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Long-term low greenhouse gas emission development strategies for achieving the 1.5 °C target – insights from a comparison of German bottom-up energy scenarios

Sascha Samadi, Julia Terrapon-Pfaff, Stefan Lechtenböhmer and Katharina Knoop

Wuppertal Institute for Climate, Environment and Energy, Wuppertal, Germany

ABSTRACT

The Paris Agreement calls on all nations to pursue efforts to contribute to limiting the global temperature increase to 1.5 °C above pre-industrial levels. However, due to limited global, regional and country-specific analysis of highly ambitious GHG mitigation pathways, there is currently a lack of knowledge about the transformational changes needed in the coming decades to reach this target. Through a meta-analysis of mitigation scenarios for Germany, this article aims to contribute to an improved understanding of the changes needed in the energy system of an industrialized country. Differentiation among six key long-term energy system decarbonization strategies is suggested, and an analysis is presented of how these strategies will be pursued until 2050 in selected technologically detailed energy scenarios for Germany. The findings show, that certain strategies, including the widespread use of electricity-derived synthetic fuels in end-use sectors as well as behavioral changes, are typically applied to a greater extent in mitigation scenarios aiming at high GHG emission reductions compared to more moderate mitigation scenarios. The analysis also highlights that the pace of historical changes observed in Germany between 2000 and 2015 is clearly insufficient to adequately contribute to not only the 1.5 °C target, but also the 2 °C long-term global target.

KEYWORDS

comparative analysis; decarbonization; energy scenarios; climate change mitigation; Paris Agreement

Introduction

In the 2015 Paris agreement on climate change, which represents the first universal, legally binding global climate agreement, 195 countries agreed on limiting the increase in the global average temperature to ‘well below 2 °C’ and pursuing efforts to limit the temperature increase to 1.5 °C relative to pre-industrial levels. Therewith, the Paris agreement has set the long-term temperature goal below the previous threshold of 2 °C, which despite its role as a reference point in previous mitigation debates has often been criticized for being inadequate to avoid severe negative impacts of climate change [1]. By lowering the long-term temperature goal to ‘well below’ 2 °C and possibly to 1.5 °C, the concerns of both scientists and countries most vulnerable to climate change have been accounted for by the global community of states. Yet, despite this fact and the prominence of these two temperature limits, so far only limited knowledge exists on the one hand about the actual influence a half-degree difference in the global temperature increase can have on the severity of climate change impacts [2] and on the other hand regarding what mitigation pathways in line with a 1.5 °C limit might look like and how they may differ from mitigation pathways in line with a 2 °C warming.

While there have been numerous assessments of the 2 °C target, trajectories below 2 °C have long been regarded as technologically unfeasible and/or politically unenforceable, which has led to a lack of research assessing the climate and policy implications of lower temperature limits [3,4]. Hence, to better understand the greenhouse gas (GHG) emission pathways and impacts, the Intergovernmental Panel on Climate Change (IPCC) has been asked by the United Nations Framework Convention on Climate Change (UNFCCC) to prepare a special report on the impacts of global warming of 1.5 °C and related global GHG emission pathways. To inform this assessment and the political debate, further research efforts dedicated to addressing the differences between 2 and 1.5 °C global warming and the associated mitigation pathways are called for [3,5,6].

In regards to the climate change impacts, the existing research already indicates that the half-degree difference in global temperature increase can have a significant influence on the severity of the climate change effects. Although a temperature increase of 0.5 °C itself may not seem significant, the probability of extreme heat, floods, droughts and storms is expected to increase significantly with 2 °C warming compared to 1.5 °C warming [2,7–9].

With the available assessments already emphasizing that a temperature limit of 1.5 °C could make an

CONTACT Sascha Samadi sascha.samadi@wupperinst.org

important difference in terms of climate-related risks, the question is how mitigation pathways in line with this long-term temperature goal could be designed. Although research is ongoing, at present only a very small number of global scenarios consistent with the 1.5 °C goal exist. According to the Emissions Gap Report 2016 of the United Nations Environment Programme (UNEP) [101] none of these published scenarios achieves the 1.5 °C limit permanently with a probability of 66% or more, and many of the existing 1.5 °C scenarios assume application of negative emissions technologies [10,11] to offset emissions. Yet there is evidence available in the scientific literature that supports the assumption that limiting global warming to 1.5 °C might still be achievable [101,12,13]. This could essentially be accomplished by means of radical and early GHG emission reductions. According to Rogelj *et al*. [13], this implies that carbon emissions worldwide need to be reduced to net zero between 2045 and 2060. Similarly, Robiou du Pont *et al*. [14] set the year of net zero emissions for the EU at 2057.

However, the sum of current (Intended) Nationally Determined Contributions ((I)NDCs) fall substantially short of enabling the 1.5 °C or even the 2 °C temperature limit to be reached [14]. Hence, in order to achieve such far-reaching emission reductions in a relatively short amount of time, country- and region-specific analyses and quantifications of emissions reduction pathways are required to provide decision makers with reliable information on necessary climate mitigation measures. Country- or region-specific analysis is needed (in addition to global analysis) because regional requirements might differ strongly from the global developments and local stakeholders and decision makers are more likely to relate to local objectives than to targets for the global level [15]. However, so far systematic assessments and a common understanding of the challenges to achieving the long-term mitigation goals on a regional or country level are sparse.

This is also true for the energy sector, for which few studies exist that focus specifically on energy-system characteristics that would be in line with a 1.5 °C target [13]. As globally the energy sector is responsible for the majority of GHG emissions, mitigation pathways for this sector will have to play a key role in keeping the temperature rise within the 1.5 °C limit. Analyzing the implications a temperature limit of either 2 or 1.5 °C could have for the development of the energy sector is therefore of high importance, particularly as investment decisions in the energy sector are usually long term, and therefore bear the risks of technology lock-ins [16]. Furthermore, in order to reach net-zero CO_2 emission by about 2060, a scaled-up deployment of a portfolio of technologies, including renewables, high−efficiency technologies, low-carbon transport options and possibly also negative emissions technologies (e.g. bioenergy with carbon capture and storage, BECCS) will be needed [17]. To achieve these developments, increased efforts and sustained political commitment will be required [18].

Addressing these two research needs of additional country-level studies on the one hand and analysis of the energy system characteristics in line with a 1.5 °C target on the other hand, this paper aims to contribute to the debate by analyzing the implications of the 1.5 °C temperature target compared to the previous 'below 2 °C' trajectory for the energy system transition in Germany. To date, Germany's 2050 GHG emission reduction target range is quite broad, aiming at an 80 to 95% reduction relative to 1990. Considering that limiting warming to 1.5 °C will require global GHG emissions to be reduced to net zero during the next 40 years, the upper limit of the target range with 95% GHG emission reductions by 2050 seems to be more in line with the 1.5 °C target [102], while the lower end of the target range with about 80% GHG emission reductions is more likely to be consistent with 2 °C global warming. Therefore, comparing scenarios for Germany aiming at either 80% or 95% GHG emission reductions by 2050 allows an analysis of the differences implied in transitions to low-carbon energy futures consistent with either 2 or 1.5 °C global warming.

Accordingly, the research objective of this paper is to better understand the systematic differences between an 80% and a 95% GHG emissions reduction strategy and the implications of these differences for policy decisions in Germany. In particular, the aim is to contribute to answering the following questions: How do developments differ in an 80% reduction scenario compared with a 95% reduction scenario? and, What are the risks of lock-in in a scenario that reaches an 80% reduction by mid-century, given rapid additional post-2050 reductions would be needed?

Following a description of the applied comparative scenario analysis approach in the second section, the third section describes the scenario selection process and compares the selected scenarios along six mitigation strategies and additional sub-strategies. Following this comparison, the fourth section discusses the key differences between 80% and 95% reduction scenarios. Finally, conclusions and recommendations are provided in the fifth section.

Methods and materials

In Germany, scenarios have frequently been used as instruments to provide scientific policy advice since the 1970s [19]. Particularly, for complex and interrelated matters like the energy transition and mitigation of climate change, results of analytical scenario models have been employed to inform the policy decision-making process [20]. Accordingly, a large number of long-term low-carbon (energy) scenario studies for Germany exist. Although most of these scenarios have several characteristics in common, as they all describe the future emission development and emission reduction potential for Germany, the modeling techniques, assumptions or underlying political objectives can vary significantly. Hence, the results and recommendations of scenario studies also show considerable differences, as for example shown for German energy scenarios by Kronenberg *et al*. [21].

So for Germany, rather than having a lack of analytical information, the challenge for the policymaking process is to interpret these numerous studies and recommendations [22]. This study therefore applies a comparative assessment approach to analyze a range of existing decarbonization scenario studies for Germany, in order to provide more systematic and robust answers regarding the differences the 1.5 °C temperature target entails for the energy system transition in Germany compared to the previous 'below 2 °C' trajectory.

A comparative assessment in the context of scenario analysis can be understood as a systematic review of scenarios in order to identify common features, differences and uncertainties. This type of comparison-based scenario analysis has the advantage that results of a wide range of studies with different premises can be taken into account, allowing for a broader and more systematic perspective [23]. In this study, drawing on existing low-carbon scenario studies and modeling work for Germany allows the identification of potential opportunities and risks, such as technology lock-ins, that might not have become apparent in a single study.

Despite the advantages, applying a comparative approach inevitably also has its limitations, namely that it has to deal with diverse input factors, assumptions and modeling techniques, which makes it difficult to offer reliable explanations for differences, especially when dealing with many variables and only a small number of cases [24]. Furthermore, several authors have found [19,22] that in low-carbon (energy) scenario studies for Germany, the premises are often not made explicit or are not presented openly. In the present study, these challenges of comparing the mitigation strategies and outcomes of the different scenario studies was helped by the fact that the analyzed scenarios were selected based on a common criteria set, and under the premise that the studies provide sufficient data, thereby reducing the number of variables and providing a sound foundation for identifying common strategies as well as substantial differences.

Similar comparative scenario analysis have, for example, been conducted by Lechtenböhmer *et al*. [20] in order to analyze the role of energy efficiency in German low-carbon energy scenarios, or by Öko Institut *et al*. [103], who analyzed existing scenario studies in regards to guiding strategies for Germany's Climate Action Plan 2050. Likewise, Hillebrandt *et al*. [25] applied a comparative scenario analysis to explore the requirements to achieve deep decarbonization in Germany, and Schmid *et al*. [26] conducted a meta-analysis of 10 German mitigation scenarios in regards to how and at what cost the transformation of the German electricity sector could be achieved. Similarly, Söderholm *et al*. [27] reviewed mainly global energy scenarios with a special focus on the societal and institutional transition required to achieve low-carbon futures, while Loftus *et al*. [28] analyzed the feasibility of 12 different global decarbonization scenarios by benchmarking the assumed pace of energy system transformation regarding energy and carbon intensity as well as low-carbon technology deployment against historical experience. Taking the findings from these previous studies into account, the analysis presented in this paper assesses the systematic differences that result from aiming at the different ends of the German government's current 2050 emission reduction target range.

For comparing energy system scenarios, most studies directly or indirectly refer to rather simple system representations known as IPAT (Impact, Population, Affluence, and Technology), or ImPACT (Impact, Population, Affluence, Consumption, and Technology) equations [29] or as Kaya identity [30,31]. These generic models typically use three values, affluence (typically expressed as gross domestic product [GDP]/capita), energy intensity (primary energy per unit of GDP) and emission intensity (GHG or CO_2 emissions per unit of primary energy) to represent the driving factors of energy-related GHG or CO_2 emissions in a country or globally. It has often been acknowledged, however, that these models are rather simplistic and that influencing factors should be looked at in much more detail to give sufficient insights into the strategies the analyzed scenarios assume [32–34].

For the analysis, this metric is therefore expanded to a system of six key mitigations strategies, on which most country-level or global bottom-up mitigation scenarios are based. As scenario studies usually do not set restrictions in regards to economic growth[1] or even population growth, strategies that target the **affluence** element of the Kaya identity are not discussed in this analysis.

Energy intensity improvements are typically a decisive factor in mitigation scenarios [35]. As final energy intensity improvements can be the result of technical energy efficiency improvements, changes in consumption as well as structural effects [36,37], the following three strategies are identified that can lead to energy intensity improvements:

- Final energy demand reductions through conventional energy efficiency improvements (e.g. building insulation);
- Final energy demand reductions through behavioral changes;[2]
- Direct and indirect electrification – that is, substitution of fossil fuels through low-carbon

electricity or through renewable energy-based H_2 or synthetic fuels/gases.

The emission intensity of energy supply can mainly[3] be addressed by the following three separate strategies:

- Increasing the domestic use of zero-carbon energy sources, either by electricity generation from domestic renewables or nuclear power or the use of domestic renewable energy sources in transport and heating;
- Importing carbon-free (at the point of use) or carbon-neutral energy sources/carriers, which can be net electricity imports, net imports of biomass or net imports of H_2 or synthetic fuels/gases; and
- Using carbon capture and storage (CCS) technology to reduce GHG emissions from electricity generation or from industrial plants.[4]

Selection and comparison of German decarbonization scenarios

Selection of scenarios

As mentioned above, there is a long tradition in Germany of scenario development to support energy policy decisions. Therefore, a large number of energy scenario studies are available for Germany. For the meta-analysis in this paper, energy scenarios were sought that fulfill the following criteria:

- **Topicality:** The scenarios should be released in 2014 or later;
- **Timescale:** Scenarios should analyze a time horizon until at least 2050;
- **Coverage and level of detail:** The scenarios should cover the entire energy system, including its end use sectors, in sufficient detail, and should account for all energy-related CO_2 emissions; and
- **GHG emission reduction:** The scenarios should explore trajectories that are roughly consistent with either the lower end (– 80%) or the upper end (– 95%) of the German government's 2050 GHG emissions reduction targets.

Scenarios from the following four studies fulfill all four established criteria:

- UBA [38]: Germany in 2050 – a greenhouse gas-neutral country, prepared by the Umweltbundesamt, the German environmental protection agency;
- BMWi [39]: Development of Energy Markets – Energy Reference Forecast, commissioned by the German Federal Ministry for Economic Affairs and Energy;
- BMUB [40]: Climate Protection Scenario 2050, commissioned by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety; and
- Nitsch [41]: Successful energy transition only with improved energy efficiency and a climate-adapted energy market, prepared by Joachim Nitsch, with previous editions commissioned by the German Renewable Energy Federation (BEE).

From these four studies, the following five scenarios will be considered:

- 'THGND' from [38]
- 'Zielszenario' (abbreviated ZS) from BMWi [39]
- 'KS 80' and 'KS 90' from BMUB [40]
- 'KLIMA-17 MEFF' (abbreviated K17 M) from Nitsch [41]

The methodology used for developing the scenarios is relatively similar in all of the four studies. Each of the scenarios is developed based on several sector-specific and technologically detailed bottom-up models. Future energy demand in the various sectors is derived based on a range of assumptions, including population development, GDP growth and diffusion of new technologies in the energy transformation sector and the end-use sectors. The studies generally apply a simulation modeling approach, although the dispatch of non-renewable power plants is modeled by some of the studies using optimization (cost-minimization) models. The modeling framework for all analyzed studies is therefore generally similar and the differences in scenario outcomes can be attributed to a great extent on differences in input assumptions such as technology availability and diffusion.

Two of the five selected scenarios (ZS, KS 80) describe reductions of energy-related GHG emissions of 80 to 85% by 2050 (relative to 1990), and thus relate to the lower end of the German government's 2050 emission reduction target. The other three scenarios (KS 95, K17 M, THGND) describe reductions of 95 to 100% by 2050, thus resembling (or exceeding) the upper end of the government's long-term target. Table 1 provides an overview of the respective development of energy-related GHG (or CO_2) emissions in the five scenarios.

In regards to the future population and GDP developments, the four scenarios that provide data on these indicators (ZS, KS 80, KS 95 and THGND) make similar assumptions. Across these scenarios, the population in Germany is expected to decline from 82.5 million at the end of 2016 to about 72–74 million in 2050. Similarly, all five scenarios assume roughly similar GDP growth averaging annually 0.7 to 0.9% (in real terms) over the period 2010 to 2050.

The THGND scenario is unique among the five analyzed scenarios in that it only provides one quantitative description of a possible future energy system for the year 2050, while the other scenarios also include

Table 1. **Reductions in energy-related GHG emissions in Germany relative to 1990 (%).**

		2000	2010	2020	2030	2040	2050
Historical		− 16	− 23				
− 80% to − 85% scenarios	ZS			− 43	− 56	− 70	− 80
	KS 80			− 38	− 55	− 71	− 85
− 95% to − 100% scenarios	KS 95			− 44	− 67	− 84	− 96
	K17 M†			− 35	− 61	− 82	− 96
	THGND			n.s.	n.s.	n.s.	− 100

†For this scenario, instead of energy-related GHG emissions only the sum of energy-related CO_2 emissions plus process-related CO_2 emissions from the industrial sector is available. Their development is presented here.
Source: UBA [104] for historical data.

descriptions of how the energy system might develop over time by providing energy system descriptions also for the years 2020, 2030 and 2040.

Scenario comparison by key decarbonization strategies

Final energy demand reductions through conventional energy efficiency improvements

The potential for conventional energy efficiency improvements[5] can be found in all end-use sectors and includes building renovation to upgrade energy performance, improvements in the efficiency of electric motors in the industry sector and improvements in the efficiency of fossil-fuel powered vehicles.

Building renovation is a key measure that could considerably reduce energy demand in the building sector. The average annual rate of renovation to upgrade energy performance assumed by the scenarios is shown in Table 2. The comparison indicates that all scenarios expect this rate to grow in the future, but that the rate is by far the highest in the KS 95 scenario, followed by the THGND scenario.[6]

A comparison between the scenarios of other underlying assumptions regarding conventional energy efficiency improvements (beyond the rate of renovation) is not possible, as the studies do not provide comparable information in other fields.

Final energy demand reductions through behavioral changes

Besides efficiency improvements, final energy demand can also be cut by reducing the demand for energy services or by shifting demand from highly energy-intensive to less energy-intensive services. Table 3 provides examples of behavioral (or lifestyle) changes that can contribute considerably to final energy demand reductions. The table also shows which behavioral changes (relative to a respective reference case) are assumed to be realized in each of the analyzed mitigation scenarios.[7] The table illustrates that the vast majority of behavioral changes assumed in the analyzed scenarios focus on reducing energy demand in the passenger transport sector. Furthermore, the table suggests that with the exception of the THGND scenario, the more ambitious mitigation scenarios (especially the KS 95 scenario) assume more behavioral changes than the less ambitious ones.

Table 2. **Average annual rate of energy-related renovations in the existing building stock in Germany.**

	Time period	Average annual rate of energy-related renovations (%)
Historical	2005–2008	0.8
ZS	2009–2050	1.8
KS 80	2010–2050	2.2
KS 95	2010–2050	3.1
K17 M	2020–2050	2.0
THGND	2020–2050	2.7

Sources: IWU and BEI [105] for historical data; [41]; [Nitsch J Pers. Comm].

Table 3. **Final energy demand reducing lifestyle changes (relative to the respective reference case development) assumed in the scenarios.**

	ZS	KS 80	KS 95	K17 M	THGND
Passenger transport					
Shift toward more energy efficient modes of transportation		(X)†	X	X	
Use of smaller cars				X	
Introduction of a general speed limit on motorways			X	X	
Higher passenger car occupancy rate			X		
Other areas					
Reduction in room temperatures in winter			X		
Decrease in the per-capita consumption of meat‡		X	X		X

†Only a small modal shift is assumed.
‡This lifestyle change's effects on final energy demand are expected to be small. The main reason why a reduction in the consumption of meat is assumed to be realized in some of the scenarios is that it reduces methane and nitrous oxide emissions in the agricultural sector.

Additional conceivable lifestyle changes, such as reductions in the floor space per person (which would reverse the historical trend[8]) or reductions – compared to a baseline development – in the number and size of household appliances (or consumer goods in general) and their use are not assumed in any of the analyzed scenarios.

Direct and indirect electrification

Direct and indirect electrification refers to the substitution of fossil fuel energy carriers in end-use sectors either through electricity (direct electrification) or through energy carriers derived from electricity (such as hydrogen or synthetic fuels) [35]. Electrification can significantly facilitate the decarbonization of end-use

Table 4. Role of electrification: share of electricity ('direct') and hydrogen/synthetic fuels ('indirect') in total final energy demand (%).

		1990	2000	2010	2015	2020	2030	2040	2050
Historical	Direct	17	19	20	21				
	Indirect	0	0	0	0				
ZS	Direct					22	24	26	29
	Indirect					0	0	0	0
KS 80	Direct					23	27	34	41
	Indirect					0	0	0	0
KS 95	Direct					23	28	40	50
	Indirect					0	0	4	4
K17 M	Direct					22	26	31	38
	Indirect					0	3	9	15
THGND	Direct					n.s.	n.s.	n.s.	35
	Indirect								65

Source: AG Energiebilanzen [106] for historical data.

sectors in two ways. For one, and as mentioned above, electrification in some cases allows for the use of more efficient end-use technologies, enabling final energy demand to be reduced. All else being equal, the substitution of electric cars for conventional cars, for example, leads to final energy demand reductions as electric engines are more efficient than combustion engines [42]. Similarly, the substitution of conventional cupola furnaces by induction melting furnaces can significantly increase energy efficiency [43]. Second, electrification allows energy carriers (electricity or electricity-derived fuels or gases) to be used, which in principle can be made available at very low CO_2 emissions and in large quantities (and at relatively low costs in the case of electricity) [44–47].

Consequently, direct and indirect electrification are popular strategies in decarbonization scenarios, as Table 4 illustrates for total final energy demand and Table 5 shows for each sector. Table 4 highlights that in all analyzed scenarios, the historical trend of an increasing share of electricity in final energy demand is expected not only to continue, but to significantly accelerate.

However, the extent and structure of electrification differs considerably between the scenarios: The two analyzed scenarios achieving emission reductions at the lower end of the current government target (ZS and KS 80) do not envision that hydrogen and/or synthetic fuels will play a role by 2050. In contrast, the three most ambitious scenarios (KS 95, K17 M and especially THGND) expect these electricity-derived energy carriers to play a relevant or even dominant role by then. The combined share of electricity and electricity-derived energy carriers in total final energy demand in 2050 is similar in two of the more ambitious scenarios, at 53% (K17 M) and 54% (KS 95). It amounts to 100% in the radical THGND scenario, which explicitly aims to describe a future energy system that is entirely based on the direct and indirect use of renewable-based electricity generation. The combined share of electricity and electricity-derived energy sources is much lower in the two less ambitious mitigation scenarios.

Looking at the share of electricity and electricity-derived energy carriers in final energy demand of each end-use sector (Table 5), it is shown that the electrification strategy is applied across the entire economy. All sectors are expected to be electrified to a greater extent in the three more ambitious decarbonization scenarios compared to the other two analyzed scenarios.[9] The strongest difference between the scenarios in terms of electrification can be found in the transport sector. While the combined share of electricity and electricity-derived energy carriers grows from a negligible 2% in 2015 to 13% (ZS) and 25% (KS 80) in the two less ambitious scenarios, the share increases to 62% (KS 95), 65% (K17 M) and 100% (THGND), respectively, in the three scenarios aiming at higher emission reductions.[10] The comparison also shows that there are currently diverging views among researchers on the likely or preferable ratio and interdependency of direct and indirect electrification in the transport sector in a deeply decarbonized future.

Table 5. Role of electrification: share of electricity ('direct') and hydrogen/synthetic fuels ('indirect') in final energy demand of the end-use sectors (%).

		Historical		ZS	KS 80	KS 95	K17 M	THGND
		1990	2015	2050				
Industry	Direct	25	32	36	37	44	42	47
	Indirect	0	0	0	0	0	11	53
Commercial	Direct	24	38	51	63	66	65	53
	Indirect	0	0	0	0	0	0	47
Residential	Direct	18	20	26	36	42	30	70
	Indirect	0	0	0	0	0	0	30
Transport	Direct	2	2	12	25	37	25	15
	Indirect	0	0	1	0	25	40	85

Source: AG Energiebilanzen [106] for historical data.

Increasing the use of domestic carbon-free energy sources

The use of domestic carbon-free energy sources can be differentiated into the following three types:

- Electricity generation from domestic renewable energy sources;
- (Non-electricity) use of domestic renewable energy sources in transport and for heating; and
- Electricity generation from nuclear power.

Table 6. **Domestic electricity generation from renewable energy sources in Germany (in TWh/a).**[†]

	Historical		ZS	KS 80	KS 95	K17 M	ZS	KS 80	KS 95	K17 M
	1990	2015	2030				2050			
Wind onshore	0	71	111	140	154	182	150	221	390	284
Wind offshore	0	8	44	59	51	94	64	122	180	274
Hydro	20	19	19	23	23	23	19	25	25	24
Biomass	2	50	63	21	24	66	60	5	4	73
Solar photovoltaics	0	39	70	65	66	113	75	115	123	192
Other renewables	0	0	7	4	4	4	7	12	12	17
TOTAL	**21**	**187**	**314**	**312**	**323**	**482**	**375**	**500**	**734**	**864**

[†]No detailed electricity generation data is available for the THGND scenario, but it is roughly assumed that the foreseen (direct) demand for electricity in the end-use sectors can be met by domestic renewable electricity generation, which would require an electricity generation of about 600 TWh/a. For comparison: German gross electricity generation in 2015 amounted to 647 TWh, with 52 TWh of net exports [106].
Source: AG Energiebilanzen [106] for historical data.

In the following, the role of these three types of domestic carbon-free energy sources in the analyzed scenarios will be discussed separately. The focus will be on electricity generation from domestic renewable energy sources, as this is widely expected to become the most relevant carbon-free energy source in Germany.

Electricity generation from domestic renewable energy sources. The further increase of electricity generation from renewable energy sources and the associated reduction of fossil fuel-based power generation is widely regarded as a key strategy for Germany to reduce its CO_2 emissions in the future. Since the beginning of the last decade, the country has achieved a considerable increase in electricity generation from renewable energy sources. This development was supported by the feed-in-tariffs stipulated in its Renewable Energy Sources Act, which came into effect in the year 2000. Gross renewable electricity generation in Germany increased from 38 TWh in 2000 to 187 TWh in 2015,[11] equivalent to an average annual increase of 10 TWh/a.

As Table 6 shows, all analyzed scenarios foresee further increases in electricity generation from renewables, with the increases coming largely from wind power (both onshore and offshore) and solar photovoltaics (PV). These renewable energy sources are generally thought to provide the largest additional technical and economic potential in the country.[12]

However, as indicated in Table 6, the extent of the further deployment of renewable energy technologies differs considerably between the analyzed scenarios. By the middle of the century, domestic electricity generation from renewables reaches 375 TWh/a in the ZS scenario and 500 TWh/a in the KS 80 scenario, while much higher values of 734 TWh/a (KS 95) and 864 TWh/a (K17 M) are projected in the two more ambitious scenarios that provide specific data. While these two scenarios differ in regard to the ratio of onshore and offshore wind power they envision, they are similar in the total contribution of wind power by 2050. Both scenarios suggest that about 560 to 570 TWh/a of wind power will be required in Germany for deep decarbonization, which would mean a massive increase of more than 600% compared to 2015.

Table 7 highlights that in the ZS and KS 80 scenarios the average annual increase in electricity generation from renewables does not need to increase relative to the observed growth between 2000 and 2015. In contrast, a considerable further increase (roughly a doubling) will be needed in the future – at least in the 2030 to 2050 period – according to the two scenarios KS 95 and K17 M, which aim at higher GHG emission reduction targets.

(Non-electricity) use of domestic renewable energy sources in transport and for heating. Currently, the use of renewables in Germany in transport and for heating is dominated by the use of biomass. Most of the analyzed scenarios expect only modest increases in the final energy use of biomass, owing to the limited availability of sustainable biomass in Germany. The use of environmental heat and solar thermal energy, mainly for the purpose of heating in buildings, on the other hand, is expected to increase considerably in all scenarios compared to today's use, with the exception of the THGND scenario (see the note to Table 8). However, unlike in the case of electricity generation, no clear link between the extent of the use of renewables for transport and heating and the level of ambition of the scenarios can be discerned. In the case of domestic biomass, its role in meeting final energy demand depends on different assumptions in the respective

Table 7. **Average annual increase in electricity generation from renewable energy sources in Germany (in TWh/a).**[†]

	Historical	ZS	KS 80	KS 95	K17 M	ZS	KS 80	KS 95	K17 M
	2000–2015	Base year to 2030				2030–2050			
All renewables	10.0	10.0	9.5	10.1	21.0	3.1	9.4	20.6	19.1

[†]No detailed electricity generation data is available for the THGND scenario.
Source: AG Energiebilanzen [106] for historical data.

Table 8. Use of domestic renewable energy sources in Germany for transport and heating in the end-use sectors (in PJ/a).†

	Historical	ZS	KS 80	KS 95	K17 M	ZS	KS 80	KS 95	K17 M
	2015	2030				2050			
Biomass (heating)	503	593	502	633	578	605	706	691	583
Biofuels	108	373	107	90	200	442‡	116	109	260
Environmental heat	41	164	104	142	180	240	221	254	445
Solar thermal	28	162	136	134	124	246	149	131	351
TOTAL	**680**	**1292**	**849**	**999**	**1082**	**1533**	**1192**	**1185**	**1639**

†The sustainable and economic potential of the direct use of renewables in the end-use sectors is considered to be very small by the authors of the THGND scenario and they therefore do not consider these energy sources in their quantitative modelling.
‡An additional 215 PJ of biofuels are used in the ZS scenario in 2050 (for a total of 657 PJ). However, in the ZS scenario, 215 PJ of net biomass imports are realized in 2050 (see Table 9 below) and it is assumed here that this biomass is imported in the form of biofuels.
Source: AG Energiebilanzen [106] for historical data.

scenarios. These assumptions concern the availability of sustainably sourced domestic biomass and the share of it used for non-end use purposes, such as electricity generation and central heating.

Electricity generation from nuclear power. In accordance with the decision of the German government to phase out nuclear power by the end of 2022, the decarbonization strategy of increased electricity generation from nuclear power is not pursued in any of the analyzed German decarbonization scenarios.

Importing low-carbon or carbon-free energy sources

Importing low-carbon or carbon-free energy sources is another option to reduce the consumption of fossil fuel energy sources. Currently, Germany is a net exporter of biomass and especially of electricity (see Table 9). The sizeable current net electricity exports are a consequence of power plant overcapacities in Germany, combined with the fact that a large amount of those capacities exhibit lower variable generation costs than most power plants in neighboring European countries [48–50]. However, decarbonization scenarios expect Germany to become a net importer of low- or zero-carbon energy sources in the future. This is because Europe's coasts (onshore and offshore wind) [51] and its south (solar PV and concentrating solar power) [52] exhibit considerable renewable energy potentials that are expected to be relatively inexpensive to tap [53,54]. Consequently, it is expected to be cheaper for Germany to cover part of its future energy demand through renewables-based electricity generation (and, in some scenarios, electricity-derived energy carriers) from abroad.

While only one of the analyzed scenarios (ZS) describes sizeable net biomass imports in the year 2050, all five scenarios expect Germany to become a net importer of electricity by then (see Table 9). However, the extent of imported electricity varies considerably, ranging from a modest 29 PJ/a in the KS 95 scenario to a massive 583 PJ/a in the K17 M scenario and possibly even more in the THGND scenario. The KS 95 scenario further assumes that by the middle of the century, electricity-derived synthetic fuels for the transport sector are imported from abroad.[13] The THGND scenario does not provide a specific estimate of the shares between electricity and electricity-derived energy carriers in imports (see note to Table 9), but expects that between about 4000 and 8200 PJ of energy will need to be imported by 2050. Energy imports in this scenario are much higher than in the others as it is assumed that end-use sectors heavily rely on synthetic fuels (with considerable associated energy transformation losses), that the realizable potential for domestic renewable electricity generation is limited compared to assumptions in other scenarios and that synthetic fuels (about 1000 PJ per year) will be needed for material use in the chemical industry.

Using CCS technology

It is generally assumed that for economic reasons as well as for a lack of public acceptance [55], coal or natural gas power plants using CCS will not play a significant role in Germany in the future [56]. Indeed, none of the analyzed scenarios relies on CCS technology to

Table 9. Net primary energy imports of low-/zero-carbon energy sources (in PJ/a).

	Historical	ZS	KS 80	KS 95	K17 M	ZS	KS 80	KS 95	K17 M	THGND
	2015	2030				2050				
Biomass	− 22	0	261	252	0	215	14	0	0	0
Electricity	− 186	− 25	0	77	61	57	238	29	583	~ 4000 to 8200†
Hydrogen, synthetic fuels	0	0	0	0	0	0	0	143	0	
TOTAL	**− 208**	**− 25**	**0**	**77**	**61**	**272**	**238**	**172**	**583**	**~ 4000 to 8200**

†The THGND scenario does not specify exactly how much of the synthetic fuel for which domestic renewable energy potential is assumed to be insufficient will be imported from abroad and how much will be produced domestically using imported electricity. The low-end figure in this table assumes that only synthetic fuels will be imported (and conversion losses would occur outside of Germany), while the high-end figure assumes that only electricity will be imported and transformed into synthetic fuels in Germany.
Source: AG Energiebilanzen [106] for historical data.

decarbonize electricity supply. However, one of the two ambitious scenarios (KS 95) assumes that from 2030 on CCS technology will be used to reduce CO_2 emissions from the industrial sector. Specifically, CCS in this scenario is assumed to be used to capture and sequester both process and energy-related CO_2 emissions from several industries such as cement production, crude steel production and the production of certain chemicals. The annual amount of sequestered CO_2 is assumed to increase from 12 Mt in 2030 to 29 Mt in 2040 and 41 Mt in 2050. According to the authors of the KS 95 scenario, domestic storage capacities would allow for a long-term use of the technology even if the most conservative estimates for the CO_2 storage potential in Germany were accurate.

Discussion: what can be learned from the differences between 80% and 95% GHG reduction scenarios?

Based on the scenario meta-analysis performed in the above section on "Scenario comparison by key decarbonization strategies", Table 10 provides a comparative overview of whether and to what extent the six energy system mitigation strategies (or their respective sub-strategies) differentiated in this article are pursued in each of the five analyzed scenarios.

The summary of the results from the meta-analysis of German mitigation scenarios allows the following four key insights to be derived:

- The pace of historical changes observed in Germany between 2000 and 2015 is insufficient to adequately contribute to not only the 1.5 °C target, but also the 2 °C long-term global target;
- The type of mitigation strategies applied can vary strongly from one scenario to another, even for scenarios with similar 2050 emission reduction targets;
- Energy scenarios for Germany more in line with the Paris Agreement's 'well below 2 °C' target tend to use more strategies and to use certain strategies to a greater extent; and
- Following the pathway of an 80% GHG emission reduction by the middle of the century may make it increasingly difficult to achieve timely further reductions after 2050.

In regard to the first point it can be shown that in almost all of the differentiated mitigation strategies, the pace of historical changes observed in Germany between 2000 and 2015 is clearly insufficient to reach an 80% GHG emission reduction by 2050 (relative to 1990).[14] The only exception is the pace of past increases of electricity generation from domestic renewable energy sources. If, however, a 95% GHG emission reduction is aimed for, the implementation of even this strategy will need to be strengthened, the scenarios suggest.

Focusing on the type of mitigation strategies, it can be observed that even for similar 2050 emission reduction targets there are varying views among researchers on whether and how much to rely on individual strategies. Researchers apparently associate different levels of risks and uncertainties with the realization of certain strategies. On the demand side, for example, views differ on whether widespread behavioral changes toward less energy-intensive lifestyles should be pursued or can potentially be successful. On the supply side, assessments differ, for example, in regard to the question of whether CCS use in industry will be socially acceptable and whether economic conditions will ever allow for a widespread implementation of this technology. Similarly, some authors argue the expected costs of indirect electrification are too high for this strategy to be pursued substantially [39]. Undoubtedly, risks and uncertainties exist for each of the differentiated strategies, suggesting that from today's perspective it is sensible to pursue as many (sustainable) strategies as possible, if achieving long-term climate targets are indeed a priority for policymakers and society. After all, it is likely that some will fail or underachieve [28,57,58].

Table 10. Comparative overview of reliance on individual mitigation strategies in each of the analyzed scenarios.

	ZS	KS 80	KS 95	K17 M	THGND
Final energy demand reductions through conventional energy efficiency improvements	++	++	+++	++	+++
Final energy demand reductions through behavioral changes	o	+	+++	++	+
Direct and indirect electrification					
Direct electrification	+	++	+++	++	++
Indirect electrification	o	o	+	++	+++
Increasing the use of domestic carbon-free energy sources					
Use of domestic renewables for electricity generation	+	++	+++	+++	++
Use of domestic renewables for transport and heating	+++	++	++	+++	o
Use of nuclear power	o	o	o	o	o
Importing low-carbon or carbon-free energy sources/carriers					
Biomass	++	o	o	o	o
Electricity	+	++	+	+++	+++
Hydrogen and synthetic fuels	o	o	++	o	
Using carbon capture and storage (CCS) technology					
Carbon capture and storage (CCS) for emissions from power plants	o	o	o	o	o
Carbon capture and storage (CCS) for emissions from industry	o	o	++	o	o

A circle indicates that a strategy is not relied upon, while a '+' indicates that a certain strategy is used to a limited extent, '++' indicates that it is used to an intermediate extent and '+++' indicates that the strategy is relied upon strongly.

Concerning the number of strategies it is not a surprise that more ambitious energy scenarios for Germany, and those that are more in line with the Paris Agreement's 'well below 2 °C' target, tend to use more strategies and tend to use certain strategies, which are listed below, to a greater extent.

- Behavioral changes toward less energy-intensive lifestyles are not assumed to occur in all scenarios and are much more likely to be assumed (and to be assumed to a stronger extent) in the more ambitious mitigation scenarios;
- Electrification, both direct and, especially, indirect in the form of the use of electricity-based synthetic fuels, is clearly used to a greater extent in more ambitious mitigation scenarios;
- Electricity generation from domestic renewables tends to be exploited to a greater extent;
- Imports of electricity and/or hydrogen and synthetic fuels are also assumed to a much greater extent in the highly ambitious scenarios; and
- While the use of CCS for industry is assumed in only one of the analyzed scenarios, this scenario is one of the more ambitious ones, suggesting that the use of this technology might be needed in the future, if other strategies (such as importing low-carbon or carbon-free energy sources/carriers) are not to be pursued to a very significant extent.

The above analysis suggests that aiming initially for an 80% GHG emission reduction by the middle of the century will sooner or later make it increasingly difficult to achieve a more ambitious reduction after 2050, or to achieve a more ambitious reduction target for 2050, in case it is decided to aim at higher reductions at a later point in time. While a more in-depth analysis of branching points between the more ambitious and less ambitious scenarios would be needed to derive a comprehensive and temporally detailed assessment of lock-in risks, there are indications that focusing on moderate emission reduction targets today can lead to significant barriers for achieving higher emission reduction targets in the future. The following strategies provide examples for this hypothesis:

- Strong efficiency improvements in the building sector require early action, as it will require time to renovate all or even most of today's building stock by 2050 [57,59];
- More research is needed on whether and how behavioral change can be initiated or supported [60], especially as these aspects often play no, or only a secondary, role in scenario development [28]. Yet, finding consensus on changes in societal norms will likely require significant amounts of time given that such changes will be controversial as they are potentially not in line with the objectives of influential interest groups. Therefore, society should discuss early on whether and to what extent behavioral changes will be pursued for the sake of reducing GHG emissions – or perhaps for other reasons as well;
- A considerable increase in the use of domestic renewable energy sources for electricity generation will require significant modifications and expansions of the transmission and distribution grids, which typically take many years to be planned, agreed upon and implemented [61,62];
- Before indirect electrification can contribute to energy-system CO_2 reductions, individual technologies need to be further developed, system knowledge needs to be accumulated and new infrastructure needs to be built to considerable dimensions [63–65]. And, prior to that, decisions on the desired system structure need to be made, for example in regard to the questions of whether (mainly) H_2 will be used in end-use sectors or whether (mainly) synthetic fuels will be used; whether fuel production should be centralized or rather decentralized; and whether fuels will be imported or (mainly) produced domestically. These decisions are substantial as from today's perspective, net-neutral emissions in the German energy system are very difficult to imagine without a strong use of H_2 and/or synthetic fuels. Consequently, relying on this strategy is likely to be required in the future, at least in the second half of the century. Therefore, it appears to be sensible to set course in this direction early on, instead of going to extremes to be able to avoid these developments in the coming decades.
- In regard to CCS in industry, early investments would be required for industrial plants as well as in transport and storage infrastructure. This implies that there will likely be at least a decade or two between planning and implementing this strategy and actually realizing the expected levels of emission reductions [28].

Conclusion

This article seeks to improve our understanding of the nature of the energy system transformation that would be needed in the coming decades in Germany and other countries with similar energy systems to adequately contribute to the 1.5 °C or the 'well below 2 °C' targets of the Paris Agreement. To this end, five recently published, technologically detailed energy-system scenarios for Germany, with different levels of mid-century emission reductions, have been analyzed and compared. A differentiation of six key energy-system decarbonization strategies – three targeting the demand side and three targeting the supply side – has been proposed for the analysis. Differentiating among these strategies, and several additional sub-strategies, appears to be suitable to compare energy-system transformation visions of different scenarios and – more generally – to enable a nuanced analysis and discussion of the available options to considerably reduce energy-related GHG emissions in the future.

Our meta-analysis highlights that the more ambitious energy scenarios for Germany, and those that are more in line with the Paris Agreement's 'well below 2 °C' target, tend to use more decarbonization strategies and use certain strategies, such as the extent of demand-side energy efficiency, lifestyle changes and indirect electrification via (domestically produced and/or imported) synthetic energy carriers to a greater extent.[15] Furthermore, a comparison with past energy-system changes in Germany underscores the fact that the pace of historical changes observed in Germany between 2000 and 2015 is clearly insufficient to achieve an 80% reduction in GHG emission by 2050 (relative to 1990).

The discussion of the differences in several key decarbonization strategies between scenarios that might be compatible with 2 °C warming and those that might be compatible with a warming 'well below 2 °C' suggests that the 'lock-in' phenomenon needs to be taken into account in any present-day decarbonization strategy and policy. The time period in which countries can remain uncommitted regarding their level of ambition in terms of mid-century emission reductions appears to be coming to an end, as certain decarbonization strategies (such as widespread and deep renovation of buildings, considerable further expansion of renewable electricity generation and production of synthetic fuels and the introduction of CCS) which are most likely needed to achieve deep emission reductions will require several decades to be successfully implemented. This is the case because of the high number of political and economic actors involved, the infrastructural expansions required and/or the technological advances needed.

While the present study provides important insights, the chosen approach also entails some limitations. One of the key limitations of this study is the low number of scenarios that could be included in the meta-analysis. The implications drawn from this analysis are therefore currently only transferable to a limited extent. This limitation could be overcome by future studies performing similar analyses with bottom-up energy scenarios available for other countries.

It should also be noted that while scenarios are helpful tools to show the potential differences in mitigation pathways consistent with 2 or 1.5 °C, in order to achieve deep decarbonization in practice far more detailed information would be required for the policy-making process. Therefore, further research, for example in regards to the feasibility of mitigation strategies, their respective barriers and risks, and their respective macroeconomic implications, should be conducted on global, regional and country-specific scales. Such analyses should also attempt to consider the particularities of individual sectors such as industry and transport. Additional research is especially important and urgent in regard to the 1.5 °C target, as only very limited research in line with this target is available and as far-reaching policy decisions and actions need to be taken very soon to keep this target within reach.

Notes

1. However, it is discussed whether reduced growth or 'de-growth' should be pursued (among other things) to reduce GHG emissions [66]. It should further be noted that a certain impact on GDP is possible if the second mitigation strategy (behavioral changes) is pursued strongly.
2. Behavioral changes are defined as any changes in consumption patterns leading to lower final energy demand. Such changes can take the form of lower demand for certain products (e.g. cars) and energy services (e.g. distance travelled by car) or a shift from one product or type of energy service to another one with lower energy intensity (e.g. switching from car use to public transportation use). Behavioral changes can either reduce final energy demand directly in the household or passenger transport sectors or it can do so indirectly in the commercial, industry and freight transport sectors as a consequence of lower demand for certain products and energy services.
3. In deep decarbonization scenarios, the fuel switch from high-carbon to lower carbon fossil fuel sources (e.g. from coal to natural gas) is typically of only minor importance, especially in the longer term. This mitigation strategy is therefore not included within the key strategies discussed here.
4. This strategy includes the use of biomass with carbon capture and storage (BECCS), but does not include any other so-called negative emissions technologies (NETs) such as direct air capture, as these are not related directly to the energy system. In German decarbonization scenarios, typically no utilization of these technologies (either BECCS or other NETs) is foreseen. Germany neither has very large biomass resources, nor are significant CO_2 storage potentials available. Furthermore, the implementation of BECCS as well as of other NETs is associated with various social, economic and biophysical challenges, which are anticipated to considerably constrain their widespread application [11].
5. The term 'conventional' is chosen to point out that this strategy only refers to efficiency improvements that are not related to electrification measures.
6. The authors of the KS 95 scenario mention that further studies are required to investigate whether the high rate of renovation they assume can indeed be realized by craftsmanship and industry.
7. The behavioral and lifestyle changes listed in the table are either explicitly assumed by the scenario developers and taken into account in their quantitative modeling, or they are mentioned as one way (alongside efficiency improvements through technological change) to

achieve the energy demand reductions assumed by the respective scenarios.

8. Floor space per person in Germany grew by about 1% annually on average between 2000 and 2015 [67]. All of the scenarios analyzed in this article assume that floor space per person will continue to grow until 2050, although future growth rates are expected to become smaller.
9. The only exception is the residential sector, in which electrification in the K17 M scenario is less pronounced than in the KS 80 scenario.
10. The strict emission limits in the highly ambitious scenarios do not allow for significant fossil fuel-related emissions in the transport sector by the middle of the century. Other decarbonization strategies are either not available in the transport sector (such as the use of solar or geothermal heat or the use of CCS) or severely restricted due to limited potential (such as the use of sustainably sourced biofuels).
11. These 187 TWh were equivalent to a 29% share of renewables in Germany's gross electricity generation [106].
12. Based on several available potential studies, the German Environment Agency [38] derived estimates for the technical-ecological potential of renewable energy sources for electricity generation in Germany and concluded that up to about 1500 TWh of electricity from renewable energy sources could be generated by 2050, with up to 1000 TWh coming from onshore wind power and up to about 250 TWh coming from solar PV plants installed on available structures.
13. These imports of synthetic fuels partly substitute for the lower net electricity imports compared to the same study's KS 80 scenario.
14. Similar findings of insufficient progress in various areas of the energy transition were recently derived for Europe as a whole [18].
15. It should be noted that due to the current legal framework and especially a lack of public acceptance in Germany, the strategies of expanding the use of nuclear power and using CCS technology for power plants are typically not pursued in decarbonization scenarios for Germany. This is also true for the five scenarios analyzed in this article.

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ORCID

Sascha Samadi http://orcid.org/0000-0002-4939-2872
Stefan Lechtenböhmer http://orcid.org/0000-0001-5987-5416

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