Exploring long-term strategies for the German Energy Transition - A Review of Multi-Sector Energy Scenarios

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Abstract

This article systematically compares 26 different scenarios of climate-friendly energy systems, aiming at a reduction of CO_2 emissions of at least 90% for Germany in 2050. Technical strategies in terms of technology or energy carrier mixes in the end-use sectors industry, buildings, and transport as well as in the conversion sectors are examined. In addition, the consequences of those different strategies in terms of electricity demand, installed capacity for electricity generation, demand for synthetic fuels and gases (P2X), etc. are looked at. Furthermore, imports of electricity and P2X are compared. In conclusion, there is a wide range of transformation pathways that are projected for Germany, and there is far from consensus on how to technically achieve a reduction in CO_2 emissions of at least 90% by 2050 in comparison to 1990 levels. This, in turn, illustrates that there is still much need for research and discussion to identify feasible and sustainable transformation strategies towards a "net zero" energy system for Germany.

Keywords: Energy system analysis, German energy transition, Scenario modeling, Scenario comparison

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1. Introduction

The energy transition towards low carbon emissions, or even carbon neutrality, requires highly ambitious strategies to change the way we generate and use energy. Views and expectations of energy experts varies widely regarding the future structures of energy systems and the technologies required for ensuring a sustainable, efficient, and secure energy supply. The broad analysis and assessment of possible options and alternatives is usually done by means of quantitative scenarios. For decades, such model-based studies have been an established instrument to inform decision-makers about possible pathways, options and their effects [1].

Given that the multitude of scenarios presented so far (here for the case of Germany) have been constructed on the basis of different methods, and taking different assumptions on future technological, societal, and other developments, it is neither surprising nor problematic that the

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technical decarbonization strategies and the calculated values, e. g., for installed capacities of various energy generation and storage technologies, differ across scenarios. Nonetheless, the analysis of their commonalities and major discrepancies can provide valuable insights into what can be considered as a scientific consensus and which questions seem to be the most difficult to answer and require further research.

In this paper, we provide an overview of scenarios formulated by expert groups in 15 studies. All of them have been widely discussed in the public debate on the energy transition in Germany. This may mean that they were commissioned and published by government institutions (such as the German Federal Ministry for Economic Affairs and Energy) or by influential industry associations and received corresponding attention, or that they were produced by renowned research institutions whose publications were carefully registered and discussed within the research community, but also by the general public. The technical decarbonization strategies in the different sectors were analyzed according to their main distinguishing features. Our focus is on studies that look far into the future of the year 2050, which is associated with great uncertainties and, thus, rather large differences between the studies.

We identified the most important scenario studies that cover all areas of final energy demand, i. e., including freight and passenger transportation, process heat and space heating. Our analysis follows the research goal to identify robust findings from the scenario projects, which are all differently designed and implemented. We do not seek to quantify the influence that individual methodological choices, assumptions and data inputs have on the scenario outcomes. In principle, such an in-depth analysis can only be carried out by the institutions originally involved, which have access to all the models and data used for scenario development. Given the high heterogeneity in the quantitative presentation and documentation of scenarios, and different levels of transparency of the underlying modeling [2, 3], it is not possible to identify causal relationships between the model inputs and the quantitative outcomes as, e.g., in [4]. Instead, differences and commonalities in the scenario study approaches are qualitatively analyzed and presented here. The comparative presentation of the formulated decarbonization strategies is given in the form of quantitative results for shares of different technologies in different application sectors.

Scenarios are not predictions, but they describe possible developments of the future that arise under certain boundary conditions ("what if...?). A special type of scenarios are normative scenarios that describe possible paths toward a given goal. The scenarios examined here all belong to this second type of scenarios. Depending on the study, the goals are either to reduce all greenhouse gas (GHG) emissions or only energy-related CO_2 emissions (which account for the majority of GHG emissions) by at least 90%. Although the targets, system boundaries, and assumptions may vary from study to study, all of the selected scenarios describe transformation pathways for the full energy system (including transportation), and they all have the primary focus to describe a future energy system is either carbon neutral or has at least a high level of greenhouse gas emission avoidance. In this respect, despite the differences between the approaches, the comparison of the studies' results for the energy system yields important insights that can help guiding the transformation process.

On the one hand, the analysis helps to identify those structural features of a future largely climate-neutral German energy system on which there is broad agreement within the scientific community. On the other hand, it also identifies those sectors and structural elements for which very different decarbonization strategies are still proposed. Here in particular, the analysis then highlights further research needs in order to identify more clearly which strategies are associated with which technical, economic, ecological and social advantages and disadvantages. Thus, the analysis can make an important contribution to the discussion about the concrete design of the energy transition in Germany. The novelty of the analysis lies on the one hand in its scope and focus on scenarios for the entire energy system, and on the other hand in the fact that the aim is not a comparison of models and an understanding of the results, but a comparison of results that illustrates in particular uncertainties and research needs in decarbonization strategies for the German energy system.

The remainder of the paper is structured as follows: Section 2 discusses other meta-studies on energy scenarios, and shows how this work contributes to the scientific debate. In Section 3, the criteria for selecting the scenario studies analyzed here are presented. Section 4 provides the results of the scenario comparisons, at the level of their different methods used and regarding the outcoming technical decarbonization strategies. Section 5 discusses and Section 6 finally concludes the findings.

2. State of research

There have been numerous meta-studies and comparisons of scenarios describing a future energy system with different thematic and geographical scope. For example, at a global scale, Loftus et al. analyzed 17 scenarios for decarbonizing the energy sector, and compared them according to a set of empirical benchmarks, which they took as an indicator for the feasibility of the suggested scenarios [5]. By comparing the rate of change in energy and carbon intensity and low-carbon technology deployment rates implied by each scenario with historical experience and industry projections, they find that all of the scenarios envision historically unprecedented improvements in energy intensity. They also find that most studies focus on decarbonizing the power sector, while the industrial and transportation sectors are not specified in detail.

Cochran et al. looked at twelve scenario studies with very different national to global scopes, focusing on high renewable penetration scenarios for the power sector [6]. They compare the chosen approaches, data inputs, results, and policy implications. They come to the conclusion that the technology mix for highly renewable energy scenarios varies considerably regionally and globally. Jenkins et al. provide an overview of 40 studies that vary in geographic coverage up to the global level. They selected studies that feature at least one scenario in which CO_2 emissions are reduced by more than 80% below contemporary levels [7]. The review focuses on the electricity sector, and their geographic scope was national in the majority of cases (mostly USA). The authors derive the most important challenges for achieving zero carbon emissions in the electricity sector on the basis of the main scenario statements.

There are also numerous meta-studies of national scenarios for individual countries worldwide; we can only mention a few exemplary ones here: Kwon and Østergard [8] look into three studies for Denmark, all of them describing a 100% renewable energy system. They compare the chosen assumptions and methods in two of the three studies in detail and show that the main differences lie in the assessed biomass potential, in development paths in transportation, and in the future power grid, which is only treated explicitly in one of the models. Another interesting meta-study applying a novel systematic method can be found for the Swiss power system in 2050 from Densing et al. [9]. They followed a four-step mixed qualitative/quantitative analysis by carrying out a taxonomy of modeling approaches, a principal component analysis of scenario results using a distance measure, an evaluation of extremality of a scenario, and finally a selection of a representative set of scenarios [9]. With the taxonomy, they tried to make the influence of methods and scopes on the results more transparent. The study shows that policy decisions to support or phase out nuclear power, to develop centralized thermal versus distributed renewable generation, and to allow net electricity imports versus largely domestic generation are the three principal components of the scenarios. However, another important conclusion was that "the proposed meta-analyses cannot substitute knowledge of the individual scenarios". Deason [10] compares different national scenarios for 100% renewable energy power systems. He screened 45 studies of different geographical scope, and selected eight of them for a further detailed analysis by comparing results of flexibility demand, variable power generation and power generation costs. The results show different strategies and technologies to provide flexibility in the future, and that dispatchable capacities are expected to still play an important role in the long term.

There are also several studies that put their focus on the analysis of German energy transition scenarios; however, most of them considering only the electricity sector. Schmidt et al. reviewed ten scenarios for the year 2050 that are in line with a target share of renewable energy in the electricity share of 80% [11]. All of them exploit the three basic options of increasing domestic renewable power generation, reducing electricity demand and importing renewable electricity, but to substantially different extents. With the goal to make future electricity system scenarios better comparable, Lunz et al. conducted a survey of 18 power system studies with 62 different scenarios for Germany in 2050 [12]. 29 scenarios were further analyzed in detail. Out of these, eight scenarios were selected to be illustrative for specific characteristics (e. g., business as usual, ambitious climate protection including carbon capture and storage (CCS), climate protection with >80% renewable energy share, and others), and a ninth, self-defined scenario representing a share of >100% fluctuating renewable energy. They present a method for increasing the comparability of the scenarios by recalculating the amount of required supplementary technologies providing flexibility to the system in a uniform way. Their model also considered the potential of power-to-heat and demand-side management to provide flexibility to the power system.

There are far fewer studies that examine German transformation scenarios across all sectors in detail. For instance, Keles et al. reviewed four scenario studies with a time horizon of 2030, which they claim to be representative for the three groups of (international) scenarios that they identified and labeled as "moderate", "climate protection" and "resource scarcity and high fossil fuel prices" [13]. They defined a fourth scenario group that they identify as necessary in the German context, which considers nuclear energy as an option for the future.[3] A study with a similar scope to this work has been conducted by Ruhnau et al. [14]. They reviewed 22 scenarios for Germany 2050 with a specific focus on decarbonization of heat generation and road transport. They particularly compare the two strategies of direct and indirect electrification. Their study provides relevant insights, for example the range of expected additional electricity demand for heating and road transport, and the share of electrified supply in these two sectors. It is, however, limited to these questions and does not discuss the full range of aspects in the scenarios' technical decarbonization strategies.

In addition, there is a larger body of gray literature (not peer-reviewed) that compare scenarios for Germany under different aspects, such as development paths in transport or the possible future role of biomass use and synthetic gases, e. g., [15, 16, 17, 18, 19, 20, 21, 22, 23, 24].

The difference and novelty of this study compared to the existing literature is that it focuses on multi-sector energy scenarios for Germany which aim to reduce energy-related CO_2 emissions by at least 90%, in line with the goals of a largely climate neutral energy system in 2050. In this way, it is possible to analyze a number of key cross-sectoral aspects, such as the change in electricity demand due to different electrification strategies. By looking at the same geographical scope (Germany), the differences between the scenarios in terms of final energy consumption as

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[3] Their study was published before the decision to phase out nuclear power generation in Germany.

well as fuel and technology shares in the sectors can be more consistently attributed to different decarbonization strategies and represented strategies.

3. Method

In the following, the criteria for selecting the scenarios for this review (Section 3.1), and the approach for the systematic scenario comparison are described (Section 3.2).

3.1. Scenario selection

Many energy system scenarios for Germany in 2050 have been formulated in the literature. Several of the corresponding scenario studies have been carried out by larger research consortia, and were funded by federal ministries, agencies, or industry federations. They gather diverse expertise from well-established research institutes and scholars, and have received a lot of attention. This work focuses on such larger scenario studies, as they have high relevance in policy making and scientific debates alike. Table 1 gives an overview of the scenarios included in this meta-analysis. They were selected according to the following criteria:

- Geographical focus: Germany;
- Coverage of entire energy supply system (power generation, heat supply, P2X, as well as documentation of transportation technologies);
- At least 90% reduction of Germany's CO_2 emissions until 2050 (compared to 1990), in agreement with national goals [25, 26] [4];
- Sufficiently detailed documentation of the scenario results.

Our scenario review also included studies that aim at an emission reduction between 80% and 90% (see Supplementary Material). It shows that these do not simply differ gradually in their share of deployed technologies; instead, completely new technologies enter the scene with higher CO_2 reduction. In particular, power-to-X (P2X, X: heat, gas, or liquid) for air traffic and heavy-duty vehicles as well as for (high-temperature) process heat generation becomes much more relevant. Also, flexibility options in the electricity sector (e. g., storage) are over-proportionally needed due to the higher shares of intermittent renewable power generation. This makes a comparison of >90% reduction scenario particularly interesting, as the proposed solutions show a larger diversity than the 80% scenarios.

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[4] Note that Germany has further tightened its climate protection targets since the study was completed. With the June 2021 amendment to the Climate Protection Act, Germany is aiming for climate neutrality in 2045 [27].

Table 1: Scenarios analyzed in this work

Author(s) / institution(s)	Funding agency	Year	Scenario name	Abbreviation (**study**–scenario)	Ref.
DLR, FhG IWES, IfNE	BMU	2012	A	**BMU12**–THG95	[28]
UBA	UBA	2014	THGND	**UBA14**–THGND	[29]
Nitsch	BEE	2014	100%	**NIT14**–100	[30]
Öko-Institut, FhG ISI, Ziesing	BMUB	2015	Klimaschutzszenario 95	**BMUB15**–KSSz95	[31]
FhG ISE		2015	90/ambit./Mix/beschl.	**ISE15**–90-amb-mix-b	[32]
Greenpeace		2015	PLAN	**GP15**-PLAN	[33]
Ifeu, FhG IWES, CONSIDEO, Dr. Schoer SSG	UBA	2017	GreenEe	**UBA17**–GreenEe	[34]
Enervis energy advisors	INES, BWE	2017	Maximale Elektrifizierung Optimales System	**INES17**–ME **INES17**–OS	[35]
Jacobson et al.		2017	100% wind, water, and solar	**JAC17**–WWS	[36]
BCG, Prognos	BDI	2018	95%-THG-Minderung	**BDI18**–95	[37]
EWI Energy Research and Scenarios	dena	2018	Elektrifizierung 95% Technologiemix 95%	**dena18**–EL95 **dena18**–TM95	[38]
Nitsch		2019	Klima-19-OPT	**NIT19**–OPT	[39]
FZJ		2019	95%	**FZJ19**–95	[40]
UBA	UBA	2019	GreenEe1 GreenLate GreenEe2 GreenMe GreenLife GreenSupreme	**UBA19**–GreenEe1 **UBA19**–GreenLate **UBA19**–GreenEe2 **UBA19**–GreenMe **UBA19**–GreenLife **UBA19**–GreenSupr	[41]
FhG ISE		2020	Referenz Inakzeptanz Suffizienz Beharrung Referenz 100	**ISE20**–REF **ISE20**–INAKZ **ISE20**–SUF **ISE20**–BEHARR **ISE20**–REF100	[42]

3.2. Scenario comparison

The quantitative scenario comparison focuses on the year 2050. It is based on published data, which is taken either from reported tables or from figures, and, in a few cases, from the study's main text. In the cases of [28, 30, 32, 43, 42], additional data were made available by the study authors.

The scenario comparison adheres as far as possible to the definitions of sectors, technologies, and fuels in the original studies. However, the technological granularity in a given sector may differ from study to study. For example, some studies only document the shares of electric vehicles in general. Other studies clearly distinguish between battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), and fuel cell electric vehicles (FCEV), cp. Figure 6. Furthermore, the definition of sectors is not uniform throughout all studies. This implies that it was not possible to develop a uniform analysis structure for all studies and all scenarios.

In order to keep most of the original information, own calculations were avoided wherever possible, except for the simple calculation of totals, shares, etc. However, in some cases, additional assumptions were necessary to obtain a more complete picture. These calculations are documented in the Supplementary Material.

The "technological decarbonization strategies" as defined here describe technical options to provide useful energy in the end use sectors, and to generate secondary energy carriers in the conversion sector. In the end-use sectors, the technological decarbonization strategies describe strategies to provide low temperature heat for space heating and hot water, and process heat to residential, industrial and commercial consumers. They also show technological options for power trains and fuels for road passenger and freight transport, aviation, navigation, and rail transport, respectively. In the conversion sector, the decarbonization strategies describe options for generating electricity and district heat. For the purpose of this study, the "technical decarbonization strategies" are identified as the shares of particular technologies and/or energy carriers in the end use and conversion sectors analyzed.

In addition, it is worth looking at cross-cutting or aggregating sector aspects, such as the demand for electricity in different applications, the use of biomass, or the role of power-to-gas (P2G) and power-to-liquid (P2L) in the different sectors.

4. Results

A review of the methods applied for the scenario construction in the selected studies is discussed in Section 4.1. More specifically, the assumptions made for the emission reduction paths are laid out in Section 4.2. In Section 4.3, the main technical decarbonization strategies in the analyzed scenarios are compared. Section 4.4 compares the resulting power demand, installed capacities for power generation, consumption of synthetic fuels and gases, and biomass as well as the final energy demand per sector.

4.1. Methods applied in the scenario creation

The analyzed scenario studies apply a variety of methods for defining the proposed energy systems in 2050. All scenarios build on model-based assumptions on the future (final) energy demand in the main sectors electricity, heat and transportation. These are formulated on the basis of various bottom-up models. Capital vintage models that assume an initial stock of, e. g., buildings or vehicles, and consider replacements with more efficient units at the end of their lifetime, are widely used for several demand categories. For other residential, TCS (trade, commerce, and service), and industrial demand categories, specific energy intensities (e. g., per employee, per m^2, or per monetary unit of value added) are used for demand projections. For drafting the technical decarbonization strategies that make up the scenarios, three general approaches have been identified: accounting frameworks only, accounting frameworks combined with power market simulations, and integrated models that apply some form of optimization approach to find the least-cost system that meets the emission targets and all other imposed constraints. Figure 1 shows which study belongs to which of these three rough categories.

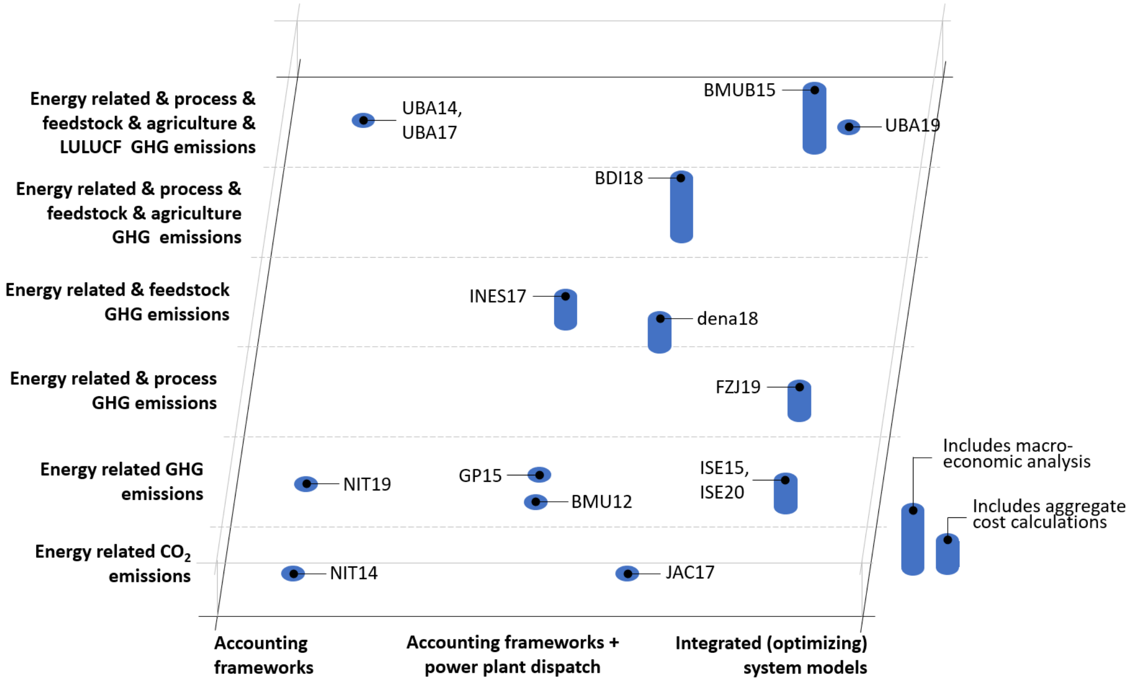

Figure 1: Classification of the scenario studies considered according to the methods used, the definition of the emission target, and the scope of analysis.

Accounting frameworks allow modeling the energy system according to a normative scenario technique that produces consistent scenarios in line with politically stated goals (e. g., regarding emission targets or targeted energy consumption reduction). NIT14 and NIT19 used the accounting framework ARES/SZENAR, which models consistent renewable energy supply quantities and the overall energy system. For UBA14 and UBA17, no specific method is mentioned; different potentials are estimated, and a consistent and secure energy supply is argued from external studies. No dispatch model is used in these studies for the power sector. The system behavior of the scenario formulated in UBA17 has been evaluated with the system dynamics model GEE(R) – Globale Erneuerbare Energie und Rohstoffe, for determining the resource requirements and energy-related GHG emissions over the course of time.

Accounting frameworks with power plant dispatch use additional power sector models for verifying that demand and supply of electricity can be matched in every hour of a year, and that enough reserves ensure the security of supply. In this category, the larger part of the transition pathways comes from explorative scenario creation methods using expert judgements. In the cases of Jac17, BDI18, and dena18, some technology expansion decisions, especially for storage capacities, come from the power sector model as a result of an optimization procedure; these are then closer to the integrated modeling approach, and therefore depicted between the second and third method class in Figure 1. In BMU12, the ARES/SZENAR scenarios were validated with a linear programming based cost minimizing energy system model. In GP15, INES17 and BDI18, power market models (EuroMod, enervis and Prognos, respectively) are used for calculating the plant dispatch. Those power market simulation models follow the merit order principle. In the Prognos model used in BDI18, parts of the expansion decisions are made endogenously based on calculated power market prices. In Jac17, the LOADMATCH grid-integration model [44] serves the purpose of obtaining low-cost plant dispatch and also the sizes of installed capacities for storage and demand-response. In the dena18 study, the DIMENSION+ model is used, which simulates the European power market. The model determines installed capacities of power plants and storage units, and models plant dispatch and flexibility deployment.

Integrated (optimization) models derive the main scenario characteristics from the outcomes of one or several integrated energy system models. These typically calculate the cost-optimal investment and divestment pathways and the plant dispatch in all time intervals, usually in hourly time resolution. In that optimization, CO_2 or GHG reduction targets are typically formulated as constraints that must be satisfied, in the same way as other technical constraints imposed for the individual technologies. Among the optimization methods, linear programming (LP) and mixed-integer linear programming (MILP) is most popular. This was applied by UBA19 with the cross-sectoral dispatch and expansion model SCOPE. BMUB15 applied the LP/MILP model PowerFlex for plant dispatch, and linked it with electricity import and export time series from the agent-based simulation model PowerACE; the capital vintage simulation model ELIAS was used for calculating decommissioning of old and (lowest cost) investment into new power plants, and also linked to PowerFlex. FZJ19 used FINE – Framework for Integrated Energy System Assessment, which is an MILP model, but also provides the option to model nonlinear (quadratic) investment cost functions; it is an open-source model. The scenarios in ISE15 and ISE20 were calculated with the integrated model REMod – Regenerative Energien Modell that consists of two components, i. e., a yearly dispatch model and a transformation pathway component for investment decisions. This model is not an LP model, but uses meta-heuristics to find the optimal solution (particle swarm optimization in the case of ISE15, and covariance matrix adaptation - evolution strategy (CMA-ES) for ISE20).

In addition to the general methods, some studies include statements on the system costs associated with the assumed scenarios, such as in ISE15, ISE20, INES17 and dena18. These studies sum up investment and operation costs of all identified technologies, and compare the overall costs across several scenarios. The two studies BMUB15 and BDI18 further model the macro-economic effects associated with the scenario realization in a broader scope, and quantify, e. g., effects on the gross domestic product or on employment within the country of Germany. To this end, they apply general equilibrium models and input-output tables [45] that can account for inter-sectoral feedbacks resulting from the policy measures driving the scenarios. In BMUB15, the models used for this are ASTRA-D and FARM-EU, and in BDI18, the model VIEW by Prognos AG is employed. Figure 1 visualizes the consideration of this additional economic dimension by vertical bars representing the respective scenario study.

To some extent, the studies examined here assume very different developments in socio-economic driver variables (see Figure 2): Estimates of the annual average change in Germany's population range between an annual decrease of 0.2% and 0.4%. The gross domestic product (GDP) is expected to increase between 0.2% and 1.0% per year, gross value added (GVA) be-

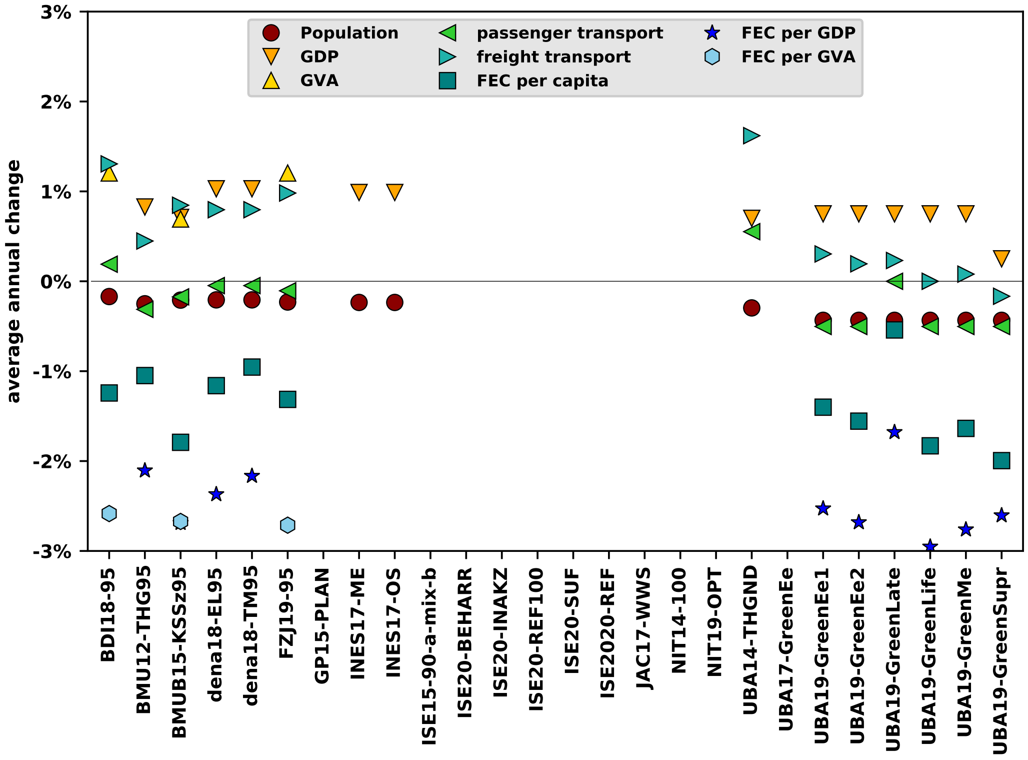

Figure 2: Drivers and intensities: Average annual change (GDP: gross domestic product, GVA: gross value added, FEC: final energy consumption)

tween 0.7 and 1.2%. Estimates of the annual change in the passenger transport service range between an average *decrease* of 0.5% and an *increase* of 0.6%, for freight transport between a *decrease* by -0.2% and an *increase* by 1.6%. Note that not all studies report those quantities (see gaps in Figure 2).

The classification of the studies' methodological approaches is no statement about their respective quality or validity. Integrating more aspects or applying more models does not necessarily raise a scenario's quality. After all, each modeling team had to find a suitable compromise between the scope and level of detail on the one hand, which quickly raises a model's complexity, and the traceability and comprehensibility of the results on the other hand, allowing to derive meaningful conclusions and cause-effect relationships. The fact that the study approaches are quite diverse makes a comparison of their results even more interesting.

4.2. *Scopes of greenhouse gas emission reduction targets*

At the level of emission reduction goals, the scope of sectors that can contribute to either CO_2 or GHG emissions varies, too. In Figure 1, these sectors are visualized along the ordinate. None of the scenario studies reviewed here considers full life-cycle emissions, but only direct emissions that occur during the plant operation. On the one hand, this is a severe limitation as huge investments are assumed for the envisioned future energy systems, which then also imply additional emissions from the construction of those plants. On the other hand, "prospective" life-cycle assessments of far-future energy scenarios are challenging due to open methodological questions and limited data availability [46, 47].

Another commonality across studies is that they apply the sources principle, which is consistent with internationally applied emission accounting procedures. The source principle states that emissions are reported where they occur and are accounted for within the national borders of a country. Consequently, emissions from aviation and navigation are mostly considered only for domestic traffic and international transport that departs from Germany. Not all studies describe exactly how they account for aviation and navigation, however.

The purely energy-related studies in this review either only consider an emission reduction goal for the energy domain, or they calculate mitigation targets that remain after exogenously defined *residual emissions* from other sectors have been subtracted from the overall emission target or budget. Some of these studies provide explicit information about these other sectors and the assumed emission paths (e. g., GP15, dena18 and ISE15).

Three studies consider either feedstocks or process emissions or both, in addition to energy-related emissions. Feedstocks are non-energy uses of fuels that are nowadays obtained from fossil resources, and that need to be substituted by renewable sources for decarbonizing the economy. Feedstocks are explicitly considered in INES17, a study that focuses on renewable gases and was funded, among others, by a federation of gas storage operators. Another important source of emissions are those from industrial processes. dena18 only formulates gross pathways for feedstock and process emission developments along the transformation scenarios. In that, different scenarios within the study assume different rates of substitution of conventional processes (e. g., for the production of steel, aluminium, copper, cement, glass, ceramics, paper, and chemicals). FZJ19 only makes assumptions for alternative technologies to avoid process-related CO_2 emissions in the steel and cement production, as these are the major emitters.

Five studies also include the agriculture sector (esp. fertilization and animal husbandry), or emissions from land use, land-use change and forestry (LULUCF). BDI18 name emissions from fermentation in digestion, fertilizer usage, agricultural land usage, liming, urea application, and those related to energy plant fermentation as emission categories explicitly modeled. Besides, they consider emissions from waste management, fugitive emissions and emissions from military, process emissions from mineral and metal processing as well as chemical industries, and emissions from the use of non-energy products made from fuels and solvents, from the electronics industry, from substitution products for ozone depleting substances (ODS) and from other processes (e. g., nitrous oxide in medicine). Similarly broad is the range of emissions modeled by BMUB15 and the UBA studies (UBA14, UBA17, UBA19), but these also modeled LULUCF emissions and formulated scenarios for different developments of these. This involved, for instance, that less animals, less fertilizer usage, and also less agricultural area was assumed to be used in the 95% GHG mitigation scenarios.

4.3. Technical decarbonization strategies in the energy sectors heat in buildings, process heat, transport, power and district heat generation

The following sections describe the technical decarbonization strategies analyzed in this review: decarbonization strategies for low temperature heat generation in buildings (Section 4.3.1) and process heat generation (Section 4.3.2), power train technologies in individual road passenger transport (Section 4.3.3) and in road freight transport (Section 4.3.4), the technology mix in power generation (Section 4.3.5), the role of imports of power and synthetic gases and fuels (Section 4.3.6), and finally technological options for district heat generation (Section 4.3.7).

If no values are shown for a scenario in the following figures, this means that the study in question does not make any statement on the variable shown in the figure.

4.3.1. Low-temperature heat in buildings

The fuel resp. technology shares for space heat and hot water in buildings is shown for the selected scenarios in Figure 3. The main strategies to provide low-temperature heat space heat and hot water in buildings are shown in Figure 3. Most studies suggest one of the following two strategies: **Electric heat pumps as the dominant heat source**, as documented by the high shares of environmental energy in, e. g., FZJ19-95, ISE15-90-amb-mix-b or UBA17-GreenEe, or **district heat as the dominant heat source**[5], which is advocated in BMU12-THG95, NIT14-100, NIT19-OPT. Only two studies consider natural gas from fossil and synthetic origins as relevant contributors to low-temperature heat provision, namely dena18-TM95 and ISE20-BEHARR.

In some scenarios, gas (and even oil) boilers are still used to provide space heat and hot water. However, as they use an increasing share of synthetic methane as fuel (e. g., dena18-EL95, dena18-TM95, BDI18-95, UBA14-THG95), their emissions of fossil CO_2 are low.

Solar thermal energy plays a (minor) role in only a few scenarios. Its share in the provision of space heat and hot water does not exceed 14% in any of the scenarios. Many studies avoid the use of biomass in the building sector altogether. At most, 15% of space heat and hot water in the building sector are provided by biomass (BMUB15-KSSz95).

A radical solution is proposed in JAC17-WWS, which assumes 100% electrification of the heat demand in buildings. However, it is not clear which technology (electric heat pumps, electric resistance heaters, or other solutions) is assumed to be applied here.

4.3.2. Process heat generation and industrial energy demand

Fuel shares for process heat generation are documented only for a few scenarios (Figure 4). Strategies are more diverse for process heat provision than for low-temperature heat (Section 4.3.1). **Electricity** is an important source in all but one scenario (ISE15-90-a-mix-b), contributing 25 to 45% of the process heat. Different from the low-temperature heat strategies, all scenarios that report on process heat in detail consider **biomass** as an important contributor, with shares between 10% and 43%. The three scenarios that had the highest district heat shares for low-temperature heat, BMU12-THG95, NIT14-100, and NIT19-OPT, also assume considerable contributions from **district heat** for process heat, which are in the order of 24 to 30%. Synthetic gases (partially) replace natural gas in all scenarios but BMU12-THG95 with shares between 8% and 23%. Solarthermal shares mostly lie between 5% and 12% (exception: FZJ19-95).

Process heat accounts for approximately two thirds of the industry's energy demand in Germany [48]. Therefore, an analysis of the final energy demand of the industrial sector also allows conclusions to be drawn on the underlying strategies of process heat supply in those scenarios which do not explicitly report details on process heat. However, the different system boundaries (industry vs. processes) of the various studies make it difficult to accurately compare the underlying decarbonization strategies. In these scenarios, **electricity** is a far more prominent solution, contributing at least 30% in all, and more than half the industry's energy demand in some scenarios. The second most important source of energy supply in all scenarios of UBA14, UBA17 and UBA19 is **synthetic methane**. Besides, many studies see hydrogen as an important source, with contributions in the order of 5 to 30%. Biomass plays an important role only in one scenario

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[5] For details on energy carriers used to generate district heat, see Section 4.3.7.

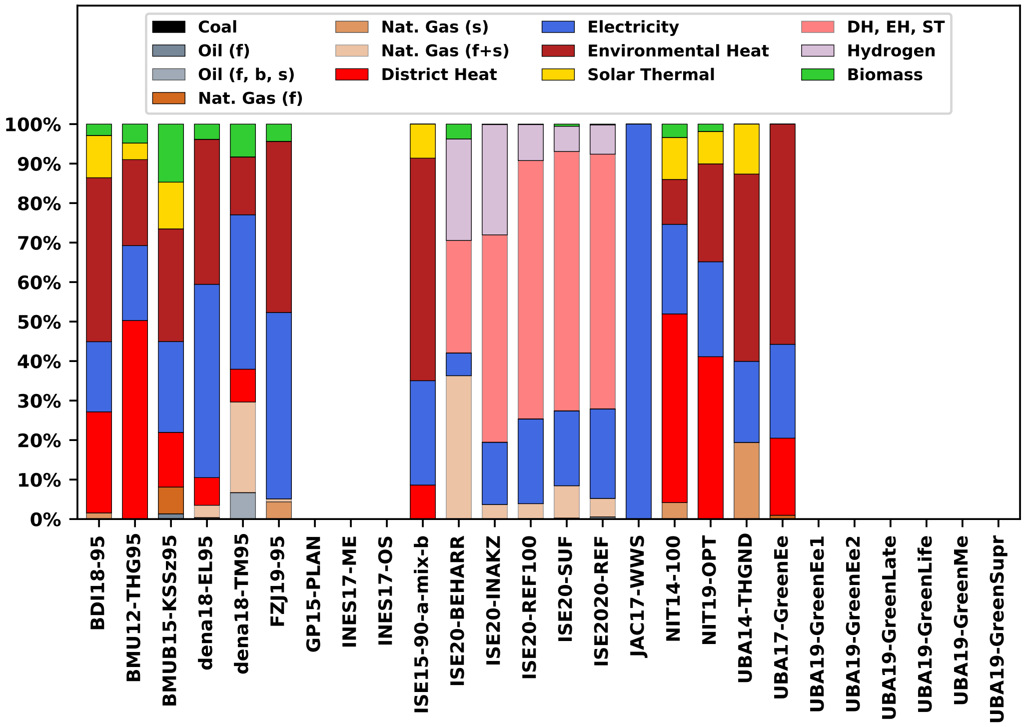

Figure 3: Fuel shares in final energy demand in buildings (low-temperature heat for space heat and hot water) in 2050 (residential buildings and trade, commerce, services (TCS), and industry). Letters f, b and s indicate energy carriers of fossil, biogenic or synthetic origin. DH, EH, ST is the sum of district heat, environmental heat and solar thermal energy.

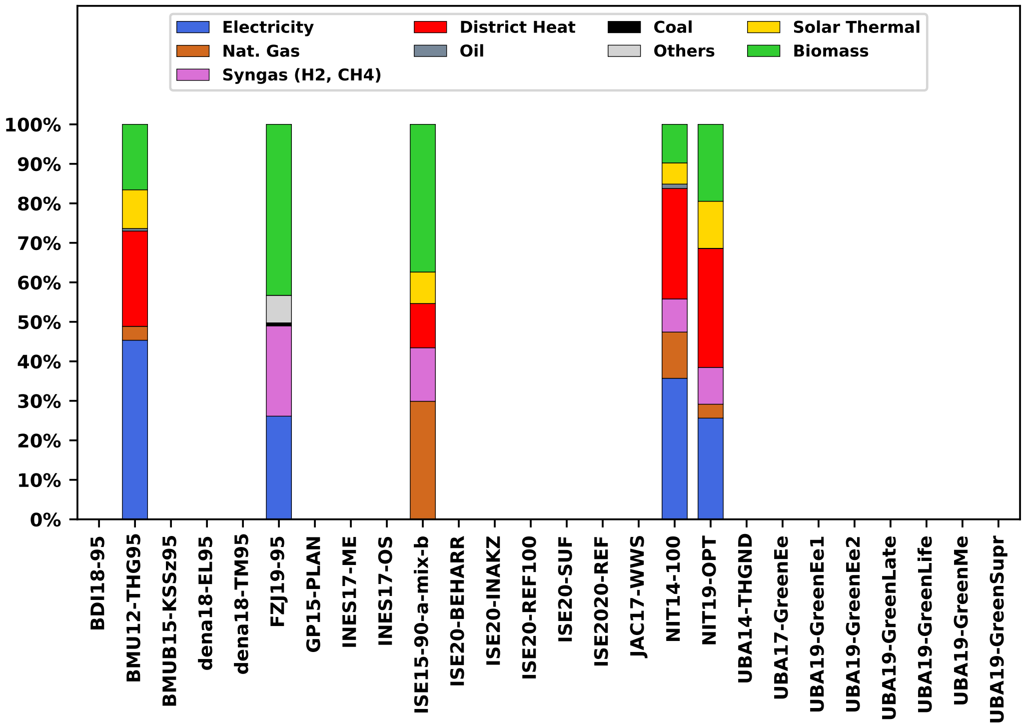

Figure 4: Fuel shares in final energy demand for process heat in 2050 in the selected scenarios.

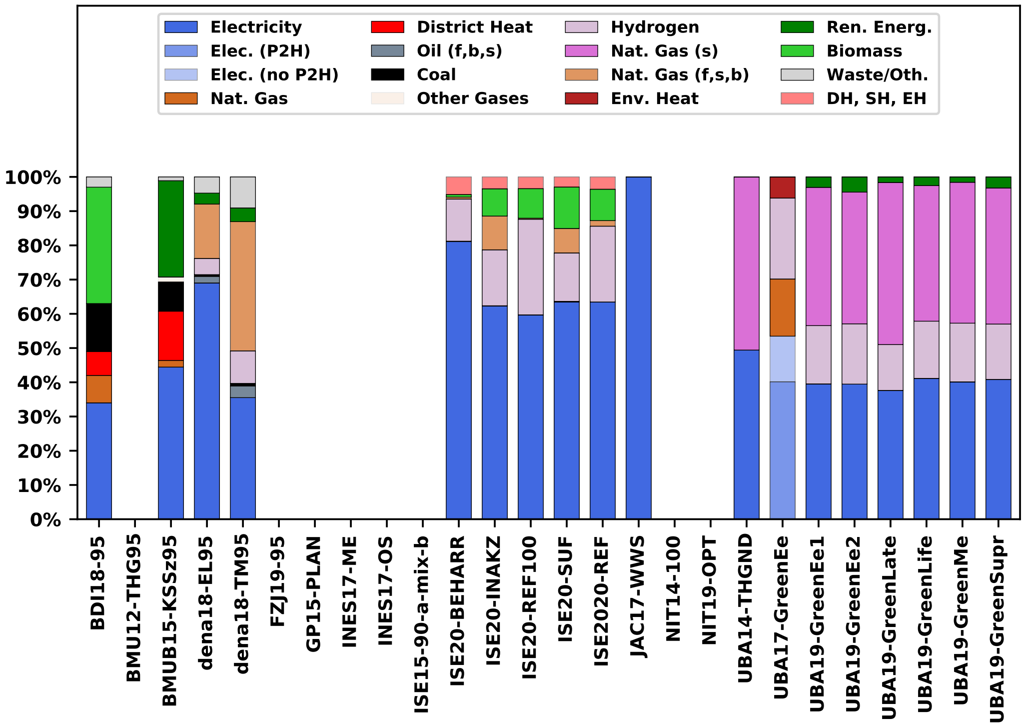

Figure 5: Fuel shares in final energy demand in the industry sector in 2050. Letters f, b and s indicate energy carriers of fossil, biogenic or synthetic origin. DH, SH, EH is the sum of district heat, solar thermal heat and environmental heat.

(BDI18-95, with 34%). Solar thermal energy is not considered in any of the industrial energy supply portfolios in Figure 5.

It is notable that BMUB15-KSSz95 and BDI18-95 still assume significant coal usage in the industry in 2050. This is mainly due to the difficult substitution of coal with less carbon intensive energy carriers, for example in the blast furnace process. The fact that both studies consider GHG emission reductions beyond energy-related emissions (cp. Figure 1) can explain the difference to other scenarios, which do not have coal in their mixes, probably because they neglect process emissions.

Looking at Figures 4 and 5 together, it can be seen that biomass is expected to continue to play a role in providing industrial process heat in the future in most scenarios. However, the extent of biomass use for industrial process heat is still unclear.

In general, the studies reviewed elaborate on the fact that different industrial processes require heat at quite different temperature levels. Especially for the high-temperature range, renewable heat sources such as solar thermal energy, heat pumps or even (solid) biomass are not considered. In the future, it would be important to focus more on the required temperature levels in scenarios for the decarbonization of industry.

4.3.3. Power train technologies individual road passenger transport

The shares of different power trains in the total passenger car fleet in 2050 is illustrated in Figure 6. As expected, the passenger car fleet is dominated by **electric vehicles** – either battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), or fuel-cell electric vehicles (FCEV) in almost all scenarios. In those scenarios which still rely on (non-hybridized) internal combustion engines (ICE), they play only a comparably small role, with shares less than ca. 20%. Only ISE10-BEHARR is an exception here, with still half of the passenger vehicles driven by ICEs. Some scenarios further assume a shift towards gas motors in the ICE segment. However, many studies assume a complete phase-out of pure ICE vehicles until 2050.

Four of the analyzed scenarios assume a share of BEVs of 100% in the passenger car fleet. The role of FCEVs is seen very differently in the various scenarios: While some scenarios expect a share of FCEVs of roughly a third of all passenger cars in 2050 (FZJ19-95, NIT19-OPT), other scenarios assume that FCEVs will not penetrate the passenger car market at all.

The remaining ICE vehicles in 2050 may use biofuels and/or synthetic fuels in addition (or as an alternative) to fossil fuels. Unfortunately, the blending quota for both biofuels and synthetic fuels are rarely documented in detail in the studies. Sections 4.4.3 and 4.4.2 provide an overview of the use of bioenergy and synthetic fuels (and gases) in the scenarios.

4.3.4. Power train technologies (road) freight transport

The scenarios report on power train technologies for freight transport in different ways. Some provide numbers for all as a sum of road, rail, air and seaborne transports (or a subset). Others specify each mode individually. Moreover, some studies report the shares of different vehicle technologies, others report the shares of energy carriers used. In Figure 7, only results from studies that provide the energy mixes for road transport are depicted.

It can be observed that **hydrogen (used in fuel-cell electric vehicles)** is an important source or technology across scenarios. Only BMUB15-KSSz95 and GP15-PLAN do not report any hydrogen use for freight transport. Besides, **electrification** of light and heavy-duty vehicles is a prominent decarbonization strategy. This can be in the form of battery-electric vehicles or trolley trucks.

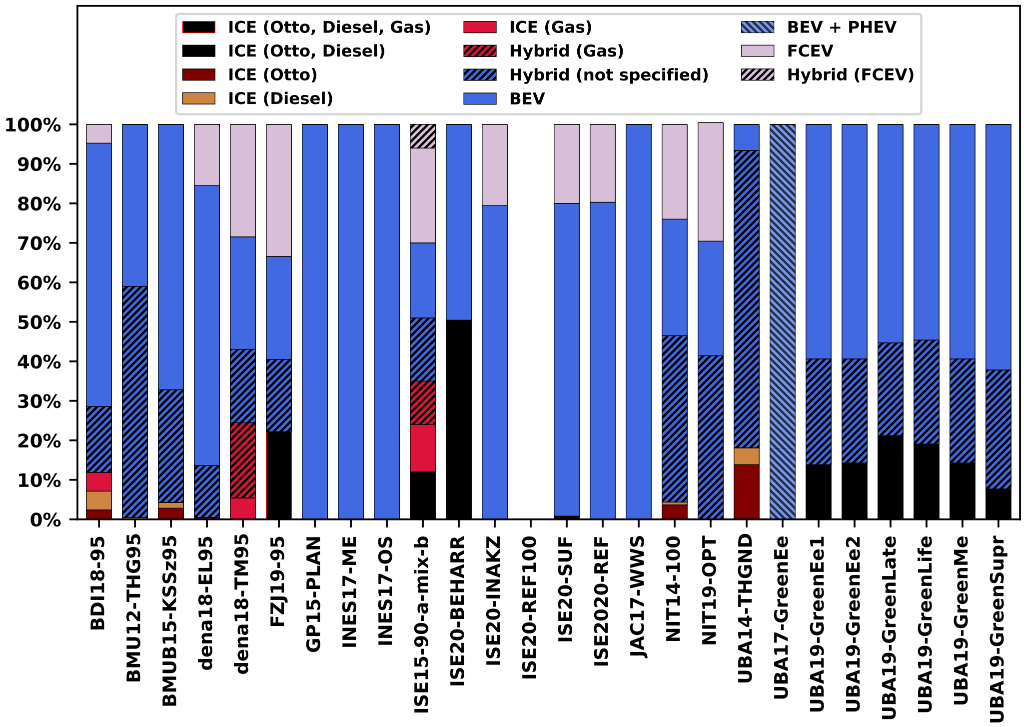

Figure 6: Shares in power train technologies for passenger cars in 2050 in the selected scenarios.

If one includes the studies that report on vehicle shares, the general observation from all studies is that **more diversity in power train technologies** used in 2050 is assumed, as opposed to the strong homogeneity in today's technologies, i. e., largely building on fossil-fueled ICEs. In most scenarios for 2050, a mix of electric, fuel cell, ICE (Diesel, methane) and hybrid trucks is assumed. Another commonality of all scenarios is that a strong **shift of freight transportation from road to rail traffic** is assumed, because of the higher efficiency and the much easier electrification of freight transportation.

Regarding the more specific question of the role of **trolley trucks** in future energy scenarios, there is no consensus, but a tendency towards an increasing importance of this technology for freight transportation. Some studies do not specify the (direct) electric power train technology at all, and of those who do, only FZJ19 argues that trolley (and also BEV) trucks will not be part of the power train mix due to too high cost. BMUB15 and BDI18 report considerable shares of trolley trucks in their scenario(s), and dena18, ISE20, UBA14, UBA17 as well as UBA19 argue that trolley trucks, along with BEVs, can play an important role for reducing CO_2 emissions in road freight transport.

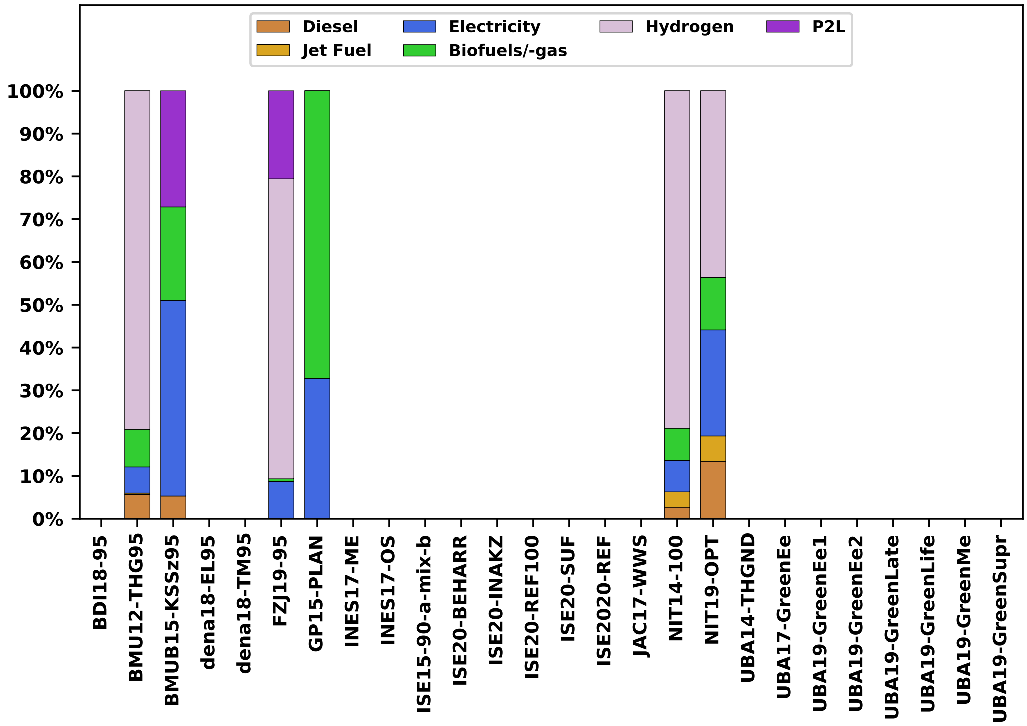

Figure 7: Fuel shares in freight transport in 2050 in the selected scenarios.

4.3.5. Technology mix power generation

It does not surprise to see that **onshore and offshore wind** as well as **photovoltaic (PV) generation** form the backbone of future power generation in all scenarios (see Figure 8). These technologies produce at least 72% (BMUB12-THG95, NIT14-100) of Germany's electricity.

INES17-ME and INES17-OS even assume that no other technology will produce power. However, the relative shares of onshore and offshore wind as well as PV differ significantly across scenarios.

The share of PV in the national power generation in 2050 ranges between 11% (BMUB12-THG95) and 59% (INES17-OS), of onshore wind between 16% (ISE20-INAKZ) and 57% (UBA19-GreenSupr) and that of offshore wind between 12% (INES17-OS) and 37% (BDI18-95).

It does not surprise that neither hard coal nor lignite fired power plants contribute significantly to total power generation in 2050 (see Figure 8). Some other notable features of the analysis of these scenarios are:

- **Gas-fired power plants** required for grid stabilization increasingly use hydrogen or synthetic natural gas (BDI19-95, BMU12-THG95, dena18-EL95, dena18-TM95, FZJ19-95, NIT14-100, NIT19-OPT, BDI18-95, and the dena18 scenarios). However, both INES17 scenarios and JAC17-WWS show no more gas-based electricity generation in 2050.
- **Geothermal power generation** is relevant only in BMU12-THG95, GP15-PLAN, NIT14-100, and NIT19-OPT.
- **Biomass** plays only a minor role for power generation in all scenarios. Its share in total power generation does not exceed 10% in any scenario, and is often explicitly used in CHP plants.
- If reported explicitly, power generation in **CHP** plants (based on biomass, gas, or other conventional energy carriers), contributes 15% or less to the total power generation.

According to German legislation, nuclear power generation will be phased out by 2022. Consequently, neither of the studies assumes that nuclear energy will be part of the power generation mix in 2050. Furthermore, no study includes the option of fossil power generation with CCS, due to the lack of social acceptance in Germany.

4.3.6. Import balance of electricity and synthetic gases and fuels

According to the studies analyzed, Germany could become either a net importer or exporter of electricity in 2050, depending on the scenario and assumptions around the development of the European power system (Figure 9). Net power imports up to 270 TWh per year (967 PJ/a) and annual net power exports up to 64 TWh (229 PJ/a) can be found in the studies.

Imports of synthetic fuels and gases (P2X) may become another important strategy to reduce national GHG emissions: Assumed imports are largest in dena 18-TM95 (almost 2 700 PJ/a), but also dena18-EL95, ISE20-BEHARR, ISE20-INAKZ and UBA17-GreenEe P2X assume imports of more than 1 000 PJ/a in 2050 (Figure 9).

mports of biomass are rarely reported in the studies. Therefore biomass imports where not included in this analysis.

4.3.7. District heat generation

In the studies evaluated here, the technical options to provide district heat vary strongly. However, it has to be stressed that technologies and fuels/sources for district heat generation are not documented in detail in many studies.

The scenarios put different emphasis on district heat for the heat supply in buildings and for processes (see Figures 3 and 5). Figure 10, in turn, shows the scenarios' fuel shares in district

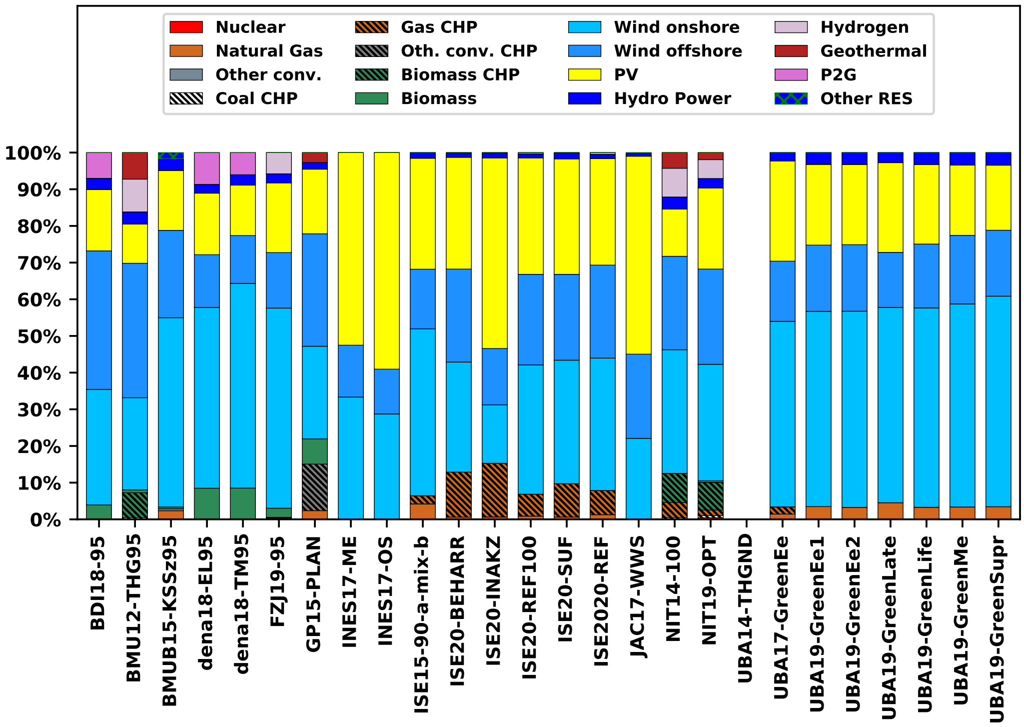

Figure 8: Technology shares in power generation in 2050 in the selected scenarios.

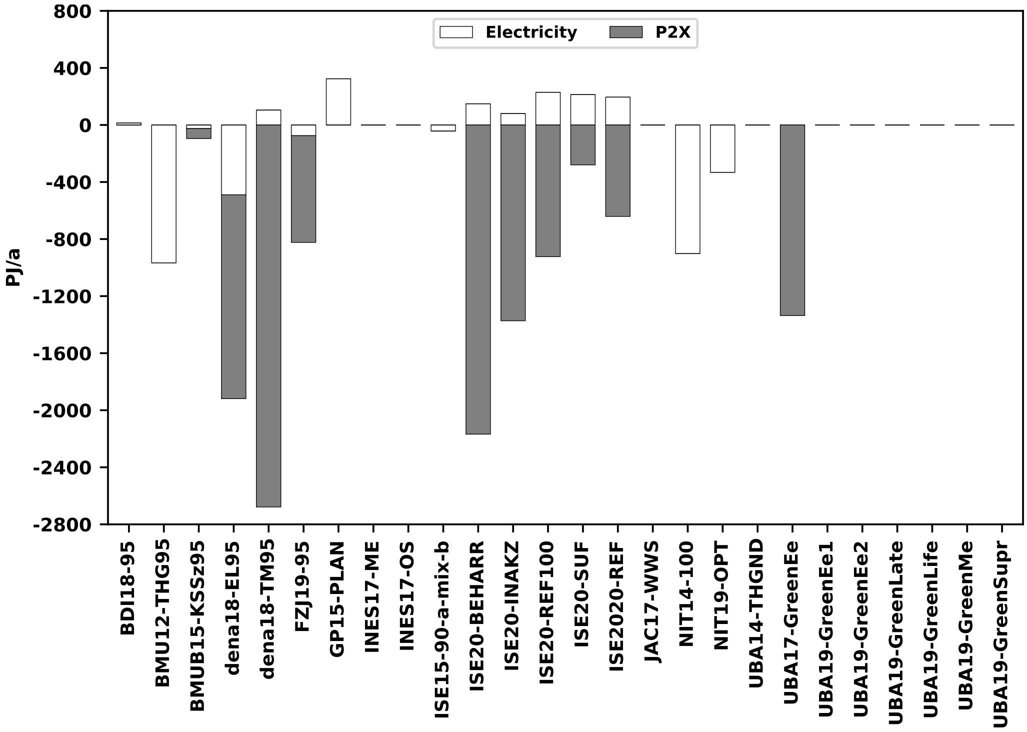

Figure 9: Power and P2X imports (negative values) and exports (positive values) in 2050 in the selected scenarios.

heat generation. BMU12-THG95, NIT14-100 and NIT19-OPT opt for important shares of both **fossil fuels and biomass used in CHP plants**, with additional solar thermal and, in two cases, geothermal energy. The fuel mix to provide district heat in ISE15-90-a-mix-b and BDI19-95 is rather broad. In the latter, **“surplus” electricity** plays a major role. While **solar thermal energy** is assumed to play a minor role in low temperature and process heat provisioning, there are two scenarios in Figure 10 that see a considerable fraction of district heat provided from that source (BMUB12-THG95: 19%, ISE15-90-a-mix-b: 32%).

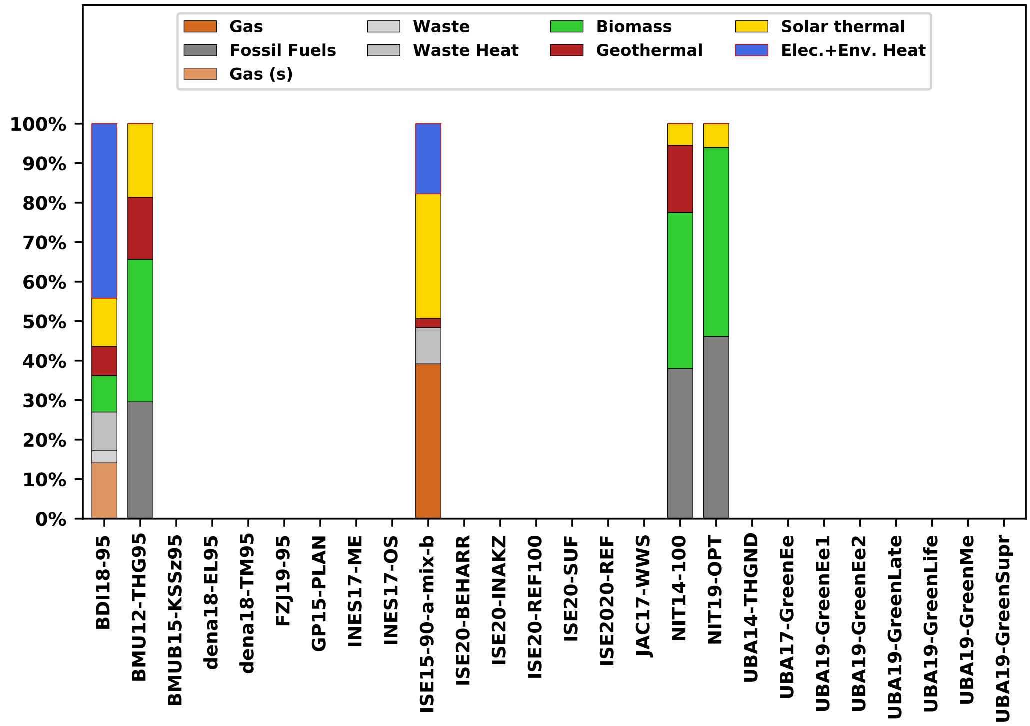

Figure 10: Fuel shares in district heat generation in 2050. The white bars indicate that district heat is considered explicitly in the scenario, but no details on fuels are given.

4.4. Cross-cutting issues

In this section, the consequences of the reported technical decarbonization strategies for cross-cutting issues such as power demand and generation capacities (Section 4.4.1), the role of synthetic fuels and gases for heat and mobility (Section 4.4.2), the use of bioenergy (Section 4.4.3), and the final energy demand in all scenarios (Section 4.4.4) are compared.

The aspects examined here provide only some weak indications of possible consequences or risks of ecological and economic nature, resulting from the strong expansion of generation infrastructures (resource demand, land use, necessary investment, ...), for example for electricity generation and P2X, but also social aspects (e.g., social acceptance in the case of the envisaged strong expansion of onshore wind power). However, impact assessments were not in the scope of the scenarios analyzed here.

4.4.1. Power demand, electrification and power generation capacities

While all scenarios assume increased energy efficiency and, therefore, decreasing per unit final energy consumption in general, the electricity demand in the scenarios is rather diverse. Depending on the level of electrification, the power demand might strongly increase. Figure 11 illustrates the (gross) power demand in the scenarios. The differences between the scenarios also reflect different estimates on the development of the useful energy demand in industry, households, and service, trade and commerce, as well as different estimates on the future passenger and freight transport services. Wherever the information is provided, the conventional uses of electricity are shown in the blue bars. Their differences are due to varying assumptions on the population and economic development, technical efficiency gains, change in user behavior and consumption patterns, etc. More important for the development of the power demand are different views on the future degree of direct and indirect electrification of the heat and transport sectors, i. e., on the future role of power-to-heat (electric heat pumps, electric resistance heaters, etc.), electric mobility (BEV, PHEV, trolley trucks, etc.), and P2X (H_2, CH_4, and synthetic liquid fuels). Furthermore, the national power demand depends on assumptions on P2X imports (see Section 4.3.6), as the electricity required for the generation of imported synthetic fuels and gases is not included in the national electricity balance.

Estimates for Germany's power demand in 2050 range from 550 TWh per year (GP15-PLAN) to nearly 2 000 TWh per year or more (INES17-OS, INES17-ME, JAC17-WWS). It should be noted that in particular, dena18-EL95, dena18-TM95, ISE20-BEHARR, ISE20-INAKZ, ISE20-REF100 and UBA17-GreenEe assume large P2X imports, which implies a higher overall power demand than the national demand depicted in Figure 11.

The expected domestic installed capacities for power generation vary strongly between the scenarios, cp. Figure 12. The lowest estimate is 284 GW overall (BMU12-THG95), and the highest estimates is 1 309 GW (INES17-OS). This wide range is also reflected in the estimates on the future deployment of wind onshore, wind offshore and PV generation capacity: Wind onshore ranges from 72 GW (BMU12-THG95) to roughly 230 GW (FZJ-95), offshore wind from 26 GW (dena18-TM95) to 124 GW (JAC17-WWS), and PV from 86 GW (BMU12-THG95) to more than 1 000 GW (INES17-OS). Note that those scenarios with significant power and/or P2X imports (see Figure 9) additionally require significant installations of (renewable) power generation technologies abroad to produce the respective energy exports to Germany.

The high capacities of intermittent power generation are expected to go hand in hand with high storage demand. Unfortunately, storage demand is rarely reported in the studies, and can, therefore, not reasonably be compared here.

4.4.2. Synthetic fuels and gases for heat and mobility

Figure 13 illustrate the demand for synthetic gases (H_2, CH_4) and synthetic liquid fuels in the scenarios. Wherever possible, application sectors are differentiated. The data for these plots had to be compiled from several sources in each publication (tables, figures, text). It can thus not be guaranteed that the P2X demand is fully represented in the figure.

The total P2X demand is the effect of P2X strategies in different sub-sectors. For example, it can comprise H_2 in FCEVs, synthetic CH_4 in gas motors, or synthetic liquid fuels as replacement of fossil fuels in internal combustion engines in the transport sector. Both H_2 and/or CH_4 can be fed into the natural gas grid, or used directly for heat generation or to generate power.

None of the highly ambitious scenarios can do without P2X, except for GP15-PLAN. Here again, all scenarios assume that P2G or P2L is necessary at least in the transport sector, but also for heat generation and/or as a long-term storage option for power generation. The absolute

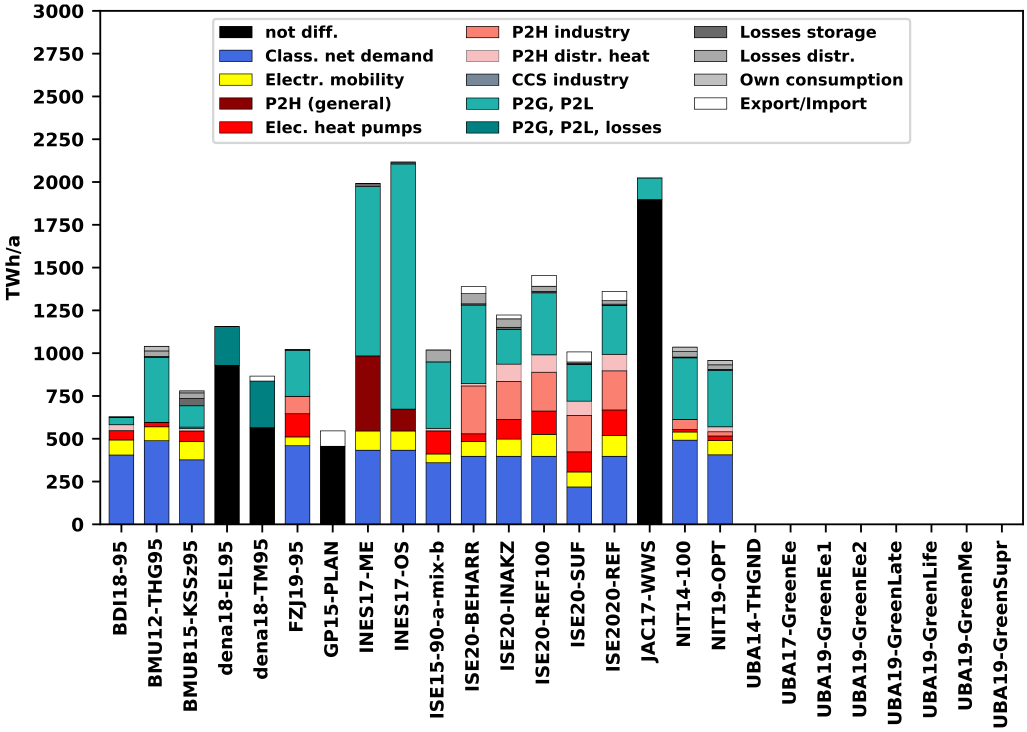

Figure 11: Domestic gross power demand in 2050 in the selected scenarios.

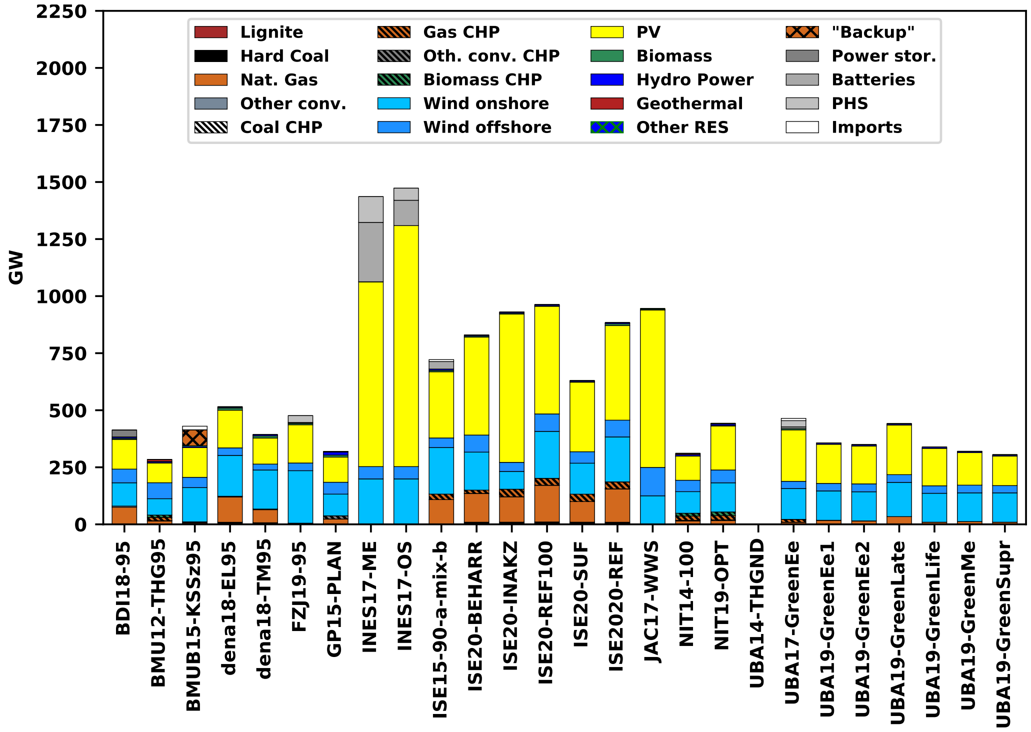

Figure 12: Installed capacities for power generation (and storage, where available) in 2050 in the selected scenarios.

amount of P2X differs drastically across scenarios: Whereas BDI18-95, BMUB15-KSSz95, and JAC17-WWS assume that only between 140 and 500 PJ/a of P2X are required to almost completely decarbonize the energy system, other scenarios assume a P2X consumption of 3 000 PJ/a and more in 2050 (dena18-TM95, ISE20-BEHARR).

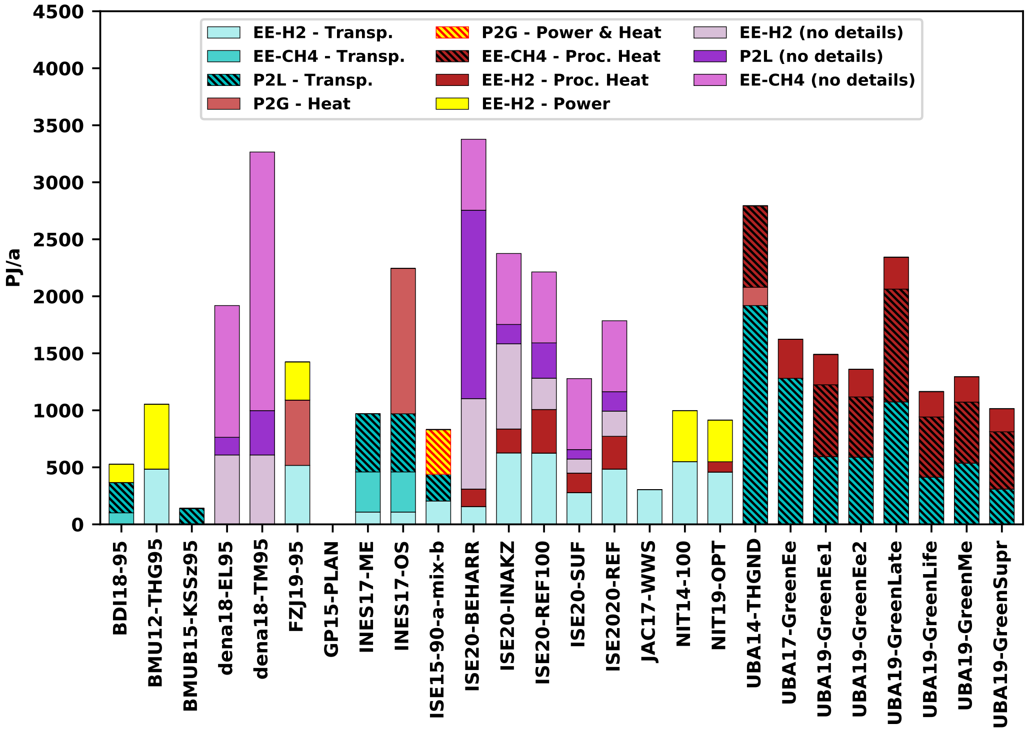

Figure 13: Consumption of P2G (H_2, CH_4) and P2L in 2050 in the selected scenarios.

4.4.3. Bioenergy

The documentation of biomass use in the studies is very heterogeneous (Figure 14). Most studies assume a sustainable biomass potential between 1 000 and 1 600 PJ/a. Due to stricter sustainability criteria, UBA14, UBA17 and UBA19 assume significantly lower potentials. Also, the allocation of primary biomass to different conversion routes, e. g, power, district heat, biomethane, biofuels, etc., or to end-use differs significantly.

Due to incomplete information given in the studies, the stacked bars in Figure 14 for GP15-PLAN and the INES17, UBA17 and UBA19 scenarios do *not* represent the full primary biomass potential.

4.4.4. Final energy demand

The final energy demand in the scenarios depends on assumptions regarding the development of different drivers like gross domestic product, population, or passenger and freight transport services. Furthermore, user behavior, modal split in the transport sector, and energy efficiency

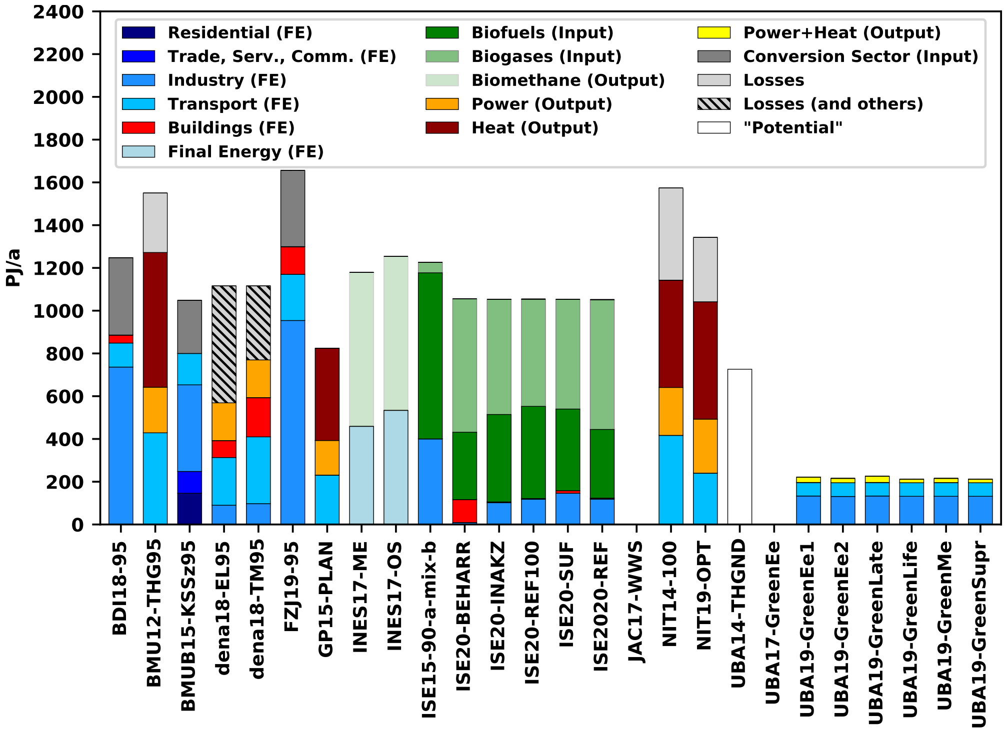

Figure 14: Bioenergy uses in 2050 in the selected scenarios.

developments of end-use technologies play a role. Figure 15 summarizes the final energy demand in the sectors.

In the scenarios, estimates on the final energy demand in 2050 differ by almost a factor of two: Whereas lowest estimate for the final energy demand in 2050 is a bit below 4 000 PJ/a (BMUB15-KSSz95), the highest estimate is more than 7 800 PJ/a (ISE20-BEHARR). Estimates for the final energy demand in each sector differ by a similar order of magnitude across studies. As a reference, the final energy demand in Germany in 2019 was 9 050 PJ.

Figure 2 also summarizes the available information on the development of energy intensities such as final energy consumption (FEC) per GDP, per GVA, or per capita. It illustrates that estimates on efficiency improvements in the enduse-sectors differ strongly between scenarios: The reduction of FEC per capita ranges between 0.5%/a (UBA19-GreenLate) and 2.0%/a (UBA19-GreenSupreme), FEC per GDP from 1.7%/a (UBA19-GreenLate) and 3.0%/a (UBA19-GreenLife).

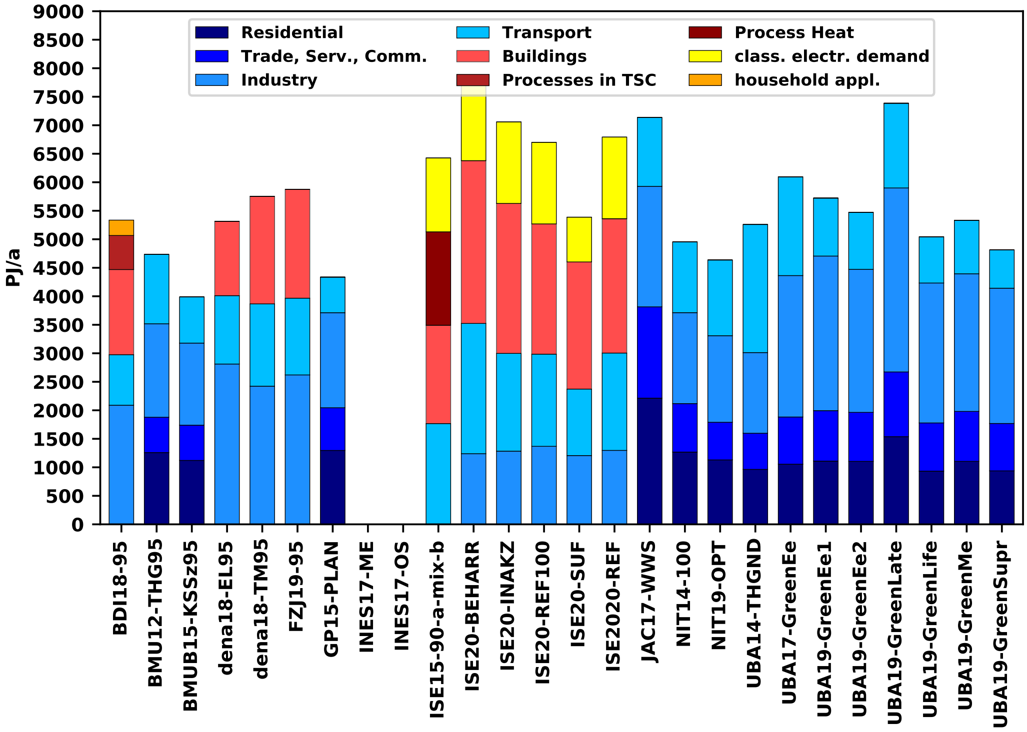

Figure 15: Final energy demand in 2050 in the selected scenarios.

5. Discussion and caveats

The results presented in this work were compiled to the best of our knowledge. Nevertheless, there are a few points that should be considered when interpreting the results. First, the quantitative analysis relies mainly on published tables and data read from figures. Only in a few cases, explicit information from the study text was included. Thus, the analysis might not take into account all the information available. Furthermore, data extraction from figures is prone to errors. Besides, the reported scenario data is not always consistent. In a few cases, own assumptions were necessary (see Supplementary Material) in order to complete the published energy balances. In some cases, the energy balances reported here are based on a compilation of several sources within the original study (figures, tables, text).

The qualitative analysis of methods applied in the scenario creation is based on the study text. It classifies the different approaches and models used, and demonstrates the various scopes and definitions used in the scenario studies. This diversity makes the scenarios and the underlying assumed transformation strategies less comparable. Each study is based on its own estimates of driving factors, such as the development of economic indicators, population, living space, transport services, etc. Furthermore, estimates of realizable increases in energy efficiency in all sectors are different. The analysis here neglects the fact that there might be interdependencies between, e. g., efficiency and technology options, or between economic development and technology innovation. For example, the efficient use of electric heat pumps in the building stock requires the ambitious energetic renovation of most existing buildings, so the choice of a heating technology is not independent of the advances in building energy standards.

The review in this work does not make a difference between older and younger scenarios. The range of publication dates is 2012 to 2020. Reality has overtaken some scenarios already today. Some scenarios discussed here have been updated on a regular basis, although with always slightly changing focus, as it is the case for the series of BMUB12 → NIT14 → NIT19. This means that the older scenarios not necessarily represent the best (or latest) state of knowledge on possible transformation paths for Germany which is available today.

As a consequence of the approach followed here, the results presented in this study have to be interpreted with caution. If further conclusions are to be drawn from this compilation, it is preferable to refer to the original publication and to contact its authors for further information.

6. Summary and conclusion

The comparative scenario analysis provided in this work shows that there is by no means a uniform picture of what a largely climate-neutral energy system for Germany in 2050 could look like. The surprisingly little consensus, even in the most fundamental underlying estimates, such as the final energy demand, reveals the high level of uncertainty involved in long-term scenario modeling. What *is* certain, however, is that all formulated 2050 scenarios are fundamentally different from today's energy system. While the generation technologies assumed, i. e., wind and PV power plants, are available today, a nearly or fully carbon neutral energy system also relies to a considerable extent on new, and in parts immature technologies. As their further development – in terms of effectiveness, efficiency and cost – is difficult to estimate, their future deployment is very sensitive to the assumptions made by the modelers. That, in turn, explains the large variety of solutions presented in the studies.

We could show that the general methodological approaches of the reviewed scenarios are quite diverse, ranging from accounting frameworks to integrated optimization system models;

they also address different scopes of greenhouse gas emission mitigation, ranging from only energy-related CO_2 emissions to all greenhouse gas emissions related to energy and process emissions, feedstocks, agriculture and even LULUCF. There are hardly any two models that have the same combination of methodological approach and GHG reduction scope (see Figure 1. Despite the differences, we were able to identify only a few technical decarbonization strategies per sector. In some sectors, there is more clarity than in others. For example, all scenario reviewed here assume passenger cars to be electrified for at least 80% of all vehicles. Among the electric vehicles again, BEVs are the dominant solution, but FCEVs or PHEVs are also considered in most studies.

Among the controversial aspects, from a technical view, the following questions are particularly noteworthy: What market share of and constraints for the deployment of electric heat pumps, district heat and/or synthetic gaseous energy carriers can we expect for the provision of space heat and hot water in the buildings sector? Will the industry sector primarily be decarbonized through direct electrification or via indirect route using hydrogen or synthetic fuels and gases? What will be the share of FCEVs, BEVs, and PHEVs in the future passenger car fleet? How can the road freight transport be decarbonized – via trolley trucks, FCEVs or synthetic liquid energy carriers as a replacement of diesel fuels in ICEs? What amount of renewable electricity, synthetic gases and liquids will be imported? What are the ideal shares of PV, onshore wind and offshore wind power plants in national power generation? Is there a role for bioenergy in the future energy system, and if yes, where should it be used with priority?

The wide variation in strategies for these sectors indicates that more research is needed: On the one hand, to better understand why different studies propose such different decarbonization strategies for these sectors, it would be helpful to compare models and assumptions in detail. This is a task that only the modelers of the original studies can undertake. On the other hand, it may be interesting to conduct a comprehensive impact assessment to determine advantages and disadvantages of different strategies not only on a technical-economic level, but also e.g. regarding environmental impacts and social effects.

Furthermore, this analysis has also shown that many studies document both their assumptions and their results incompletely and in ways that make further work with the results difficult. Therefore, it would be desirable for future scenario studies to have a minimum set of input and result data that is made available to the scientific community in a machine-readable format. The specifications and requirements of suitable data templates by public funding bodies, such as ministries or agencies, could be helpful in this regard.

One other observation from the scenario comparison is that none of the studies, except for FZJ19, are based on open-source models, or publish the input-data set used for parametrization. Moreover, some of the models are poorly documented, i. e., no proper description of the method and its implementation is available. As the resulting scenarios are targeted for influencing the public debate on energy policies, this is a major concern, because the outcomes cannot be fully replicated by other researchers.

All in all, the analysis shows that a systematic and detailed comparison of scenario data, despite all difficulties regarding transparency and consistency, is suitable to examine to what extent there is a scientific consensus on key strategies for energy transition pathways, and what quantitative differences exist. It also shows that there is still a great need for research on which strategies should be pursued in order to achieve a climate-friendly energy system that is technically feasible, economically reasonable and socially and ecologically beneficial.

Acknowledgments

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Declarations of interest: none

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