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Strategies for climate neutrality. Lessons from a meta-analysis of German energy scenarios

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A B S T R A C T

The ambition to reach climate-neutral energy systems requires profound energy transitions. Various scenario studies exist which present different options to reach that goal. In this paper, key strategies for the transition to climate neutrality in Germany are identified through a meta-analysis of published studies, including scenarios which achieve at least a 95 % greenhouse gas emissions reduction by 2050 compared to 1990. Reduction in energy demand, an expansion of domestic wind and solar energy, increased use of biomass as well as the importation of synthetic energy carriers are key strategies in the scenarios, with nuclear energy playing no role, and carbon capture and storage playing a very limited role. Demand-side solutions that reduce the energy demand have a very high potential to diminish the significant challenges of other strategies, which are all facing certain limitations regarding their potential. The level and type of demand reductions differ significantly within the scenarios, especially regarding the options of reducing energy service demand.

1. Introduction

Climate neutrality is a pivotal goal for keeping global warming at manageable levels [1] and more than 100 countries have already announced or are considering neutrality targets [2]. China aims for climate neutrality before 2060 [3]. Europe's goal for climate neutrality is set for 2050 [4,5], and intermediate targets for 2030 have recently been raised to -55 % [6]. Sweden is the first country to already announce 2045 as the year of climate neutrality in the Swedish Climate Act [7], and in 2021, Germany has followed the same ambition [8].

An important tool for assessing pathways for meeting long-term climate objectives are scenario studies which apply different modelling techniques [9]. For a while the focus was on the power sector and calculating 100 % renewable electricity systems [10], but with the goal of a complete energy transition, the integrated view including power, heat, transport and industry has received increased attention[11–13]. The broad scope of these kind of studies requires thorough data work and processing, often the coupling of different sectoral models and the collaboration of different knowledge fields and institutions [14].

Although the goal is ambitious in regard to the deep changes it requires, the options of how climate-neutral futures may look are manifold. At the same time, the options are highly relevant to policy-making, as the frameworks for these pathways need to be designed accordingly. The challenge of presenting this variety is commonly dealt with comparing and assessing different scenarios in studies as they open up a certain solution space [15,16].

The results of scenario studies heavily depend on assumptions and constraints set by the authors of the studies, or their respective contractors [17]. Their perceptions of the future influence the many settings and assumptions that have to be given as framework conditions to the models. It is sometimes argued that biases can be decreased by making all provisions restricting the unbiasedness of an analysis transparent in the respective study [18]. However, the number of assumptions to be taken, including sectors and issues not directly covered by the models (e.g. often resources or world-wide competition for synthetic energy carriers), and the high complexity of the applied models [19] complicates the comprehension of the impact of taken assumptions. In addition, the stakeholders/institutions involved may have particular interests or perspectives that can influence the focus of a study, which additionally can affect the way in which scenarios, data and model settings are chosen [17]. Thus not only the resulting numbers, but also the resulting insights provided by different studies, diverge.

Energy- and climate scenario studies are an important basis for the societal discussion of possible pathways, knowledge input and guidance for energy and climate policy [20].

In conclusion, there are three main challenges regarding climate neutrality studies: (1) a wide range of options, (2) unavoidable biases and (3) importance of robust findings.

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Therefore, a meta-analysis of studies aiming towards climate neutrality helps to give a more comprehensive picture on options and strategies than individual studies can provide.

For such a meta-analysis, studies with a similar geographical and sectoral scope are required. In Germany, several studies aiming at minimum 95 % climate neutrality have been published since 2018. These vary in focus, perspectives and applied models, as in Germany a diverse landscape of research institutions exists which develops models and energy transition scenarios. This forms a good analytical base for a meta-analysis. Also, recent meta-studies of German climate pathways exist which have a different focus than this study. [21] compares three German energy transition studies in order to derive main policy recommendations, where four out of six compared scenarios have less than a 95 % emission reduction and thus are already outdated in terms of the current German climate targets. A more ambitious focus has been set by [22], which analyses German climate pathway studies with respect to their compatibility of limiting global warming to 1.5 °C or 1.75 °C. In concluding that none of the existing scenarios keep within a German carbon budget the authors of this study developed a goal to derive strategies for the structure of a climate-neutral energy system in Germany and discusses speed-up options.

Hansen et al. [23] have evaluated 180 articles since 2004 dealing with 100% renewable energy systems and conclude that while being a fairly new topic, it has gained increased attention. There is a concordance, that or climate neutrality pathways, renewable power generation needs to be sped up, and end-use sectors need to be intensively electrified - directly or indirectly (see for example [24] for worldwide, [4] for European and [21,22] for German scale studies). There has been a consensus, that for climate neutrality pathways, renewable power generation needs to be sped up, and end-use sectors need to be intensively electrified - directly or indirectly. This apparent concordance vanishes, when looking deeper into the details. The amount of renewables, the type of renewables, the level of direct electrification, and the level of export requirements, among other components, are decisive for the pathway design – and opinions vary largely. Furthermore, the role of biomass and carbon capture and storage (CCS) is handled diversely in different countries and also within different studies of the same country.

At the time of writing this article, Germany is the largest national economy committing to a climate neutrality goal in 2045. Furthermore, Germany is an especially interesting case, as German studies exclude nuclear energy as a supply option in a German climate-neutral system. Since nuclear continues to be questioned to a large extent for its potential contribution to climate neutrality historically [25] and also due to the broader sustainability perspective, pathways to climate neutrality for a large national economy without nuclear can be of special interest. Furthermore, there is a high societal opposition against CCS, which leads to high restrictions of its usage in most German energy transition studies. This increases the pressure on other climate neutrality options in a densely populated country.

While assessing similarities and differences in an extensive analysis of the input and output data of the different scenarios and studies for Germany, this study compares to which extent the main options for climate neutrality are applied within the different studies, attempts to derive robust findings supported by all of the studies, and examines which assumptions and scenario story-lines cause significant differences. We especially focus on the aspect of reduction of energy demand and energy service demand in relation to the other options. Although this option for reaching climate neutrality intensively interacts with all the other ones, it is underrepresented in current studies as well as in meta-analyses.

In the following, we first describe the methods (Section 2) for the selection of the studies, data compilation and consistency checks. Then, we present results of the comparison (Section 3) regarding options chosen for reaching climate neutrality with a special focus on the demand reduction. We go on to discuss (Section 4) the robustness of our findings and further research needs in this area and finally conclude with (Section 5) our main findings.

2. Methods

2.1. Selection of studies and scenarios

There are different options to perform meta-analyses of energy transitions. Sovacool et al. [26] applies a meta-theoretical framework to integrate certain aspects of the energy transition and applies this to selected case-studies of different countries. In contrast to that, we concentrate on studies which have the same geographical scope and a similar sector coverage that meet certain criteria for the energy transition. While other meta-analysis studies then aim at approximating a given, multidimensional scenario result across studies by a few, more simple quantities [27], our approach is to make similarities both and differences visible to be able to detect scenario characteristics that lead to such differences. Like similar meta-analyses made for European countries [28], the EU [29] or Germany [21,22], we identify indicators of common aspects which appear in each of the studies.

We defined the following criteria for scenarios in studies to be included in the meta-analysis:

- Level of greenhouse gas (GHG) mitigation ambition: at least 95 % GHG reduction for the energy sector (by 2050 latest)
- Sectors coverage: transport, industry, buildings, energy (agriculture and waste possible but not required)
- Geographical scope: Germany
- Publication year: 2018 or later

We selected eight different studies with at least one scenario meeting our criteria. The sector coverage however still differs regarding the inclusion of international transport in the transport and process emissions in the industry sector (see subsection 2.2 and Table 2). An overview of the investigated scenarios including their abbreviations applied in the following can be found in Table 1, and the most important scenario inputs in the results section in Table 3. The scenarios by Hansen [30], which have been published in a scientific journal and the scenarios by Nitsch [31] which have been published by a single author are referred to with the names of the main author. The other studies included are referred to by the name of the institution initiating the study or by the conducting institution itself if there is no institution which has initiated the study. 2050 is the target year for all scenarios in the studies we have chosen and we consider that year for comparison. The only study which additionally includes the year 2060 is Nitsch. In this case, the GHG reduction in the year 2060 is just slightly higher than in 2050 (97.4 %), and yet we use the 2050 data for a better comparison and due to more detailed data provision given for that year.

2.2. Data compilation and comparability

Meta-data and data on emissions, demand, installed generation capacities, domestic energy generation, storage and imports have been extracted from the published studies and respective data publications to have a detailed insight into the studies and to compare them (see Table 1 for references and institution abbreviations). If any numbers or values were missing from a study, we contacted the respective authors for additional data provision. The compiled data table is included in the supplementary material.

While the different scenarios within each study are well comparable, the studies differ slightly in scope. The main differences which arose from the emission types covered and sectors included, is summarised in Table 2. In this paper, we cover all energy- and process-related CO_2equivalent (CO_2eq) emissions for the buildings, industry and transport sectors, including international transport. Agriculture and waste are not considered in the direct comparison of the studies since only half of the studies examined include those sectors. If the emission goal of the study is given for all sectors, including agriculture and waste, we deduced the emission target for the energy sector (transport, industry and buildings) from additional information on sectoral target to have

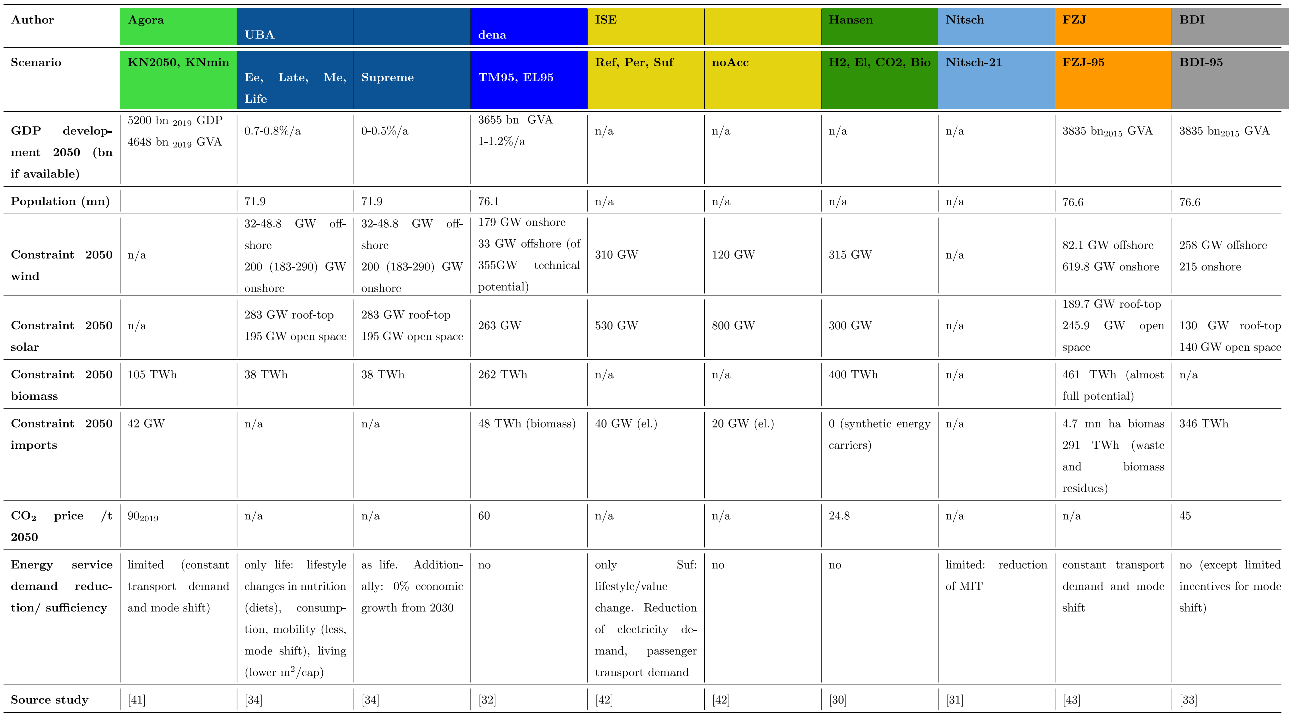
Table 1
Studies and scenarios included in the meta-analysis; scenario names are partly originally in German and thus translated for this table, abbreviations are used in this paper .

Reference	Initiator or Author	Publ. year	Scenario	Abbreviation
[32]	Deutsche Energieagentur (dena)	2018	Electrification95	dena-EL95
[32]	[German Energy Agency]		TechnologyMix95	dena-TM95
[33]	Bundesverband der Deutschen Industrie (BDI) [Federal Association of German Industry]	2018	Global climate protection	BDI-95
[34–36]	Umweltbundesamt (UBA)	2019	GreenEe	UBA-Ee
[34,36,37]	[Federal Environment Agency]		GreenLate	UBA-Late
[34,36,38]			GreenMe	UBA-Me
[34,36,39]			GreenLife	UBA-Life
[34,36,40]			GreenSupreme	UBA-Supreme
[30]	Kenneth Hansen and	2019	Hydrogen	Hansen-H2
[30]	Brian Vad Mathiesen and		Electricity	Hansen-El
[30]	Iva Ridjan Skov		CO_2-Electrofuel	Hansen-CO_2
[30]			Bio-Electrofuel	Hansen-Bio
[41]	Agora Energiewende/Verkehrswende	2020	climate-neutral 2050	Agora-KN2050
[41]	and Stiftung Klimaneutralität (Agora)		Klimaneutral Minimalvariante	Agora-KNmin
[42]	Fraunhofer Institute for Solar Energy Systems (ISE)	2020	Reference	ISE-Ref
[42]			Persistence	ISE-Per
[42]			Non-acceptance	ISE-noAcc
[42]			Sufficiency	ISE-Suf
[43]	Forschungszentrum Jülich (FZJ) [Research Center Jülich]	2020	Scenario 95	FZJ-95
[31]	Joachim Nitsch	2021	KLIMA-21	Nitsch-21

Table 2
Sectors, energy and emissions covered in the studies considered and in the meta-analysis .

	CO_2eq	process emissions	international transport	all sectors considered
dena	✓	✓	no	no
BDI	✓	✓	no	✓
UBA	✓	✓	✓	✓
Hansen	no	no	no	no
Agora	✓	✓	✓	✓
ISE	no	no	no	no
FZJ	no	✓	no	no
Nitsch	✓	✓	✓	✓
Meta-analysis	✓	✓	✓	no

Table 3
Key inputs to analysed scenarios (Note: study colours are consistent with colouring in the following figures).



Author	**Agora**	**UBA**		**dena**	**ISE**		**Hansen**	**Nitsch**	**FZJ**	**BDI**
Scenario	**KN2050, KNmin**	**Ee, Late, Me, Life**	**Supreme**	**TM95, EL95**	**Ref, Per, Suf**	**noAcc**	**H2, El, CO2, Bio**	**Nitsch-21**	**FZJ-95**	**BDI-95**
GDP development 2050 (bn if available)	5200 bn $_{2019}$ GDP 4648 bn $_{2019}$ GVA	0.7-0.8%/a	0-0.5%/a	3655 bn GVA 1-1.2%/a	n/a	n/a	n/a	n/a	3835 bn$_{2015}$ GVA	3835 bn$_{2015}$ GVA
Population (mn)		71.9	71.9	76.1	n/a	n/a	n/a	n/a	76.6	76.6
Constraint 2050 wind	n/a	32-48.8 GW offshore 200 (183-290) GW onshore	32-48.8 GW offshore 200 (183-290) GW onshore	179 GW onshore 33 GW offshore (of 355GW technical potential)	310 GW	120 GW	315 GW	n/a	82.1 GW offshore 619.8 GW onshore	258 GW offshore 215 onshore
Constraint 2050 solar	n/a	283 GW roof-top 195 GW open space	283 GW roof-top 195 GW open space	263 GW	530 GW	800 GW	300 GW	n/a	189.7 GW roof-top 245.9 GW open space	130 GW roof-top 140 GW open space
Constraint 2050 biomass	105 TWh	38 TWh	38 TWh	262 TWh	n/a	n/a	400 TWh	n/a	461 TWh (almost full potential)	n/a
Constraint 2050 imports	42 GW	n/a	n/a	48 TWh (biomass)	40 GW (el.)	20 GW (el.)	0 (synthetic energy carriers)	n/a	4.7 mn ha biomas 291 TWh (waste and biomass residues)	346 TWh
CO_2 price /t 2050	90_{2019}	n/a	n/a	60	n/a	n/a	24.8	n/a	n/a	45
Energy service demand reduction/ sufficiency	limited (constant transport demand and mode shift)	only life: lifestyle changes in nutrition (diets), consumption, mobility (less, mode shift), living (lower m^2/cap)	as life. Additionally: 0% economic growth from 2030	no	only Suf: lifestyle/value change. Reduction of electricity demand, passenger transport demand	no	no	limited: reduction of MIT	constant transport demand and mode shift	no (except limited incentives for mode shift)
Source study	[41]	[34]	[34]	[32]	[42]	[42]	[30]	[31]	[43]	[33]

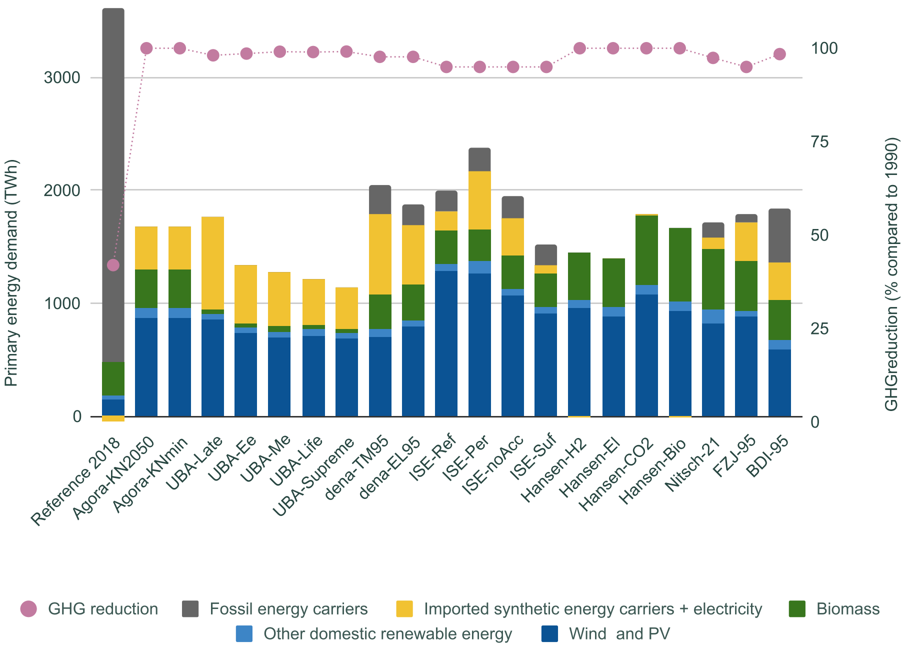


Fig. 1. Primary energy demand for a 95–100 % climate-neutral German energy system, ordered by the studies including the scenarios, bar on the left (2018) for comparison. The GHG-reduction target relates to all energy- and process-related CO_2eq emissions for the sectors buildings/industry/transport.

a better comparison. Thus, the GHG reduction target displayed in Fig. 1 relates to all energy- and process-related CO_2eq emissions for the buildings, industry, and transport sectors, except for the study by FZJ (CO_2 only), Hansen and ISE (no process emissions, and only CO_2).

Although some of the studies do not include other emissions than CO_2, and do not include process emissions, we assume the studies to be comparable regarding the energy sector since energy-related CO_2 emissions are the predominant climate emissions in the sectors mentioned [44].

Another source of potential inconsistencies in the comparison is international transport. Five out of the eight studies do not include international transport at all and the demand numbers for international air and ship transport for the reference years differ between the studies due to differently chosen system boundaries for flights and ships to and from international locations. In the results section, we thus present the relative *changes* between base and target year regarding transport demand, but only include energy demand for international transport in the energy demand numbers, when the studies include it.

The sector definitions also vary between some of the studies. For comparability, we summarise private households, commercial/service and room heating to the sector *buildings*; process heat and other industrial demand to *industry*; passenger and freight transport to *transport*. In two studies (Hansen and ISE), a category of *classic electricity demand* exists. For comparability, we distributed this demand to the buildings and industry sector, applying fractions of other studies with the respective same base year (ISE according to Agora; base year 2018; Hansen according to the average of all studies with base year 2015 - BDI, FZJ, dena, UBA; For calculations, see supplementary material). The calculated distribution factor of classic electricity to buildings and industry is then also applied for 2050 values. Agriculture and waste are excluded regarding their emissions and demand in this meta-analysis.

For an overall consistency check of the scope and sectors covered in the studies, we compare the values of final energy demands in the respective reference year which is presented in subsection 3.1.

2.3. Key scenario input data

Scenario outcomes are expected to vary substantially according to key input data, assumptions and parameters. For each scenario exercise, every model relies on a multitude of assumptions, parameter relations, methods and data. It is therefore impossible to compare them exhaustively. However, an overview of several parameters that are central to any carbon neutrality scenario helps to comprehend outcomes. In Table 3 we thus list the most important framework data of the studies (and if varying, by scenario) such as the projected GDP and population development, constraints assumed for wind/solar/biomass renewable energy carriers, carbon prices and a brief note on the extent of energy service demand reduction.

As expected, the variance between scenarios within a single study is relatively small on most parameters and higher between the different studies, as this reflects the consistent conclusions or convictions of the authors or their respective contractors. This is a common finding in studies with political stakeholders [17]. For example, population projections are consistent within individual studies and their scenarios, but vary between studies (with UBA having lowest projections of 71.9 million inhabitants in 2050 and Agora projecting 79 million). All studies project increases in GDP, but to a varying degree. The only scenario which assumes no economic growth after 2030 is UBA Green Supreme. This is an example of sensitivities/variations of scenarios within a single study.

Similarly, the limits argued and set, based on external analyses for the different renewable energy capacity expansion and for energy imports vary greatly between the different studies. These are the key and standard constraints used in energy system optimisation models (although not explicitly stated in all studies). Again, they vary widely between studies but not within studies (except for ISE noACC that varies constraints assuming lower acceptance for wind energy). The various UBA and dena scenarios have similar ranges of offshore/onshore wind potentials, but they are substantially higher than in all other sources. Solar potentials are smallest in dena (263 GW) and BDI (270) and range up to 800 GW in the ISE-noAcc scenario. This is similar for biomass potentials, where most studies have either no constraints or very high constraints, but all scenarios within the UBA study assume a very low potential for domestic biomass use in Germany of 38 TWh/a. This is reasoned by the main utilisation of biomass as a material input for industry, leaving only residues for energetic use. The picture is very different for synthetic renewable energy imports that are inhibited by Hansen, and to certain albeit high limits by BDI, the other studies have either lower

Table 4
Efficiencies and factors for PtG/PtL applied for estimating the electricity required for import of energy carriers .

	Conversion efficiency	Factor for required electricity	Reference
PtH_2	72.2	1.39	[45, Table 2]
$PtCH_4$	58.4	1.71	[45, Table 2]
PtL	43.2	2.31	[46, Tables 39–43]

constraints, no import constraints, or no constraints mentioned. Carbon prices used by several studies also vary widely from 24.8–90 €/ton CO_2. Finally, and of key importance to this study, most of the analysed studies do not include reductions in energy service demand levels or only include them to a small extent. The only scenarios explicitly incorporating reductions in energy service demand levels are the UBA Life and Supreme scenarios, and within ISE the Suf scenario.

2.4. Implicit electricity demand for energy imports

For comparability and deeper analysis, we analyse the importation of hydrogen, methane and synthetic fuels energy carriers not only in terms of TWh energy content of the carrier, but additionally in terms of TWh of energy required for the generation of those. To that purpose, we use factors from the literature for the main synthetic fuels and verify them with values provided in some of the scenario-studies.Table 2 provides an overview of expected future conversion efficiencies for power-to-hydrogen and power-to-methane based on six different studies. From these values we derive an average value of 72.2 % (hydrogen) and 58.4 % (methane). For power to different liquids, [46] estimates the overall efficiency of five different Power-to-Liquid-routes in 2050 to be

- 39 % - Fischer-Tropsch route combined with low temperature electrolysis, CO_2 captured from air via electrodialysis
- 40 % - methanol route combined with low temperature electrolysis, CO_2 captured from air via electrodialysis
- 45 % - Fischer-Tropsch route combined with high temperature electrolysis, CO_2 captured from air via electrodialysis
- 45 % - methanol route combined with high temperature electrolysis, CO_2 captured from air via electrodialysis
- 47 % - Fischer-Tropsch route combined with high temperature electrolysis, CO_2 captured from air via temperature swing adsorption

We thus apply an average conversion efficiency of 43.2 % for power to liquid in this paper. A more detailed distinction between different synthetic liquid fuels is not possible in this meta-analysis due to the level of detail in the assessed studies – as only hydrogen, methane and liquids are differentiated in most of the studies. The factors applied for the analysis in this paper are summarised in Table 4. For the UBA scenarios, the energy required abroad for generating the synthetic energy carriers for import are provided and thus directly used for the comparison. The blended efficiency for all imported Power-to-Gas/Power-to-Liquid (PtG/PtL) of the UBA scenarios amounts to 46 %, i.e. a factor of 2.16.

2.5. Base year 2018 for comparison

As a reference/base year, 2018 has been chosen and the respective data of the *Agora* study is considered. We chose this reference year because the sector division suits our analysis structure and because it is the latest base year with statistical data applied in the analysed studies (with the exception of the *ISE* study, but in this case, the division of the sectors does not correspond to ours). Statistical 2020 data in addition would introduce a Covid-19 pandemic bias that is avoided with the use of 2018 data.

The full data table including the graphs presented in the following section is provided in the supplementary material.

3. Results

3.1. Consistency check

The final energy demand for the reference year 2015 (UBA, Hansen, dena, BDI) lies within the range 2468–2519 TWh, and for the reference year 2018 (Agora, ISE, Nitsch, FZJ) it lies within the range 2460–2489 TWh. We consider the variance as acceptable for the further analysis.

3.2. Primary energy demand

Fig. 1 illustrates the primary energy demand of all scenarios for the German energy sector with a GHG reduction of at least 95 % in 2050 compared to 1990. For comparison, the primary energy supply for 2018 is shown in the left bar. It has to be noted that ambient heat is not included in the figures for primary energy.

In 2018, the bulk of energy is supplied by fossil carriers, achieving a 41 % GHG-reduction compared to 1990. 2050 scenarios project that the energy supply will change largely towards wind and solar, other renewables, biomass, imported synthetic energy carriers (mostly hydrogen and liquids) and in some cases still include residual fossil carriers. Additionally a decrease of total primary energy demand to a varying degree between 33 % (ISE-Per) and 68 % (UBA-Supreme) is clearly visible. Furthermore, the graph shows that the difference in target of climate neutrality between 95 % and 100 % is not clearly linked to either lower energy consumption or higher quantity of renewable energy supply.

While all scenarios are based on wind, solar, biomass to some extent, and other renewables, many scenarios also rely on the importation of gaseous or liquid energy carriers, and a few still use fossil fuels. By grouping the primary energy supply bars of the scenarios by study, the greatest variance is observable between the studies, and to a lesser extent, between different scenarios within a single study. This supports the need for meta-studies in order to discuss a wider solution space and the key differences among studies.

The most prominent options for meeting the demand while under climate emission constraints are with the use of wind power, solar power, biomass, import of synthetic energy carriers based on renewable electricity and other renewables (hydro, geothermal, solar thermal, etc.), as well as through the reduction of the demand and the residual use of fossils in combination with negative emissions. Fig. 2 illustrates the large ranges and to which extent those options are applied in the unit of TWh. For comparison, the reference year (2018) is highlighted with a red dot.

Domestic solar and wind power play a pivotal role in all scenarios and support the finding that they are one of the main pillars for future German climate-neutral energy systems (587-1291 TWh compared to 155 TWh in 2018). The total amount of on- and off-shore wind as well as the contribution of solar photovoltaics varies greatly between studies due to different assumptions about the respective potentials. Nevertheless, all scenarios present an extension compared to today. The contribution of onshore wind lies within the range of 203 TWh (ISE-noAcc - scenario assuming strong resistance against onshore wind) and 541 TWh (FZJ-95) compared to 90 TWh in 2018. The contribution of offshore wind is assumed to be lower within the range of 110 TWh (dena-TM95) and 367 TWh (ISE-Per) compared to 19 TWh in 2018. For PV, the range lies within 114 TWh (BDI-95) and 674 TWh (ISE-noAcc) compared to 46 TWh in 2018. The deviations between the different studies are gen-

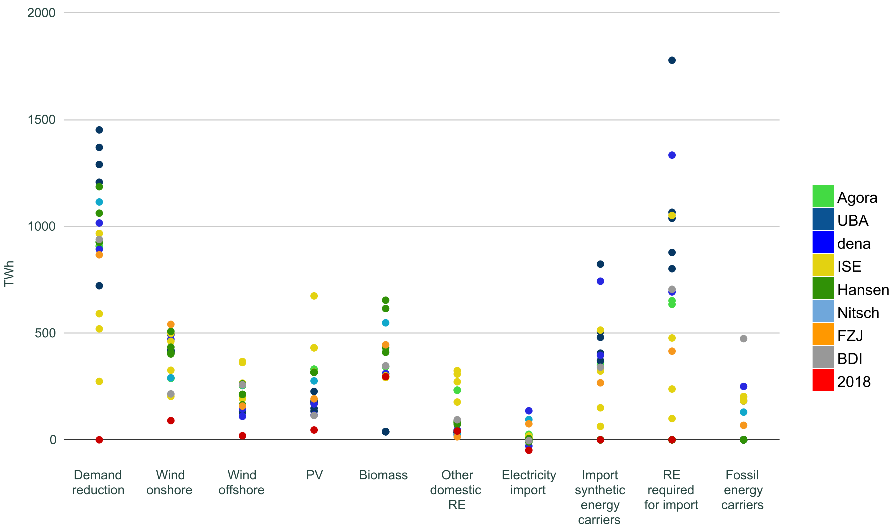


Fig. 2. Ranges to which extent different options are applied in the scenarios for reaching 95–100 % climate neutrality (2050). For demand reduction final energy demand is indicated, for all other options primary energy demand. The renewable electricity required for import is an own estimate, calculated on base of different efficiency factors for generating those energy carriers abroad as described in subsection 2.4. The red dot for fossils (reference 2018) amounts to 3136 TWh and is not displayed in the graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

erally high, but smaller between the scenarios within the studies due to respective similar assumptions for all scenarios within the same study. An exception can be seen in the ISE scenarios. The high deviation of the ISE-noAcc and partly of the ISE-Per scenario originates from the scenario setting that takes possible citizen resistance against infrastructures and onshore wind into account and increasing the PV-potential to compensate for the reduced wind potential.

For **biomass**, studies provide their own estimates or references regarding its availability for energy supply. Only the UBA scenarios see a drastically reduced potential of 38 TWh compared to today's energy usage level of 296 TWh (high sustainability criteria, competing use as material input in industry and construction material), the maximum is a factor of 2.2. Further results on biomass are described in 3.3.2. The full exploitation (or even over-exploitation in Hansen) of the respective given potentials in all scenarios indicates the scarcity and high value of biomass for energy use in our future energy systems.

The amount of **other domestic renewable energy** sources varies between the level of today (28 TWh) and 121 TWh. Main shares stem from solar thermal energy, geothermal energy and run-of-river electricity. In climate-neutral systems, **fossil energy carriers** can only be applied in combination with negative emissions. Some scenarios additionally leave room for some fossils by targeting below 100 % reduction, leading to a maximum 474 TWh of fossil energy in the BDI scenario, compared to 3136 TWh in 2018.

For most scenarios, the problem of filling the gap between demand and available domestic renewable supply is solved by **importing synthetic energy carriers (hydrogen, methane, PtL-fuels)** of up to more than 800 TWh in the year 2050. While the majority of scenarios lie within the range of 267–514 TWh, there are outliers to both sides. Hansen and Nitsch assume no import of syn-fuels, letting biomass and imports of electricity be the free parameter to fill the gap. On the upper side, the UBA-Late scenario compensates the restricted domestic potential and lower demand reduction ambitions than in the other scenarios with 823 TWh import of synthetic energy carriers. The dena-TM95 scenario is called the technology mix scenario and imports significant amounts of energy - 743 TWh compared to their electricity scenario dena-EL95, which requires less imports of synthetic energy carriers (396 TWh) but relies on 136 TWh of **electricity imports** compared to -29 TWh in dena-TM95.

The production of synthetic energy carriers abroad requires electricity in the countries exporting respective energy carriers. Setting the condition that the synthetic energy carriers have to be generated from renewable energies would be in line with the overall goal of reaching climate neutrality worldwide. Thus this additional renewable electricity is required as well as the renewable energy amount required for the domestic energy consumption in the respective countries. Applying the required energy factors of hydrogen, methane and PtL-fuels as described in subsection 2.4 leads to a range of 0 TWh (all Hansen-scenarios and Nitsch) to 1778 TWh (UBA-late) of additional renewable electricity produced abroad needed to supply the energy imports for Germany considered in the different studies.

The **reduction of final energy demand** is a key option for lowering the pressure on the other climate neutrality options. A lower energy demand leads to a lower need for energy generation and thus generation capacities. This option is applied in all scenarios, but with variation ranging from 274 TWh / 21 % (ISE-Per) to 1452 TWh / 58 % (UBA-Supreme) of demand reduction as compared to 2018.

3.3. *Final energy demand vs. supply options*

All emission abatement options come with certain constraints, barriers and side-effects regarding other sustainability dimensions than just the climate. The maximum potential of available space for wind and solar, sustainable biomass available for energy use, available imports of synthetic energy carriers and negative emissions are estimated differently within the studies according to different focuses of the authors, but all scenarios are reaching one of the limits of those options. Thus, the reduction of final energy demand turns out to be a decisive pillar in the transformation towards a climate-neutral German energy system, especially when considering other sustainability dimensions. In the following graphs, we thus plot the demand-side option against the other main GHG mitigation options: wind and solar, biomass, and the importation of (renewables-based) energy carriers to illustrate the interrelations.

3.3.1. *Wind and solar*

Fig. 3 plots the final energy demand against the installed capacity of wind and solar in 95–100 % climate-neutral energy systems in Germany. The range of installed wind and PV capacity varies between 289 and 767 GW. Compared to the installed capacity of 103 GW in 2020, this represents an increase by a factor in the range of 2.8 (UBA-scenarios, dena-TM95, BDI-95) – 7.4 (ISE-noAcc). Although scenarios with higher demand levels also exhibit higher installed domestic wind and solar capacities, the scenarios do not show a definite correlation (Pearson's R2=0.63) between the final energy demand and the sum of installed capacity of wind and solar, which is partly due to demand coverage by other sources (biomass, imports, see below) and due to different shares of solar and on- and offshore wind installations. Since the full load hours vary significantly, a higher share of solar and a lower share of offshore wind results in more installed capacity for the same amount of TWh. Additional explanations for relatively few installed capacities in a situation

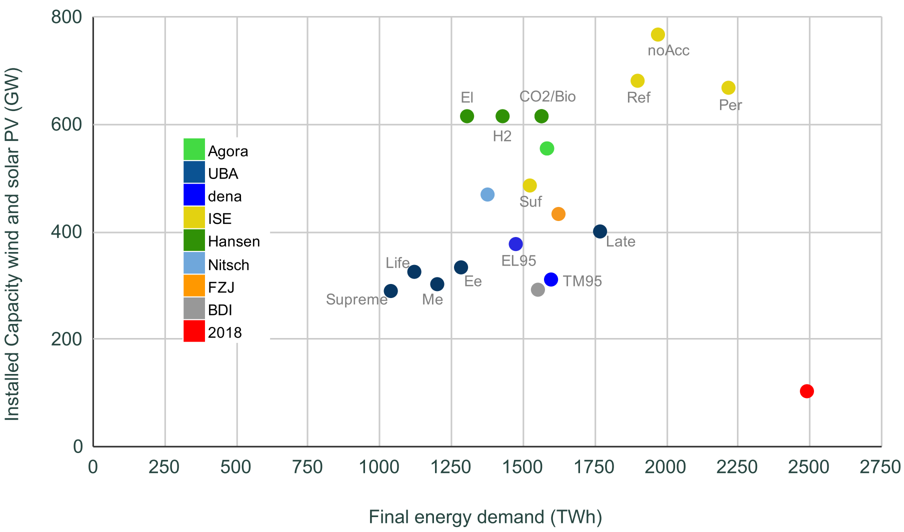


Fig. 3. Final energy demand plotted against the sum of installed capacity of wind and solar in the 95–100 % climate-neutral state (2050). Each dot represents one scenario, with colours indicating study author/initiator and labels individual scenarios. The red dot represents the numbers for the year 2018 in Germany. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

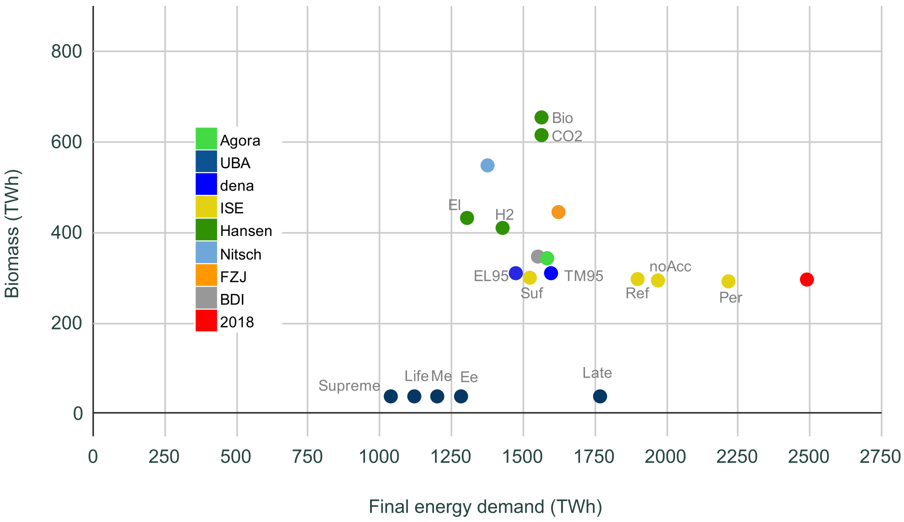


Fig. 4. Final energy demand plotted against the biomass applied for energy use in the 95–100 % climate-neutral state (2050). Each dot represents one scenario, with colours indicating study author/initiator and labels individual scenarios. The red dot represents the numbers for the year 2018 in Germany. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of higher energy demand can be explained by a low degree of electrification (dena TM95), high biomass use (Hansen), a higher amount of fossils combined with carbon capture and storage (BDI) or a high amount of import of synthetic energy carries (UBA-Late). Per 1000 TWh of final energy demand, the sum of wind and solar installed varies between 188 GW (BDI) and 473 GW (Hansen-EL).

3.3.2. Biomass and import

The amount of biomass available for energy use varies largely between the studies as shown in Fig. 2. While due to consistent potential assessments or assumptions, the absolute amount of biomass used is relatively consistent between scenarios within a study, and it appears to be minimally influenced by the final energy demand in the respective studies (see Fig. 4). In most studies, the potential is assessed and determined as a constraint and then consistently applied in the individual scenarios. We have identified three biomass potential groups. (1) As biomass is used mainly as material input, only residual amounts are available for energy generation, represented by UBA, leading to 38 TWh of biomass use and thus significantly lower amounts of biomass being available for energy use than today. This is due to their integrated view on not only energy but also resource potentials in general. (2) Domestic potentials are exploited including residual biomass and energy crops which is to some extent similar to the level used today represented by ISE, Agora, BDI, dena. (3) A higher amount of biomass is used than today, represented by Nitsch, FZJ and Hansen. The latter follows a different approach than setting a maximum condition: Biomass is used as the free parameter in the optimisation, leading to higher use of biomass than today. While stating 400 TWh as the biomass potential in Germany in their paper, they evaluate how much biomass would be required for a climate-neutral system, not allowing any imports of synthetic energy carriers, leading to a doubling (over 654 TWh) of the 2018 level (about 296 TWh).

For most of the other studies, it is not biomass, but rather the importation of synthetic gases and fuels, that needs to fill the gap between demand and potential domestic supply (see Fig. 5). In most studies, the imports are not constrained in absolute numbers but rather, the importation prices determine the amount. Imports thus vary strongly. The association of a higher final energy demand with a higher use of synthetic energy carriers from abroad can be seen in the scenarios of UBA and ISE. In the ISE and UBA scenarios, the quantity of synthetic fuels imported correlates to some extent to additional final energy demand compared to the respective scenario with the lowest demand. For UBA, it increases from 371 to 823 TWh and for ISE from 63 to 514 TWh, respectively. ISE applies a higher share of domestic renewable options (biomass, wind, solar, other) compared to UBA, which explains the lower level of hydrogen and syn-fuel use in ISE scenarios. The two dena scenarios differ greatly in the importation of synthetic fuels due to the idea of the scenarios. The electrification scenario (dena-EL95) requires significantly less

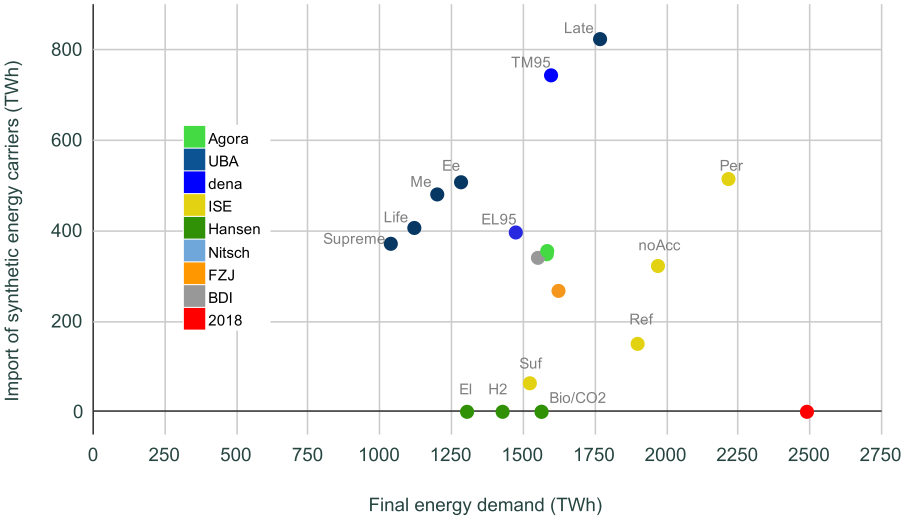


Fig. 5. Final energy demand plotted against the sum of import of synthetic energy carriers in the 95–100 % climate-neutral state (2050). Each dot represents one scenario, with colours indicating study author/initiator and labels individual scenarios. The red dot represents the numbers for the year 2018 in Germany. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

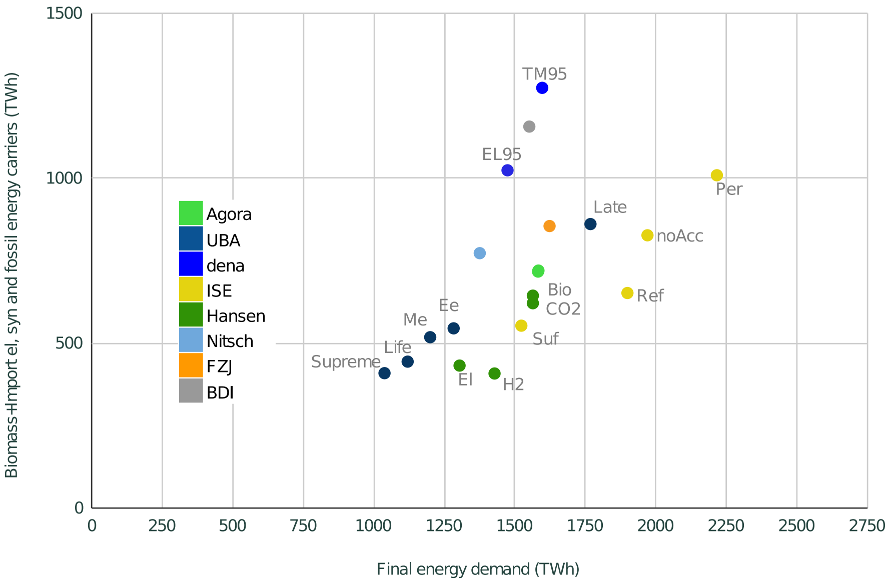


Fig. 6. Final energy demand plotted against the import of energy carriers (synthetic, fossil, electricity) plus biomass applied for energy use in the 95–100 % climate-neutral state (2050). Each dot represents one scenario, with colours indicating study author/initiator and labels individual scenarios.

imports of synthetic energy carriers than the scenario that also focuses on applying fuels in sectors that could potentially be electrified (dena-TM95). In the dena-EL95, the direct electricity imports are higher and amount to 136 TWh which is the highest electricity import value of all the scenarios, followed by Nitsch (95 TWh) and FZJ (75 TWh).

When summing up all imported primary energy carriers (synthetic, fossil, electricity) and domestic biomass, an interrelation to the final energy demand can be detected as expected (Fig. 6). The range of the total sum is very large and lies between 408 TWh (Hansen-H2, UBA-Surpeme) and 1274 TWh (dena-TM95). This is however a significant reduction to the 2018 energy imports of 3383 TWh (not included in the graph). Of these, the fossil energy carriers (3136 TWh) are by far the largest fraction. Comparing those current import numbers with the amount of imports assumed in the scenarios indicates that the import dependency is reduced in all studies and can be further counteracted with a reduction of final energy demand. The exportation of electricity is included in the calculation by using net import values for electricity. In four scenarios, there is a net export of electricity: dena-TM95: 29 TWh, Hansen-H2: 2 TWh, Hansen-Bio: 10 TWh and BDI95: 4 TWh. Exports of synthetic energy carriers has not been reported in the studies.

3.3.3. Fossil energy carriers and negative emissions

Another potential option on the path to a climate-neutral energy system is the continued use of fossil fuels in combination with carbon capture and storage (CCS) or carbon capture and utilisation (CCU). Some of the studies point to several difficulties for the implementation and usage of CCS (dena, BDI, UBA, ISE). These range from hindering legal framework conditions, to major acceptance problems among the population in Germany, to high energy consumption and costs, and to possible environmental damage and risks for people. However, consequences for modelling assumptions drawn from those mentioned difficulties are dealt with in different ways in the different studies. Only three of the studies considered and discussed negative emissions other than natural sinks. Within the assumption framework of these three studies, an emission reduction of 95% (BDI and dena) or climate neutrality (Agora) is not possible without CCS. The Agora scenarios determine emissions of 62 million tons of CO_2eq in the agricultural sector (biological processes due to fertilizers, livestock farming), in the industrial sector (process emission) and in the waste sector which cannot be avoided assuming that the same level of service or product has to be provided. To comply with the 100 % reduction goal, the use of the following negative emis-

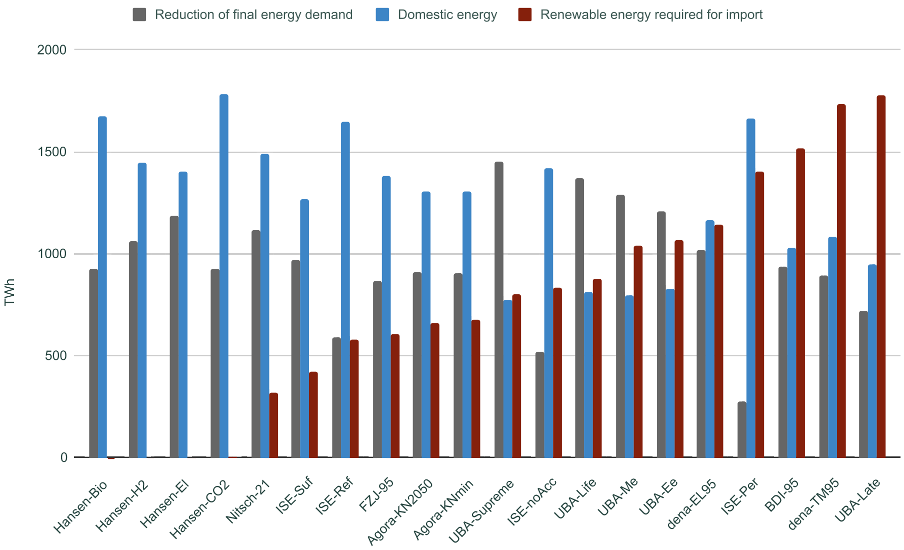


Fig. 7. Reduction of final energy demand compared to 2018 (grey), domestic renewable energy: solar, wind, biomass, geothermal, hydro (blue) and electricity generation required outside Germany for the generation of synthetic energy carriers that are imported, the respective equivalent of fossil fuels and direct electricity import (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sion options have been assumed: BECCS (Bioenergy with carbon capture and storage), DACCS (Direct Air Capture and Storage) and Green Naphta (Material-based binding of CO_2eq in green polymeres). Dena detects 42 million tons of CO_2eq emissions from industrial processes that are left and would need to be reduced by negative emissions. Although only aiming for a 95 % reduction, BDI already applies CCS (93 million tons of CO_2) and CCU (19 million tons of CO_2 from biomass for PtG/PtL).

All other studies do not assume any CCS. ISE, FZJ and Nitsch scenarios only use fossil carriers to the extent allowed within the 5 % remaining GHG-emissions of the 100 % total. The UBA study does not include CCS either, but also finds that the target cannot be reached without negative emissions. Instead of CCS, however, natural sinks are assumed, which, unlike CCS, do not risk environmental damage and risks to humans, but are even expected to have positive effects, such as strengthening biodiversity.

3.4. Degree of energy supply externalisation: Implicit electricity demand of PtG/PtL imports

Individual scenarios and especially the different studies vary to a great extent in their reliance on either domestic energy or importation options. Domestic options include all renewable potentials within Germany and the reduction of final energy demand. Here, biomass is included in the domestic options. Importation options include electricity, synthetic fuels and fossils from other countries. Fig. 7 shows the contributions of the three categories: demand reduction, domestic energy and imports. While demand reduction is shown in the final energy demand, domestic supply is shown in primary energy. In the red import bar, energy required for electricity imports, synthetic energy carrier imports and fossil fuel imports are included. In order to compare how much renewable energy is produced in Germany and how much electricity has to be produced abroad for supplying the imports, the red import bar in Fig. 7 does not show the energy content of the synthetic energy carriers but the renewable energy required for the generation of those – as a transposition of the primary energy concept of a world with 100 % renewable energy (see subsection 2.4). Electricity imports and the remaining fossil fuel imports are added. The latter are also displayed as electricity required to generate their synthetic equivalent for better comparability. For comparison, the values for 2018 are 479 TWh (domestic energy) and 5364 TWh (renewable energy that would be required to replace the synthetic equivalent of the fossil imports plus electricity import).

Thus, in all scenarios, the fraction of domestic energy increases significantly compared to today. The resulting balance however still varies greatly between the scenarios. While the Hansen scenarios do not rely on imports, their domestic energy contribution is the highest and demand reduction is at the upper end compared to the other scenarios. With increased reliance on energy generated abroad (in Fig. 7, the scenarios are ordered by the amount of renewable energy required for import), the mix of the domestic options (demand reduction and domestic energy) decreases. Four out of five UBA-scenarios are characterised by having medium import reliance, rather low domestic supply and high demand reduction. This combination strongly differs from the other scenarios. Nitsch-21, ISE-Suf, ISE-Ref, FZJ-95, Agora-KN2050, Agora-KNmin, and ISE-noAcc rely on domestic energy to a large extent but also on demand reduction and imports. The scenarios with the highest reliance on energy generated outside of Germany by far are UBA-Late, dena-TM95, BDI-95, which have medium domestic energy and medium to low demand reduction. A particularly divergent distribution can be seen in the ISE-Per scenario which has very high imports and domestic energy, but a very low demand reduction. This is due to their scenario assumption that efficient technologies such as heat pumps and electric engines energetic restoration are taken up quite slowly due to the inertia of people sticking to conventional technologies.

3.5. Reduction of final energy demand

All of the discussed climate neutrality options have certain limits. Although assessed with great variation in the studies, it becomes clear, that domestic biomass potential is restricted due to sustainability concerns and its usage competition as a resource. Wind and solar, the main pillars of domestic energy supply, are restricted by available space under social and environmental constraints. Fossils in combination with CCS/CCU pose other sustainability concerns and are rarely applied in the studies. Negative emissions are only applied for non-avoidable process emissions or emissions in agriculture (exception: BDI-95). The widely assumed importation of synthetic energy carriers requires substantial additional electricity generation in the exporting countries, which implies the requirement of a respective additional renewable energy generation capacity to be climate-neutral. The question remains whether other countries can achieve climate targets in a sustainable way and are still able to export renewable-based synthetic energy carriers in the magnitude and for the price that is assumed in different scenarios today, beyond their domestic demand. Consequently, in light of the Paris Agreement and the implied goal of reaching climate neutrality, as well as the other sustainability and development goals and respecting planetary boundaries,

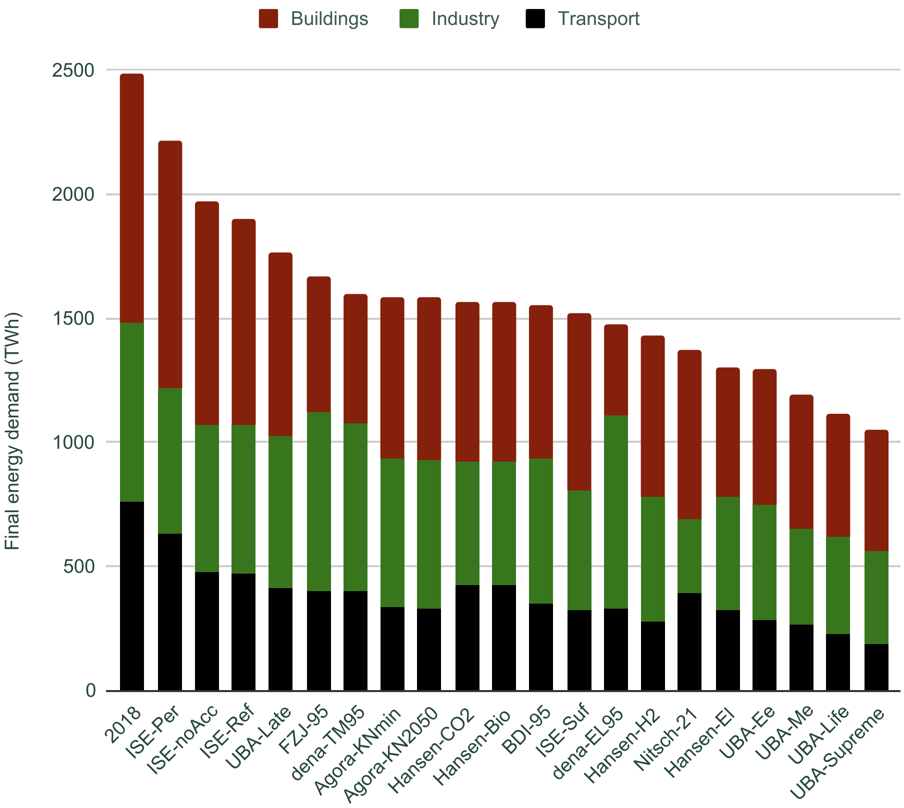


Fig. 8. Final energy demand in 2050 clustered in three sectors, compared to 2018.

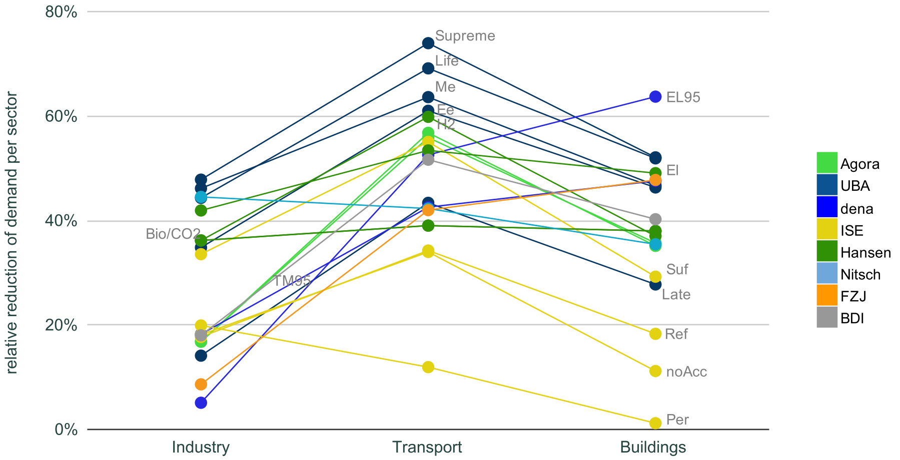


Fig. 9. Relative reduction of demand in 2050 compared to the respective base year in the study. Each dot represents one scenario, with colours indicating study author/initiator and labels individual scenarios.

the reduction of demand appears a pivotal pillar of reaching climate neutrality in Germany.

3.5.1. *Demand reduction by sectors*

Energy demand reduction potentials may vary between sectors. We thus analyse the demand reduction that the scenario studies see within the sectors of buildings, industry and transport (for sectoral definition see subsection 2.2). Fig. 8 and Fig. 9 show that the range is very large, but energy demand is reduced in all sectors and all scenarios compared to 2018. In relative terms, transport is the sector reducing the most (in average 49 %) followed by buildings with 38 % and industry with 28 %. The high reduction in the transport sector is partly an effect of the fuel switch from fossil fuels to electric cars, implying higher efficiencies and partly due to a different modal split and varying volumes of person-km demand. In the upper end of the relative reduction of demand are the UBA studies (except the Green Late scenario) and the Hansen-EL scenario. Outlier with quite low reduction for the transport and building sector are the ISE-Per and ISE-noAcc scenarios due to low acceptance levels of more efficient technologies in the transport and heat sector, scepticism towards energetic renovation and higher service demands. The dena-EL95 scenario has the highest reduction of demand in the buildings sector which stems from a high renovation rate and use of heat pumps. The high degree of electrification in the industry sector in the dena-EL95 scenario, however, leads to a very small reduction in this sector compared to other scenarios, which rely more on alternative production pathways or efficiency gains.

3.5.2. *Reduction of energy service demand*

Two main strategies of reducing energy demand can be detected: a technical demand reduction by efficiency on the one side and a reduction of energy service demand (sufficiency) on the other. Only two studies explicitly include the latter in their studies. In the UBA scenarios,

Table 5
Indicators for changes of energy service demand in 2050 .

	UBA-Supreme	Agora-KN2050	reference (year)
billion person-km	958	1200	1200 (2016)
share car use in %	51	54	78 (2016)
billion ton-km	739	900	660 (2016)
avg. living space m^2/person	41	52	45 (2018)
material consumption t/person*a	5.7	not provided	16.8 (2010)

strong efficiency and reduction of energy service demand is an integrative part of the study throughout all sectors. This might be partly due to their additional focus on raw material consumption, for which sufficiency aspects are also an important strategy. The ISE-study includes one explicit sufficiency scenario, but numbers on the level of energy service demand and assumptions which lead to a reduction of energy demand are not provided. In contrast to those scenarios explicitly naming sufficiency as part of their strategies, the Agora-study explicitly states that no sufficiency assumptions are included. In the other studies, reduction of energy service demand is not explicitly mentioned. Table 5 shows quantitative indicators for changes in energy service demand for the UBA scenario, which is most ambitious in sufficiency aspects, and the Agora study, which states that it does not include sufficiency. However, depending on the definition of sufficiency, the share of car use for person-km decreases from 78 % in 2016 to 54 % in 2050, similar to UBA-Supreme with 51 %. A higher difference between the studies can be detected in the average living space per person, with UBA-Supreme assuming a slight reduction and Agora extrapolating historic trends of growing living space. Comparing indicators of efficiency and sufficiency for all scenarios and studies is not possible due to the varying level of detail in which the studies include demand-side options and provide data on the level of energy service demand.

4. Discussion

4.1. Demand reduction as an important strategy

The future GHG neutral energy system is characterised by the trivial equation of the energy demand needing to be met by sustainable supply. The solution of this, however, is by nature, a highly challenging task. A high demand on the left side of the equation can be met on the right side by either high domestic renewable generation capacities, by high biomass exploitation or high imports (or a combination of the options). If there are limits to any of these strategies, there will be pressure to focus on the others. Alternatively, the left-hand side of the equation, energy demand, may be reduced, alleviating pressure on supply-side strategies. For the German case, various studies (see also Table 3) argue that certain limits exist, such as domestic and sustainable biomass potentials [30,34,47], total available areas for wind [48] and solar energy [49] and its expansion rates. Regarding imports, there is a high range of expected costs and amounts of available energy imports in the studies considered. However, regarding the worldwide challenge for climate neutrality, other countries will not be able to export infinite amounts of renewable-based fuels and electricity, as they need to complete their domestic energy transitions and also face restricted potentials, such as limited possible space of implementation and other general resource restrictions. The formulation of sustainability indicators for the importation of synthetic energy carriers is still at an early stage, but it is apparent that the sustainable potential for imports is limited and will be highly contested by an increasing worldwide demand. In light of these energy and space restrictions, demand reduction is pivotal for reducing the pressure on the other climate neutrality options [50–52].

While efficiency is the dominant strategy applied in the scenario studies for reducing demand, some of the studies additionally include options of reducing energy demand already at the service level (mainly in UBA and ISE-Suf, see also Table 3). Reasons for considering a reduction of pkm, m^2/person, or amount of products produced, are not only due to its necessity for keeping within the red lines of sustainable potentials of other options, but also the co-benefit of easing the pressure on other planetary boundaries and sustainability dimensions (e.g. resource consumption of efficiency measures). Although absolute demand reduction is clearly effective and has a positive impact on the energy system and other goals, this option is underrepresented in scenario studies based on energy system models (ESM) [53], most of which do not explicitly model the demand side. This may be due to two main reasons. On the one hand, the typical design of supply-side focused ESM, which is often based on optimisation techniques, complicates covering energy service demand dimensions. To achieve this, other sectoral models and model types and their linking are required. In addition, policy measures and instruments aiming at sufficiency are not as well known as established efficiency options [54], or perceived as “difficult” or of having low acceptance levels, and thus are explicitly excluded [33].

4.2. Results beyond the German case

Many of the conclusions and pathways encountered in this meta-analysis of German climate neutrality studies may also be transferable to other demand-intensive countries, including the main strategic options such as the massive uptake of wind and solar energy, importance of demand reduction and potential dependence on imports. We find that technologies bearing high environmental and ecological risks (nuclear and CCS) are not or have been minimally applied in German scenario studies. On the one hand, this may be a specific finding for Germany due to the resistance of society against nuclear energy (agreed phase-out 2022) and geoengineering technologies like CCS and the respective political setting. On the other hand, it shows that high degrees of climate neutrality for a energy-demand intensive country are possible even without nuclear or the application of CCS even to a very small degree. However, an international perspective on climate neutrality might reveal the limitations on the importation of climate-neutral energy carriers, and would thus, increase the pressure on options within the country, like demand reduction.

4.3. Diversity of the studies

The depicted possible futures for the German energy system vary, and different focus areas can be detected depending on the authors and the contractors of the studies. In contrast to that, there is less variation between the scenarios within each study. This limited variance can be explained, on the one hand, by the need to keep scenarios within one study comparable (keeping key assumptions and parameters constant). On the other side, convictions, perceptions, and emphasis of the researchers performing the analysis, and of their contractors regarding possible energy futures, also influence the assumptions, and thus, narrow the solution space for each study. Eventually, key assumptions determine, to a great extent, whether and how a GHG neutral energy system state, and the pathway up to it, is perceived as possible and consequently modelled. Thus, a single study with different scenarios is not sufficient to draw the full picture of potential climate-neutral energy futures. This emphasises the need for meta-studies. Furthermore, scenarios that explicitly test the effect of different societal trends, like the

ISE-scenarios, widen the picture of possible futures, which is an important part of the scenario work. Acceptance or persistence can heavily influence the feasibility of certain scenario pathways and thus the available potentials or assumed implementation rates. Furthermore, widening the perspective of climate neutrality studies which regard resource consumption and land usage, as the UBA-scenarios [34] do, is essential in detecting potential trade-offs of technical climate mitigation options regarding climate protection and resource usage.

4.4. Transparency, comparability and further research needs

The diversity of studies on the energy transition is beneficial for an overview of options which is required for the public discussion, but the diverse presentation of data and results is a barrier for meta-analyses and comparisons. A precondition for a thorough analysis of similarities and differences of the studies is transparency, i.e. completely open code, open data, and transparent method descriptions. This approach is already pursued by part of the energy system modelling community (for example projects connected to the open energy modelling initiative [55] and the Open Energy Modelling Platform [56]), but not implemented by all researchers and all studies in this field yet. In addition, consistent sector definitions, use of units and naming conventions for all studies would facilitate common progress in knowledge about the energy transition. These preconditions are not currently (fully) met.

All possible pathways include profound system changes. Further research is required on the impacts of the different options regarding other sustainability dimensions (e.g. biodiversity, resources, fair distribution) as a foundation for a societal and political discussion on priorities to design the best possible energy system for the society. A more integrated and holistic view in the scenarios, including more societal and political dimensions, would be desirable for good policy advice. However, although such scenario work is an essential input for policy advice, it can only provide one part of the information required for decisions on how to proceed with the energy transition. Results of scenario studies are not necessarily the best option/pathway from a societal welfare perspective, they onlyprovide potential cost-optimal solutions under certain preconditions.

5. Conclusion

The studies considered in this meta-analysis show a wide solution space in combining the various strategies for reaching 95–100 % GHG emissions reduction for the geographical scope of Germany and similar sectoral coverage. Studies rely on strategies for the reduction of energy demand, the expansion of domestic wind and solar energy (an increase by a factor in the range of 2.8-7.4 compared to installed capacity today), biomass, and imports of electricity or synthetic energy carriers as the main pillars of the future energy system. Following German political decisions, nuclear energy does not play any role, and CCS plays a very limited role, in reducing energy-related emissions. Although imports of energy carriers are significantly reduced compared to today, it remains an open question whether the assumed imported amounts of electricity, hydrogen and synthetic fuels can actually be produced outside Germany in a carbon-neutral way, while not hindering the energy transition of the exporting countries. As all considered options have certain limits in their potentials, the importance of energy demand reduction to relax the pressure on the supply side is apparent. Demand reduction is however still underrepresented within most energy system models and the respective linked sector-models, particularly referring to the modelling of energy service demand reduction that goes beyond technical efficiency options.

Findings from this analysis of Germany are of high general relevance, as the high diversity of study authoring research institutions yields a high diversity of scenarios and GHG neutrality strategies. This large solution space can inform other constituencies when deciding on pathways towards GHG neutrality.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

The compiled data table, data for the graphs and calculations can be found in the supplementary material of this article. Supplementary material associated with this article can be found, in the online version, at 10.1016/j.rset.2021.100015

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