study only refers to the biomass potential for generating electricity using CHP technologies. To ensure sustainable use, SRU strictly limits the biomass potential to organic residues and waste and only exploits 50% of the available potential. The untapped potential are explained by the SRU through a cost comparison of all the renewable energy sources (excluding geothermal): electricity generation from solid biomass has the highest and biogas the second highest generation cost per KWh.

3.2.1.2. Specific aspects of the study "Energy target 2050: 100% renewable electricity supply" [13]. The UBA study uses quite a similar approach to that of SRU when calculating domestic biomass potential: to ensure the sustainable use of biomass and to avoid any conflicts, the techno-ecological potential (using the most efficient conversion technologies and adhering to strict sustainability safety rails) is limited to organic residues and wastes [27,29], with sustainable domestic biomass potential totaling 726 PJ. The total amount of biomass potential is used either for energy or material production. UBA limits the use of biomass in the electricity generation sector to 143 PJ of biogas and the remaining 583 PJ of solid biomass is used for energetic purposes in the transport sector or for material use in the industrial sector. Considering that the amount of biomass used for heating, electricity generation and biofuel production reached approximately 730 PJ in 2011 [13], the UBA study does not consider the increased use of biomass by 2050.

3.2.1.3. Specific aspects of the study "Long-term scenarios and strategies for the deployment of renewable energies in Germany in view of European and global developments – Lead Study 2011" [26]. The Lead Study also builds upon previous research on the German biomass potential [38-41]. Stressing the unfavorable ratio of land requirements and energy yield in bioenergy production, combined with an ultimate cap of 4.2 Mha land for biomass cultivation, the lead study limits the sustainable biomass potential to 1550 PJ/year, of which 800 PJ are designated organic residues and wastes. This study highlights that 50% of the agricultural land used for biomass production was already being cultivated in 2011 – almost exclusively for biofuel production. In addition, the potential arising from organic residues was already exploited by 60% in 2011. Thus, a moderate increase in the use of biomass for energy production is possible, but the sustainable domestic potential will be completely exploited around the year 2030. For energy efficiency reasons, the majority of the domestic biomass potential (1,100 PJ/year) will be used in stationary heat generation technologies or in CHP technologies. Assuming that second-generation biofuels will penetrate the market, a share of 300 PJ/year of biomass for biofuel production will be achieved by 2050.

3.2.1.4. Specific aspects of the study "Blueprint Germany – A strategy for a climate safe 2050" [28]. Blueprint Germany, a study commissioned by the WWF, also applies safety rails in calculating the sustainable domestic biomass potential. This study refers to previous publications by the Öko-Institut [36], German Aerospace Centre (DLR) [37] and the German Advisory Council on Global Change (WBGU) [38]. Assuming 4 Mha of land available for energy crop cultivation (slightly less than the lead study), with primary energy production ranging from 415 to 522 PJ per year and 700 PJ from various residues annually, the total amount of available biomass is calculated to be 1200 PJ per year in 2050. Even though biomass is highly energy efficient in electricity generation, only a moderate amount, 148 PJ, will be used to produce electricity. The study expects biomass to play a major role in the production of second and third generation biofuels because the sector is lacking alternative substitutes.

In the innovation scenario, 987 PJ of biomass is converted into biofuels. The innovation scenario estimates an "electrification" of the transport sector and a complete market penetration of alternative technologies such as fuel cells, hybrids, e-mobility and (liquid) gas. In the reference scenario, biofuel production reaches only 340 PJ by 2050 because of the continuing dominance of conventional fuels. In turn, biogas production increases to 60 PJ per annum, of which two-thirds are used for residential consumption. In both scenarios, electricity generation from biomass ranges between 41.3 and 44.7 TW/h in 2050. Final energy consumption based on biomass in residential heating drops to 1242 PJ (reference) and 315 PJ (innovation), wood being a major player at 342 PJ (reference) and 90 PJ (innovation). The demand for biomass in the reference scenario will be slightly below the domestic German potential of 1200 PJ (1,089 PJ), leaving approximately 9% of the potential untapped. In the innovation scenario, biomass demand exceeds the sustainable domestic potential. Even the implementation of further efficiency measures and a reduction in transport is unable to bridge this gap and approximately 520 PJ of excess demand needs to be satisfied by importing biomass.

3.2.1.5. Specific aspects of the study "Climate protection: Plan B – A national energy concept to 2050" [29]. The Greenpeace Target Scenario assumes that the German biomass potential has already been significantly exploited for energetic purposes and thus maintains that there is a limited amount left over to produce further energy. The study only calculates domestic biomass potential in order to avoid leakages and food for energy competition that could occur when biomass is imported. For sustainability reasons, the study's target scenario assumes that various residues, such as manure, will be comprehensively used and that areas with low utilization rivalries will be cultivated. These strict safety rails lead to moderate growth in the amount of biomass available by 2030. In 2050, biomass availability will almost double to a potential of 1180 PJ, with an increase in sustainable arable land for energy crop production. The limited potential for energy crop cultivation restricts the use of biomass in CHP electricity generation to 45 TW/h-33% of CHP energy generation and 10% of final electricity demand.

3.2.1.6. Specific aspects of the study "Scenarios for an Energy Policy Concept of the German Government" [27]. Finally, the BMWi scenarios consider biomass to be the most important renewable energy source in 2050, making up approximately three-fifths of all renewables. Gaseous, liquid and solid biomass contributes 28–29% to energy consumption within the target scenarios. The overall sustainable biomass potential (incl. imports) is assumed to be 2200 PJ for all scenarios, 80% of which is generated in Germany, and 20% is imported. In the electricity sector, bioenergy contributes only approximately 40 TWh (144 PJ) because of competition for use in the transportation sector. In particular, biomass plays an important role in reducing GHG emissions in this sector, accounting for approximately 56% of end-use energy consumption.

3.2.2. Share of biomass in final energy consumption

This indicator compares the percentage of bioenergy in the final energy consumption of one international study and four national studies (see Fig. 3). All scenarios foresee an increase in bioenergy to between 9% and 25% (2010 level: 8%) of final energy consumption by 2050, except for UBA (ca. 5%). This may be the

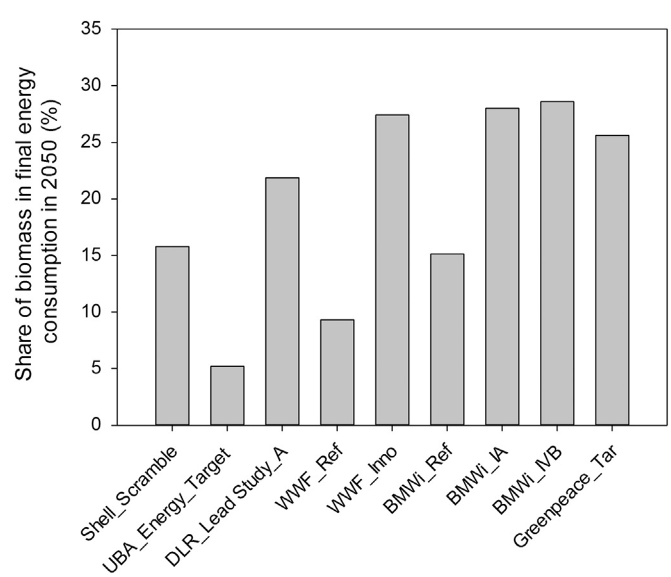

Fig. 3. Share of biomass in final energy consumption in 2050.

result of the different assumptions made in the UBA scenarios: (i) the biomass potential is limited to residues and no imports are allowed, (ii) electricity generation from biomass is among the most expensive and thus its application is limited to peak production or balancing power, and (iii) it is assumed that biomass will be of more economic value in material use, i.e. bio-based products and platform chemicals.

All target and explorative scenarios of the BMWi [27], WWF [28] and the DLR lead studies [26] foresee bioenergy making up well above 20% of the final energy consumption. In all of these scenarios, bioenergy becomes an established renewable energy resource by 2050. In the reference WWF and BMWi scenarios, bioenergy contributes to a comparably lower extent to the energy mix, however it still above 2011 levels. The further development of biomass for fuel and electricity supply is hampered by the fact that conventional fuels still play a significant role in these scenarios.

When comparing the results of the expected final energy consumption among the studies for both energy and bioenergy, the following statements can be made:

i. There is an insufficient amount of data available on the bioenergy sector, and only four of the eight revised studies include this information.
ii. The forecasted per capita consumption values have a higher uncertainty when it comes to bioenergy, which is reflected in the resulting maximum vs minimum ratio (i.e. 2.4 for energy and 12.9 for bioenergy, almost four times higher). This issue is further discussed in Section 4.

3.2.3. Biofuels in the transport sector

Fig. 4 shows the amount of biofuels used in 2050 for transportation purposes, amounting to between 1 and 15 GJ per capita.

All five national and international studies expect the use of biofuels to increase, and it is assumed that second-generation biofuels will be produced on a large scale and penetrate the market by 2050. The BMWi [27] target scenarios foresee biofuels having an approximately 85% share in the transport sector. The WWF [28] innovation scenarios indicate that except for the aviation sector, all fossil-based oil products in the transport sector will be replaced by biofuels, accompanied by natural gas, liquid gas and hydrogen. The lead study [26] and reference scenarios of WWF [28] and BMWi [27] do not forecast multiple growth rates in biofuels, assuming instead that a higher share in e-mobility will reduce the demand for biofuels. The reference scenarios indicate that fossil fuels remain dominant in the transport sector. The low share of biofuels in the Greenpeace scenarios [29] can be explained by the significant drop in the amount of passenger cars that is expected due to the enhanced availability of public transport, a shift in commercial road transport to rail, and a switch from private and commercial transport to e-mobility. Within this context, biofuels are expected to be used in areas of transport where it is most difficult to substitute fossil resources (i.e. heavy vehicles). The aviation sector is not included in the Greenpeace [29] analysis.

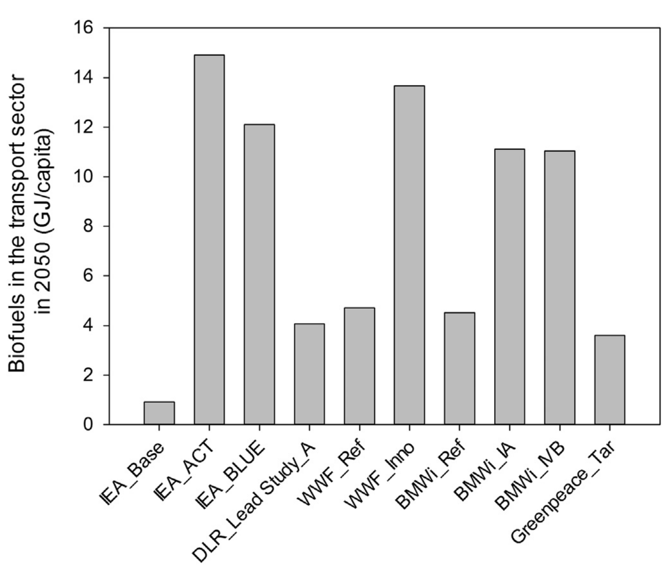

Fig. 4. Biofuels in the transport sector in GJ per capita in 2050.

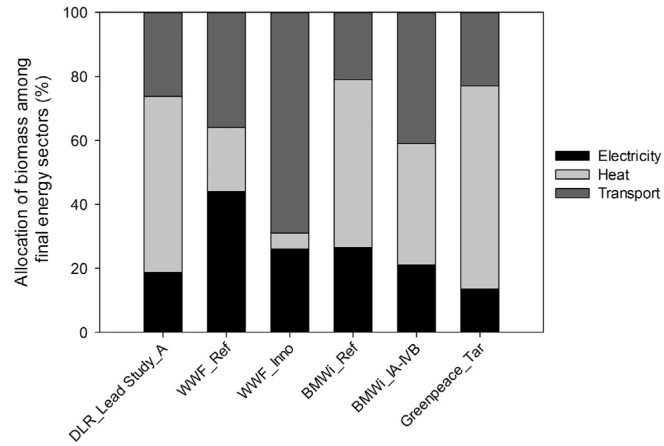

Fig. 5. Allocation of biomass among final energy sectors in 2050.

3.2.4. Allocation of biomass among final energy sectors

Fig. 5 shows the composition of biomass usage among the three major end-use sectors, calculated according to the biomass used in GJ per capita.

Fig. 5 highlights that, despite current discussions about the future role of biomass, all scenarios foresee the existence of biomass in all three end-use sectors by 2050. Moreover, in the scenarios that assume a high proportion of e-mobility (Greenpeace), the proportion of biomass in the transport sector remains low. The low use of biomass in the heating sector in the WWF study [28] can be explained by the assumption that there will be very high energy efficiency in the building sector. It is furthermore to be expected that, as the use of biomass increases, competition for resources, also among the final energy sectors, will also increase. This would require a detailed analysis of the processes within each sector. The project MS2030 [42] has provided valuable findings in this regard. It shows that similar energy sources will be used in different sectors, depending on the applied scenarios.

4. Conclusions and suggestions for policy makers

The aim of our study was to increase the transparency of the results in the bioenergy field of different energy scenario studies by describing and explaining their contexts and results, in a scientifically sound and robust manner. For this purpose we reviewed eight illustrative energy scenarios for Germany at the national level for 2050, with a main focus on renewables, and which particularly considered bioenergy, in both quantitative and normative terms. The scenarios were grouped in two main groups according to their type, namely (i) target scenarios, which are strategies or pathways for reaching the set goals, and (ii) explorative scenarios, which show the consequences of certain (energy-) policy decisions. All studies display similarities in the socio-economic

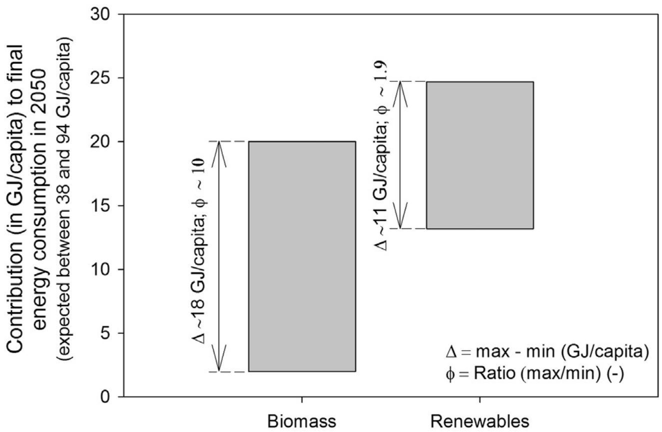

Fig. 6. Biomass and renewables in final energy consumption.

framework conditions and in the assumptions and results regarding general aspects of the energy sector in Germany (e.g. final energy demand and the considered energy conversion technology portfolio).

Almost all German studies, particularly the target scenarios, expect a lower primary energy demand, in contrast to the expected developments at the global level. This reduction is foreseen due to very ambitious assumptions on the implementation of efficiency measures, such as building insulation, which influence directly the national energy demands.

Moreover, all studies predict an increase in biofuels over the current rates by 4–14%, and foresee that biomass remains in use in all sectors (power, heat and transport). However, significant differences among the studies can be identified when describing the whole bioenergy pathway. Biomass potential, for example, varies between 350 PJ and 1700 PJ, and the share of bioenergy in the energy system varies between 5% and 28% (as shown previously in Fig. 3). This results in high statistical differences within the national studies with regard to the contribution of biomass (factor of 10) and renewables (factor of 2) in the final energy sector, as depicted in Fig. 6.

Based on the findings of this study, the following recommendations are provided for the use, comparison and interpretation of long-term scenarios by policy and research in the bioenergy field. On the one hand, *transparency* and *quality assurance* are important to select appropriate scenarios, including the following aspects:

- Transparent and traceable methods and data. Scenario results should be published and include transparent methods and traceable, well documented and official data. The sensitivity and uncertainty of the results should be well described for their use by different scenario users. Moreover, for specific bioenergy questions, studies with detailed information and data about bioenergy conversion, provision and supply should be used. Transparent assumptions. The assumptions of the studies should be derived by a neutral and sound scientific approach, based on clearly documented data and explained approach. Traceable conclusions. The conclusions of the study should be traceable, i.e. they must be explained and supported by the results presented in the study. Moreover, the link between the model results, their interpretation, and the derivation of the conclusions must be soundly presented. On the other hand, energy scenarios need *contextulisation* for their interpretation. For this purposes, the following aspects should be considered:
- Publishing year. The year in which the study was conducted should be taken into account, since the (bio)energy sector shows a very dynamic development in terms of the technological maturity, economic figures or policy goals.
- Goal of the study. The study's main goal (e.g. share of renewables or decrease of CO_2 emissions) influences often the resulting set of technologies (e.g. mainly low-emission technologies). The goal can often include only specific energy use sectors (e.g. power).
- Commissioning of the scenarios. Take into consideration the purpose for which the study was commissioned and the institution behind.
- Type of study. Take into consideration the different characteristics of the study types. Target scenarios often include only a set of pre-selected technologies, aiming to monitor e.g. the achievement of set goals. Explorative scenarios, on the other hand, are more adequate to analyze a broader range of future options, and therefore the set of assessed technological alternatives could be broadened as well
- Supply chain. In case of bioenergy scenarios, the whole provision chain - from biomass provision to end energy use – should be viewed. In this regard, the biomass potential considered as basis for the calculations should always be considered as a major part of the analysis and interpretation of the study's results.
- Finally, the results of a scenario should always be interpreted within its context as whole, including all the above mentioned aspects.

For scenario users, both transparency aspects (for the selection of appropriate scenarios) and contextualization aspects (for the interpretation of the scenarios) are recommended. For the development of future scenarios with an increased transparency it is furthermore recommended to introduce standards for definitions and methodologies or a minimum requirements for data quality and documentation.

Appendix A. Comparative analysis of long-term energy scenarios with selected indicators that characterize the energy sector

This appendix provides a comparison of the various energy systems developed in the analyzed studies. For this purpose, we use four selected indicators that represent the basic characteristics of an energy system, namely per capita primary energy consumption, per capita final energy consumption, per capita CO_2 emissions and share of renewable energy in the power sector.

A.1. Per capita primary energy consumption

Primary energy consumption refers to the direct use at the source, or a supply to users without transformation or conversion, of either renewable or non-renewable crude energy. This indicator is used to calculate per capita consumption (see Fig. A.1) in order to compare the results for both national and international studies.

All German scenarios foresee a decline over the baseline year of 2011. The reduction in primary energy consumption is mostly a result of two main trends:

- Energy efficiency and energy saving measures, as most savings are realized in private households through renovation and the use of heat pumps, followed by the service sector and industry through increased energy productivity.
- The substitution effect of increased renewables in the energy mix, which decreases fossil fuel use and transformation as well as transmission losses (decentralized energy supply).

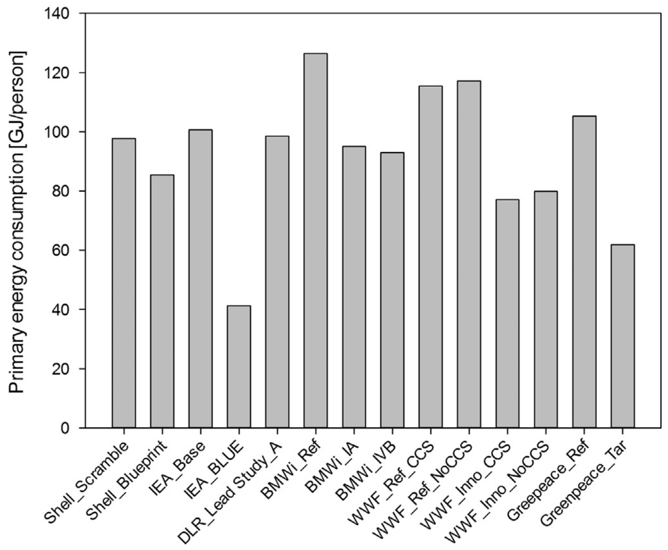

Fig. A1. Overview of the various primary energy consumptions (in GJ per capita) for 2050.

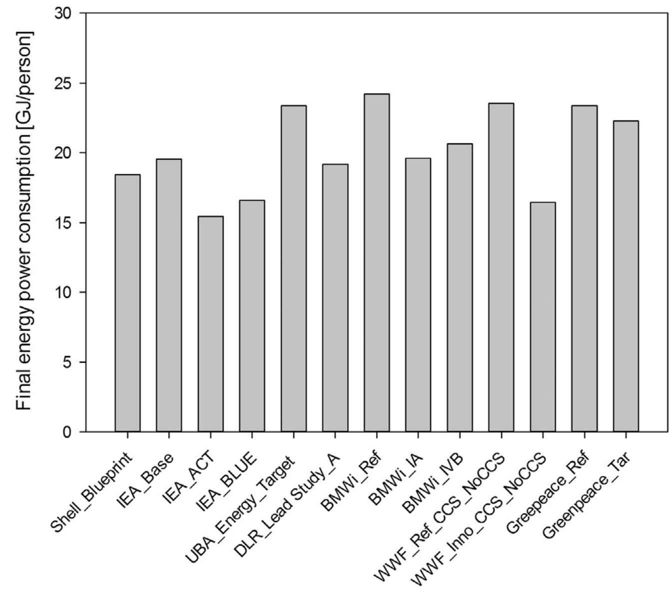

Fig. A2. Overview of the various final energy power consumptions (in GJ per capita) for 2050.

With regard to the annual increase in energy efficiency, all studies assume very ambitious energy efficiency gains. For example, the WWF innovation scenario contains an average yearly efficiency gain of 2.7%, and the BMWi assumes an annual 2.5 % increase in energy productivity for all target scenarios (German electricity productivity increased an average of 1.0 % per year between 1990 and 2011). The scenarios differ in per capita primary energy consumption, with Greenpeace's target scenario showing the lowest (62 GJ per capita) and the BMWi reference scenario the highest values (126 GJ per capita). This is the result of different assumptions about the quantity and quality of the German and European policy instruments required to increase the restoration rate of the German housing inventory (heating efficiency), the share of renewable energies in electricity and heat generation, the market penetration of CHP technologies and heat pumps, as well as efficient product design of household and office appliances and in the automotive sector.

In addition, the assumed substitutability of fossil fuels in the transport sector (e-mobility, hydrogen, and biofuels) has a significant influence on primary energy consumption among the studies. In contrast to the national studies, almost all scenarios expect an increase in primary energy consumption at the international level. The continuously high GDP growth rates predicted in non-OECD countries such as India and China will be energy intensive, and moderate growth rates with declining energy intensity in OECD countries cannot compensate for the increase in energy consumption.

A.2. Final energy power consumption per capita

Fig. A.2 summarizes the final energy power consumption per capita by 2050 in the 15 scenarios compared with the international reference value in 2010 and the German reference value in 2011. The figure shows relatively similar consumption per capita in the power sector in the future, which can be explained by the low level of savings potential in power for mobility by 2050. Moreover, Fig. A.2 provides an overview of selected studies for both the energy and bioenergy sector. In addition to an increase in primary energy consumption on the global level, the global average of final energy power consumption per capita is also projected to increase.

Fig. A.3 again highlights that uncertainty about the expectations of the bioenergy sector is much higher than the uncertainty about the energy sector. The range between smallest and largest values for the energy sector is 1.6, whereas the range for bioenergy is almost nine times higher (8.7).

Given the economic growth in populous Asian countries, access to modern energy supply and services will increase in developing countries and result in additional electricity consumption. The German scenarios are split into three groups displaying either a slight increase or near stabilization with values in the range of 22.3 GJ per capita (Greenpeace_Tar) to 24.2 GJ per capita (BMWi_Ref), or a reduction in final energy power consumption per capita of between 16.5 GJ (WWF_Inno_CCS_NoCCS) and 20.6 GJ (BMWi_IVB). All reference scenarios that do not foresee any significant reductions in final energy power consumption belong to the first group. The second group includes UBA Energy Target scenario and Greenpeace Climate Protection Plan B (Greenpeace_Tar). In both studies, the final power consumption almost remains at 2011 levels because transport sector electricity will be significantly substituted in terms of fossil fuels (UBA 72 TWh, Greenpeace 99TWh). A second driver for the comparatively high final energy power consumption in both scenarios is the fuel switch for space heating and cooling. Especially in the private and service sector, electricity (solar thermal or CHP technologies) will act as a substitute for fossil fuel consumption. The third group of studies (BMWi, WWF_Inno_CCS_NoCCS and DLR_Lead_Study) assumes a decrease in final energy power consumption. This is due to a lower degree of market penetration of e-mobility in the transport sector or the expected market readiness of additional technologies (hydrogen) and higher energy efficiency rates for the industrial sector that overcompensate for the increase in electricity demand following the expansion of e-vehicles. Fig. A4 shows the difference in per capita power consumption for e-mobility in five scenarios.

A.3. Per capita CO_2 emissions

Fig. A.5 shows the per capita CO_2 emissions in tons per year as presented in the scenarios of five studies. For better comparability, only direct CO_2 emissions and not CO_2 equivalents of other greenhouse gases are included. The UBA, SRU and Shell studies are excluded because their scope is limited to the electricity generation sector. CO_2 emissions in 2050 vary significantly among the scenarios, depending on the type of scenario and the CO_2

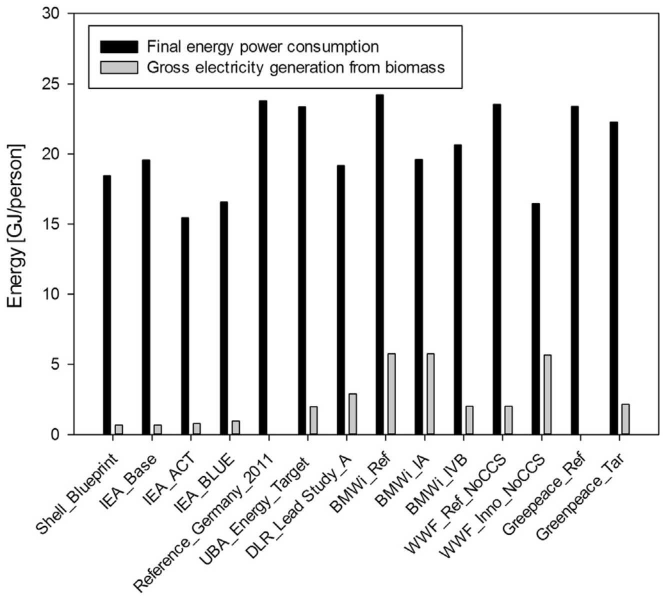

Fig. A3. Comparison of GJ per capita final energy power consumption and power generation from biomass in 2050, as predicted by the analyzed scenarios.

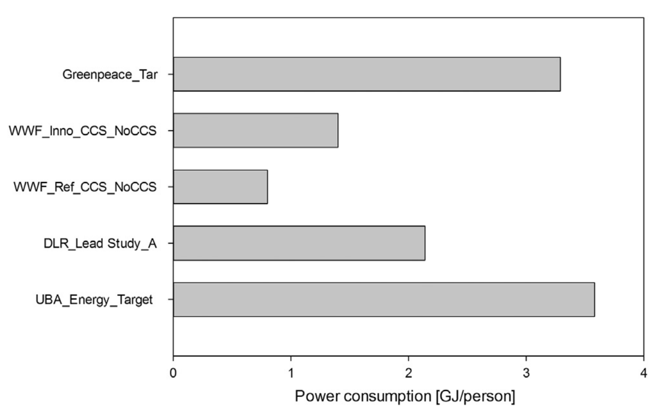

Fig. A4. E-mobility power consumption in GJ per capita in 2050, according to selected scenarios.

reduction goals and policies. Except for the DLR Lead Study, all other studies quantified CO_2/CO_2-equivalent reduction goals with a lower-bound target (reference case) and an upper-bound target (ambitious reduction target). Accordingly, the spread of per capita CO_2 emissions is more significant between the scenarios of each study than among the studies themselves. In the German case, the upper-bound target scenarios foresee per capita emissions of 1.09 tons/year (Greenpeace) to 1.9 tons/year (BMWi). All less-ambitious scenarios remain below current levels of 9.78 tons/year. Thus, all German scenarios indicate it is technologically feasible to reduce CO_2 emissions significantly.

A.4. Share of renewables in the power sector

Fig. A.6 shows the proportion of renewables and fossils in electricity generation across selected German scenarios compared with their levels in 2011. The UBA, SRU and Greenpeace (target scenario) studies are calculated with a predefined goal of 100% renewable electricity supply in 2050. All other studies expect renewables to contribute to between 36% (WWF reference scenarios) and 86% (Greenpeace reference scenario). Except for the WWF reference scenarios, all other scenarios highlight the

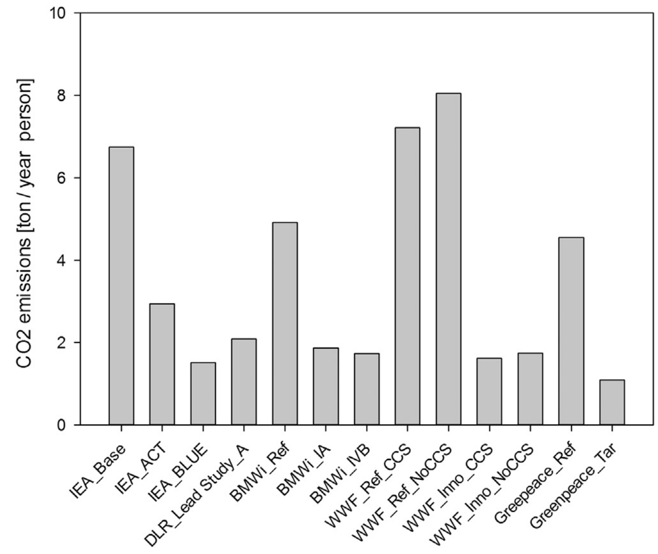

Fig. A5. Overview of the expected CO_2 emissions (in annual tons per capita) for the year 2050, according to the analyzed scenarios.

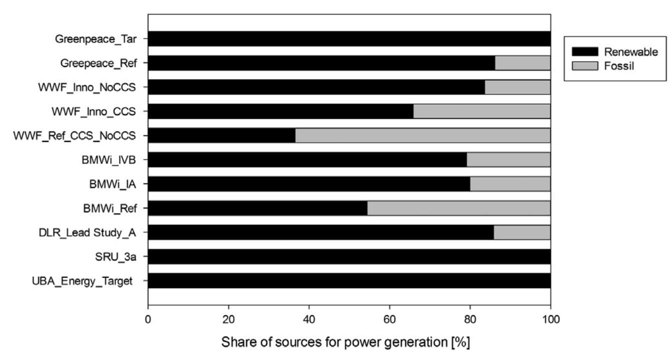

Fig. A6. Overview of the expected share of renewables in the power sector in 2050 according to the analyzed scenarios.

technological capacity to increase the current share of renewables in the electricity mix by a factor of 2.5–4 by 2050. Each of the reviewed studies present at least one scenario which reaches the 80% renewable energy target as spelled out in the German Energy Policy Concept.

An interesting development highlights the comparison of the WWF innovation scenario, with and without CCS technologies. The application of carbon capture and storage in Germany would increase the use of coal to approximately 750 PJ per year (without CCS: 80 PJ) and also slightly increase the share of natural gas in electricity generation. Simultaneously, the share of renewables would be reduced by approximately 20% (approximately 700 PJ less in geothermal generation and 250 PJ less in wind generation).

References

[1] VDU, ISI. Zwischenergebnis 3 – Forschungs- und Technologieperspektiven 2030, BMBF-Foresight-Zyklus II. Suchphase 2012-2014. Berlin: VDU Technologiezentrum & Fraunhofer ISI im Auftrag des Bundesministerium für Bildung und Forschung; 2014.

[2] Ferroukhi R, Nagpal D, Lopez-Peña A, Hodges T, Mohtar RH, Daher B, et al. Renewable energy in the water, energy & food nexus. Paris: IRENA – Int. Renew. Energy Agency; 2015.

[3] BMWI, BMU. Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. Berlin: Bundesministerium für Wirtschaft und Technologie (BMWi), Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU); 2010.

[4] BMWI. Forschung für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. Das 6. Energieforschungsprogramm der Bundesregierung. In: Technologie BfWu, editor. Berlin: Bundesminister für Wirtschaft und Technologie; 2011. p. 132.
[5] AGEB. Energieverbrauch in Deutschland im Jahr 2011. Köln: Arbeitsgemeinschaft Energiebilanzen e. V.; 2012. p. 39.
[6] BMU. Erneuerbare Energien in Zahlen. Berlin: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit; 2012.
[7] Winter CJ. SUNRISE – a caesura after nuclear has gone: Energy in Germany (and in other potentially de-nuclearizing countries). Int. J. Hydrog. Energy 2012;37(9):7317–42.
[8] Lechtenböhmer S, Samadi S. Blown by the wind. Replacing nuclear power in German electricity generation. Environ. Sci. Policy 2013;25:234–41.
[9] AGEB. Stromerzeugung nach Energieträgern 1990-2014. Berlin, Köln: Arbeitsgemeinschaft Energiebilanzen e.V.; 2015.
[10] BMWI. Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland Bundesministerium für Wirtschaft und Technologie. Stand: December 2015. Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat); 2015.
[11] AtomG. Dreizehntes Gesetz zur Änderung des Atomgesetzes. Bonn: Bundesgesetzblatt; 2011.
[12] Schütz D, Klusmann B. Die Zukunft des Strommarktes Anregungen für den Weg zu 100 Prozent Erneuerbare Energien. Bochum: (c) Ponte Press GmbH; 2011.
[13] UBA. Energy target 2050: 100% renewable electricity supply. Dessau-Roßlau, Kassel: Federal Environment Agency (Umweltbundesamt), Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES); 2010. p. 43.
[14] Faulstich M, Foth H, Calliess C, Hohmeyer O, Holm-Müller K, Niekisch M. Pathways towards a 100% renewable electricity system. Berlin: German Advisory Council on the Environment (SRU); 2011. p. 447.
[15] Carpenter SR, Pingali PL, Bennet EM, Zurek MB. Ecosystems and Human Wellbeing: Scenarios, Vol. II, Millennium Ecosystem Assessment (MA). Chicago; 2005. p. 561.
[16] ISI. Tangible ways towards climate protection in the European Union (EU Long-term scenarios 2050). Karlsruhe: Fraunhofer Institute for Systems and Innovation Research ISI; 2011.
[17] IVL. Swedish long-term low carbon scenario – exploratory study on opportunities and barriers. Stockholm: Swedish Environmental Research Institute; 2010.
[18] Dieckhoff C, Appelrath HJ, Fischedick M, Grunwald A, Höffler F, Mayer C, et al. Zur Interpretation von Energieszenarien. München: Schriftenreihe Energiesysteme der Zukunft; 2014.
[19] Keegan D, Kretschmer B, Elbersen B, Panoutsou C. Cascading use: a systematic approach to biomass beyond the energy sector. Biofuels, Bioprod. Biorefining 2013:7.
[20] BMBF. National research strategybioeconomy 2030 – our route towards a biobased economy. Berlin: Federal Ministry of Education and Research (BMBF), Division Bioeconomy; 2011.
[21] BMBF. Destination bioeconomy – research for a biobased and sustainable economic growth. Berlin: Federal Ministry of Education and Research (BMBF), Division Bioeconomy; 2014.
[22] BMEL. National Policy Strategyon Bioeconomy – Renewable resources and biotechnological processes as a basis for food,industry and energy. Berlin: Federal Ministry of Food and Agriculture, Division 531 – Strategy and Coordination of the Directorate-General"Biobased business, sustainable agriculture and forestry"; 2014.
[23] Mai T, Logan J, Nate B, Sullivan P, Bazilian M. Re- Assume. A decision maker's guide to evaluating energy scenarios, modeling, and assumptions. National Renewable Energy Laboratory, Joint Institute for Strategic Energy Analysis; 2013.
[24] BVSI. Signals & signposts shell energy scenarios to 2050 – an era of volatile transitions. The Hague; 2011. p. 40.
[25] IEA. Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050. Paris: International Energy Agency IEA/OECD; 2008.
[26] Nitsch J, Pregger T, Naegler T, Heide D, Tena DLd, Trieb F, et al. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global – Leitstudie 2011. Stuttgart, Kassel, Teltow: Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Technische Thermodynamik, Abt. Systemanalyse und Technikbewertung Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES), Ingenieurbüro für neue Energien (IFNE); 2012. p. 345.
[27] Schlesinger M, Lindenberger D, Lutz C. Energieszenarien für ein Energiekonzept der Bundesregierung. Basel, Köln, Osnabrück: Prognos AG, Energiewirtschaftliches Institut an der Universität zu Köln (EWI), Gesellschaft für Wirtschaftliche Strukturforschung mbH (GWS); 2010.
[28] Kirchner A, Schlesinger M, Weinmann B, Hofer P, Rits V, Wünsch M, et al. Blueprint Germany – a strategy for a climate-safe 2050. Berlin, Basel: Institut für angewandte Ökologie Öko-Institut e.V., Prognos AG; 2009. p. 510.
[29] Barzantny K, Achner S, Vomberg S. Klimaschutz: Plan B 2050 – Energiekonzept für Deutschland (Langfassung). Hamburg: Eutech Energie und Management GmbH; 2009. p. 154.
[30] Thrän D, Szarka N. Die Rolle der Bioenergie in einer zukünftigen Energieversorgung. online article, Leibnitz-Institut LIFIS ONLINE, ⟨http://www.leibniz-institut.de/archiv/thraen_04_10_11.pdf⟩; 2011.
[31] Smart Bioenergy. In: Thrän D, editor. New York, Dordrecht: Cham, Heidelberg; 2015.
[32] Rosillo-Calle F, Teelucksingh S, Thrän D, Seiffert M. The Potential and Role of Biofuels in Commercial Air Transport - Biojetfuel. London, Leipzig: IEA UK Task 40 & Centre for Environmental Policy, Imperial College London, IEA DE Task 40 & Helmholtz Centre for EnvironmentalResearch, Department Bioenergy with Deutsches Biomasseforschungszentrum gGmbH, Department Bioenergy Systems, Deutsches Biomasseforschungszentrum gGmbH, Department biorefineries, Energy Future Lab, Electrical Engineering, ImperialCollege London; 2012. p. 56.
[33] Toop G, Cuijpers M, Borkent B, Spöttle M. Accounting methods for biojet fuel. Berlin: ECOFYS Germany GmbH; 2014.
[34] Aireg. Klimafreundlicher fliegen: Zehn Prozent alternative Flugkraftstoffe bis 2025. Aviation Initiative for Renewable Energy in Germany e.V.; 2012.
[35] BMWI. National Research Strategy BioEconomy 2030 – Our Route towards a biobased economy. Berlin: Federal Ministry of Education and Research (BMBF)); 2011.
[36] Fritsche UR, Dehoust G, Jenseit W, Hünecke K, Rausch L, Schüler D, et al. Stoffstromanalysen zur nachhaltigen energetischen Nutzung von Biomasse. Darmstadt, Berlin, Oberhausen, Leipzig, Heidelberg, Saarbrücken, Braunschweig, München: Institut für angewandte Ökologie (Öko-Institut e.V.), Institut Umwelt-, Sicherheits-, Energietechnik UMSICHT (IUSE), Institut für Energetik und Umwelt (IE), Institut für Energie- und Umweltforschung Heidelberg GmbH (ifeu), Institut für Zukunftsenergiesysteme gGmbH (izes), Institut für Geoökologie, Technische Universität Braunschweig, Lehrstuhl für Wirtschaftslehre des Landbaus - Technische Universität München; 2004. p. 294.
[37] Nitsch J, Krewitt W, Nast M, Viebahn P, Gärtner S, Pehnt M, et al. Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland. Stuttgart, Heidelberg, Wuppertal: Institut für Technische Thermodynamik, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Energie- und Umweltforschung (ifeu), Wuppertal Institut für Klima, Umwelt und Energie; 2004.
[38] Schubert R, Schellnhuber HJ, Buchmann N, Epiney A, Grießhammer R, Kulessa ME, et al. Welt im Wandel - Zukunftsfähige Bioenergie und nachhaltige Landnutzung. Berlin: Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen; 2008. p. 421.
[39] Nitsch J, Pregger T, Scholz Y, Naegler T, Sterner M, Gerhardt N, et al. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global – Leitstudie 2010 – Stuttgart, Kassel, Teltow: Institut für Technische Thermodynamik, Abt. Systemanalyse und Technikbewertung, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES), Ingenieurbüro für neue Energien (IFNE); 2010. p. 273.
[40] WBA. Nutzung von Biomasse zur Energiegewinnung – Empfehlungen an die Politik. Berlin: Wissenschaftlicher Beirat für Agrarpolitik bei BundesMinisterium für Ernährung. Landwirtsch. und Verbraucherschutz 2007.
[41] SRU. Klimaschutz durch Biomasse. Berlin: Sachverständigenrat für Umweltfragen (SRU); 2007.
[42] Thrän D, Arendt O, Ponitka J, Braun J, Millinger M, Wolf V, et al. Meilensteine 2030-Elemente und Meilensteine für die Entwicklung einer tragfähigen und nachhaltigen Bioenergiestrategie. Schriftenreihe des Förderprogramms Energetische Biomassenutzung. Thrän, Daniela und Pfeifer, Diana ed. Leipzig; 2015.