Bioenergy beyond the German „Energiewende“– Assessment framework for integrated bioenergy strategies

Daniela Thrän[a,b*] (daniela.thraen@ufz.de), Martin Bauschmann[a] (martin.bauschmann@dbfz.de), Nicolaus Dahmen[c] (nicolaus.dahmen@kit.edu), Berit Erlach[d] (erlach@acatech.de), Katharina Heinbach[e] (katharina.heinbach@ioew.de), Bernd Hirschl[e,f] (bernd.hirschl@ioew.de), Jan Hildebrand[g] (hildebrand@izes.de), Irina Rau[g] (rau@izes.de) , Stefan Majer[a] (stefan.majer@dbfz.de), Katja Oehmichen[a] (katja.oehmichen@dbfz.de), Petra Schweizer-Ries[g] (petra.schweizer-ries@hs-bochum.de), Christiane Hennig[a] (christiane.hennig@dbfz.de)

[a] Deutsches Biomasseforschungszentrum gemeinnützige GmbH—DBFZ, Torgauer Straße 116, 04347 Leipzig, Germany, Tel: +493412434435

[b] Helmoltz-Centre for Environmental Research – UFZ, Permoserstraße 15, 04318 Leipzig, Germany

[c] Karlsruhe Institute of Technology (KIT) - Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

[d] acatech – National Academy of Science and Engineering, Pariser Platz 4a, 10117 Berlin, Germany

[e] Institut für ökologische Wirtschaftsforschung (IÖW) GmbH, gemeinnützig, Potsdamer Str. 105, 10785 Berlin, Germany

[f] Brandenburgische Technische Universität Cottbus-Senftenberg, Universitätsplatz 1, 01968 Senftenberg

[g] Institut für ZukunftsEnergie- und Stoffstromsysteme, Altenkesseler Str. 17, D-66115 Saarbrücken

* Corresponding author

Highlights:

- Today‘s bioenergy provision needs transformation to serve renewable energy systems
- With 29 criteria several bioenergy transformation pathways are holistically assessed
- Results show hot spots, where effort for a successful transformation is necessary
- Large bioenergy systems are more suitable for BECCS integration
- Small systems tend to show better social performance

Abstract:

To fulfil the ambitious greenhouse gas reduction targets in Germany requires a fundamental transformation of the energy system. Accordingly, today’s bioenergy value chains are faced with substantial transformations to find their role in 2050’s low carbon emission energy and supply systems. In this regard, not only economic, environmental, and social aspects need to be taken into consideration. The technology maturity, flexible energy generation and supply and the ability to combine the technologies with CO_2 capture are relevant aspects for future bioenergy systems. To evaluate appropriate options for a future energy system an assessment framework with 29 criteria was developed in form of an assessment matrix, and applied for several bioenergy technology pathways.

The results show much larger challenges for the implementation and transformation of lignocelluse-based pathways, than of biogas-based ones. Trade-offs of the assessment criteria are shown in a heat map. Results might support policy decision makers to develop and implement a long term bioenergy strategy and thus a successful transformation towards a sustainable energy system 2050.

Keywords:

Bioenergy, Germany, renewable energy systems, bioenergy carbon capture and storage, integrated assessment, climate policy

Abbreviations:

BECCS Bioenergy with carbon capture and storage, CHP Combined heat and power, GHG Greenhouse gas, MRL Market readiness level, PtX Power-to-X, PV Photovoltaic, SDGs Sustainable development goals

1 Introduction

Bioenergy is currently the most versatile among the renewable energy sources and provides more energy than wind and hydro, solar and geothermal energy altogether combined [1]. It can be generated from agricultural and forest biomass as well as from biogenic residues and organic waste streams and can be processed to solid, liquid and gaseous biofuels and finally used in heat, power and transport sector (Fig. 1). The energy flow from the biogenic resources to the energy carriers in Germany for the year 2017 is shown based on the sectoral energy outputs in combination with published data on the resources used and the efficiencies of the conversion paths, taking into consideration the by-products and residues still have an significant energy content (i.e. fermentation residues from biomethane and biogas contain 0.5 times the energy of the gases produced while slops and press cake – the residues of bioethanol, vegetable oil and other liquid biofuel production – contain the same energy as the energy carrier produced [2]). Biomass - both domestic and imported – was converted into 440 TWh primary energy and 231 TWh final energy. Forestry (including wood residues), primarily providing solid biofuels for the heating sector, and agriculture, mainly supplying biomass for gaseous biofuels in the power sector and for liquid biofuels in the power sector, are the dominant sources of energy from biomass in Germany.

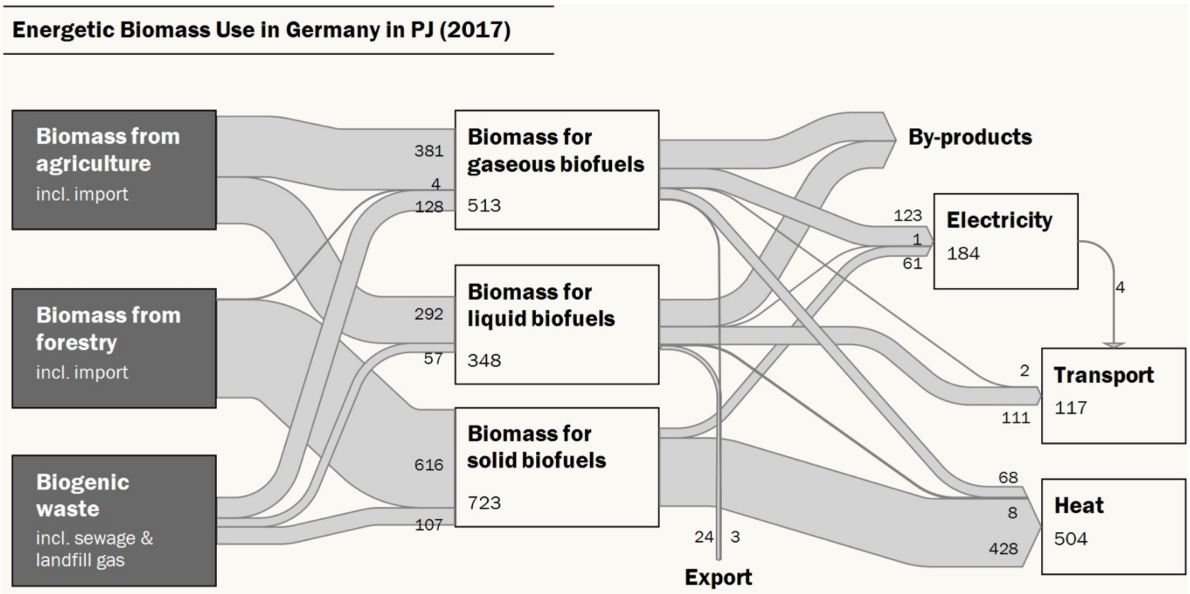

Figure 1: Energetic biomass use in Germany in PJ; data for 2017 based on AGEB [3], AGEE [4], BLE [5], BNetzA [6], DBFZ [7, 8, 9], DENA [10], StBA [11-13]. By-products are any material that is fed into material usage-paths. Energy losses are not depicted.

Fulfilling the ambitious greenhouse gas (GHG) reduction targets in Germany requires a fundamental transformation of the energy system. The future contribution of biomass in the German energy system is discussed controversially: Existing long term scenarios highlight bioenergy in all three sectors, heat, power and transport [14]. Despite the high relevance and potential of carbon capture and storage combined with bioenergy (BECCS), reported by IPCC [15], the revised national energy scenarios do not include that alternatives and additional option which might also influence the role of bioenergy in the longer term [16, 17]. However, biomass can only cover a limited share of the German energy demand by the longer term: If unexploited potentials from timber residues, cereal straw and animal excrements were tapped and primary energy consumption was reduced to 2 PWh/a by 2050, as targeted by the federal government, residues and waste materials could provide 13 to 17 % of final energy [18, 19]. To unlock this potential, pre-treatment will be necessary, i.e. homogenisation of different qualities, reduction of pollutants, removal of contaminants, and increasing the energy density, which usually makes waste materials more costly and more complicated to process than using forest wood or energy crops [20]. Additional bioenergy from forest and agricultural lands by more intensive harvesting or purpose grown plants are related to certain risks, i.e. on land use change and carbon loss, which can be reduced in international agreements or sustainable supply chain certification [21]. A coherent bioenergy policy must ensure that bioenergy use has no negative social and environmental consequences, and makes the greatest possible contribution to climate change mitigation. Sustainable Development Goals (SDGs) of the United Nations [22] and the Global Bioenergy Partnership (GBEP) [23] are two globally guiding initiatives that underline the importance of considering all dimensions of sustainability.

Taking all those demands and constrains together, today’s bioenergy provision chains in Germany are faced with substantial transformation challenges to find their role in 2050’s low carbon emission energy and supply systems: not only economic, environmental, and social aspects need to be taken into consideration. Also, the availability of new technologies, flexibility within the energy system and the possibility to combine the technologies with CO_2 capture are relevant aspects for future bioenergy systems.

Against this background, the aim of this work is to develop an assessment framework that supports the design of future long-term bioenergy strategies in 100% renewable energy scenarios by touching upon a transparent and inclusive sustainability approach.

2 Material and methods

2.1 Overview on the approach

To develop an integrated assessment framework for current and future bioenergy utilisation pathways in Germany the following approach was taken:

1. Selection of **bioenergy technologies** that represent the relevant **utilisation pathways for 2018 and 2050** including a reference systems for the assessment
2. Definition of **criteria and indicators** to achieve a comprehensive evaluation
3. Creation of an **evaluation scale** for each indicator with five colour ratings (traffic light system)
4. Summarising the results in **holistic, comprehensible matrix**.

2.2 Representative bioenergy technology pathways

The focus on the assessment was on biomass by-products, residues and wastes, which are considered as the robust resource potential for bioenergy [19, 24]. The raw materials regarded were fermentable waste and lignocellulosic material as these are likely to continue to offer the greatest potential in Germany for producing bioenergy in the future. The technologies selected for 2018 are the currently prevailing utilisation concepts biogas combined heat and power (CHP) and wood combustion for mainly domestic heating. The 2018 processes were based on the status quo of mature technologies, with typical resource input, conversion efficiencies and average use of heat and other by-products [9, 25]. System designs and system boundaries are shown in Figure 2.

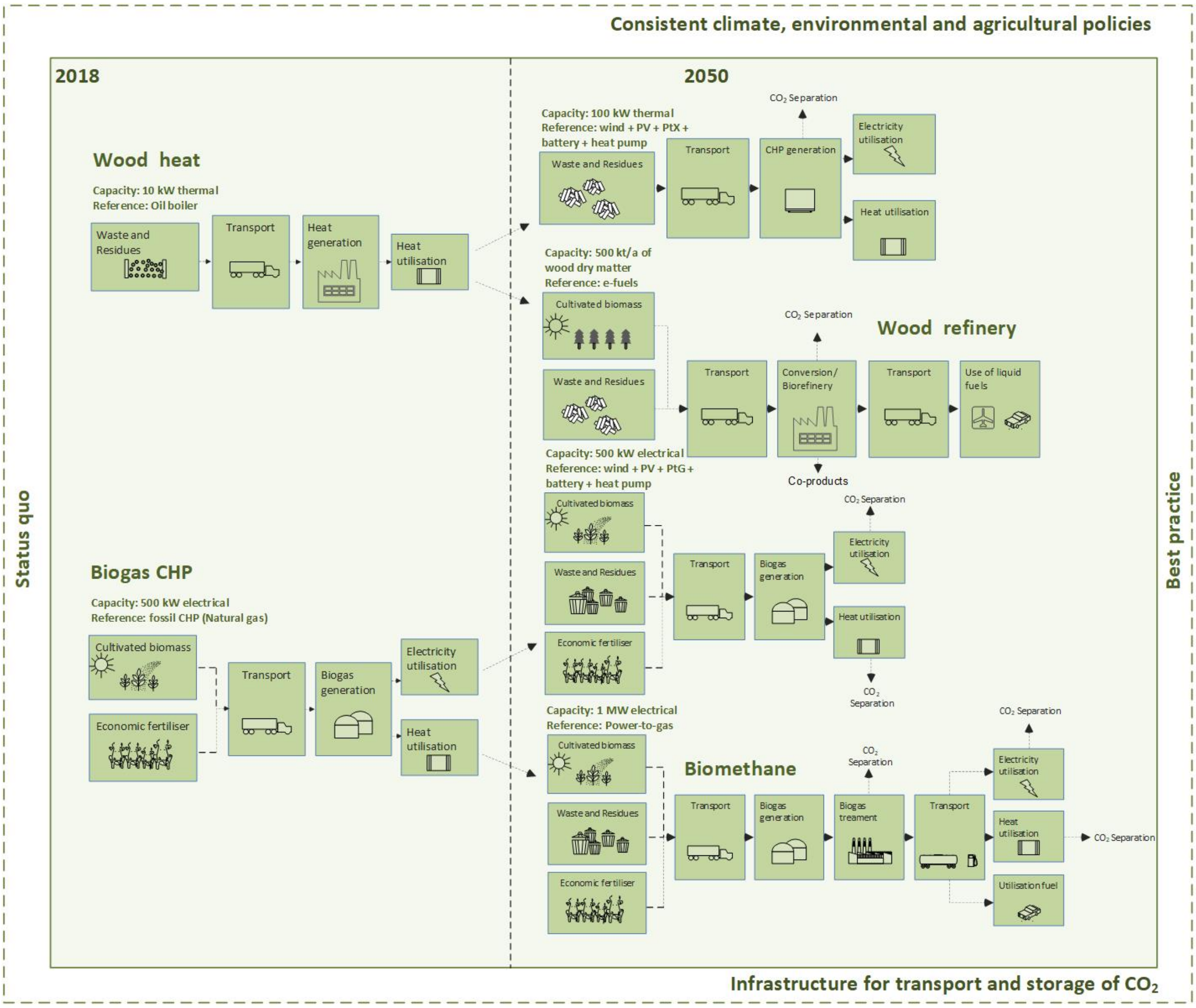

Figure 2: Examined transformation pathways and their system boundaries.

The technologies selected for 2050 included the gradual enhancement of the technology used today (CHP from biogas and CHP from lignocellulosic material) and a technology that is likely to gain in importance in the future and which would provide fuel for the transport sector (biomethane and synthetic fuels from biorefineries by biomass-to-liquids for transport). Prospective best practice sample plants were determined for the 2050 technologies as described by Thrän et al. [26] and Millinger et al. [27]. For example, the annual production of the biogas CHP plant is lower in 2050 than in 2018 since the electricity is generated on a demand-oriented basis in times when wind and solar power is not available, and can provide flexible ratios of heat and power. One plant with the same installed electrical capacity therefore will require less biomass in 2050 than it did in 2018.

Also, the alternative energy provision plants (reference systems), to which the bioenergy systems are compared, are local or regional concepts and differ between 2018 and 2050: in 2018 the reference systems are fossil dominated, in 2050 they are renewable: A natural gas-fired CHP plant was used as the reference technology for the 2018 biogas CHP plant. In contrast, as reference technology for the 2050 CHP plants a technology mix for the generation of CO_2-free electricity and heat based on demand was selected: Demand-driven power generation is provided by wind power and photovoltaic (PV) systems in combination with short-term storage (batteries) and long-term storage with chemical energy carriers (power-to-X (PtX)) [28]. Heat is provided by heat pumps using heat from groundwater or air and run by wind power and PV electricity. The production of synthetic methane using power-to-gas from wind and PV electricity was used as the exemplary reference system for the 2050 biomethane plant; the reference system for the supply of liquid fuels to the biorefinery is the production of synthetic fuels in a PtX plant (e-fuels).

2.3 Definition of criteria

As relevant assessment dimensions the economic, environmental and social aspects were taken into consideration, but also technology, energy system integration, and compatibility with CO_2 capture related aspects. The work was conducted as part of the project “Energy systems of the future (ESYS)”, an initiative of the German Academies of Sciences, which develops policy options for the German energy transition. An interdisciplinary expert group developed the different criteria and indicators in a three-round discussion process within the working group bioenergy, involving thirteen scientists from the fields of engineering, economics, ecology, geosciences, climate science, social and political sciences. Details on the working group and the project ESYS are given in [18]”. The evaluation process was carried out in consensus among the experts. Figure 3 gives an overview of all the criteria generated by the expert groups. The criteria and their indicators will be explained below.

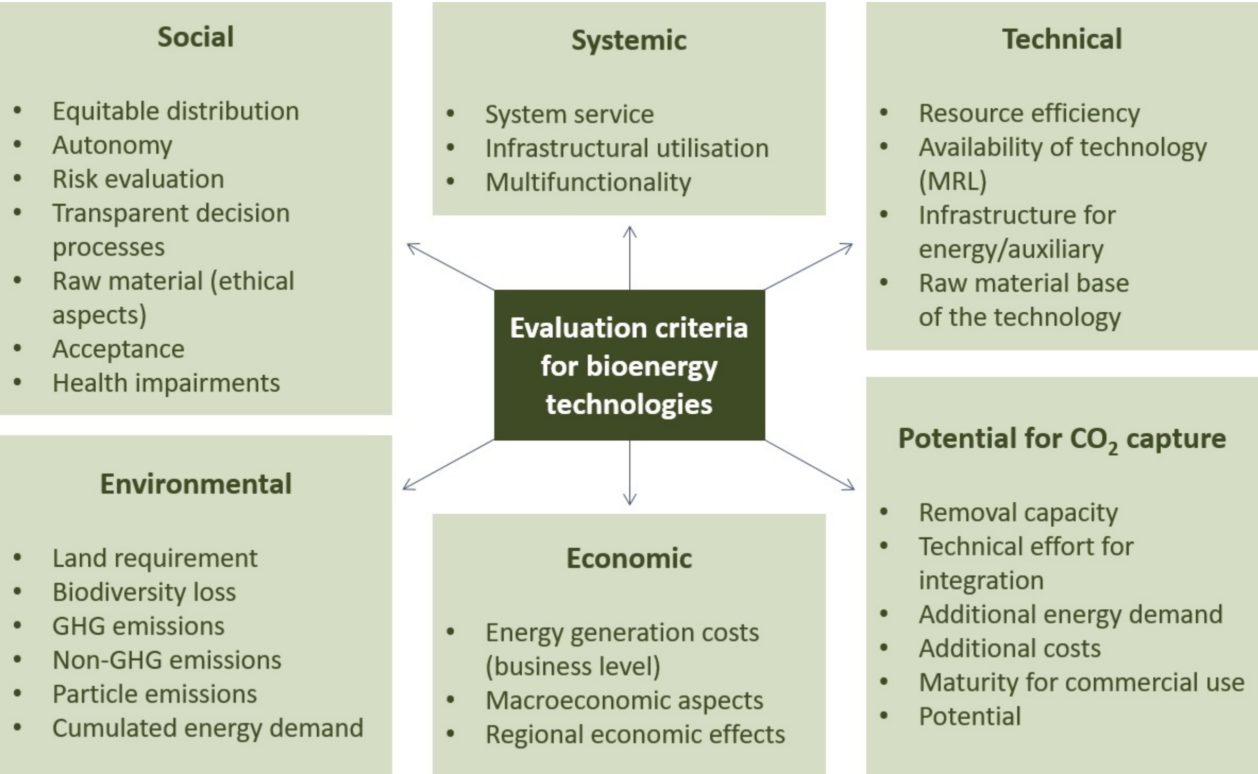

Figure 3: 6 criteria dimensions and the 29 criteria derived for evaluating bioenergy technologies.

2.4 Evaluation scales

For all indicators target functions were defined and the assessment was conducted using a traffic light system. There are five colour ratings: dark green, light green, yellow, orange and red. Green means that the technology largely meets the target system of the criterion, red means that the technology does not meet the criterion. Depending on the target dimension the criterion is determined by target values or by comparison with the aforementioned reference system.

Target functions are described in absolute values, if quantitative numbers for the targets are available. This is especially the case for technical, systemic and CO_2 capture related aspects were included.

For other criteria, namely for environmental and economic aspects, the target function is described in relative values (i.e. that the bioenergy technology performs better than the reference system). Yellow means that the bioenergy technology and the reference system meet the criterion to the same extent, green means a better performance, red a worse performance; for 2018 and 2050 different reference systems are selected (see figure 2).

The results of the assessments is presented in an assessment matrix with coloured fields. For some criteria the evaluation does not lead to a clear result, then more than one colour is given in the assessment matrix. If the information is not sufficient to come to an evaluation, the fields are coloured in grey.

2.4.1 Technical criteria

The criterion **resource efficiency** addresses two aspects: the efficient energetic use of the resources used in the plant and the coupling capabilities, i.e. material efficiency in the form of cascading or parallel provision and use of non-energy products such as nutrient recycling and CO_2 use. **Availability of the technology** is used to assess the extent to which a technology is commercially available on the market; it is described by the manufacturing readiness level (MRL). Another very relevant aspect for the use of a technology is the **infrastructural need for energy and auxiliaries supply** to run the plant, like pipelines for natural gas or hydrogen. Here the question is addressed, whether a suitable infrastructure already exists, or if it has to be created first. The criterion **raw material base** of a technology addresses the diversity (number of different types) of resources that can be used by a technology, considering also the related effort needed to tap these resources and make them available for use. A broad raw material base allows a technology to be used more diversely, may provide higher production capacities, and reduces the risk of dependencies. The assessment is done by absolute values.

2.4.2 Systemic criteria

The criterion **system service** is intended to describe a technology's potential to close the gaps in the energy system expected in the year 2050 and thus contribute to the security of supply by providing services which other carbon-free technologies cannot provide (without high costs). Clear target values can be defined and the assessment is done with absolute values. The criterion **infrastructure utilisation** addresses the infrastructure requirements or the infrastructure compatibilities to transport and systemically integrate the bioenergy. This applies to both the infrastructural integration for procuring the raw materials and to the transport of the generated (energy) product. The target is to be able to use existing infrastructure where possible. **Multifunctionality** indicates the extent to which flexible use of the generated products as energy carrier and advanced biobased material is possible. It is important to note that, for there to be a high system contribution, it must be deployable in all energy sectors (electricity, heat, fuels) as well as for material use.

2.4.3 Environmental criteria

For the environmental assessment, six criteria have been selected. These criteria do reflect the most prominent topics in the well-established debate regarding the sustainability of bioenergy [29-31].

In the discussion on the sustainability of bioenergy, the question of land use or land requirements is often a central element [32, 33]. For this reason, the **land requirement** criterion reflects the ratio of land use to energy yield. The various land requirements of the technology pathways discussed here (or their raw materials) and the possible future design of cultivation systems can be used to identify any differences between the pathways. Another intensively discussed criterion is the risk of **biodiversity loss** [34, 35]. In particular, the intensity of cultivation, the use of pesticides and the size of the intake radius of the conversion plants are important parameters for assessing the risk. Beside these local risks, climate change is a severe global risk for biodiversity which is not included here. Additional typical environmental performance of criteria from life cycle assessment (LCA) are evaluated in comparison with alternative options to provide renewable energy in the future (reference system): **GHG emissions** or emission reductions are a key parameter for estimating the potential of the various technologies to contribute to the climate protection goals of the energy system. Here, depending on the demands placed on the climate protection goal, it is assumed that the energy system in 2050 will largely be GHG-neutral in order to achieve the German targets for the reduction of GHG emissions. **Non-GHG emissions** mainly include aspects such as acidification and eutrophication. These criteria are relevant assessment parameter, especially with regard to existing connection points to agricultural production systems and corresponding inputs of nutrients. **Particle emissions** are a relevant assessment parameter, especially with respect to potential local effects, for example impact on human health. The **cumulative energy demand** aggregates the energy balance, i.e. the renewable and non-renewable energy used to provide the bioenergy via the respective pathway. In addition to the question of “energy efficiency”, the distribution of renewable and non-renewable energy is of particular interest.

The overall assessment of the pathways analysed was based on a structured discussion amongst the members of the respective working groups, using available literature sources and studies. A more detailed description of the criteria evaluation for the respective pathways is included in the supplementary materials.

2.4.4 Economic criteria

On business level, overall **energy generation costs** and raw material costs are chosen as indicators. Raw material costs and fuel costs respectively are included in the calculation of energy generation costs, but are assessed separately due to the high importance of raw materials in the use of biomass. **Macroeconomic aspects** are described by using the indicators *value added* and *employment*, considering only the domestic share. External costs on the other hand were not included in the economic criteria as impacts on human health and the environment are covered by the environmental and social criteria. An additional monetary assessment of damages in other dimensions would therefore distort the evaluation. For the economic criteria described above the traffic light system is applied by comparing bioenergy technologies with the reference system. For the criterion **regional economic effects**, the potential of a bioenergy technology to create added value and employment effects at the regional level was considered in absolute terms for an average region. Here, the plant technology and size as well as its design at the location (e.g. inclusion of regional stakeholders in operating and financing the plant) are of particular importance. This results in the need for a case-by-case assessment, rather than the comparison to a reference technology, however the potential effects can be estimated.

2.4.5 Social criteria

The social criteria of a sustainable bioenergy strategy include public acceptance [36], as well as aspects that generate acceptance of the selected bioenergy technologies [37]. These criteria also consider, that beliefs play a role and those do not always have to correspond to the actual situation. Therefore, moderation and communication are key issues [38]. If nothing else is stated, for social indicators the traffic light system was applied for absolute assessment categories.

The criterion **equitable distribution** reflects perceived justice of project outcomes (which can be monetary or non-monetary) in a region, i.e. which stakeholders can participate and benefit economically or otherwise – the local community, affected community, affected population, etc. [39]. Thus, the perception can be seen on the three dimensions intrapersonal, interpersonal and intergenerational distributive fairness, and is considered to be more positive if the perceived benefits (mostly regional) have the potential to a variety of stakeholders. **Autonomy** addresses the degree of energy self-sufficiency, which is reflected in the potential for regional self-sufficiency or individual self-sufficiency. This aspect repeatedly plays a key role in discussions concerning a (de)centralised energy system and corresponds to a basic need. The **risk evaluation** criterion examines the stakeholder's assessment of the operation and location of a power station as well as the hazards associated with possible transport and includes for example potential impacts on human health and physical integrity. The assessment takes into account the raw materials used, the product and, where necessary, the type of transport. **Transparent decision processes** includes the need for process management on regional and national scale: *regional planning processes* include the design of formal and informal participation procedures which are important in terms of the perceived fairness of procedures (i.e. how fair the planning processes are deemed to be) [40]. The same applies to a *national dialogue process*, where this is yet to be implemented for a sustainable bioenergy strategy. Regardless of the choice of technology options, is imperative to ensure that a good option is not rejected simply because stakeholders were not involved [41]. This can only be assessed on a case-by-case basis because they do not relate directly to the technology; this is why the options for a general assessment are limited and no colour rating is done. The criterion **(ethical aspects surrounding the) raw material** evaluates the raw material's potential to compete with food as well as other aspects such as the potential use of genetic engineering, land use requirements and associated landscape change. The criterion **acceptance** of a technology means that the technology is generally positively perceived by the population (acceptance) which can affect supportive actions (active acceptance). Other acceptance-related social criteria are also taken into account in the assessment. Finally, **health impairment** describes the concern that emissions such as noise, odours and particulates can cause health impairments and is assessed in comparison with the reference system.

2.4.6 Potential for CO_2 capture

The last dimension of the assessment is the future integration of CO_2 capture in the bioenergy technology concept. The focus is on capture at the plant site, the following up processes compression, transport and storage of CO_2 are not included as they are not dependent on the respective bioenergy technology as such and have been examined in other publications [42-45].

The **removal capacity of the individual technology** describes the amount of CO_2 that can be removed annually from one plant using the specific technology and conversion capacity under evaluation. It provides no information about the comprehensiveness of the capture. The removal capacity is calculated based on typical conversion rates and CO_2 outputs of the different bioenergy technologies. The criterion **technical effort for integrating CO_2 capture** evaluates the potential for integrating CO_2 capture into the plant concepts and uses the indicator of the CO_2 concentration in the process streams of the bioenergy plant. Also, the size of the plant plays an important role, as biomass processing capacities increase, the efforts related to the input material or product quantities go down due to economies of scale. This also widely applies to energy consumption and costs (following two criteria): **Additional energy demand for CO_2 separation** describes the effects from separating CO_2 using energy-intensive scrubbing processes and the compression of the gaseous CO_2 into a transportable liquid and is expressed as a proportion of product energy (which is also a measure of a reduction in efficiency over a process without CO_2 capture). The criterion **additional costs for CO_2 capture** accounts for the technical and energetic requirements involved in CO_2 removal expressed by their relative share of the total investment of a plant. The size of the plant is the largest influencing factor when estimating additional costs for CO_2 removal. Differences due to retrofitting compared to the construction of a new plant with integrated CC-system are not taken into account. The criterion **maturity for the commercial use of CO_2 capture** uses the MRL (manufacturing readiness level) to assess actual and expected market availability. The criterion **potential for complete**

CO_2 capture assesses the possibility of maximising the comprehensiveness of CO_2 capture. This can almost be done completely when carbon dioxide is separated in combustion processes or during the production of hydrogen, since the bioenergy plant converts (almost) all of the carbon into CO_2, which can then be captured. The assessment is done in absolute values. All estimates are based on simplified reaction equations and idealised assumptions described in Thrän et al. [46].

3 Results of the Evaluation

3.1 Evaluation matrix

By applying the assessment framework to the specific bioenergy technology pathways an evaluation matrix was developed, which is shown in figure 4-1 and 4-2. The criteria are summarised in rows, the columns include the assessed energy concepts for 2018 (first 2 columns) and 2050 (last 4 columns). The results illustrate where trade-offs concerning the different criteria occur, when focussing on one or the other option over time. This allows for a holistic evaluation of technology options.

Technology pathways			2018		2050			
			Biogas CHP	Wood heat	Biogas CHP	Biomethane	Wood CHP	Wood refinery
Criteria	**Indicators**	**TO**						
Technical criteria								
Ressource efficiency	*Overall efficiency*	A↑	≥ 70 % (no specific heat use)	85 – 95 % sometimes higher	≥ 80 %	≥ 80 %	≥ 90 %	≥ 80 %
	Coupling capability (CO_2, nutrients, …)	A↑	limited: no CO_2 use, but nutrient recycling	no, however nutrient recycling possible	given: low level of CO_2 use and nutrient recycling	extensive: CO_2 use and nutrient recycling	very limited: CO_2 use possible	given: CO_2 use possible, electricity
Availability of technology	*Market maturity (MRL)*	A↑	MRL 10	MRL 10	MRL 10	MRL 10	MRL 10	pilot plant operation (MRL 7-8)
Infrastructure for energy/auxiliary	*Suitability of current infrastructure*	A↑	infrastructure can be fully utilised	infrastructure can be fully utilised	infrastructure can be fully utilised	infrastructure can be fully utilised	infrastructure can be fully utilised	synergies with refineries can be utilised
Raw material base	*Diversity (& effort) of input biomass*	A↑	broad spectrum possible raw materials	broad spectrum possible raw materials	broad spectrum possible raw materials	broad spectrum possible raw materials	broad spectrum possible raw materials	broad spectrum possible raw materials
Systemic criteria								
System service	*Potential to support REs in 2050*	A↑			flexible generation of heat & electricity	flexible generation of fuel, heat & electricity	flexible generation of heat & electricity	fuels for specialty applications (jet fuel!)
Infrastructure utilisation	*Supply channels of raw materials*	A↑	infrastructure can be fully utilised	infrastructure can be fully utilised	infrastructure can be fully utilised	adaption/expansion of infrastructure needed	infrastructure can be fully utilised	infrastructure can be fully utilised
	Distribution of energy products	A↑	extensive expansion needed (heat grids)	infrastructure can be fully utilised	extensive expansion needed (heat grids)	infrastructure can be fully utilised	extensive expansion needed (heat grids)	infrastructure can be fully utilised
Multifuncionality	*Use in all energy sectors is possible*	A↑	use in electricity and heat sector, fixed ratio	use in only one energy sector possible (heat)	use in electricity and heat sector, fixed ratio	all energy sectors and as a material	use in electricity and heat sector, fixed ratio	all energy sectors and as a material
Environmental criteria								
Land requirement	*Land use over energy yield*	R↓	higher than reference, due to ECP	equal to reference, due to use of residues	higher than reference due to ECP	higher than reference due to ECP	lower than reference, due to very efficient use of residues	higher than reference due to ECP
Biodiversity loss	*Biodiversity risks from ECP and infrastructure*	R↓	higher than reference, due to current ECP	equal to reference, due to use of residues	equal to reference, when ECP in small scale and eco-friendly	higher than reference, due to ECP even with eco-friendly product.	equal to reference, due to use of residues	higher than reference, due to ECP even with eco-friendly product.
GHG emissions	*GHG emissions*	R↓	lower than reference, due to fossil fuel substitution	lower than reference, due to fossil fuel substitution	higher than reference, due to soil-borne emissions*	equal to reference, when ECP offsets soil-borne emissions*	equal to reference, when residues are used*	higher than reference, due to soil-borne emissions*
Non-GHG emissions	*Eutrophying/acidifying emissions*	R↓	higher than reference, due to fertiliser use for ECP	higher than reference, due to harvest, supply, transport, conversion	equal to reference, when nutrient applic. for ECP is optimised*	equal to reference, when nutrient applic. for ECP is optimised*	equal to reference, when conversion processes are optimised*	equal to reference, when nutrient applic. for ECP is optimised*
Particle emissions	*PM10 emissions*	R↓	lower than reference, due to CHP efficiencies	equal to reference in modern heat plants	equal to reference, when incineration is optimised*	equal to reference, when incineration is optimised*	equal to reference, when incineration is optimised*	equal to reference, when incineration is optimised*
Cumulated energy demand	*Sum of primary energy input*	R↓	lower than reference, by providing RE power & heat	lower than reference, by providing RE heat	slightly lower than reference, due to by-product use*	slightly lower than reference, due to by-product use*	slightly lower than reference, due to by-product use*	slightly lower than reference, due to by-product use*

Technology pathways			2018		2050			
			Biogas CHP	Wood heat	Biogas CHP	Biomethane	Wood CHP	Wood refinery
Criteria	**Indicators**	**TO**						
Economic criteria								
Energy generation costs (business level)	*Energy generation costs*	R↓	higher than reference (fossil CHP plants)	higher than reference (oil-fired boiler)	depending on costs for reference (energy storage and coupling)	expected to be lower than reference (Power-to-Gas)	depending on costs for reference (energy storage and coupling)	expected to be lower than reference (eFuels)
	Fuel and raw material costs	R↓	higher than reference (natural gas)	lower than reference (heating oil)	reference is a fuel free system	reference is a fuel free system	reference is a fuel free system	reference is a fuel free system
Macroeconomic aspects	*Domestic share of employment*	R↑	higher than reference (educated guess)	higher than reference, due to plant building & operation/supply	higher than reference, due to labour at the plant/biomass supply	higher than reference, due to operating the plant/biomass supply	higher than reference, due to operating the plant/biomass supply	higher than reference, due to operating the plant/biomass supply
	Domestic share of value added	R↑	higher than reference (educated guess)	higher than reference, due to use of regional resources				
Regional economic effects	*Potential for value added/employment at the regional level*	A↑	small scale plants across the country	small scale plants across the country	small scale plants across the country	medium scale biogas plants in many regions	small scale plants across the country	larger plants at only few sites, regional biomass provision
Social criteria								
Equitable distribution	*Number of benefitting stakeholders*	A↑	several different stakeholders	many different regional stakeholders (SMEs!)	several different stakeholders	only a specific group of regional stakeholders	several different regional stakeholders	centralised plants rule out positive effects
Autonomy	*Regional and individual self-sufficiency*	A↑	very possible	very possible	very possible	regional possible, on individual level difficult	very possible	centralised plants rule out positive effects
Risk evaluation	*Subjective perception of risk*	A↑	deemed risk free, except gas related risks	deemed risk free for individual use	deemed risk free, except gas related risks	deemed risk free, except gas related risks	deemed risk free, except gas related risks	small risks deemed in production, transport & use
Transparent decision processes	*National dialogue; Regional planning*	/	*no colour rating, due to need for case-by-case analysis*					
Raw material (ethical aspects)	*Ethical reservations of resource use*	A↑	social reservations on food-vs.-fuel, genetic engineering, land use	quantities for use at household level are of low reservation	slightly to non-critical, due to use of waste, residues & "bio"crops	slightly to non-critical, due to use of waste, residues & "bio"crops	slightly to non-critical, if sustainable and certified biomass is used	high wood demand conflicts with emotional weight of forests
Acceptance	*Different factors (see criteria above)*	A↑	positive, except for raw material issues	positive, due to characteristics of influencing factors above	positive, due to regional effects, raw material dependent	no contribution to equitable distribution and autonomy, raw material dependent	raw material dependent (design and choice); positive as to first 3 factors above	critical, due to negative equitable distribution, autonomy and raw material used
Health impairments	*Occurrence of health impairments*	R↓	comparable to reference (fossil CHP plants)	comparable to reference (oil-fired boiler)	comparable to reference, if reduction is achieved	comparable to reference (power-to-gas)	comparable to or worse than reference (multi-system)	comparable to reference, if reduction is achieved
Potential for CO_2 capture								
Removal capacity (at a single plant)	*kt of CO_2 per year*	A↑	1-10 kt/a; calculated for 1 Nm³ CH_4/h	< 1 kt/a	1-10 kt/a; calculated for 1 Nm³ CH_4/h	1-10 kt/a; calculated for 2 Nm³ CH_4/h	< 1 kt/a	100-1000 kt
Technical effort for integration	*CO_2 concentration in gas*	A↑	< 20 %	< 1%	< 20 %	CO_2 is already captured in the process	10-20 %	CO_2 is already captured in the process.
Additional energy demand	*% of product energy*	A↑	< 20 %	> 50 %	< 20 %	< 20 %	> 30 %	< 20 %
Additional costs	*% of total investment*	A↑	> 30 %	> 50 %	> 30 %	< 20 %	> 50 %	< 20 %
Maturity for commercial use	*Market maturity (MRL)*	A↑	MRL 9	MRL 4-5	MRL 9	MRL 10	MRL 9	MRL 10
Potential	*CO_2 capture rate and related effort*	A↑	complete capture with increased effort	complete capture with significant effort	complete capture with increased effort	complete capture with little effort	complete capture with significant effort	complete capture possible

Figure 4: Evaluation matrix. For each criteria dimension there are criteria with their associated indicators. A column for target orientation (TO) denotes whether evaluation is made based on absolute data (A) or comparison with the reference system (R) and if a high (□) or low (□) indicator is the target for a positive evaluation. The evaluation ranges from positive to negative with a range of 5 colours (green, light green, yellow, orange, red). * Assumption for evaluation in 2050: GHG-neutrality, optimised conversion processes, adopted optimised ECP. MRL: Market readiness level. RE: regenerative energy. ECP: energy crop production.

3.2 Explanation of the evaluation results

3.2.1 Technical criteria

The technologies considered here are, for the most part, technically mature and already available on the market and can build on infrastructure for energy and auxiliaries. Only the wood-based biorefinery has not yet been established on the market as commercial process. All of the technologies defined for 2050 allow for an efficient use of resources by expected technical adaption and improvements based on ongoing research and development activities with overall efficiencies of at least 80 %.

3.2.2 Systemic criteria

All the technologies under consideration can meaningfully contribute to the future supply of energy. With a view to 2050, fuel production in the biorefinery and the production of biomethane, which can be used flexibly in all sectors to replace natural gas, are of greater value to the energy system than electricity and heat production. Particularly for the latter development pathways, the expansion of heating networks is an important prerequisite for good systemic integration. If these pathways are to be pursued further, an overarching energy policy is required that focuses on the expansion of heating networks. In contrast, the infrastructures for biomethane and biofuels are already in place.

3.2.3 Environmental criteria

In general the bioenergy concepts defined for 2050 are based on either combinations of residues and wastes or on innovative and more dedicated feedstock. Due to this shift in the resource base, the assessment showed a quite positive development regarding to criteria such as land requirements, biodiversity and non-GHG emissions. The discussion of the GHG implications from the various bioenergy concepts and the reference concepts assessed here shows that the main drivers for this criterion exist in the areas of agricultural production (application of nitrogen fertilisers) and the use of process energy (along the entire process chain). Anaerobic fermentation can also lead to methane emissions from the biogas/biomethane plant. Positive drivers include potentially reduced emissions in the agriculture sector through avoided emissions from slurry storage as well as possible carbon sequestering effects when innovative crop rotation is used in biogas production in 2050, which for example support carbon accumulation and avoid or reduce soil-related emissions. It is also assumed, that processes for incinerating and converting biomass will be further optimised throughout the timeframe of 2050. With regard to the cumulative energy demand we will assume a full transformation from fossil to renewables. Furthermore, our pathway selection and optimisation will allow for a more efficient and complete utilisation of by-product and waste streams. This development might influence the outcome for the criteria of the cumulative energy demand. Nevertheless, the bioenergy technologies of the future are equal or worse compared to the reference systems. In conclusion, the results show clearly that technical and management effort is necessary to control the environmental effects all along the value chain.

3.2.4 Economic criteria

The economic criteria also show changing challenges between 2018 and 2050: Today's energy generation costs of biogas technology are higher than fossil references, while small scale biomass combustion is competitive. The economic efficiency of bioenergy in the future energy system is highly dependent on the development of costs for technologies such as batteries, power-to-gas and power-to-fuel up to the year 2050. Those can provide similar products and will therefore directly compete with bioenergy technologies. Energy scenarios for 2050 indicate lower energy production costs for biomethane compared to renewable methane via power-to-gas [28, 47]. However, there is high uncertainty with respect to technology development, pathways chosen towards 2050 and the associated decrease in costs. Compared to a reference system without fuel or raw material costs, operational risks of bioenergy plants associated with fluctuating raw material prices are estimated to be significantly higher in 2050. With regard to the domestic share of employment, bioenergy technologies in 2050 are expected to generate higher effects compared to the reference system, due to the higher intensity of labour linked to operating the bioenergy plants and the employment caused by biomass provision [48]. In terms of the manufacture of plants and components, however, the domestic share of the effects is highly dependent on the future development of the related industries in Germany. In addition, there was no sufficient information for an evaluation of the domestic share of value added in 2050.

Plant size is a crucial aspect when it comes to the potential for regional value added and employment. Decentralised plant concepts are implemented widely distributed throughout Germany and are therefore highly likely to exist in an average region. The likelihood, that small plants are financed and operated by a large number of different, generally regionally anchored players, and that the biomass is provided locally is high. Decentralised plant concepts thus offer value added and employment potential in a comparatively high number of regions. With central plant concepts (wood-based biorefinery), the value added and employment effects are concentrated on a smaller number of stakeholders and plant locations. Transitioning from decentralised to large-scale bioenergy technologies would therefore be associated with a change in provision concepts and the involvement of stakeholders.

3.2.5 Social criteria

Continuing the trend, this dimension also shows a clear relation to technology scales: The criteria “autonomy”, “equitable distribution” and “acceptance” were positively assessed for all technology pathways except two future technology paths, biomethane as a natural gas substitute and wood-based biorefineries, where those are deemed to be critical. As a consequence, particular attention should be paid to the concrete design of these options. Additionally, they should be closely coordinated with the population when choosing one of these pathways, so that an acceptable implementation can be developed.

Other social criteria depend more on technical characteristics: The risk evaluation of the technology pathways is generally positive, beside a principal risk perception associated to gas utilisation, caused by implicit associations for the individual non-visible but principally explosive substance. Ethical aspects of raw materials are rated critically for “biogas CHP 2018” and “wood-based biorefinery 2050”, because of societal discourses on food-vs.-fuel, genetic engineering, land use conflicts related to CHP 2018, and potential conflicts resulting of high wood demand in terms of wood-based refinery competing with the frequently stated emotional weight of forest in society [49, 50]. The other technology pathways indicate the actual design is very important and will continue to be a sensitive issue in future developments. For health impairments, when compared to the reference systems, in all future options the yellow category is assessed, and it is stated, that effort is necessary to realise the necessary particle emission reductions. This is in line with the findings of the environmental assessment.

In addition to the pathway-related criteria above, a transparent communication in planning and permitting procedures as well as the traceable embedment in an overall energy transition strategy through public dialogue is a crucial context factor.

3.2.6 Potential for CO_2 capture

In all technologies considered, CO_2 can be, in principle, separated from the biogas, combustion flue gas and raw synthesis gas.

In practice, CO_2 capture in actual wood combustion units is very difficult, due to the small scale and the low CO_2 concentration in the process gas (combustion flue gas): all indicators are orange to red. No commercial technology is currently commercially implemented, e.g. for 10 kW wood-based heat generation. In principle, existing technologies can be applied here, but the technical effort seems to be extremely high in proportion to the processing capacity of the plants.

In contrast, the wood based biorefinery is most promising: CO_2 from a synthesis gas biorefinery can be captured to varying degrees. Roughly, about half of the carbon contained in the feedstock can be obtained as a synthetic fuel and about >90 % of the formed CO_2 (by oxygen blown gasifier and water-gas shift reaction) can be captured after gasification. When hydrogen is the main product, all carbon is obtained as CO_2 in a concentrated form with low energy and cost effort and technologies being commercial available from synthesis gas production from fossil feedstock.

In the case of biomethane production, capturing CO_2 when upgrading biogas into biomethane is also commercially available (i.e. gas scrubbers), and it is therefore feasible that production capacities will be developed alongside this. During the production of fuels or biomethane, part of the carbon remains in the product. Therefore, only the amount of CO_2 generated during the production of these energy sources can be separated. Complementary, the CO_2 generated by clean methane combustion could also be captured and thus almost complete removal of CO_2 throughout the entire process chain (from 40 to almost 100 %) could be achieved.

In the biogas CHP plant, capturing CO_2 from biogas could be integrated in the same way as in the production of biomethane, but smaller plant scale requires more technical and economic effort. Finally, in the wood based CHP plant CO_2 is generated during the combustion; however capturing this CO_2 would be more difficult as it is more diluted. For economic effort the performance is not better than the smaller heat producing wood burning plant because the size of the plant is - with regard to the existing carbon capture units - not much larger.

4 Discussion

The holistic assessment of different bioenergy pathways provided insight into environmental, economic, energy system related and social hot spots for the transformation process of bioenergy utilisation in the German context. The key outcomes can be summarised as:

- Compliance with comprehensive environmental and economic criteria is challenging for all bioenergy systems.
- Procurement of the biomass raw material is a decisive factor both for environmental sustainability as well as for regional economic benefits and public acceptance.
- The competitiveness of the bioenergy pathways assessed is partly influenced by infrastructural aspects, such as a need for an expanded heat infrastructure.
- Transport fuels from lignocellulosic biomass still have to show the competitiveness in the market.
- Smaller installations are better ranked in the social indicators.
- Integration of CO_2 removal in existing or future bioenergy plants is preferable in large conversion plants.
- Carbon capture and storage in general expands to a critical discussion in Germany comprising issues beyond bioenergy.

The results show much larger challenges for the transformation of the utilization of lignocellulosic bioenergy than for the biogas based pathways. The current biogas use can be stepwise developed into a biomethane pathway, without major changes in the raw materials supply chain and actors involved. For lignocellulosic biomass, on the other hand, it is an open question whether it will continue to be used in small, decentral plants, which has high public acceptance but is not so valuable for the overall energy system, or whether it will be used in central biorefineries and BECCS plants. The latter requires substantial changes in the supply chains and actors involved, which may be challenging regarding public acceptance.

With regard to the different dimensions of assessment, the study does not provide any weighting of the indicators but is intended to be a heat map, giving decision maker guidance, where effort is necessary to successfully implement a long term bioenergy strategy arranging the successful transformation from today’s bioenergy use into 2050 systems. In this respect, the described ethical aspects related to the potential roles of bioenergy pathways in the energy system, considering the perspectives and interests of different stakeholder groups should be taken into account. Therefore, public dialogue and communication measures both on the level of project related planning and approval procedures, and in terms of an overarching societal dialogue about the future energy system composition are relevant approaches which can use the results of the holistic assessment.

It is interesting to note that the pathways which usually are found to be “optimal” by techno-economic assessments such as integrated assessment models, namely large scale transport fuel production and BECCS, face the biggest challenges in respect of the social indicators. The holistic approach can alert policy-makers to such trade-offs and complement the results from technoeconomic energy modelling, which typically aim at minimizing the overall costs of the energy system for a given greenhouse gas emission target, but does not include other dimensions for assessment. For example, while minimal overall system cost is doubtlessly a key criterion for energy policy, the economic criteria considered here, such as the risk of rising fuel and raw material cost or regional employment may influence investment decisions of plant operators or public acceptance on a local level and can inform policy makers about where stakeholder preferences are likely to deviate from a least cost energy system as identified by techno-economic modelling studies. Additionally, techno-economic energy modelling often applies perfect foresight, i.e. the optimization model minimizes the overall cost from today to, for, instance 2050, assuming that the learning curves of technologies and future potentials of raw materials and land are known. The models therefore cannot assess the risk of failure of a chosen path due to, for example, a technology not achieving the projected performance or public acceptance for a key technology dwindling. The range of criteria presented here can inform policy makers about such issues, thereby allowing a better assessment of possible hurdles for the implementation of various energy scenarios. The systemic criteria “system service” and “multifunctionality” give some indication of the resilience of a bioenergy pathway against path dependencies: A bioenergy pathway which can provide vital energy services in several sectors can more easily find an alternative niche when the application originally projected proves to be no longer viable, e.g. because the bioenergy technology is outcompeted by other renewable technologies. The results show that the best contribution of bioenergy to a sustainable energy and climate system is also driven by various decisions and developments, which results in path dependencies when developing the long term bioenergy strategy. For example, for efficient climate protection bioenergy with CCS is one of the best performing bioenergy options. But its implementation is dependent on a political and societal decision to apply CCS. Similarly, using bioenergy in the heating sector most efficiently requires an extension of the heating grids and thus an overarching strategy for the energy transition in the heating sector.

In no way should the presented results be used to make blanket statements or provide the sole basis for decisions. It should be particularly noted that some expansion scenarios can only really be evaluated in the course of their expansion. Not only do technologies and their cost develop differently than expected (the massive reduction in production cost of PV in the last years being a case in point), but also do public attitudes change. For example, the public resistance against wind turbines has grown in the last years with the extension of wind energy and will possibly increase further. There is a subjective feeling in many regions of a limit having been reached, with people complaining of being “visually hemmed in” by wind farms [51]. Empirical surveys and accompanying research are indispensable for this - not only with regard to developing the technology, but also with fostering acceptance by taking into account social values and international obligations.

The novelty of this research is two-folded: on the one hand it is an inclusive approach reflecting both, the energy system demand and the different sustainability dimensions and thus the SDGs as well. On the other hand also the results of the Integrated Assessment

Models underlying the IPCC scenarios and their implications on the biomass use within a 1.5 and 2 degree world have been taken into consideration. Here, BECCS plays a vital role in generating negative emissions as one component in keeping the global warming to the anticipated levels while still pursuing certain energy consumption patterns. On the communication side, it is clearly necessary to engage with different stakeholder groups and get them actively involved in the sustainable energy transformation.

The developed assessment framework has been exemplarily illustrated for some transformation pathways in Germany, but it can also be applied to other transformation pathways and for other countries. While the same criteria could be applied, the assessment could come to different results for other countries, due to a different role of bioenergy in the energy system today, but also due to different public attitudes, for example in relation to genetic engineering of bioenergy crops, CCS, the value of autarky provided by decentral solutions, and the emotional connection with forests.

5 Outlook and further work

In the framework of this study, four bioenergy pathways were assessed. However, there are many more possible bioenergy feedstocks and technologies, which can be assessed and compared when applying the develop approach. Shortcomings of the assessed pathways could be taken into account in order to identify improved pathways with the same benefits but fewer downsides. For example, biorefineries rate high in terms of usefulness for the overall system, but the social criteria reveal many potential problems due to low acceptance of wood utilization in big, centralised plants. Therefore, decentralised pre-treatment hubs which integrate better into local wood supply chains and supply pre-treated bioenergy to the central refineries could be an interesting option.

Also, the developed indicators and their ranges can be further specified considering the ongoing discussions on the sustainable development goals and their implementation for bioenergy and it can be extended to the material use of biomass (bioeconomy).

The results from the holistic assessment can also give guidance to further assess bioenergy pathways in techno-economic energy system modelling, to answer questions such as: How much more expensive is a certain pathway which has higher public acceptance than the least cost pathway?

The systematic assessment of various bioenergy pathways could be useful to provide structured information not only to policy makers but also to citizen and stakeholder participation processes, which may become more relevant in order to find transformation pathways supported by society.

6 Conclusions

The holistic assessment of bioenergy pathways with 29 technical, systemic, environmental, economic and social criteria shows opportunities and challenges for the transformation of bioenergy provision and use in the context of the overall energy transition in Germany. The challenges are greater for lignocellulosic biomass than for biogas. The results of the assessment show hot spots which need to be addressed in research and development, but in policy strategies to progress the successful transformation of bioenergy use towards 2050. One important finding is that small-scale systems tend to show better performance in regard to social criteria. On the other hand, large-scale systems, namely biorefineries and bioenergy plants with CCS, rate higher in terms of usefulness for the overall energy systems, because they provide services (liquid fuel generation, CO_2 removal from the atmosphere) which other renewable energy concepts cannot provide, or only at very high cost. If bioenergy with CCS is rejected, because of low acceptance for CCS and/or large bioenergy plants, alternative pathways have to be established to compensate unavoidable emissions and reach the climate goal of net greenhouse-gas neutrality until 2050. These trade-offs need to be recognized and addressed in the political and societal debate about future bioenergy use.

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