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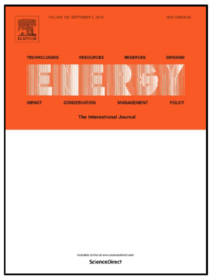

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THE CRUCIAL ROLE OF BIOMASS-BASED HEAT IN A CLIMATE-FRIENDLY GERMANY - A SCENARIO ANALYSIS

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Highlights

- 95 % GHG goals by 2050 require power grid stabilization and heat supply security
- CHP will grow in importance and proportion in case of 95 % GHG goals
- High-tech preparation of biomass will become important in the 95 % GHG scenarios
- Biomass-to-heat is expected in buildings with high heat demand per unit of space
- Bioenergy can play a role in industries with high temperature requirements

Abstract

The future provision of heat from biomass in Germany is strongly influenced by the country's climate policy goals, such as the target of reducing GHG emissions by 80 % - 95 % over 1990 levels by 2050. Emphasizing one goal over the other could significantly shape the bioenergy and heating sector. The aim of this paper is to analyze long-term energy scenario results and interpret the possible influence of different GHG goals on biomass utilization in the heating sector. The findings show that a 95 % reduction in GHG emissions in Germany would lead to an energy system that is almost completely based on renewables. A significant proportion would be fluctuating energies, such as direct heating from surplus wind and PV power, as well as solar-thermal and ambient heat from electrical air-to-water heat pumps. In this case, the role of bioenergy would shift away from being an efficient source for base-load generation, towards being an effective "stabilizer" of the heat and combined power system. The study presents comparative results of scenario parameters and analyzes the consequences for bioenergy in the heating sector. Finally, it concludes with recommendations for policy adjustment.

Keywords: biomass-to-heat, GHG targets, energy scenarios

1. Introduction

Biomass is traditionally a very important source of heat generation, providing more than 80 % of renewable heat worldwide and in Germany as well [1] despite only little financial support for biomass-to-heat concepts. How the use of biomass for heat provision will be shaped in the future depends on several factors, with policies playing a significant role. Such policies include the Energy Saving Ordinance (EnEV, [2]), which introduces mandatory standards for energy-efficient building - defining structural and heating system standards - and the refurbishment of existing buildings; the Renewable Energy Heat Act (EEWärmeG [3]), which aims to achieve a 14 % share of renewables in the heating of buildings by 2020; the Heat and Power Cogeneration Act (KWKG [4]), which is designed to increase combined heat and power (CHP) generation in Germany to 120 TWh by 2025; and the Technical Instructions on Air Quality Control [5], which sets requirements for heat plants based on particle emissions, CO2-emissions and, depending on the size of the installation, also NOx and other airborne pollutants. In addition, the German government's energy concept ("Energiekonzept") [6] aims to reduce GHG emissions by 80 – 95 % over 1990 levels by 2050. In this regard, the Climate Action Plan 2050 [7] provides guidance towards achieving the climate goals confirmed in the Paris Agreement for all areas of activities and measures, especially for the 2030 interim targets. The Climate Action Plan concludes that, by 2030, the energy sector will have to play a major role in climate change activities, cutting GHG emissions by 61 – 62 % over 1990 levels.

In order to reduce GHG emissions, the energy supply needs to be decarbonized in all final energy sectors, including power, heat and transport. Using renewable energies can be one effective way to contribute to this goal. The heat sector, which makes up 56 % of the final energy in Germany, is one significant energy consumer with only 13 % of the heat being generated by renewable energies, 86 % of which is based on biomass. Biomass is one way to increase the share of renewables and cover residential heat or hot water demands in households or in the trade, commerce and services sector, and to cover the process heat demands of industry. Depending on the policy goals for GHG reduction (80 % or 95 %), a shift among the final energy sectors, as well as the role of bioenergy among the sectors, but also within the heating sector, can vary significantly.

This paper aims to assess the implications of the GHG reduction goals with respect to bioenergy, with a special focus on the heating sector.

2. Methodology

For this study we reviewed long-term energy and climate studies in Germany (until 2050) that looked at future scenarios of an 80 % GHG reduction, 95% reduction or both in Germany, identifying and selecting them for further analysis. Selection criteria for the studies included their relevant impact on policy, the inclusion of long-term scenarios until 2050, and publication in the past 5 - 6 years. The studies covered different sectors (building sector only, all energy sectors), but all of them included heat demand and supply and allowed for a comparison of biomass use in this sector.

The main goal of the selected studies was to describe and, if possible, quantify the role of bioenergy in the heat sector. To reach this goal, drivers of biomass utilization in the heating sector and relevant aspects for the scenario analysis were identified at two expert workshops and one policy workshop, and questionnaires were issued to further experts in the energy, bioenergy and/or heating sector (3.1.).

Next, the selected studies were analyzed with respect to the following parameters: commissioner, year of publication, authors, GHG targets, scenarios and primary methods. In addition, information about relevant aspects identified in 3.1. was gathered, such as types of biomass, applications by sector, and material use of biomass (3.2).

Finally, since our analysis of the studies found that bioenergy technologies are not described in detail in the scenarios, the authors included their own interpretation in this regard using the scenario results (4.).

3. Results

In this section the main results are presented: first the main drivers of biomass in the heat sector (3.1.), followed by an analysis of the individual studies based on the introduced parameters (3.2.).

3.1. Main drivers of biomass in the energy sector

The main drivers of biomass in the heat sector were identified in expert workshops and applied to the analysis of the selected studies and scenarios. This resulted in the selection of the following parameters: GHG goals, biomass use by sector, biomass types, applied bioenergy technologies, further GHG reduction alternatives, negative emission technologies (NETs), and the concepts and material use of biomass. These aspects were used to describe the scenarios (3.2.).

Furthermore, important aspects of the scenario assumptions were identified, including: the year the study was published, GHG goals set, the sectors taken into consideration, and the models and approaches used.

3.2. Studies and scenarios with 80 – 95 % GHG reductions

In order to characterize the scenarios, two workshops were organized in which scientific and industry experts participated. A total of 30 parameters were identified that are relevant for the heating sector and for bioenergy concepts. The parameters were prioritized with the following parameters selected as having a high relevance: biomass potential, biomass use for transport, heat and/or power, biomass import, heat demand, power demand, share and prices of fossil fuels, material use of biomass, and decarbonization pathways, including negative emissions. Finally, the most relevant factors were identified through questionnaires and applied to the six selected studies (3.2.).

The climate goals of reducing GHG by 80 – 95 % over 1990 levels by 2050, as set in the Climate Action Plan, are only modeled in three long-term energy studies. Six additional studies model an 80 % GHG reduction. This paper analyzes all these available studies and asks what this means for biomass in the heating sector. It should be noted that the system boundaries and the model approaches vary between the different studies: The system boundaries differ in terms of the assumed biomass potential, the technology concepts under consideration and their specific indicators, as well as the consideration of carbon capture, utilization and storage. Two of the six studies use optimization approaches in their modeling. The approaches used by the other studies range from trend assumption, technical feasibility and mixed approaches including different assessments. The modeling approach can affect (1) the overall demand on heat, power and transport fuels, (2) the distribution of the biomass potential between the different sectors (heat, power and transport) and (3) the efficiency of the final energy provision within the sectors. In the following analysis we will assess the main differences between the moderate and ambitious GHG reduction scenarios generated by different modelling approaches. A detailed model comparison is not intended as it would demand a more holistic view of the entire energy system (heat, power, transport and sector coupling). Table 1 summarizes the most important parameters of the studies, including the title, who it was commissioned by, year of publication, GHG goals, scenarios and approaches. In addition, a short description of further aspects is provided for each study, including biomass use by sector, biomass types, and applied bioenergy technologies. Furthermore, the description includes brief information about the consideration of the bioeconomy and the negative emission technologies (NETs) and concepts.

The Climate Protection Scenario 2050

In the Climate Protection Scenario 2050 ("Klimaschutzszenario 2050") [8] three climate protection scenarios were developed up until 2050 for all sectors in Germany: the Existing Measures Scenario (EMS), an 80 % GHG reduction compared to 1990 levels (CS 80) and a 95 % GHG reduction scenario (CS 95). The goal of the study is to determine which sectors must provide which reductions and to set necessary measures based on goal-oriented modeling.

The study is based on several models, which are combined. The energy-related GHG emissions are, for example, based on modules of a building sector model. To build scenarios in the industry sector, an energy demand model (FORECAST) is used, while the transport sector is covered by two models: the TEMPS2 - Transport EMissions and Policy Scenarios and ASTRA-D3- ASsesment of TRAnsport Strategies Germany. Future electricity generation is modeled by combining further models (ELIAS/PowerFlex and PowerACE), while the heat demand is modeled by the ERNST/EE-Lab/INVERT.

The study considers a potential 2,100 PJ of biomass for Germany in 2050, mainly waste and residues, but also cultivated biomass from agriculture. While the availability of biomass from waste and residual materials is determined by future mass flows and alternative uses, the size of the dedicated plantations primarily depends on the available agricultural land and yields. As a result, residue potential is the same in all scenarios (796 PJ), while there is a slight difference between the 80 % and 95 % studies in terms of dedicated plants (424 PJ – 333 PJ).

According to this study, in 2050 the primary energy consumption of biomass – only domestic - is expected to be 1,107 PJ in the CS 95 scenario and 1,237 in the CS 80 scenario. These figures result from an increased use in the industrial sector and decreased use in the house-building sector. The 80 % scenario estimates 240 PJ in the building sector by 2050, whereby only 150 PJ are expected in the 95 % scenario. Energy production from biomass supply units that use wood, biogas or vegetable oil are considered to be flexible thermal.

In terms of emissions, biomass has zero emissions in the GHG inventories in terms of CO_2 emissions. Methane (CH4) and nitrous oxide emissions (N2O) arising from the combustion of biomass are taken into account. The study does not describe the concept of the bioeconomy; however, biorefineries for the production of biodiesel and bioethanol are considered in the model.

With respect to carbon capture and storage (CCS) technologies as an alternative to negative emissions, the study does not include CCS of coal and no information on the use of CCS for natural gas plants. In terms of CCS for bioenergy (BECCS), the 80 % scenarios assume that CCS will no longer be implemented in 2050 due to the lack of a legislative framework (currently 4 MT of CO_2 storage is allowed through national legislation). The 95 % scenarios count on BECCS in order to reach the set GHG reduction goal, however, only from 2040 onwards, which presumes a market availability in 2030. In terms of other negative emission technologies (NETs), diverse land use, land-use change and forestry LULUCF takes place, with a considerably higher CO_2 reduction in the 95 % scenarios (3 times the values of the 80 % scenario) due to a persistent establishment of the measures. Further NETs and carbon capture and usage (CCU) are not analyzed in the scenarios.

Table 1 Selected studies and long-term scenarios with 80 % - 95 % GHG reduction targets

Commissioned by	BMUB	UBA	UBA	BMU	BMWi	BMWi
Publication year	2015	2016	2014	2012	2015	2014
Original title	Klimaschutz-szenario 2050	Klimaneutraler Gebäude-bestand 2050	Treibhausgas neutrales Deutschland im Jahr 2050	Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global	Interaktion EE-Strom, Wärme und Verkehr	Entwicklung der Energiemärkte – Energiereferenzprognose
Authors	ÖI, ISI	ÖI, ISE		DLR, IWES, IFNE	IWES, IBP, IFEU	Prognos, EWI, GWS
GHG Goal 2050	80 – 95 %	80 %	95 %	80 – 95 %	80 %	80 %
Scenarios	CS80, CS95	KliNeG(80)	THGND(95)	LS2011(80), LS2011(95)	IWES(80), RS (80), KraftS (80), BS (80)	ERP(80)
Models used	Combination of different models, e.g. for heat demand, energy demand, power supply, transport emissions and policy	Different methods: typology of the building stock, energy balance, cost assessment	Assessment of technical feasibility	Optimization energy system model (REMix)	Optimization taking into account GHG reduction and cost. Different modules applied by sector (e.g. mobility)	Applying trends

Abbreviations: BMUB: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety; UBA: Federal Environmental Agency; BMU: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; BMWi: Federal Ministry of Economic Affairs and Energy; ÖI: Institute for Applied Ecology; ISI: Fraunhofer Institute for Systems and Innovation Research; ISE: Fraunhofer Institute for Solar Energy Systems; DLR: German Aerospace Center; IWES: Fraunhofer Institute for Wind Energy and Energy System Technologies; IFNE: Engineering office for new energies (Ingenierubüro für neue Energien); IBP: Fraunhofer Institute for Building Physics); IFEU: Institute for Energy and Environmental Research; EWI: Institute of Energy Economics at the University of Cologne; GWS: Society for Economic Structural Research (Gesellschaft für Wirtschaftliche Strukturforschung)

Climate-Neutral Building Stock 2050

The study "Climate-Neutral Building Stock 2050" ("Klimaneutraler Gebäudebestand 2050") [9] investigates how the German building stock can become climate neutral, achieving an 80 % reduction in non-renewable primary energy demand by 2050 compared to 2008 levels. In addition to reducing final energy use, alternatives to the final energy supply mix are modeled in order to analyze the feasibility of the federal government's goal of achieving a "nearly climate-neutral" building stock by 2050. Among other things, the study analyzes the energy and technology mix of the thermal conditions in buildings.

The study follows two approaches: possible concepts for (near) climate-neutral single buildings by 2050. Additionally, different target stages in 2050 have been developed in terms of the reduction in final energy consumption by 2050 (-70 % - -35 %). For the modeling, a set of models were applied, including a building stock model and a whole energy system model (ReMod-D). Technical research and development in heat insulation, heat storage and heat conversion technologies are modeled, and transformation pathways are derived. The future alternatives include biomass-based alternatives, such as wood-based condensing boilers for residential buildings. Non-residential buildings have a heterogenous structure with heat supplied by CHP technologies, condensation boilers, heat pumps and heat nets. Since the study only looks at the building sector, no information is provided about the bioeconomy or material use, nor is there any information on the negative emissions, NETs, CCU or CCs.

The study concludes that the replacement of heat conversion techniques as well as the construction and use of local heating networks will play an important role by 2050.

Greenhouse Gas Neutral Germany in 2050

All emission sources were modeled in the study "Greenhouse Gas Neutral Germany in 2050" ("Treibhausgasneutrales Deutschland im Jahr 2050") [10]. A national baseline was developed showing the technical feasibility of reducing GHG emissions in Germany by up to 95 %. The study does not include an economic assessment and does not investigate which frameworks need to be created in order to introduce specific techniques.

The study identifies a relatively low biomass potential and only assumes 726 PJ in 2050, 80 % of which is solid biomass. The cultivation of biomass for exclusively energetic use is excluded and only residues and waste are considered, including wood chips and pellets from thinning wood, landscape cutting and agro-forestry systems, as well as straw pellets. Three heat demand scenarios were developed that differ in terms of the restoration rate of the buildings. The last heat scenario leads to a high drop in final energy demand, especially by households, achieved through electricity in connection with heat pumps and solar heat. The concept of the bioeconomy is not investigated in the study. Material use of raw materials is discussed and, through the strict application of the principle of material use before energetic use, cascading wood[1] would contribute to 68 M tons of CO_2 savings by 2010. Projections beyond 2020 are not available.

The study excludes CCS because of the limited storage capacities in Germany. Afforestation, renaturation and direct air capture are considered in the study, but no quantitative information on the latter is available. Carbon capture and usage (CCU) in biogas plants plays a relevant GHG-reducing role by 2050, with the study calculating residues amounting to 5.3 M tons of CO_2. CCU is also a technology used in the chemical industry whereby 18 M tons of regenerative methane are expected in 2050.

Long-term Scenarios for Renewable Energies in Germany

The "Long-term Scenarios for Renewable Energies in Germany" ("Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global") [11] were developed in response to the new political guidelines, including an increase in fossil fuel prices and the development of renewable energy capacities. The main objective of this study is to verify the necessary transformation of electricity, heat and fuel generation in Germany to achieve 80 % to 95 % GHG reductions by developing renewable energy sources and increasing efficiency as represented by five target scenarios.

The applied model is an optimization energy system model (REMix) which was tailored to the European power supply system with a high proportion of fluctuating renewable energies. The basis of the REMix model is a GIS-based database in which the potential of the renewable energy resources (solar, wind, biomass, hydro, geothermal) are available in a high temporal (1 hour) and spatial (10 x 10 km^2) resolution. REMix calculates the cost-optimized use of the various renewable energy technologies for a user-specified share of renewable energies in a given year (e.g. 85 % renewable electricity generation in 2050), taking into account the temporal and spatial availability of renewable energy resources. The remaining conventional power plant parks are shown as a residual load.

[1] Cascading wood means that the harvested wood first goes into material use (durable wood products such as timber and furniture, or ephemeral wood products such as paper). Only at the end should the wood be used for energetic purposes.

Only domestically available biomass - with a potential of 1,550 PJ/a by 2030 - is considered in the study. Residues and organic waste have a potential of 800 PJ/a (640 PJ solid, 160 PJ liquid) and 4.1 M ha of dedicated plants are assumed to be available. According to the study's findings, between 2015 and 2030 heat generation from biomass will increase by 15 %; afterwards only a minor increase is anticipated. For the modeling, 100 % of organic residues and waste and 45 % of the cropland are used for stationary heat generation and in CHP units. The rest of the cropland (2.3 M ha) is used for biofuels, mostly for 2nd generation biofuel production. It is assumed that by 2050 there will be a strong expansion of local heating networks. CHP heat from biogas-driven technical systems will dominate, whereas solid biomass in individual heating systems will account for a smaller proportion. The paper does not include any information about the bioeconomy.

As a result, biomass will play the greatest role in the heat sector (630 PJ/a) in 2040 - 2050. In addition, 300 PJ/a of biofuels and 216 TWh/a of final energy are produced in the power sector. The study is currently being further developed in different modules. In the scenarios, CCS is available from 2025 onwards, with an installed capacity of 18 GW by 2050, based on coal as the most cost-effective solution. BECCS is not taken into consideration. CCS in the industry sector reaches 35 M tons of CO_2eq by 2050. Further NETs, like afforestation and a small amount of direct air capture (DAC) is considered, but no numbers are provided.

Interaction Renewable Power, Heat and Transport

The main objective of the study "Interaction Renewable Power, Heat and Transport" ("Interaktion EE-Strom, Wärme und Verkehr") [12] is to review the electricity demand in 2050, while reaching an 80 % reduction in GHG emissions.

A cross-sectoral expansion optimization model was used to represent the energy supply system in 2050, at which time the total costs across the electricity, heat and transport sectors are minimal. It is assumed that biomass, especially energy crops, will only be used in limited amounts for energy purposes (no imports, no expansion of the existing acreage of about 2 M ha.). Biomass in the form of pellets, wood chips and firewood is primarily concentrated in inefficient, existing buildings in settlements with low heat density (outlying and rural areas). Furthermore, biomass is deployed in industry when high process temperatures (over 100 °C and especially over 500 °C) are required. In households, district heating will become a more important source of heat, as well as the power sector (heat pumps, power-to-heat (PtH)[2]). The study does not specifically touch upon the bioeconomy, but takes into consideration the material use of biomass, especially in the chemical

[2] Power–to–heat (PtH) refers to pathways for the generation of heat with the use of electrical energy

industry. This is considered a way in which 282 TWh of regenerative methane will be used for material use and therefore less (199 TWh) will be available for energy purposes in the industry. The study does not provide any information on carbon capture and storage, or usage, and no further NETs are introduced.

Development of Energy Markets – Energy Reference Forecast

The study "Development of Energy Markets – Energy Reference Forecast" ("Entwicklung der Energiemärkte – Energiereferenzprognose") [13] was designed to forecast the development of the German energy markets until 2030, supplemented by a trend scenario extending into the year 2050. Furthermore, the study presents a scenario for the required transition of the energy system to meet the targets of the "Energy Concept" of an 80 % reduction in GHG emissions. Different models were used to project developments in the population, economy, final energy consumption, transformation sector, and global markets for energy resources and to quantify emissions from energy consumption.

Only domestic biomass is used in the models and no imports are considered. As a result, biomass retains its dominant role among renewables over the long term because it can be used to generate electricity and heat and to produce fuels as well. Although biomass use shows a 72 % increase by 2050 (1,915 PJ) over 2011 (1,111 PJ), its share in renewables as a whole falls from 76 % in 2011 to 54 % in 2030 and 52 % in 2050. The reason for this is the rapid growth of other renewable energies, especially wind and solar. In the generation of heat, biomass dominates over the entire period with a 70 % to 80 % share in renewable energies. This applies both to direct heat generation and to provision in the form of local and district heating. While the direct generation of heat, in addition to biomass, is based on roughly the same proportion in renewable energy sources as solar-thermal and ambient heat used with heat pumps, sewage gas and biogas play an important role in district and local heating. When looking at private households, biomass use shows an increase of 48 % (from 241 to 360 PJ). Twenty percent of the natural gas will be replaced by biogas in 2050. The concept of the bioeconomy is also not included in this study. In the trend scenario, final energy use decreases by 28 % by 2050 compared to 2011 levels. Major reductions (37 %) can be observed in the housing and small-scale industry sectors as well as in the trade and service sector due to energetic improvements, more efficient heating technologies, and a warmer climate. Across all sectors, heat demand (final energy) decreases by 30 %. The study only touches upon the possibility of CCS for coal and CCU in general, but they are not quantitatively included in the scenarios.

4. Biomass in the heat sector within the scenarios

The following sections are based on an analysis and the authors' own interpretation, taking into account the assumptions and results of the investigated studies. Several factors with a potential influence on the future biomass use in the heat sector have been identified by experts, analyzed and interpreted. These include GHG targets, biomass potential, heat and power demand, and possible conversion technologies.

The starting point for the analysis of the GHG targets and their influence is the carbon budget in Germany by 2050. If the target is an 80 % reduction in GHG emissions, 100 M t of CO_2 would still be permitted. This would mean a total of 60 M t for the energy sector[3]. About 5 % of the GHG emissions for all energy purposes in 1990 would still be allowed in 2050. Nearly 15 – 20 % of the required energy could be generated, for example, by natural gas, which would compensate for the fluctuation in energy demand and supply. As a consequence, bioenergy would be mainly used to optimize economic and energetic efficiency and to decrease environmental impact and GHG emissions. In this case, existing technologies should be further developed, e.g. optimized firing, emission control systems and measuring technologies. In most cases, heat would only be generated with high full load hours, possibly combined with electrical surplus heating. The decision in favor of hybrid systems – a combination with other renewables - or flexible operation would only occur if there were economic incentives or other advantages and thus a clear economic benefit over natural gas. For facilities with a high yearly heat demand, solid biomass CHP plants would gain in relevance for each scale. Biowaste disposal would probably focus on large centralized plants.

On the other hand, if policy aims to achieve a 95 % GHG reduction, the carbon budget would be 60 M t of CO_2 in 2050. The reduction of non-energy greenhouse gas emissions will be especially difficult: agriculture and waste management would emit two-thirds of the remaining emissions budget. A residual budget of less than 20 M tons of CO_2 would thus remain in 2050 for all of the energy supply and industrial processes. In fact, this would mean that the energy supply would have to be almost completely decarbonized. Due to the high share of fluctuating renewable energies in this case, not only in the power sector but also in heat supply (solar-thermal, electrical heat pumps with renewable power) [4], supply security and stability would become even harder to achieve than today. In addition to power accumulators, heat buffer tanks and all options of power-to-X (PtX)[5], flexible biomass utilization will have to contribute in both the short and long term in the form of flexible heat and power generation systems, and innovative control concepts will therefore be needed.

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[3] The total $CO2_{eq}$ emission in Germany was 1,248 M tons in 1990. A 95 % reduction by 2050 results in a carbon budget of 60 M tons, while an 80 % reduction means 100 M tons of $CO2_{eq.}$

[4] e.g. in the study “Climate Scenario 2050” 98 % of the installed power capacity is based on wind and solar.

[5] Power-to-X (PtX) refers to pathways which use surplus power – typically in periods of low power demand and high power generation, based on fluctuating energy sources – and use it in other sectors (X), for example in the heat or transport sectors.

In addition to GHG reduction goals, biomass potential has been identified as being a critical driving force for the bioenergy sector. However, among the analyzed studies (see Figure 1), there is a wide range in estimated biomass potential in Germany in 2050 of between 200 and 430 TWh.

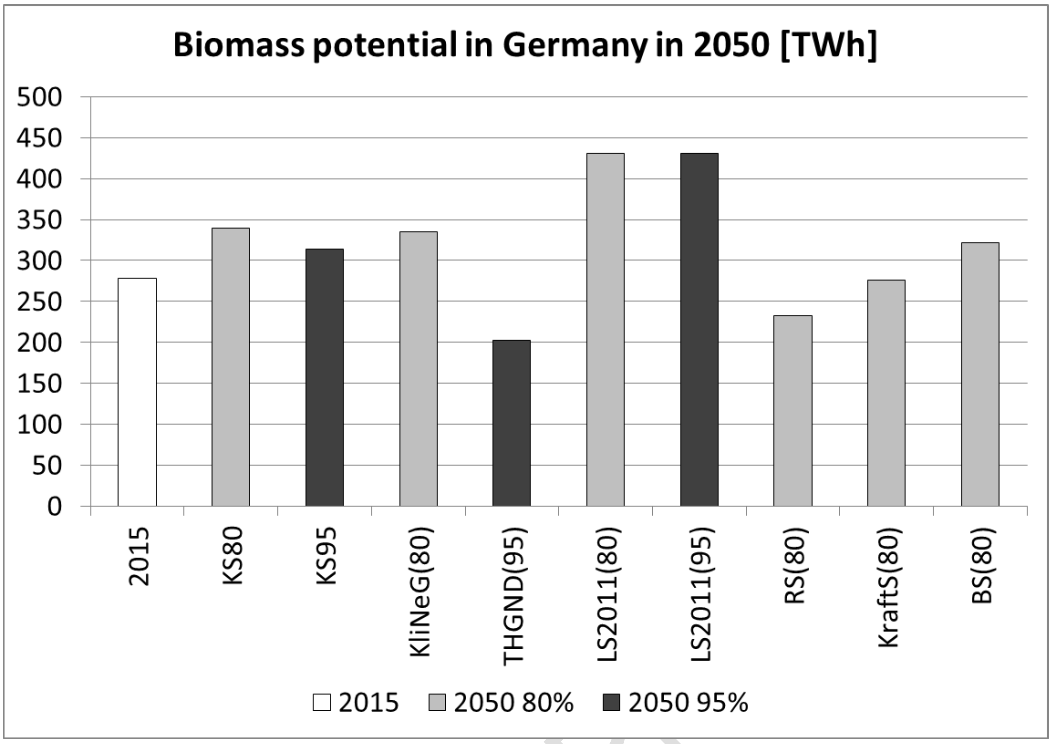

Figure 1. Biomass potential in Germany in 2050 (abbreviations as per Table 1). A reference value of the biomass potential estimated in 2015 is included.

All values are domestic primary energy potentials and exclude imports. The potential given in 2.1 (CS 80, CS 95) is the primary energy potential for energetic use, while biomass for material use and nutrition are not included. 2.2 assumes the sustainable, technical primary energy potential. 2.3 excludes the use of energy crops and assumes the technical, ecological primary energy potential of waste and residues for energetic use. 2.4 includes energy crops and uses a sustainable primary energy potential. The RS scenario of study 2.5 assumes no energy crop cultivation. The KraftS and BS scenarios allow crop cultivation.

The biomass potentials are significantly influenced by the framework conditions forming the system boundaries but are not affected by the modeling approach.

All analyzed studies agree that biomass will be used for energy purposes in large part - in some cases exclusively - in the form of residues, waste and by-products. Many studies exclude import as well (e.g. “Interaction Renewable Power, Heat and Transport” and “Development of Energy Markets – Energy Reference Forecast”). Cascading use of biomass was identified as an important driver. If cascade use increases in importance, new biomass types, qualities and amounts will be available at the end of a cascade used for energy purposes. In the 95 % scenarios, a higher emphasis on cascade use and residues can be assumed (e.g. the THGND mentions a high potential of cascade use in the industrial sector (p 76)). In all cases, biomass quality is expected to be lower in cascade use (first material and then energetic use) than in the case of it first being used for energetic purposes. The exact quality of the biomass cannot be determined due to several factors, such as the type of biomass and/or its components, the application in which the biomass has been used, and the type of technology used for the recovery.

5. Impacts on the bioenergy technologies and concepts in the heating sector

The revised studies do not include detailed information on the biomass conversion technologies, therefore no results based on the studies can be provided. The authors therefore applied the results of the studies to the bioenergy technology field in order to provide their own results and possible concepts.

Considering a target of 80 % reduction in GHG emissions, the decision concerning biomass heating is mainly influenced by economic factors. The utilization of available wood resources for heating purposes (wood chip boilers, pellet boilers and wood stoves) is expected to decrease in some scenarios (e.g. from 234 PJ in 2008 to 146 PJ in 2050 in the 95% scenario of the “Climate Protection Scenario 2050”). According to other studies, however, it would increase, for example in some scenarios of the “Climate-Neutral Building Stock” in the building sector, especially for residential buildings. To save fossil resources in material production, high quality biomass can be diverted from the energy to the material sector. In this respect, by-products and residues will increasingly be used and the adoption of technologies to achieve the often difficult qualities will be required. At the same time, biomass quality must be improved. Incineration CHP plants that are integrated into (existing) district heating systems could use the biowaste and, in addition to producing power and heat, would make use of a waste that would otherwise require proper investigation and treatment in accordance with Germany’s Biowaste Ordinance. Primary technological developments have to take place with regard to flue gas cleaning, also in small and medium-scale[6] conversion units. When approaching the 80 % rate of renewable energies in the system, there might be some emphasis on storage concepts for solid biomass including storing biowaste for six months to up to one year in order to bridge heat and power supply gaps in winter time. In the 95 % scenarios there will be an increased demand to upgrade biomass resources to storable quality fuels and a need for more flexible conversion technologies due to a growing need for energy storage and capacity back-up. Therefore, mechanical

[6] In this context, small to medium-scale means furnaces with a thermal output of less than 500 kW.

sorting, cleaning, washing, hydrothermal carbonization and torrefaction could gain in importance. In order to guarantee a certain quality of biofuel, online analysis technologies have to be improved and adapted to industrial production. Appropriate sensors and control systems are needed to adjust fuel quality and conversion units to meet fluctuating demand. It is likely that more decentralized and specialized value chains will be developed and adjusted to local waste and by-product biomass resources and local heat (and power) demand.

The analyzed studies show that heat demand will decrease in the next decades in all scenarios (see Figure 2).

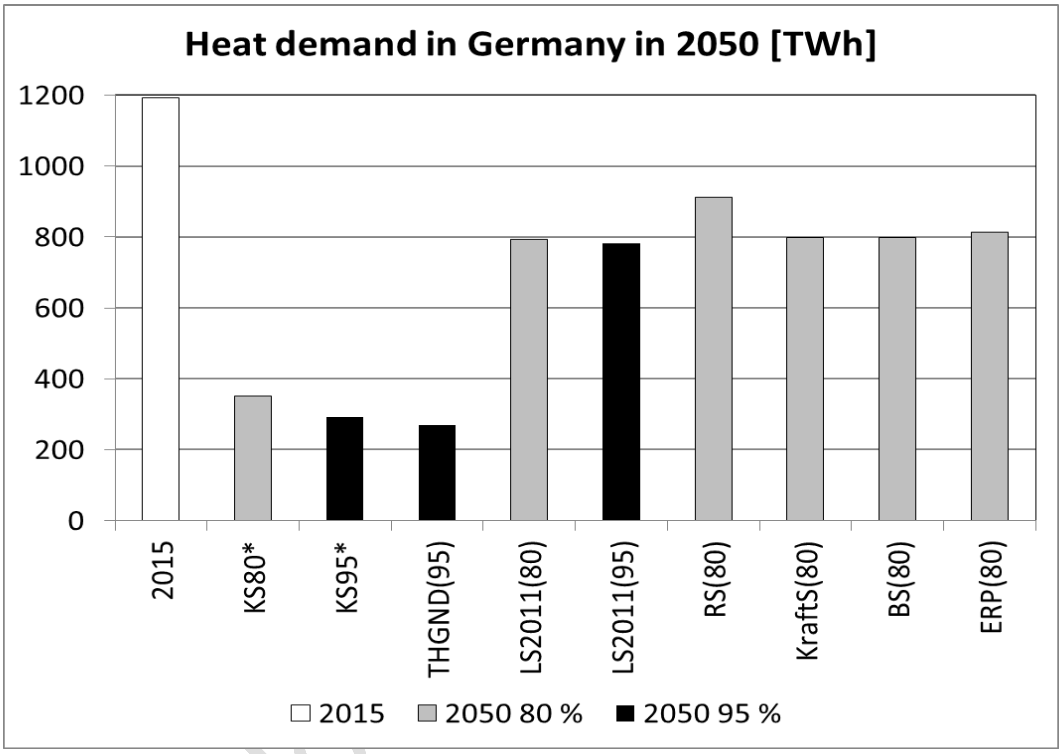

Figure 2. Final energy demand for heat in Germany in 2050 based on the scenarios (* excluding industry). A reference value of the heat demand in 2015 is included.

Most of the 80 % studies assume a heat demand of around 800 - 900 TWh in 2050 and a reduction by one third over 2015 levels; even less demand is expected in the 95% scenarios (300 - 800 TWh). This can be explained by the very strong efficiency measures used to significantly reduce energy demands. In addition to looking at the total amount of heat demand, it is also important to examine the specific demand of space heat or process heat, as well as the division between the different sectors i.e. households, industry, trade, etc. In some scenarios (e.g. “Interaction Renewable Power, Heat and Transport”) the use of biomass for high-temperature process heat in industry as well as buildings that are difficult to renovate is expected, while other scenarios (e.g. “Long-Term Scenarios for Renewable Energies in Germany") assume the role of biomass for stationary heat production and CHP plants.

For household heating, there is a trend towards a lower heat demand per square meter of living space in all cases. However, some buildings, especially those subject to historic preservation, cannot be renovated to the highest possible heat protection standard since no extensive restoration measures are allowed (for example insulation restrictions on facades). This will lead to a proportion of buildings - even in 2050 - with a higher energy consumption. "Climate-Neutral Building Stock 2050" estimates the proportion of this unrenovated building stock will be between 5 - 10 %. The net energy demand for heating these unrenovated buildings is almost four times that of fully renovated buildings (262 kWh/m^2 p.a. versus 26 kWh/m^2 p.a.) (Figure 3).

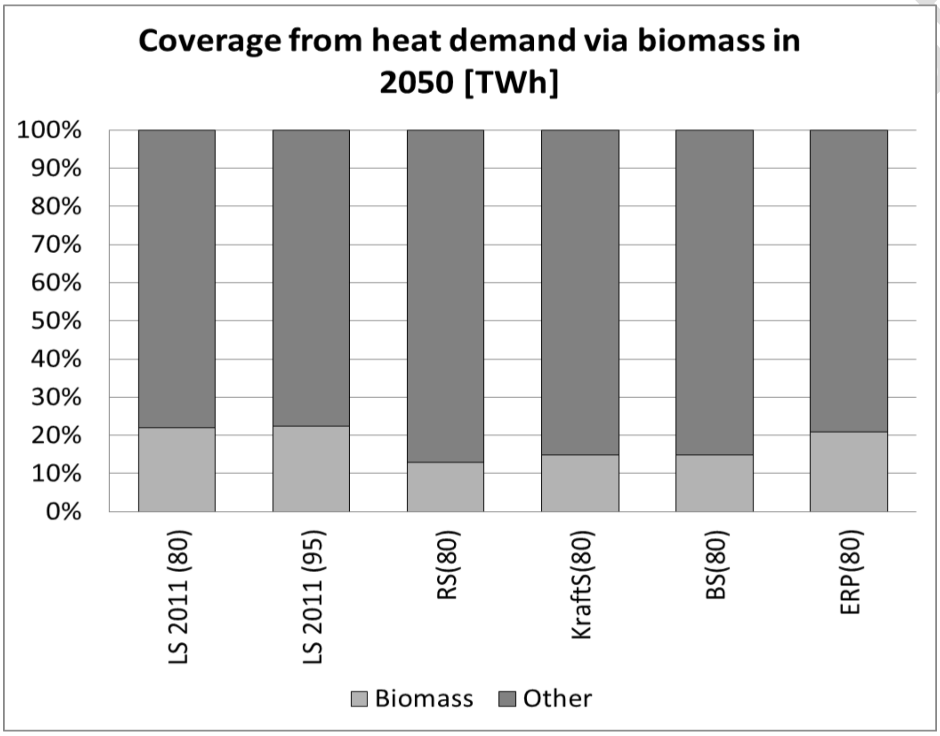

Figure 3. Share of biomass in total heat demand in 2050

There are two base scenarios where heat from biomass can be economically feasible. Either for a base load with a high number of annual full load hours (more than 3000 h p.a.) in combination with cheap biofuels, or for supply security to fill gaps and heat demands when no other renewable or waste heat options, including electricity, are available. In the 80 % scenarios, solid biomass is probably only used for heat in cases with the lowest heating costs, such as base load boilers, base load CHP, or monovalent boilers (e.g. pellet boilers). As renewable power from wind and solar increases, there might be hybrid systems that combine solid biomass conversion with power–to–heat (PtH) for surplus power. In addition, to minimize the size of biofuel and conversion technologies, solid biomass will be increasingly used for buildings with less insulation or for the renewable heat supply of district heating grids.

In the 95 % scenarios, heat pumps, electrical heating (air conditioning), waste heat utilization, solar-thermal and geothermal technologies will gain in significance to ensure security of supply when there are low heat demands per unit of space (less than 30 kWh/m² and year). In these cases, heat buffering and an intelligent combination of the above-mentioned options should be able to provide a full heat supply. Heat from biomass will probably become one of the most expensive heat sources due to increasing competition for biomass for food, feed, material purposes and energy. At the same time, along with geothermal plants, biomass is the only secure source of heat supply throughout the year. Depending on the development of power accumulators, a reasonable option may be to develop very flexible operating heat sources from solid biomass in all power dimensions – ideally as CHP technologies in order to lower power demand and simultaneously produce the needed power. This requires very constant biofuel qualities based especially on size, energy content, moisture content and ash content as well as slag-forming ingredients (variations should be below 10 %). Utilization of biomass for heat will be in conjunction with other renewables and in sectors where other options are inadequate, e.g. in the building sector, in the form of high-temperature (above 500 °C) industrial process heat (in addition to electricity or waste incineration), and to replace coal in production processes.

Figure 4 shows projections for the electricity demand until 2050 based on different scenarios. Reasons for the deviation in results may be the different assumptions about the choice of technologies, productivity or the role of PtX concepts. It is expected that, due to efficiency measures, power demands will decrease by 2030. However, an increase in consumption will occur after 2030, when PtX technologies are available on the market: a moderate increase in the 80 % scenarios, reaching the demands in 2050, which occurred in 2015. A remarkable increase in the power demand by 2050 (about 1.6 times the demand in 2050) can be observed in the 95% scenarios, probably because there will be a greater push towards climate friendly solutions.

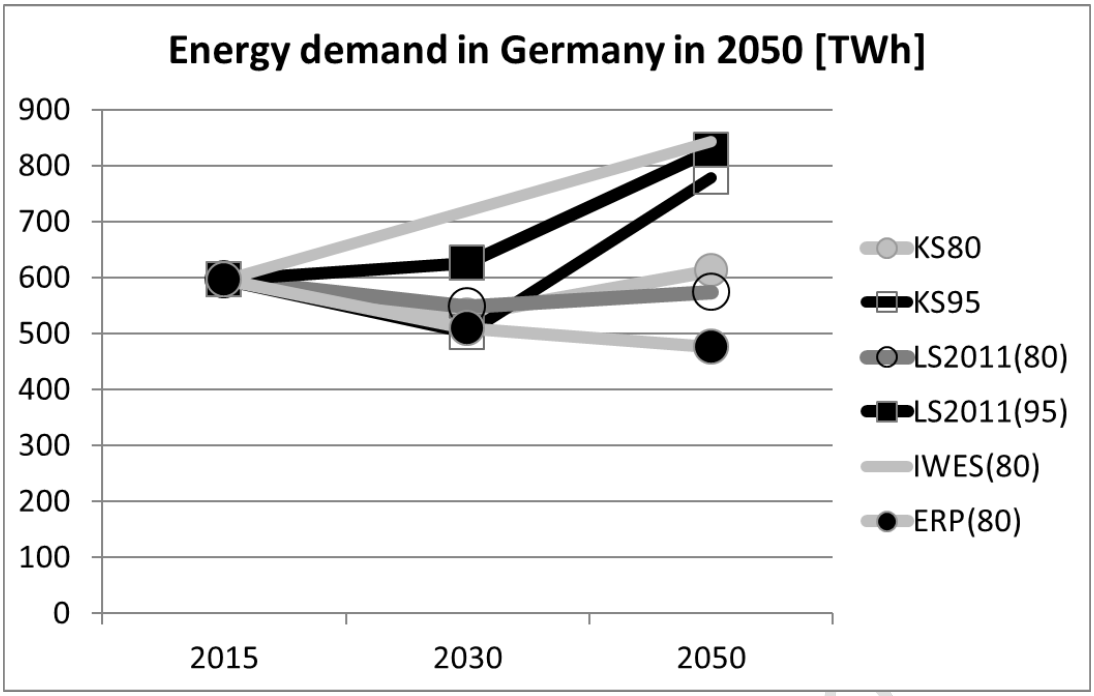

Figure 4. Energy demand in Germany in 2050 based on the analyzed scenarios

CHP technologies and solid biomass plants have advantages over systems that solely produce heat as they have the capacity to stabilize the energy system. Thus, in both cases, the ratio of CHP systems will increase in future so that, by 2050, almost all new installations will probably be CHP systems. Nevertheless, in an 80 % scenario, the biomass CHP should have as many full load hours as possible so that operation is economically feasible. If possible, intelligent control systems can be implemented to adjust, within a day, to the availability of wind and solar power to mirror today's shift in power generated by biogas plants. Ninety-five percent scenarios need to use all renewable options to stabilize the power grid as well as supply heat. Hence biomass CHP has to be very flexible and will operate based on the times of power demands and price signals from the power exchange. It will produce and store the heat for possible full utilization at other time periods, achieving the highest possible value gain from the biomass fuels.

6. Possible technology concepts

As a consequence of the above-mentioned results and impacts on the bioenergy technologies and concepts in the heating sector, some selected technologies and concepts are of special interest for the future in terms of an 80 % or 95 % reduction in GHG emissions. In any case, a change from massive biomass utilization in very big plants towards the smart use of bioenergy[7] seems to be unavoidable [14].

These selected technologies were chosen out of all options available on the market by no later than 2035 in order to have a significant impact in 2050. In other words, they could supply at least 50 % of new installations after a successful market integration. As it stands, only technologies under scientific consideration today would probably make it in time.

Even though there are some technologies with a higher relevance for future applications with respect to meeting the GHG reduction target, a wide range of different heating technologies and concepts for heating purposes will still be available in the future, at least in niche applications (e.g. pellet boiler for older buildings without insulation).

The main consequence of an 80 % reduction scenario is the fact that, in the energy supply system, gas power plants with low investment costs and high flexibility in power output (cold start within an hour, load adjustment within minutes) at different scales (some kW to some hundreds of MW of electrical output) could be used to stabilize the power and heating system. Therefore, biomass is not unessential for system stabilization and has to compete with all the other renewable energy sources on a cost basis. That means bioenergy plants have to be run – like now – at the lowest costs possible, so high full load operation hours are preferable. The utilization of biogas for heating purposes has to be compared to natural gas. With an 80 % GHG reduction target it is hard to anticipate how prices for natural gas will develop in the future. Possibly, the utilization of biomethane in the mobility sector might be of greater interest. In terms of heat from solid biofuels, a comparison to heat from heat pumps or from excess power from local PV-systems will probably push the concepts towards even higher full load hours than today (3,000 h/a) and towards facilities with high heat demands and higher temperature levels (weak or no insulation) or applications with access to very cheap solid biofuels, typically in rural areas. In most cases, new CHP installations will probably not work without significant funding (30 to 50% of the investment costs). Typical technologies and concepts will be single room heaters as an additional heating source, especially in rural areas (in urban areas in most cases only for convenience aspects). These would include wood logs, wood log boilers and wood

[7] "Smart bioenergy means that modern biomass utilization systems and integrated systems that optimally interact with various renewable energy sources are developed further. It also means material and energy use are linked within the framework of the bioeconomy. The concept consists of the following components: use of sustainable raw materials, further development of smart technologies, and integration into future bioeconomy concepts". https://www.dbfz.de/en/feature/smart-bioenergy/#c2175

pellet boilers for older detached and semi-detached houses without insulation, wood pellet and wood-chip boilers in combination with a peak load gas boiler for apartment buildings and commercial and municipal buildings with low insulation, as well as wood-chip boilers and possibly waste boilers for local heating grids in combination with a peak load gas boiler. Solid waste disposal will mainly be managed by combustion in waste heat and power plants. The amount of utilized biomass is strongly correlated to costs on the heating market and the need for the disposal of biogenic wastes. Heat from biomass CHP technologies could give some additional income to the plants, which predominately have to be financed by the production of electricity. In any of the cases named, additional electrical excess power heaters will become state-of-the-art as long as a heat buffer is installed. In this scenario, no special political adjustments in favor of bioenergy are required as the need for heat and power supply security can be achieved through low-price natural gas and existing technologies.

In a 95 % GHG reduction scenario, the energy sector has to change completely to renewable energies. Long-term fluctuations in power production as well as renewable heat generation can only be compensated for by large and cost-intensive long-term heat/power accumulators, expensive power-to-fuel technologies that are linked to high losses, or the system-adjusted utilization of storable bioenergy. High electrical peak load prices can provide the necessary refund for small and medium-scale biomass CHP technologies operated in combination with other renewables. Main technical concepts could be (1) single room heaters for log wood or high-quality biomass pellets that are connected to a central heating system by e.g. water pockets with integrated operation control in combination with other renewable heat sources like heat pumps or solar-thermal systems. With a smart control unit, operating the stove could avoid electricity demands on the heat pump during times of low renewable power generation [15]. (2) Heat and power generation systems for biogas but also for solid biofuels ranging from hundreds of watts to hundreds of kilowatts of power, which would operate in combination with different sources of renewable and waste heat. The flexible operation of the solid fuel plants require high quality fuels such as biogenic charcoal, torrefied biomass pellets, HTC-coal from biomass and biomass pellet qualities in line with wood pellet standards (ISO 17225-2 A1) - even from waste biomass. To achieve high electrical efficiencies, engines and later on fuel cells are recommended for heat and power generation [17]. Very flexible operation has already been demonstrated for a charcoal gasifier in combination with a small engine [19]. (3) Biowaste combustion in heating plants with optimized flue gas cleaning would fill gaps in the renewable heat supply of local heating grids. (4) Last but not least, a fully renewable heat supply requires options for supplying high-temperature heat for industrial purposes as well as solid energy carriers for chemical reactions like the ones used for steel production. While the first purpose could be covered by hydrogen or synthetic methane from renewable power, the latter needs a solid carbon carrier that requires little power.

7. Summary and recommendations

The results of this study can be summarized as follows: 1) There is a significant difference between 80 % and 95 % reduction alternatives in terms of the development and implementation of biomass heating technologies. 2) 80 % goals seek out the most economical cases: base load and monovalent production. 3) 95 % goals require power grid stabilization and heat supply security in combination with other renewable technologies in almost all cases. 4) In both 80 % and 95 % cases, buildings with high heat demand per unit of space and high temperature requirements are promising cases for biomass utilization. 5) CHP, also using solid biomass, will grow in importance and proportion mainly as part of the 95 % scenarios. 6) In all cases, the quality of the biomass raw material will decrease, but high-tech preparation will probably only become cost-effective in the 95 % scenarios.

After Germany signed the latest global climate agreement in Paris, the country started to revise its energy policy and develop and adopt long-term energy scenarios. Heat demand and supply has many driving forces, such as the development of the building stock (incl. insulation), the policy framework and technology development (e.g. the role of CHP or the intelligent transformation of electric energy into heat (power-to-heat)).

Based on the current review, some questions are still open, for example, the future heat demand in different long-term scenarios does not show a clear correlation with GHG goals (stricter GHG reduction goals do not lead in every case to lower heat demands). The picture is even more complex when it comes to future heat provision from biomass.

This can partially be explained by the uncertainties about the allocation of other final energy supply options (power and transport fuels), and the lack of an agreed bioenergy strategy. This heterogeneous picture is reflected in the different modeling approaches of the scenarios as well [16]. Furthermore, when analyzing energy system modeling approaches, modeling assumptions always reduce the complexity of the real world: scenarios are optimized for energy provision costs or GHG emission reduction costs and they overlook other hurdles or opportunities such as innovations from outside the energy system that affect energy demands, consumer behavior, acceptance etc. In order to deal with these constraints, research and development that is open to different technologies is very important.

To make use of the biomass-to-heat options for GHG reduction, the current uncertainties surrounding the availability and future role of bioenergy need to be reduced. Long-term bioenergy scenarios are urgently needed and a coherent bioenergy strategy with goals and milestones has to be developed. With this in mind, heat scenarios have been developed for Germany until 2050 as part of the research project Bioplan W, with the participation of research, industry and policymakers [18] [20].

Heat from biomass can offer comparable economic options for reducing GHG emissions. Scenarios for the provision of power and transport fuels based on biomass have additionally concluded that there is a high persistence of heat provision from biomass in future energy systems [21]. Biomass-to-heat systems can also contribute to the German energy transition (Energiewende) close to the final energy user e.g. by upgrading heat to CHP systems with local grid stabilization functions, through integrated heat provision from biomass, and other renewables in buildings with a significant heat demand [14].

However, the current policy and support framework does not support the development and integration of such strategically important concepts into the energy system. Adjustments are necessary, especially to the Renewable Energy Heat Act, where support for the combination of different renewables has yet to be considered.

The ongoing adjustments and debates also show that there will be no single best solution in the future. Instead, a wide range of smart technologies and concepts are necessary to provide integrated solutions for future energy supply.

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