Key strategies towards Decarbonization of Energy Use and Supply in Japan and Germany: Insights from a Comparison Study on Long-term Scenario Analyses up to 2050

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1. Introduction

1.1 Background

The main outcome of the COP 26 in Glasgow (2021), to continue the efforts to keep 1.5 degrees within reach, remains a huge challenge even for all countries, which have committed themselves to a rapid and substantial reduction of greenhouse gas emissions in the Paris Agreement (2015). Japan and Germany are among the countries that have consequently pledged to achieve greenhouse gas neutrality by 2050 and 2045, respectively. In its latest report (March 2022), the Intergovernmental Panel on Climate Change (IPCC) emphasized the urgency of more ambitious action to fight against ongoing climate change that poses a dangerous threat to the well-being of humanity. The recent floods, typhoons and other extreme weather events that occurred in Germany and Japan indicate that the current climate change trends will cause immense economic damages to national economies also in temperate climate zones. Geopolitical consequences of fossil fuel dependency emerging from the Russian aggression against Ukraine add another urgent objective for the phase-out of fossil fuels, in addition to climate change mitigation. Against this background, climate protection and achieving climate neutrality as quickly as possible are highest priority challenges to human kind, and they stand under extreme time pressure.

On the one hand, as leading industrialized countries, both Germany and Japan, are facing a particular responsibility and challenge to reduce greenhouse gas emissions. On the other hand, both countries can provide advanced economic, technological and societal capacities and innovations to meet these challenges. Thus, they can benefit from the economic and risk-minimizing opportunities that the transformation to net zero implies. The recent changes of governments in both countries have had remarkable consequences for Germany and Japan's climate mitigation policies. While maintaining the energy policy objectives of energy security, economic efficiency and environmental sustainability, the new governments increased their ambition level and, for example, raised the targets for CO_2 reduction, for expanding renewable energies and for fostering energy efficiency significantly, albeit the approaches partly differ.

In both countries, scenario studies are important instruments to provide scientifically based policy advice on complex matters such as the energy transition and to support the governments in finding technically feasible as well as economically and socially viable pathways to climate neutrality. However, methods, model assumptions, choice of technologies, policy priorities and the degree of policy integration differ between recent scenarios studies in the two countries. For example, there are different assumptions whether to rely on energy technology options only, or to include resource efficiency and Circular Economy (CE) strategies, as well as behaviour and lifestyle changes. Thus, different approaches and pathways to net zero are possible.

1.2 Rationale and objectives of the study

In 2017, the GJETC had conducted a first study on the "Energy transition as a central building block of a future industrial policy". In a comprehensive meta-analysis of scenario studies, a German-Japanese study team had examined a wide range of strategic options for the energy transition as well as the associated strengths and weaknesses of the energy transition strategies of both countries. In 2021, the GJETC decided on this follow-up study and to update the findings, albeit on a much smaller scale. The study objective was to identify current climate neutrality scenarios for Germany and Japan and to compare them based on two guiding questions: (1) Which strategic technological options are available to reach net zero emissions?, and (2) Which lessons that might be transferable can be learned from the decarbonization strategies analyzed?

The first step consisted in identifying the range of already existing research-based, long-term scenarios, including those that go beyond current official national targets. Assessment criteria for the selection of relevant studies and for the comparison of the scenarios were established. In the next step, 5 Japanese and 4 German scenario studies were selected and analyzed, comparing assumptions and results. The scenarios cover a range of long-term strategic options for both Germany and Japan. Moreover, gaps in the existing scenarios were also identified. Finally, conclusions were drawn, including potential strategies to address the shortcomings.

2. Update of assessment criteria and selection of studies

Authors: Institute of Energy Economics, Japan and Wuppertal Institute for Climate, Environment and Energy

Based on a literature screening, a range of relevant scenario studies for Japan and Germany was identified. These studies describe the medium to long-term effects of a transition towards climate neutrality and the associated economic implications.

Following the decision of the Japanese government to reach carbon neutrality by 2050 (October 2020), only scenarios considering carbon neutrality were included. Considering Germany's more ambitious target to reach climate neutrality as early as 2045, a number of scenario studies had already been published in autumn 2021. Accordingly, for the analysis in this report, the selection of scenarios for Germany was based on the following criteria:

- recent publishing date, target year of climate neutrality 2045/2050
- quantitative details for energy demand and supply side available for at least 2030
- including aspects of economic feasibility
- representing a broad range of assumptions and approaches

Applying these criteria, the scenarios shown in table 2 were selected from a more comprehensive list of relevant scenario studies.

For the Japanese side, there were chosen consultants and an institute (table 1.) that shared their own scenario analysis with the Strategic Policy Committee, in order to discuss the direction of Japan's energy policy, aside from the governmental strategies.

Against this background, this study focuses on scenarios conducted by the following organizations:

Table 1: Japan: Organizations that shared their scenario analysis up to 2050

Organization	Publication	Title	Organization characteristics
1. The Research Institute of Innovative Technology for the Earth (RITE)	2021	Scenario analysis about carbon neutrality in 2050 (Interim report)	Founded by the GOJ to promote innovative environmental technologies worldwide.
2. The National Institute for Environmental Studies (NIES)	2021	Analysis about scenarios toward decarbonization by 2050	A central institute for environmental research since 1970.
3. Renewable Energy Institute (REI)	2021	Energy mix supporting decarbonization in 2050 in Japan	Non-profit institute, founded by a company-owner to promote renewable energy.
4. Deloitte Tohmatsu Consulting	2021	Scenario analysis for carbon neutrality society	One of the Big Four accounting firms.
5. The Institute of Energy Economics, Japan (IEEJ)	2021	Model analysis for carbon neutrality in 2050	Founded by the GOJ of the research institute on energy and environmental policies.

For the German side, we attempted to map the most recent scenarios, focusing on the target year 2045 and highlighting the technical and economic feasibility, while also presenting a certain bandwidth. Hence, (innovative) approaches also played a role, such as considering the effects of a circular economy and behavioral changes. Against this background, the following scenarios were selected. This includes the UBA (2019) study, although it focuses on 2050, since particularly the GreenSupreme scenario we chose from it addresses integration aspects of climate and resource strategies that appeared to be ground-breaking and are not covered by the other studies.

Table 2: Germany: Overview and selection of long-term scenarios up to 2045

Organization	Publi-cation	Title	Organization characteristics
1. Agora Energiewende, Agora Verkehrswende, Stiftung Klimaneutralität	2021	Climate Neutral Germany 2045 - How Germany can achieve its climate targets before 2050. (Prognos et al. 2021)	The think tank searches for compromise solutions that can gain majority support in the restructuring of the electricity sector within the energy transition. Important player in the field of energy policy consultancy.
2. German Energy Agency (Dena)	2021	dena lead study – The dawn of climate neutrality. (EWI 2021)	A federally owned German company that provides services to shape and implement the German government's energy and climate policy goals on energy transition and climate protection.
3. Federation of German industries (BDI)	2021	Climate Paths 2.0 – A program for Climate and Germany´s Future Development. (BDI and BCG 2021)	Leading association of German industry and industry-related service providers, speaking for 40 industry associations and more than 100,000 companies.
4. German Federal Environment Agency (UBA, GreenSupreme 2050)	2019	Transformation process to a greenhouse gas neutral and resource-efficient Germany – GreenSupreme (UBA 2019)	Central environmental authority of the Federal Republic of Germany and part of the portfolio of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. Primary task: the scientific support of the federal government, the enforcement of environmental laws and the provision of information to the public on environmental protection based on independent research.

3. Climate policy and energy transition targets for 2045/2050

Authors: Institute of Energy Economics, Japan and Wuppertal Institute for Climate, Environment and Energy

3.1 Japan (2050)

In 2020, the Japanese government declared its objective to reduce greenhouse gas emissions (GHG) by 46% by 2030 over 2013 levels, and to reach net-zero by 2050. GHG emissions in 2018 amounted to 1.06 billion tons including emissions from the power sector (440 million tons), buildings (110 million tons), industry (300 million tons), and transport sector (200 million tons). Apparently emissions from the power sector are responsible for a large portion of total emissions.

In Oct 2021, the *6th Strategic Energy Plan* was published by the Japanese government. The plan describes the major direction of the strategy on energy demand and supply for the timeframe 2030 until 2050. Japan’s energy use accounts for over 80% of greenhouse gas emissions and thus the plan presents key information on how to reduce the GHG emissions in the energy sector: Based on assumptions related to the expected renewable energy installations or demand, the plan shows a concrete energy supply/demand balance and power sector energy mix in 2030 while also presenting related policies and measures. The 6th Strategic Energy Plan describes that apart from utilizing renewable and nuclear energy, technology innovation for hydrogen/ammonia power plant and CCUS should also be pursued. As for the non-power sectors like transportation and buildings, electrification should be expanded.

Thus, the Japanese government considers various options to realize carbon neutrality by 2050 while also considering the compatibility with a stable energy supply and reducing the national economic burden. On the other hand, the plan does not show a concrete scenario for 2050, but only describes the intended broad direction of Japan's energy policy towards 2050. This is due to the fact that an outlook on 2050 depends on several factors such as technology innovation or future energy demand, both remaining uncertain.

3.2 Germany (2045/2050)

In April 2021, Germany experienced a ground-breaking step in its climate protection legislation, when the Federal Constitutional Court (German: Bundesverfassungsgericht, BVerfG) ruled that the German state was obliged to prevent any future disproportionate restrictions in the fundamental liberties of today's young generation (Constitutional Court 2021, 1 BvR 2656/18) and by that forced the government to take immediate action. Thereafter, the targets of the climate law from 2016 were tightened so as to achieve greenhouse gas emissions neutrality no later than 2045, with interim targets for greenhouse gas reductions until 2030 (-65% compared to 1990) and 2040 (-88% compared to 1990). In addition, the sector targets for the energy, industry, transport and building sectors until 2030 have also been tightened (see table 3) and will be further specified in 2024 and 2032. It should be noted that the sector targets are binding for the responsible ministries, and a rigorous enforcement mechanism was decided in case that the reduction trajectories are missed.

Table 3: Annual emission budgets for sectors according to the German climate protection law [Million t CO_2eq]

Annual emission budgets in million t CO_{2eq}	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Energy	280	*	257	*	*	*	*	*	*	*	108
Industry	186	182	177	172	165	157	149	140	132	125	118
Buildings	118	113	108	102	97	92	87	82	77	72	67
Transport	150	145	139	134	128	123	117	112	105	96	85
Agriculture	70	68	67	66	65	63	62	61	59	57	56
Waste and others	9	9	8	8	7	7	6	6	5	5	4

Source: Climate Protection Law 2021

Details of the climate protection law shall be improved in accordance with EU legislation. The same holds true for the national CO_2 pricing instrument that, from 2024 on, shall be adjusted according to the actual development of the expected EU regulation so as to improve coordination of national measures with European strategies (Climate Protection Law 2021, DS 19/30230).

In general, as a Member State of the European Union, Germany’s energy and climate policy is deeply influenced by the regulations of the EU. With the European Green Deal, the EU proclaimed that it will become the first climate-neutral continent by 2050 (The European Green Deal 2021, COM (2019) 640 final). This general target has been specified in the *fit for 55-package,* aiming at a GHG emission reduction of 55% by 2030 and foreseeing a number of legislative proposals with which the EU seeks to encourage and, in some parts, require Member States to tackle global warming (ibid).

Following the German parliamentary elections in September 2021, a new government consisting of the Social Democratic Party, the Green Party and the Free Democratic Party came into office. Their coalition treaty proclaims a highly ambitious acceleration of green electrification and aims at 80% renewable energy coverage of gross power demand by 2030 while ‘ideally’ phasing-out coal in that same year, in addition to the nuclear phase-out in 2022. To secure these goals in all federal states, a challenging target was set to reserve 2% of the total area of each federal state for onshore wind power. Other noteworthy plans include the highly ambitious increase of renewables in heating buildings (50% up to 2030; any new heating systems from 2024 onwards shall use at least 65% of renewable energy) as well as the goal to achieve a total of 15 million all-electric vehicles by 2030. In the same year, 10 GW of domestic electrolysers for hydrogen production shall be established to be fed by offshore wind power and supplemented by a high imported volume of green hydrogen. With the exemption of some proposed measures for the building sector, energy efficiency does not play a very prominent role in the coalition treaty but will continue to be part of the implementation of Germany’s Climate Protection Law.

4. Analysis of the Japanese scenarios

Author: The Institute of Energy Economics, Japan

4.1 Methods used and key assumptions

4.1.1 Model comparison

In Japanese scenarios, almost all scenario studies use models to minimize total energy system costs including capital costs and variable costs (among others). It should be noted that although the basic approach of each model is similar, the definitions of costs can be different in each model.

These models must be understood not as forecasts, but as back-casting models assuming carbon neutrality by 2050 as a model restriction. Hence, these scenarios do not necessary assure that carbon neutrality is technically or economically feasible but draw a picture or indicate net zero issues under several conditions.

Table 4: Model comparison (Japan)

	RITE	NIES	REI	Deloitte	IEEJ
Model	Dynamic New Earth 21+ model	Integrated model (general equilibrium/ bottom-up/ generation mix)	LUT Energy System Transition modelling	IEA TIMES Model	IEEJ-NE model
Objective	Minimizing total energy system costs (capital cost, variable cost, etc...)*				
Temporal resolution	1 hour	1 hour	1 hour	4 hours per 4 seasons	1 hour
Spatial resolution	1 node	10 nodes	9 nodes	351 nodes	5 nodes

4.1.2 Macro framework

Almost all models' macro frameworks include population, GDP, service demand, etc. (table 5). These assumptions may affect the final energy consumption. However, the difference of assumptions among the models is small. As for fuel prices, many models refer to the World Energy Outlook 2020 (WEO 2020) published by the International Energy Agency (IEA). Hence, assumed fuel prices are also similar among the models.

Table 5: Macro framework in Japanese model assumptions

	RITE	NIES	REI	Deloitte	IEEJ	Min	Max
Population in 2050 [million]	96-122	101.9	101.4	n.a.	n.a.	96	122
Households in 2050 [million]	n.a.	47	n.a.	n.a.	52	47	52
GDP growth rate [%/year]	-0.1 ~ 1.2	0.5	n.a.	n.a.	1	-0.1	1
Crude steel production in 2050 [million t]	73-111	85.7	n.a.	n.a.	119.7	73	119.7
Cement production in 2050 [million t]	31-75	60.4	n.a.	n.a.	43.4	31	75
Ethylene production 2050 [million t]	n.a.	5.4	n.a.	n.a.	4.4	4.4	5.4
Paper production in 2050 [Mt]	n.a.	23.5	n.a.	n.a.	21.2	21.2	23.5
Passenger in 2050 [Trillion p-km]	0.64-0.82	1.18	n.a.	n.a.	1.23	0.64	1.23
Freight in 2050 [Billion km]	n.a.	419	n.a.	n.a.	457	419	457
Coal price (2040)[USD/t]	54	61 WEO2020	0.89 JPY/kWh	61 WEO2020	61 WEO2020	54	61
Crude oil price (2040) [USD/barrel]	76	53 WEO2020	3.45 JPY/kWh	53 WEO2020	53 WEO2020	53	76

**) 115 JPY = 1 USD, 0.88 EUR = 1 USD; n.a. = not available

4.1.3 Renewable energy capital cost

All models use capital costs of renewable energies as a parameter. However, capital costs are significantly different depending on whether domestic or international costs are assumed.

As for PV systems, NIES inserts the smallest capital costs among the models. The capital costs are international costs estimated by IRENA 2019. REI also uses international costs estimated by ETIP-PV[1] and Vartiainen 2019. The cost developments are estimated by a learning curve with a learning rate of 40%, which is larger than typical learning rates (E.S. Rubin et al. 2015). Deloitte estimates the highest capital costs among all models. The capital costs referred mirror the current costs estimated by the Japanese cost working group. IEEJ inserts capital costs by assuming a learning rate of 21% for PV modules and a learning rate of 15% for domestic balance of system (BOS) costs including racking or wiring. RITE shows approximately 50-150 USD/MWh of LCOE in 2050 instead of capital costs. The range arises from the difference of irradiance in each area.

As for onshore and offshore wind systems, NIES uses the smallest capital costs among models. The capital costs are international costs estimated by IRENA 2019. REI also assumes international costs estimated by E3 for PRIMES[2] and EC. Deloitte refers to the highest capital costs among the models in line with the current domestic costs estimated by the Japanese cost working group 2021. IEEJ estimates capital costs by assuming a learning rate of 8% for wind turbine and a learning rate of 7% for domestic BOS costs. RITE shows approximately 70-180 USD/MWh of Levelized Cost of Electricity (LCOE).

Currently, there is a gap between international costs and domestic costs, both for PV systems and onshore wind energy systems, due to technical particularities related to typhoons or earthquakes that are reflected in the domestic costs. For example, PV systems must use stronger racking systems against strong wind. Moreover, the design of wind towers can be different from the wind tower installed in Europe, because Japanese towers must be able to withstand earthquakes. Hence, technical particularities are challenges for the conversion of domestic costs into international costs.

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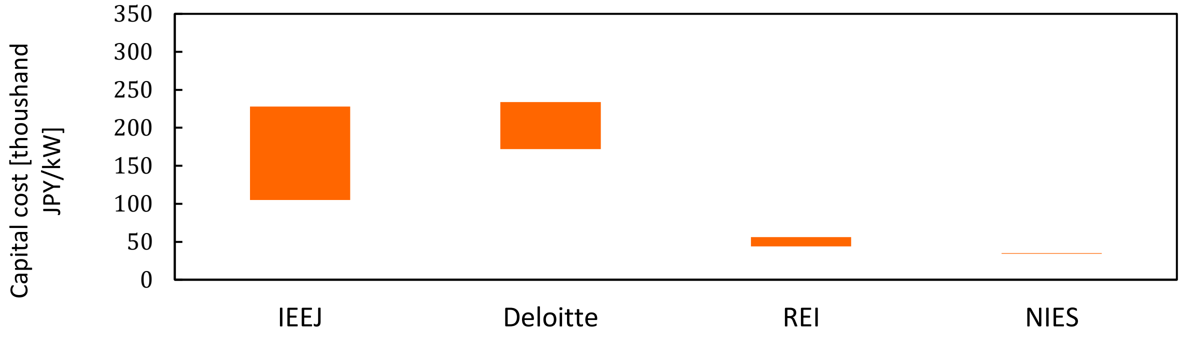
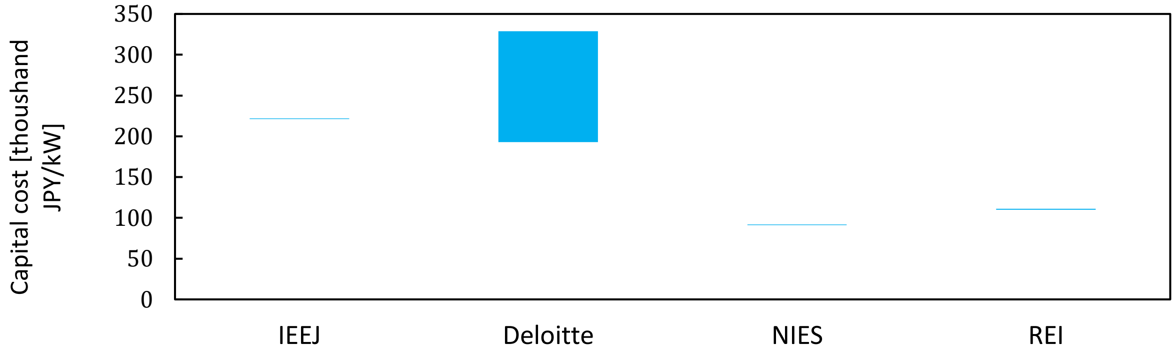
[1] Concrete publication title was not shown. For further information: https://etip-pv.eu/

[2] Concrete publication title was not shown. For further information: https://e3modelling.com/

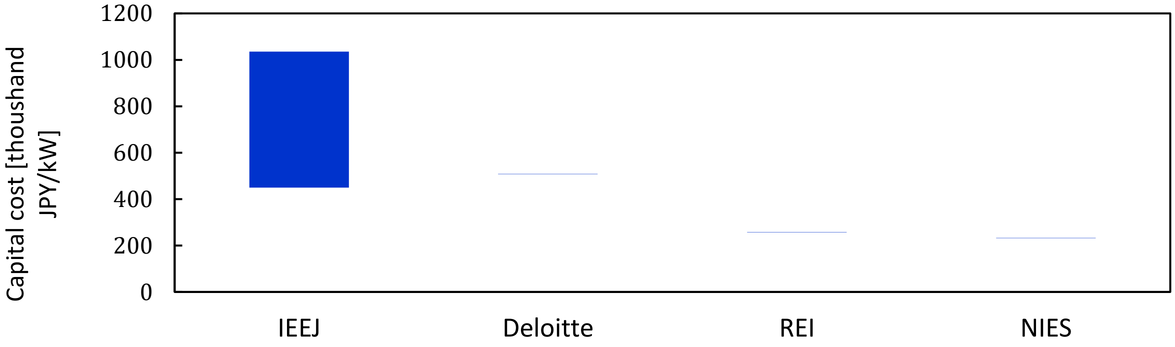
Figure 1: Assumed capital costs for PV and wind energy in 2050 [thousand JPY/kW]



a: PV system



b: Onshore wind



c: Offshore wind

* 100 thousand JPY ≒ 77 EUR
* RITE shows LCOE (PV: approx. 50-150 USD/MWh, Wind: 70-180 USD/MWh) instead of capital costs.

4.1.4 Solar and wind energy potential

Since almost all Japanese contiguous land is covered by forest, the estimated solar and wind energy potential is a key factor to influence the energy mix. The assumed potentials of these energies are significantly different depending on the installation sites (such as farmland and forests), and on the rules for zoning of offshore wind. These assumed potentials make a big difference among the model results especially for the energy mix in 2050.

As for PV systems, REI assumes the highest potential (2,746 GW) by referring to the report by the Japanese Ministry of Environment (MoE) 2021. Due to this estimated massive potential, the large majority of it is assumed to be installed on farmland (2,365 GW). Due to the Japanese agricultural law, PV systems installed on farmland must ensure enough space between PV modules to ensure sufficient crop radiation. If the agricultural production is significantly reduced after installing a PV system, the permission of agricultural land conversion will be revoked.

NIES and IEEJ assume a potential of approximately 360 GW for PV systems. This potential is assumed by installations on the roofs and walls of buildings and installations on weedland and devasted land. RITE sets an upper limit of generated electricity (750 TWh/yr.) instead of installed capacity.

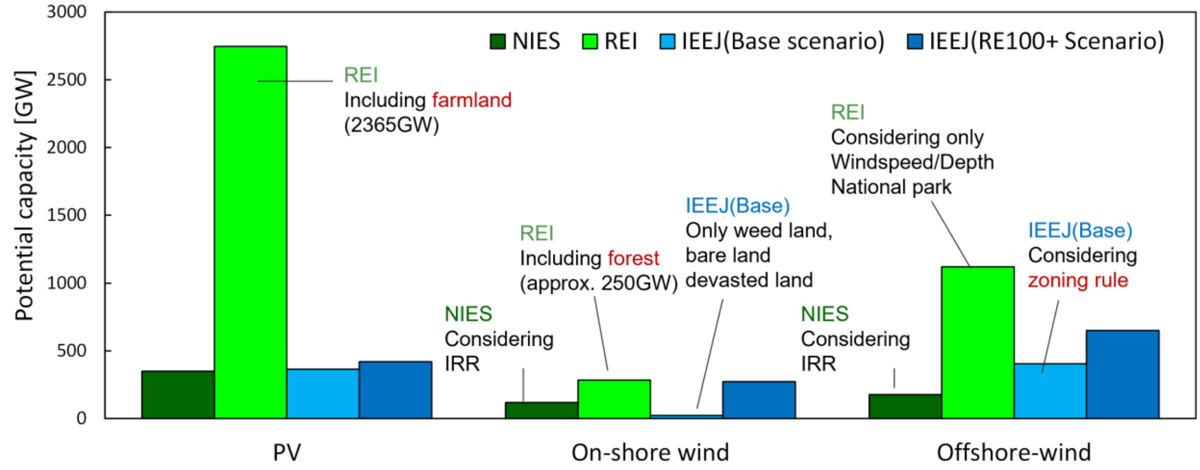
As for on-shore wind energy systems, REI assumes the highest potential (285 GW) by referring to the report by the MoE 2021. However, most of these installations are assumed to be in the forest where the annual average wind speed is $\geq$ 5.5 m/s (approximately 250 GW). Currently, local governments tend to regulate installations in forests to conserve the local nature or environment. Excluding the potential installation areas which may cause a negative impact to the local environment such as forests, only 23 GW of on-shore wind energy is possible to be installed (Obane et al 2020). Following this fact, IEEJ assumes two potentials depending on whether local environments are considered (Base scenario), or not (RE100+ scenario).

NIES assumes a potential (118 GW) that takes into consideration not only technological and legal restrictions, but also economic restrictions by referring to the report of the

MoE 2011. In the MoE report, the potential taking into consideration only technical and legal restrictions is 285 GW. If economic restrictions are further considered as well, the remaining potential is 118 GW. These potentials do not take into consideration local environments. RITE sets an upper limit of generated electricity (200 TWh/yr.) instead of installed capacity.

As for offshore wind energy systems, REI assumes the highest potential (1,120 GW) by referring to the report of the MoE 2021. The scenario assumes installations in all areas where the annual average wind speed is ≥ 6.5 m/s, the water depth is < 200 m, and the distance from shore is bigger than 30 km, while national parks are not included. NIES assumes the potential that considers economic restrictions in addition to the above-mentioned sea use restrictions (177 GW). However, offshore wind energy systems can currently be installed in areas (promoting zones) that are determined by zoning rules. For example, a promoting zone can be determined within the Japanese territorial waters (according to the international sea water jurisdiction within a radius of 22.2 km) by considering natural conditions, shipping routes, grid connection, among others. Accordingly, the base case of IEEJ assumes a potential of 405 GW by considering these zoning rules (Obane et al. 2021). However, this potential includes areas restricted by fishery rights or near the shore areas where the sea scape is possibly destroyed by a lot of turbines.

Figure 2: Assumed solar and wind energy potential in Japan in 2050

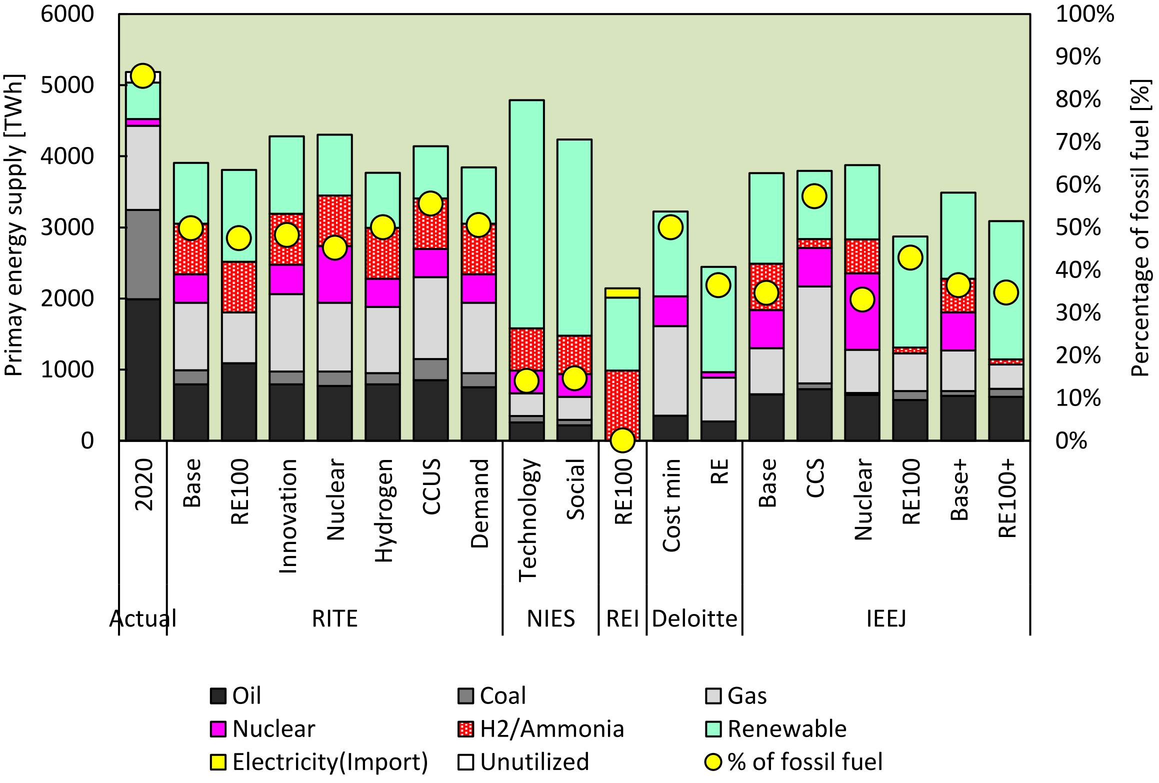


4.2 Key results

4.2.1 Primary energy supply in 2050

In 2020, the primary energy supply from fossil fuels accounted for 85%. Moreover, oil energy supply accounted for 38% of the total primary energy supply because oil was mainly used for transportation. On the other hand, all scenarios show that the primary energy supply from fossil fuels in 2050 will be significantly reduced as a result of cost optimization when carbon neutrality is assumed in back-casting models. Instead of fossil fuels, renewable energy, hydrogen, ammonia, and nuclear are assumed to fill the gap for securing the primary energy supply.

Figure 3: Primary energy supply in Japan in 2050 [TWh]



* As for REI, final energy supply is referred to. Hence, the total energy supply is not necessarily consistent to the other results.

The scenarios that include the utilization of CSS indicate higher percentages of fossil fuels in 2050, compared to the scenarios developed by NIES, where fossil fuels account for 14-15% of the total primary energy supply. Moreover, the scenarios including the strong utilization of renewable energy indicate smaller percentages of fossil fuels. REI shows results for the final energy supply instead of primary energy supply. Although the definition is different from the other scenarios, REI's scenario shows that final energy supply from fossil fuels is reduced to zero by utilizing hydrogen.

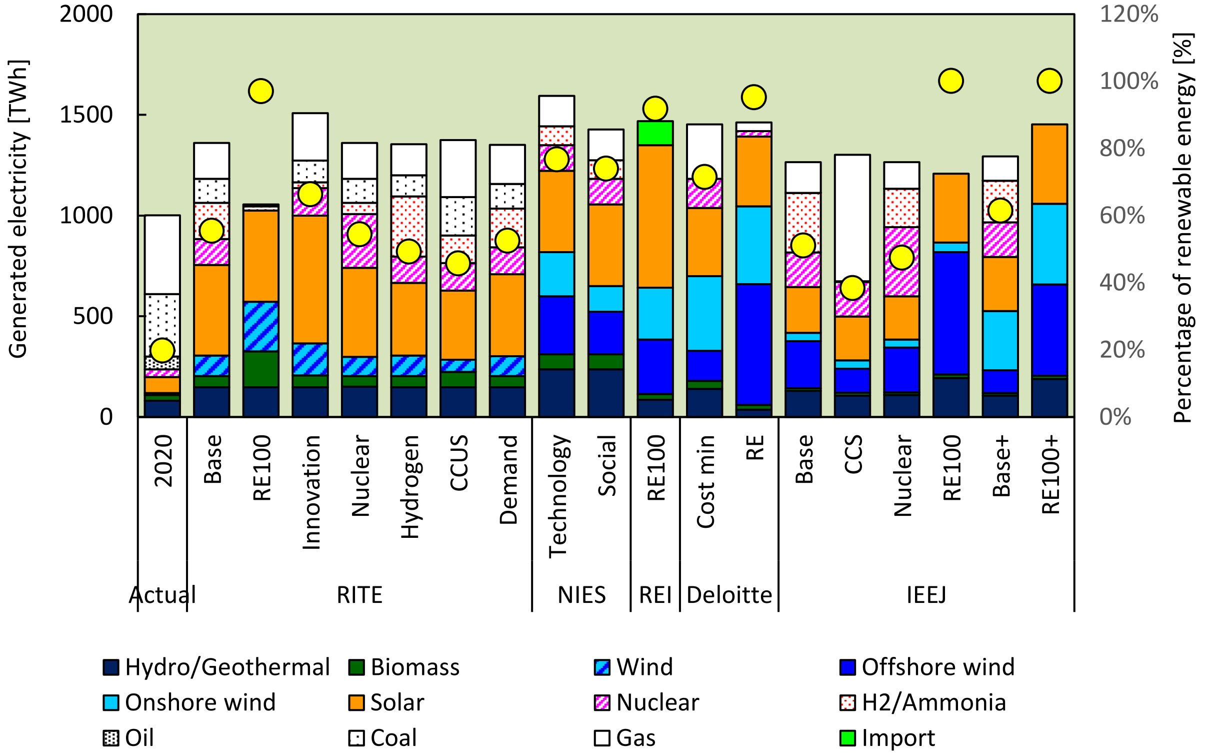
4.2.2 Electricity generation mix in 2050

In 2020, the percentage of generated electricity from renewable energy was 20%. In March 2022, only 10 of 60 nuclear power plants worked, and 24 out of 60 power plants are determined to be shut down. Although the percentage of electricity from renewables may be different among models, it is increasing to approximately 40-100% in 2050 (see Figure 4). Here, the RE100 scenarios (RITE, REI, IEEJ) intend to achieve nearly 100% renewable energy, according to the model calculations. However, the model results are not necessarily the most cost-effective. If the RE100 scenarios are excluded, the average percentage of renewable energy in electricity generation is 40%-70%.

The scenarios considering the use of nuclear energy estimate that existing nuclear power plants should be fully restarted. Moreover, many models show zero emission thermal power such as clean ammonia or CCS being utilized to cover the total electricity demand in 2050.

Some scenarios, including the RE100 scenario, show an extremely high percentage (>90%) of renewable energies. However, it should be noted that renewable energies in these scenarios are assumed to be installed in restricted areas such as farmland or forests. For example, although the REI-scenario predicts a PV capacity of 524 GW, this capacity exceeds the potentials on buildings, weedland or devasted land (MoE 2021). In order to achieve this capacity, approximately 200 GW of the PV system capacities need to be installed on farmland. In this context, it is important to carefully consider the compatibility of the PV systems with the aforementioned restrictions related to the Japanese agriculture law (see chapter 4.1).

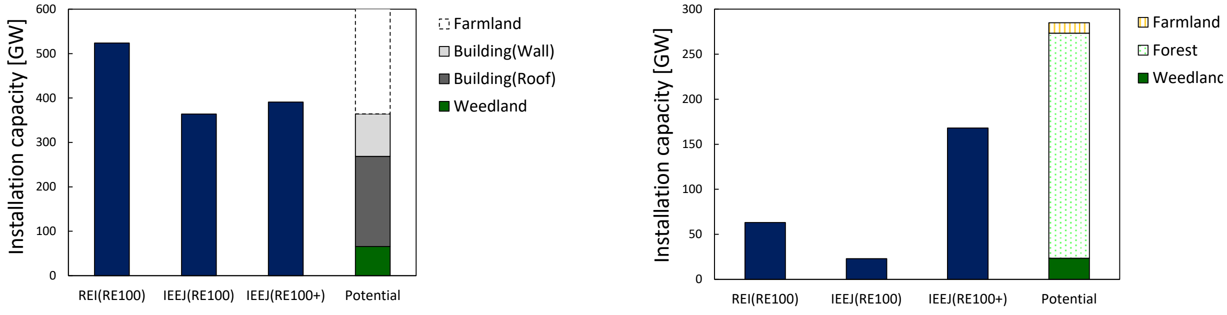
Figure 4: Generated electricity in Japan in 2050 [TWh]



Moreover, achieving a capacity that exceeds 100 GW by onshore wind installations as assumed by many scenarios, requires onshore wind energy installations in forests.

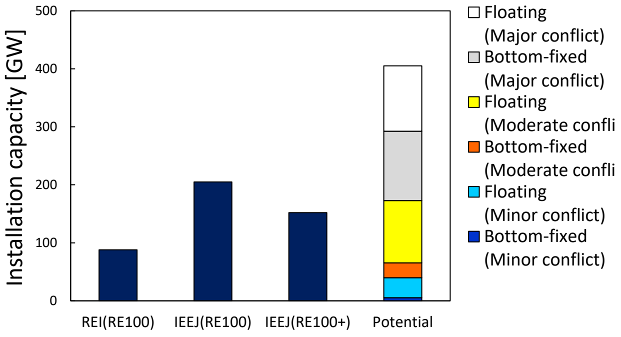
Thus, although some scenarios show a high percentage of renewable energy, local environment or social acceptance must be carefully considered if a massive installation of renewable energy is planned according to these scenarios.

Figure 5: Comparison of installed renewable energy capacity with technical potential in Japan [GW]



(A) Ground-mounted solar

(B) Onshore wind



(C) Offshore wind

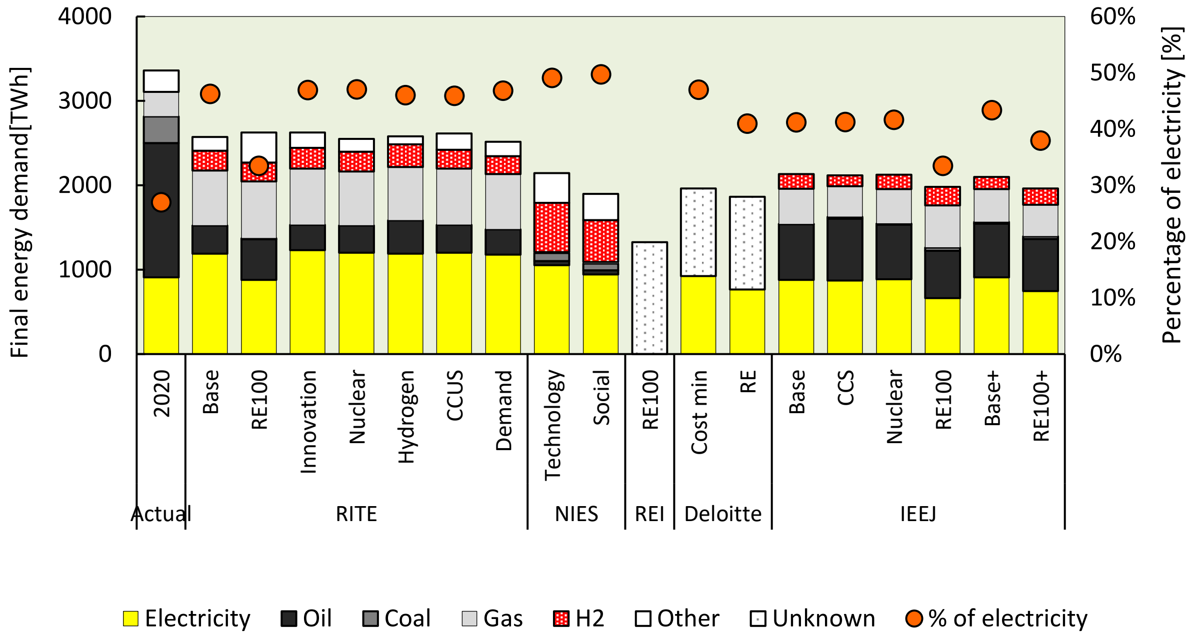
* Potential is referring to MoE 2021, Obane et al. 2021, Obane et al. 2020.

4.2.3 Final energy demand in 2050

The final energy demand in 2020 amounted to 3,361 TWh and the percentage of electricity accounted for 27%. Most of the current final energy demand is covered by fossil fuels. Many scenarios show that the final energy demand is reduced to approximately 3,000 TWh by 2050. This is mainly caused by the transition from oil to gas or hydrogen by 2050. Since the total final energy consumption will be reduced by 2050, the percentage of electricity will increase up to 40 – 50%. Although the percentage of electricity is higher, it should be noted that the absolute amount of final electricity demand is not necessarily increased.

Many scenarios show that the oil and gas demand will remain even in 2050 because some types of oil such as heavy oil must continuously be used for transportation. According to the assumptions, the combination of gasoline cars and DAC may be considered cost-efficient comparing to electric vehicles. Accordingly, in some scenarios, a certain amount of gasoline cars is still estimated for 2050. Moreover, the use of CCS with gas power plants is estimated to be cost-efficient compared to renewable energies in many scenarios, leading to a certain remaining share of gas power (see Figures 4 and 6). These results depend on assumptions such as costs for CCS/DAC and fuel prices.

Figure 6: Final energy demand in Japan in 2050 [TWh]

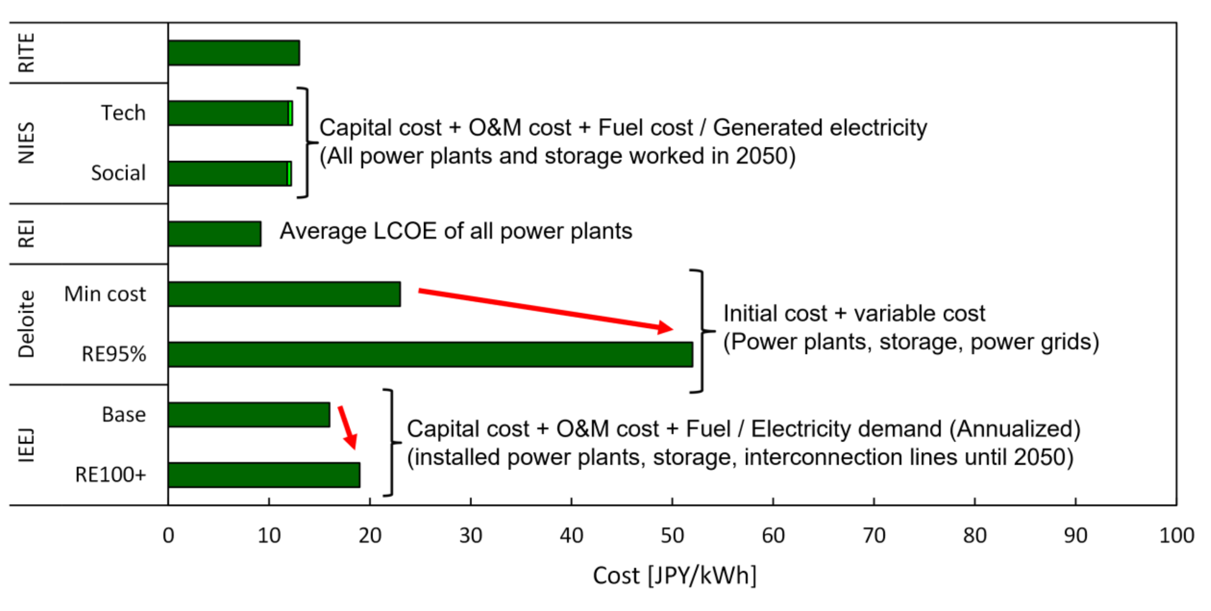


4.2.4 Average costs in the electric power sector

All scenarios show the average costs in the electric power sector. It should be noted that the definitions of average costs are different among the models. For example, while REI shows the lowest average costs, the value is defined as an average LCOE of all power plants. NIES shows costs dividing the total of capital costs, O&M costs, fuel costs of all power plants and storage by generated electricity. Deloitte shows average costs depending on initial costs and variable costs of power plants, storage, and power grids.

IEEJ defines the average costs as the value obtained by dividing the total costs including capital cost, O&M cost, fuels cost, by the annualized electricity demand of installed power plants, storage, interconnection lines. Despite these differences of definitions, the average costs tend to increase as the percentage of renewable energy increases.

Figure 7: Averaged costs in the power sector in 2050 [JPY/kWh]



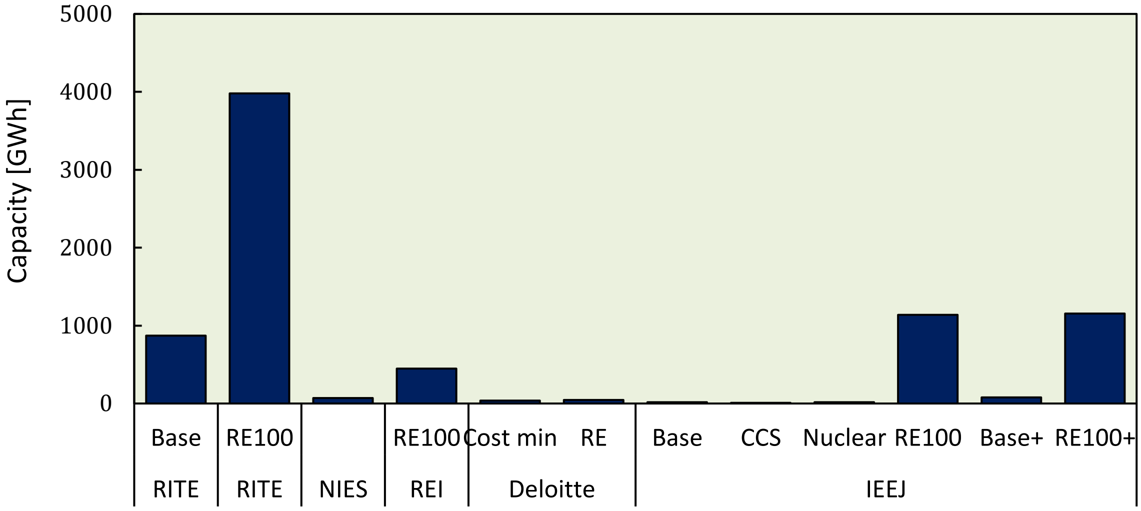
By modelling, the IEEJ estimated the average costs in 2020 to 10 JPY/kWh

4.2.5 Storage capacity

While the percentage of generated electricity from renewable energy is expected to be 40-100%, some scenarios show extremely high percentages of renewable energy. These results depend on the availability of hydrogen or the potential of electric vehicles to provide flexibility to the power system. In these scenarios, backup power plants such as thermal power plants with CCS and nuclear power plants tend to be excluded. Instead, these scenarios show a massive amount of storage capacities (> 1,000 GWh).

If 10 kWh storage systems were installed in all currently existing residential homes (29 million), the total storage capacity would be only 290 GWh (10 kWh x 29 million). Compared to this, the necessary storage capacity to assure electricity supply security is significantly larger.

Figure 8: Storage capacity in Japan [GWh] in 2050



4.2.6 Main implications

As the model approach and assumptions by each organization are different, the main results of each organization also differ.

RITE implies that various technologies and innovations such as hydrogen generation, ammonia generation and CCUS are necessary to reach carbon neutrality. Moreover, policy support for several fields is necessary. Similarly, IEEJ implies various options being utilized for carbon neutrality such as nuclear energy generation, hydrogen generation, ammonia generation, and CCUS. Moreover, a balanced energy mix is required.

NIES assumes that the decarbonization may cause losses of national wealth. Furthermore, social transformation may ensure/enable decarbonization. REI estimates that decarbonization is possible not only in the electricity supply but also in the heat and transport sectors by utilizing renewable energies.

Deloitte assumes that a percentage of renewable energy of 71% in the electricity generation may lead to a doubling of electricity prices compared to the current price levels for realizing carbon neutrality.

Thus, while some organizations stress the difficulty of achieving carbon neutrality in the power sector and the need for various technologies, others assume that decarbonization may give positive impacts.

5. Analysis of German scenarios

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5.1 Methods used and key assumptions

5.1.1 Scenario approaches, models and methods used

Most German scenarios are based on back-casting modelling approaches (policy scenarios): The necessity of reaching carbon neutrality in 2045/2050 is *presupposed* according to the Paris Agreement (2015) and a national *just* contribution to the global "well below 2 degrees"-target calculated by the so-called *budget approach*[3]. The scenarios investigate technically and economically possible strategies to reach the presupposed carbon neutrality target in 2045. Detailed information on the models used in the selected studies was only partially available.

The climate neutrality scenario 2045 of the **Agora study** (in German: Klimaneutrales Deutschland 2045, KN45; Prognos et al. 2021) is a diversified technology scenario. In comparison to a former scenario analysis with the target year 2050, KN45 scenario relies primarily on the rapidly accelerated and more comprehensive use of the already projected approaches of climate-friendly technologies and strong climate policies for climate neutrality. The basic approach: energy efficiency, renewable energies and electrification, green hydrogen and ca. 5% of negative emissions. The modelling of KN45 follows the same approach as the Agora scenario KN50 published in 2020 (Prognos et al. 2020). They are based on eight different sector models: the EU-wide electricity market model, private household model, commercial and public sector model, transport model TEMPS, agriculture model LiSE, LULUCF model FABio, waste model WaSMOD and the industry model WISEE-EDM. The approaches differ in the various sectors and range from merit-order modelling, including power imports and exports, in the electricity market

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[3] The budget approach starts with the calculation of the remaining global CO_2-budget compatible with the targets of the Paris Agreement and - by a per capita basis distribution – calculates the corresponding available residual budget e.g. for Germany under certain probability assumptions www.wbgu.de/fileadmin/user_upload/wbgu/publikationen/factsheets/fs3_2009/wbgu_factsheet_3.pdf).

model to a bottom-up approach in the end-use sector models, modelled by end-use and fuels. The power demand resulting from the end-use sector models is converted to load curves, including flexibility potentials, as an input to the hourly scheduling of power plants according to their merit order.

Hence, this study models GHG emissions from all sectors, including the often neglected sectors agriculture, waste and land use (Prognos et al. 2021: 23). The GHG emissions' assessment is based on the inventory report of the UNFCCC estimating a global warming potential for 100 years for all greenhouse gases (4th Assessment report of the IPCC, IPCC AR4).

According to the motto "Energy mix of the future: electrons and molecules", the **German Energy Agency (dena) study** (EWI 2021) generally relies on comparable four pillars as the Agora study, but with an emphasis on innovations and a higher share of hydrogen and other Power-to-X (PtX)[4] fuels but less direct electricity use compared to the Agora study. The authors emphasize additionally the importance of an integrated overall strategy with a holistic, political approach, CO_2 pricing and social transformation. As all other studies, it is based on sectoral balance sheet limits that are in line with the German Climate Protection Law (KSG21) (cf. chapter 3). Final energy consumption and greenhouse gas emissions are calculated according to the source principle, attributing CO_2 emissions to specific countries and sectors in which they were generated. Equally to the Agora and BDI scenario, the GHG reduction targets of the Climate Protection Law (KSG21) are the central parameters for the modelling of the KN100 scenario. In 2030, the sectoral reduction targets for the sectors of transport, industry, buildings and energy are each set as quantity restrictions in the EWI[5] energy system model DIMENSION, which optimizes the future development of power plants, renewable energies and flexibility options (including electrolyzers) for the provision of energy in 28 European countries. In doing so,

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[4] Various technologies for storing or otherwise using electricity surpluses in times of oversupply of variable renewable energies

[5] Institute of Energy Economics at the University of Cologne.

the model maps the cost-minimizing use and capacity expansions as well as the dismantling of various technologies. According to the EWI, the emissions of the agriculture sector are not explicitly modelled in this study, but are rather taken from the results in the Agora study.

The study of the **Federation of German Industries (BDI)** (BDI and BCG 2021) considers Germany's goal to reach GHG neutrality by 2045 the "greatest transformation in its post-war history" (Climate Paths 2.0 2021: 2, English summary) requiring fundamental changes in the energy system (including the international energy supply), the building and vehicle stock, infrastructure and large parts of energy intensive industries. More specifically, the authors mention the acceleration and intensification of energy-efficiency measures as well as the green electrification, which necessitates a significant expansion of renewable energy capacities (by a factor of 4 in 2045 compared to 2019).

The BDI study does not explicitly explain the applied modelling approach. The authors declare, however, that their "comprehensive, open to all types of technologies analysis" (Climate Path 2.0 2021: 1,2, English summary) is based on bottom-up approaches and realized in dialogue with experts from specific industries and associations of the German industry. The focus of the analysis lays on the calculation of investment and operation costs concerning a broad range of mitigation technologies and measures.

The **GreenSupreme Scenario** of the German Environment Agency (UBA 2019) is the only German scenario that focuses on both reducing THG emissions and the use of resources, while combining technical options with sufficiency policies and behavioral changes. As it was written in 2019, before the climate protection law was revised, it refers to climate neutrality by 2050. Still, it is one of the most ambitious scenarios published in Germany. Its strategies: (1) transformation of the energy system with a rapid shift to renewables across all sectors and smart sector coupling, (2) ambitious energy demand reductions through both energy efficiency and sufficiency (behavior), (3) conversion of emission-intensive industrial processes to low or zero-emission processes, (4) the reduction of production volumes through circular strategies, but also lifestyle changes, and (5) the substitution of fossil raw materials by secondary, biotic and lighter raw materials.

The scenario is based on different Input-Output models for each sector by considering specific sector assumptions. For instance, to model the effect of resource efficiency the URMOD model is used[6].

5.1.2 Framework conditions and key assumptions

The German scenarios mostly focus on potentials, demand and replacement of existing technologies in the energy, building, transport and industry sectors that constitute relevant factors for finding economic solutions on the way to climate neutrality. The agricultural and waste or land use sector, land use or GHG emissions related to biomass are only considered by the Agora and UBA studies.

In line with the revised Climate Protection Law 2021, the three recent studies refer to the new more ambitious reduction targets (Climate Protection Law 2021, KSG). Although the UBA study was published earlier and therefore is targeting on reaching climate-neutrality only by 2050, its emphasis on a fast and strong reduction of CO_2 emissions is apparent in its even stronger ambition until 2030 (-70%). Three of four scenarios assume that the current demographic and economic development will be maintained (cf. table 6). Only the UBA study follows a new path regarding the assumed economic growth. While BDI, Agora and dena expect a constant or slightly declining GDP growth rate ranging from 0,9% to 1,3% per year (2030-2050), the UBA study indicates a departure from the growth paradigm after 2030 by a growth rate of 0.[7]

The importance of market-based instruments for reaching climate neutrality is emphasized in all studies. However, only the BDI study provides explicit values of the CO_2 prices, both in the EU ETS context and in relation to the CO_2 price regulated by the

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[6] The average GDP growth rate from 1990-2020 was 1.3%, with a decreasing trend (1990-2000: 1.9%; 2000-2010:0.9%; 2010-2020: 1.1%).

national Fuel Emissions Trading Act (German: Brennstoffemissionshandelsgesetz, BEHG) for the sectors not covered by the EU ETS.[8] According to the BDI study, the latter may range from 65 €/t to no less than 150€/t depending on the policies that go along with it.

Table 6: Framework conditions assumed in German scenario studies

Indicator	year	Agora et al	Dena	BDI	UBA (2050)
GHG reduction targets compared to 1990 (in %)	2030	-65	-65	-65	-70
	2045	-100	-100	-100	2050: -100
Population (number in million)	2020	83	83	83	83
	2045	80	81	n.a.	74
Households (number in million)	2030 2045	43 43	n.a. n.a.	n.a. n.a.	n.a. n.a.
GDP growth rate (in %) per year	2018 2030 2045	1.3 ca. 1.0 ca. 1.0	1.3 0.9 0.9	1.3 1.3 n.a.	1.3 0 0
Primary energy demand (in TWh)	2018	3,646	3,646	3,646	3,646
Energy prices*) (EUR/MWh) Oil	2030 2045	34 31	45.8 60.6	29.88 n.a.	n.a.
Gas	2030 2045	20 22	17.9 23.7	13.3 n.a.	n.a.
Coal	2030 2045	8 8	10.3 10.2	6.5 n.a.	n.a.
EU ETS CO_2 Price: EUR$_{2019}$/t	2030 2045	52 80	n.a.	72 n.a.	n.a.

*): Prices in the BDI study are inflation-adjusted with the reference year 2019. The other studies give no further information about the inflation adjustment.

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[8] While the Agora study considers only the EU ETS prices under the current EU ETS system, the CO_2-pricing according to the BEHG even covers sectors beyond what is to be expected by the proposed new (expanded) EU ETS (see BDI and BCG 2021: 43).

The German scenarios also include sector- and technology-specific assumptions on energy efficiency and end-use technologies (see table 7).

Building sector

In the building sector, all studies assume a clearly increased renovation rate that improves the energy efficiency of the building stock and rises on average up to 2% per year in 2045 (compared to about 1% in the past). Again, the UBA GreenSupreme scenario is more ambitious and assumes much higher rates, both in 2030 and 2045, achieving even 3,6%. As an important condition for the decarbonization of the heating sector, all studies consider the expanded use of heat pumps and expect their numbers to rise from 1,3 million to a maximum of 6 billion in 2030 and ca. 15 million units in 2045.

Transport sector

A basic assumption of all scenarios in the transport sector is its electrification. Starting from 516,518 all-electric vehicles in 2021, the analyzed scenarios expect between 9 and 14 million battery-electric vehicles in 2030. Regarding 2045, the studies assume that the car stock is almost completely converted to BEV, however, they reveal different assumptions about the size of the car stock. While Agora, dena and BDI consider between 32 and 39 million all-electric vehicles in 2045, the UBA GreenSupreme-scenario stands out with its approach of sufficiency: In addition to the 100% electrification strategy of the motorized individual transport modes, the authors are clearly moving away from the passenger car, but emphasize a modal shift towards environmental-friendly means of transport such as public transportation, bicycle, pedestrian traffic. The number of all-electric vehicles rises to only 18 million in 2050 in this scenario, because the total number of individual vehicles is assumed to reduce by at least half.

Table 7: Key assumptions in German scenarios: sectoral assumptions

Indicator		Agora et al	Dena	BDI	UBA (2050)
Renovation rate of buildings stock (in % per year)	2030	1.6	1.8	1.9	2.5
	2045	1.7	1.9	2.1	3.6
Heat pumps Number of units (% of heat in buildings)	2030	6 mn (24%)	4 mn	6 mn	n.a.
	2045	14 mn (60%)	9 mn (42%)	15 mn (n.a.)	2050: 16 mn (75%)
Battery-electric Vehicles Number of units (% of inventory structure)	2030	9 mn (19%)	9 mn (n.a.)	14 mn (31%)	12 mn
	2045	34 mn (91%)	32 mn (n.a.)	39 mn (86%)	2050: 18 mn
Annual full-load hours 2030 (on = onshore; off = offshore)	PV	957	946	n.a.	n.a.
	Wind	On: 1,888 Off: 3,600	On: 2,348 Off: 4,043	On: 2,122 Off: 3,786	n.a. n.a.
Investment costs 2030 (in €/kW/2019)	PV	rooftop: 750 utility scale: 400	rooftop: 733 utility scale: 640	rooftop: 850 utility scale: 500	n.a.
	Wind	On: 1,100 Off: 2,000	On: 1,038 Off: 1,920	On: 950 Off: 1,490	n.a.
Crude steel production 2045 (in million t / a)		39.6	42.4	n.a.	34.5
Cement production 2045 (in million t / a)		27.5	33.0	n.a.	17
Paper production 2045 (in million t / a)		25.1	24.1	n.a.	14

Energy sector

Regarding renewable energies, the selected scenarios rather differ little in their assumptions on full-load hours or investment costs. The dena and BDI studies appear to be slightly more optimistic regarding wind energy. Regarding the investment costs for wind energy and photovoltaics, the scenarios assume different learning curve effects. But they all commonly expect decreasing costs in the future.

Industry sector

In the industry sector, production volumes of crude steel, cement and paper are similar between Agora and dena. A radical difference in the basic approach becomes apparent when considering the numbers presented by the UBA GreenSupreme scenario: the stated quantities in the paper and the cement production are significantly lower and underscore the immanent principles of sufficiency. As the BDI study only provides numbers for 2030, it has not been considered further in comparing these indicators.

5.2 Key results

The German scenarios describe what pathways to climate neutrality for the various sectors of the energy system could look like. In principle, there can be identified four common approaches and basic strategies. However, each scenario has its own characteristics and differences when compared to the others.

5.2.1 Reducing the energy demand

An ambitious reduction of the energy demand through efficiency measures in all sectors is considered to be the first important pillar to reduce the GHG emissions. It is also a basic requirement to secure the energy supply through the extensive use of renewable energy in all German scenarios. Efficiency potentials are seen especially in the building and the transport sectors, where e.g. renovation, use of heat pumps, all-electric vehicles lead to much higher degrees of efficiency. As a result, the final energy demand decreases significantly from 2,500 TWh (2018) to 1,300-1,600 TWh in 2045 (1,600 TWh would be equivalent to approximately -36% in demand). The UBA scenario combines the energy efficiency approach with resource efficiency and even reaches a final energy demand reduction of -57% until 2050, to ca. 1,050 TWh in 2050. Primary energy is calculated to see a 50% reduction between 2019 and 2045. Here, the BDI scenario achieves only 44% of reduction (cf. table 8). Figures 9 and 10 overleaf show in addition, which resulting final and primary energy mix is calculated in the German scenario studies.

Table 8: Energy demand reduction in German scenarios

		Agora et al	Dena	BDI	UBA (2050)
Final energy demand reduction (compared to 2018)	**2045**	-36,1%	-36,3%	-36%	2050: -56,8%
Savings in primary energy (compared to 2018)	**2045**	-50,8%	-50,7%	-44,2%	n.a.

It should be noted that the implementation of energy efficiency and energy conservation policies up to now does not satisfactorily correspond with the partly ambitious energy efficiency approach of the scenarios. Evaluations point out existing gaps between possible efficiency potentials and scenario results, also when compared to the targets of the government[9]: “Between 2008 and 2019, final energy productivity improved by an average of 1.4 percent annually, which is well below the target of 2.1 percent annually” (*8th Monitoring Report 2022*: p.74, own translation). This indicates that not only for renewable energy, but also for energy efficiency the ambition level of policy, industry and the civil society must be raised to catch up with the path to climate neutrality as demonstrated in all scenarios. Considering the assumptions for GDP growth rates shown above, the scenarios would result in final energy productivity improvement rates of around 3 percent annually on average.

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[9] https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-energy-of-the-future-8th-monitoring-report.pdf?__blob=publicationFile&v=6.

Figure 9: Total final energy demand and mix in German scenarios (in TWh)

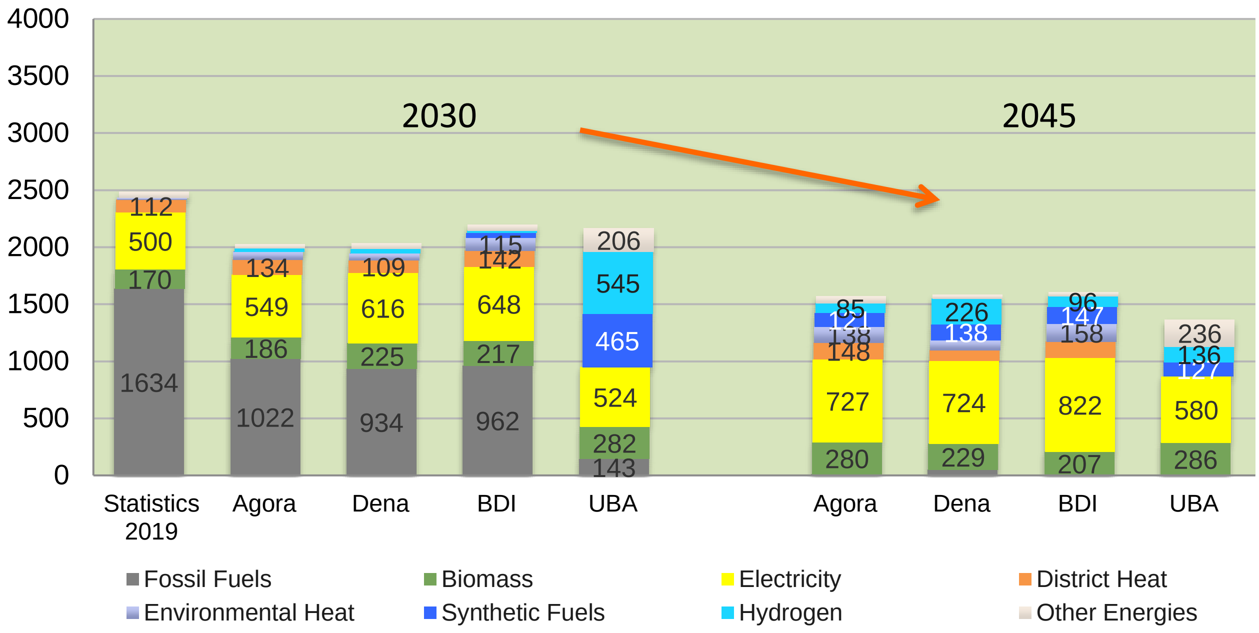
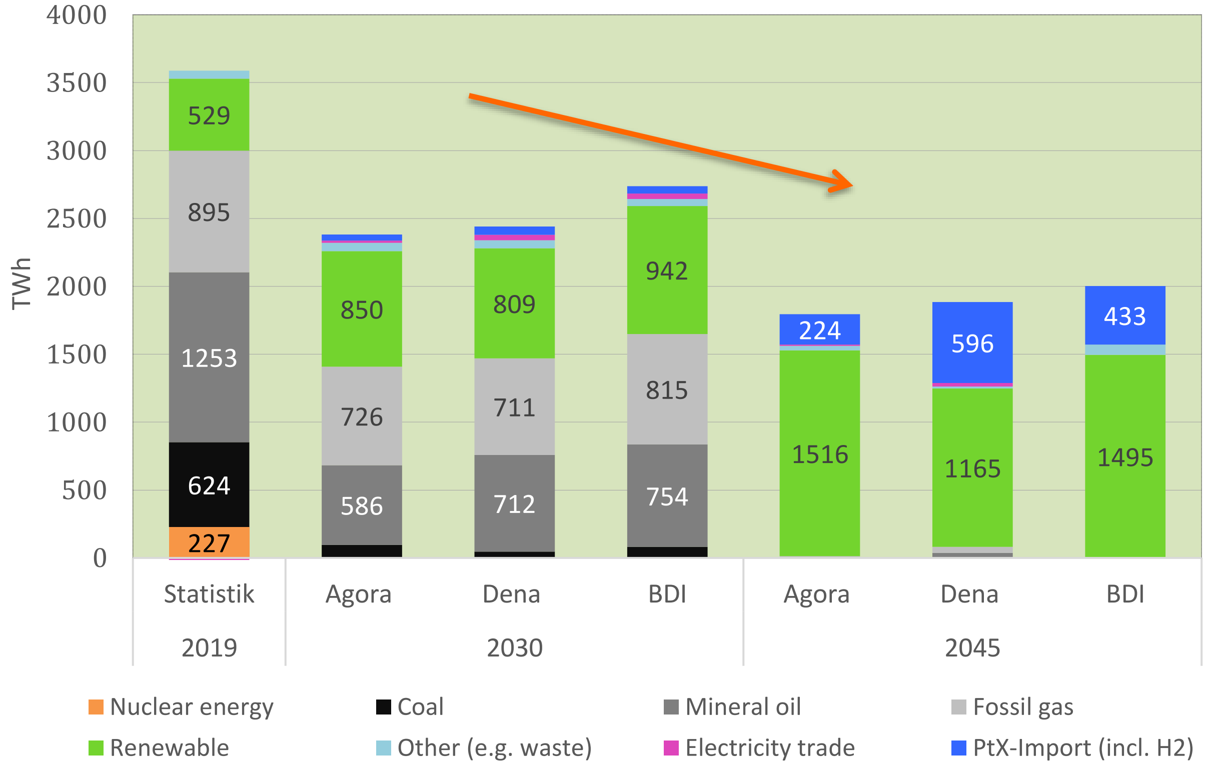


Figure 10: Primary energy demand and mix in German scenarios (in TWh)



5.2.2 Transformation of the energy mix: Renewable energy and electrification

While the energy demand is decreasing, figures 9 and 10 also show that at the same time there is a strong change in the energy mix. The scenario studies by Agora, BDI and UBA suggest a phase-out of coal until 2030, 8 years earlier than what the former government coalition decided in 2021.[10] Nuclear energy will be phased out by 2022. The share of other fossil fuels decreases to zero by 2045, meaning essentially 100% renewable energy supply, including import of green fuels and, in some scenarios, electricity. Both renewable energy as an available, cost-efficient energy source[11] and green electricity are becoming increasingly important. Moreover, hydrogen and PtX fuels become relevant after 2030.

Renewable energies

In all 4 scenarios, shifting the energy production to renewable energy sources is considered to be the second major strategy towards climate neutrality. There is an additional power demand for the domestic generation of green hydrogen and hydrogen-based PtX fuels as well as non-energetic uses in the industry.

The share of renewable energy sources in electricity generation increases from 44% (2020) to 60 to 86% in 2030 and almost 100% in 2045. The BDI study sets only 60% in 2030, because it assumes an even faster electrification, leading to higher total power demand, while the UBA study with 86% is even higher, indicating a significantly faster electrification.[12] It should be noted that the new government's target of reaching a share of 80% renewable power by 2030 exceeds the assumed share of renewables in three out

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[10] The new coalition actually seeks to phase-out coal until 2030.

[11] See for estimates of cost developments e.g. the latest analysis by Transition Zero https://static1.squarespace.com/static/605b4bcc5526904ff5589918/t/62066db231110622409e34eb/1644588483986/TransitionZero_Coal-de-sac_Report_final_full+report.pdf

[12] While the studies conducted by Agora and dena still consider a small amount of natural gas (Agora: 2%, dena: 1%) in the electricity production of 2045, in the BDI-scenario the phase-out will be already completed then. Also, contrary to Agora and dena, the electricity production refrains from net electricity imports in the BDI study. The share of renewable energy in the net power generation including net power imports, in all 4 scenarios rises to 67-84% in 2030, and reaches 100% by 2045.

of the four studies analyzed here. The same is true for the electrification goals, e.g. the number of electric vehicles.

In regards to primary energy, the share of renewable energy increases from currently 16,4% (2021) to 31%-38% in 2030 and 93%-97% in 2045.[13] Renewable energies such as geothermal and solar thermal also play an important role in the heating and cooling sector.

Germany will have to accelerate the expansion of renewable energy production significantly. Figure 11 shows the *annual gross increases* until 2030, which will double or even triple compared to the last years. The biggest annual increases are seen for PV (8-10 GW), wind onshore follows with 5-11 GW. This ambitious capacity increase underscores that the restrictive upper limits of installation, zoning rules and spatial planning of the past must be revised in favour of a very challenging expansion strategy.

The resulting *electricity production capacities* of renewable energies are expected to reach on average 140 GW for PV, 90 GW for wind onshore and 25 GW for wind offshore until 2030 (cf. table 9). In the following phase up to 2045, the scenarios show different dynamics: While Agora sees a further massive expansion of PV with 355 GW in 2045, the BDI-study and dena are more reserved with only 230-260 GW, UBA even expects only 130 GW of installed capacity. BDI sees the highest wind onshore potential, with 180 GW installed capacities in 2045.

Most of the scenarios do not focus on price developments and integration costs in particular, since they find that overall energy system costs will be more or less the same as today. The GreenSupreme Scenario, for instance, describes the direction of price developments (as constant or as shifting slightly upward) but without any quantification. However, based on the low-cost flexibility potentials that they identify, the studies do not consider *integration costs* as a major challenge for reaching climate neutrality.

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[13] While the studies conducted by Agora and dena still consider a small amount of natural gas (Agora: 2%, dena: 1%) in the electricity production of 2045, in the BDI-scenario the phase-out will be already completed then. Also, contrary to Agora and dena, the electricity production refrains from net electricity imports in the BDI study.

Table 9: Expansion of renewable energy and electricity system costs in German scenarios

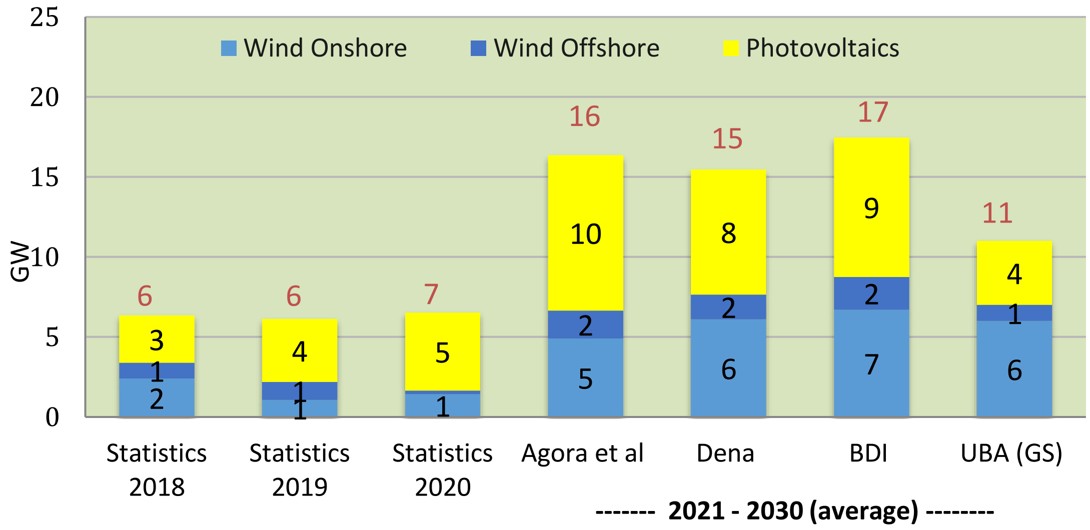
		Agora et al	**Dena**	**BDI**	**UBA** (2050)
Primary energy: Share of renewables	2030	37.6%	33.1%	31.2%	n.a.
	2045	97.0%	93.3%	n.a.	n.a.
Electricity generation: Share of renewables, including hydrogen and waste from renewables	2030	70,8%	75%	59,9%	85,5%
	2045	100%	100%	100%	100%
Installed electricity production capacities (GW)	2030	PV: 150 Wind on: 81 Wind off: 25	PV: 131 Wind on: 92 Wind off: 23	PV: 140 Wind on: 98 Wind off: 28	PV: ca. 105 Wind on: 104 Wind off: ca. 16
	2045	PV: 385 Wind on: 145 Wind off: 70	PV: 259 Wind on: 124 Wind off: 50	PV: 230 Wind on: 180 Wind off: 70	2050: PV: 130 Wind on: 127 Wind off: 30
Difference in Electricity System Costs (Eurocent/kWh, compared to reference)	2030	n.a.	n.a.	-0.1	n.a.
	2045	n.a.	n.a.	+0.6	n.a.

According to BDI, such a vast expansion of renewable energy will cause power system costs amounting to 73-104 billion Euro (BDI and BCG 2021), related to the expansion of the electricity grid (13 billion EUR), the accelerated expansion of renewable energies (13 billion EUR) and the construction of “H_2-ready” gas-run power plants (5 billion EUR). These costs are estimated to be largely passed on to the end-users (ibid). However, the electricity prices are expected to only rise slightly (+0.6 Eurocent/kWh in 2045), due to an overall increase of electricity demand related to new applications entering the market (see figure 13). Moreover, the authors of the BDI study assume that the renewable energy levy will be abolished, leading to a considerable decrease of customer prices per

MWh (BDI and BCG, 2021). This assumption corresponds with the decision of the Federal Cabinet of March 2022. [14]

Expanding renewable energies in densely populated Germany will be a challenge especially for onshore wind energy. Potential studies of the UBA (2013/2019) on the possibility of increasing wind energy onshore (UBA 2019) show that, theoretically, there is sufficient space (UBA 2013; UBA 2019a). But zoning rules, environmental and nature conservation aspects, social restrictions and lengthy approval procedures pose an obstacle so far. Further land use conflicts due to grid, storage, electrolysers and CCS/DAC are to be expected. Considering environmental and nature conservation aspects, UBA identifies an area of (roughly) 7,800 km^2 to be available for onshore wind energy use, on which an installed capacity of around 200 GW would be possible. This has not been exhausted in any of the four studies. The same is the case for the Solar PV potential. The solar PV generation potential in buildings alone has been estimated to be around 10 times higher than the use of PV calculated for 2050 in the German scenarios (Fath 2017), and most of it is cost-effective.

Figure 11: Annual gross increases of wind and PV capacities in German scenario studies (in GW)



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[14] https://www.bundesregierung.de/breg-en/news/renewable-energy-sources-act-levy-abolished-2011854.

Electrification

Technology shift and the electrification in all sectors, especially transport, building and industry sector enables displacement of conventional fossil energy sources. It thus represents an important and particularly efficient strategy to decarbonization. The share of electricity contributing to the total final energy demand increases in almost all scenarios from 20% (2019) to ca. 41-51% in 2045 (cf. figure 9). Particularly the expansion of electric vehicles, heat pumps and electrolysers for the ramp-up of green H_2 production, but also the stronger use of other power-based processes in the industry contribute to the increase in power demand (see figure 13). Differences in the assumed growth in these numbers among the 4 scenarios are also reflected in the results, showing different quantities of net power generation needed. The net power generation will nearly double from ca. 540 TWh to ca. 1,000 TWh between 2019 and 2045 (see figure 12).

Figure 12: Net power generation by fuel plus power imports (w/o pumped hydro and batteries) in Germany (in TWh)

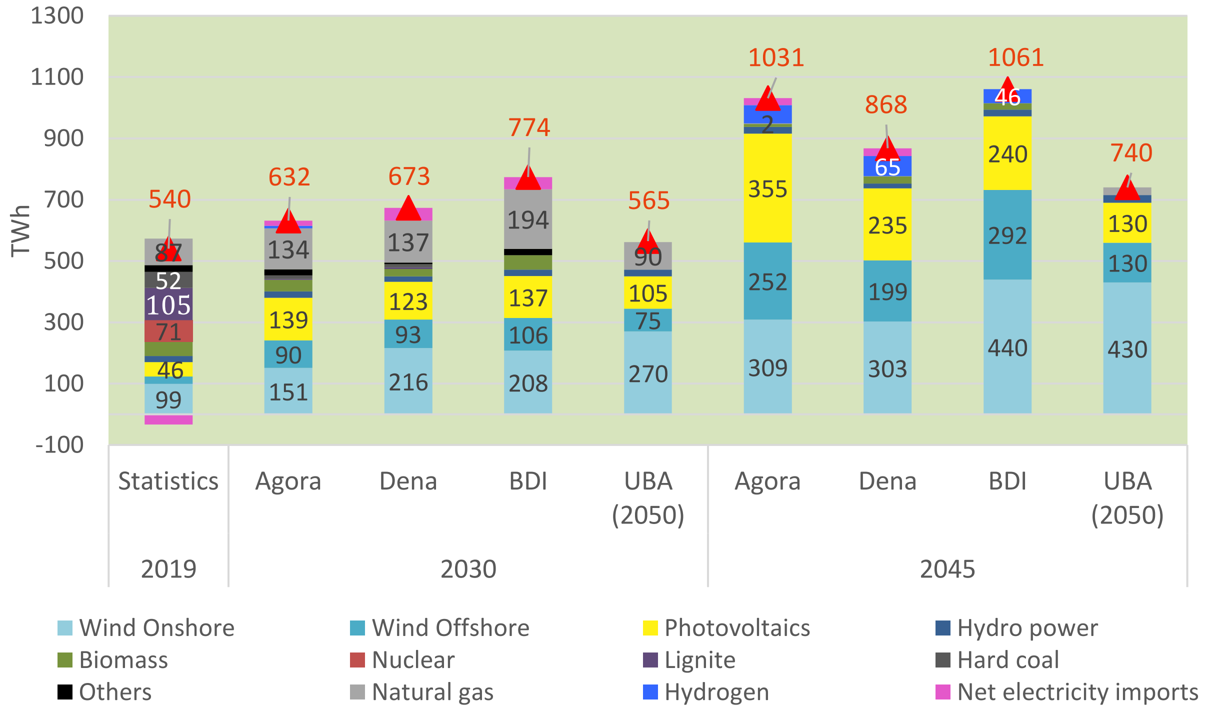
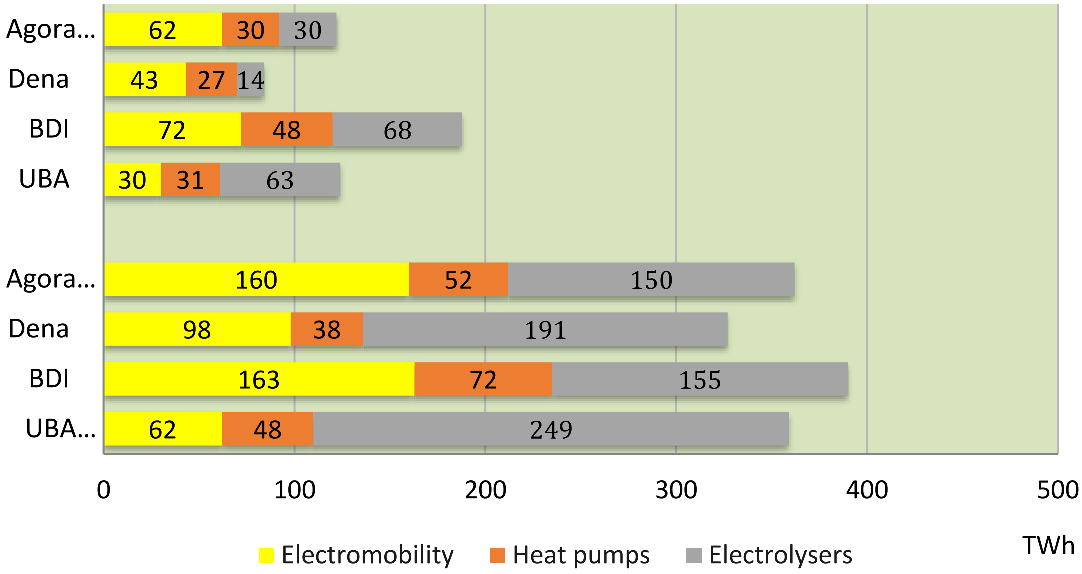


Figure 13: Power demand of "new" uses of electricity in German scenario studies (in TWh)



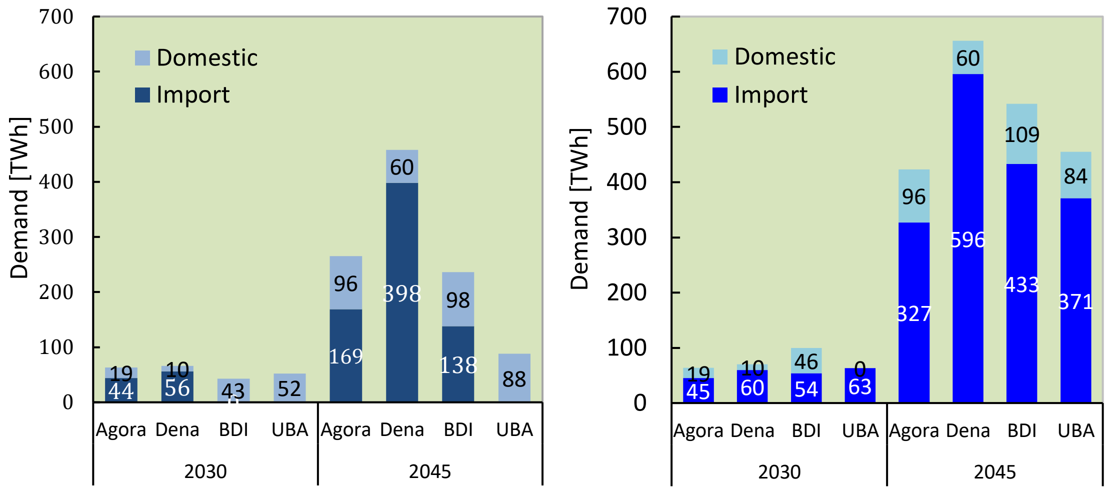
5.2.3 Hydrogen and PtX as energy source and raw material

However, renewable energy and electrification alone will not be enough to decarbonize the economy. In some fields gaseous and liquid energy sources will still be needed, so that the decarbonization of the industry, the energy and the transport sector in Germany also strongly depend on an increasing use of hydrogen and PtX. Hydrogen will be used for 5 to 10 per cent of power generation (e.g., during 'dark doldrums'), Direct Iron Reduction in steel production, as raw material in the basic industry, for process steam generation and for heavy freight, fuel cells of trucks and semi-trailers. PtX will be especially used in international shipping and air traffic, thus reaching a significant importance in 2045.

Figure 14 shows the hydrogen and PtX synfuels demand in 2030 and 2045 and it illustrates a considerable big range of expected demand and production or import amounts. This is an area, in which the four scenario studies differ most widely. The dena study estimates the highest demand, both for hydrogen (458 TWh) and synfuels (656 TWh) in 2045, most of which would have to be imported, while the UBA GreenSupreme scenario considers much lower demand (Hydrogen: 88 TWh, PtX: 455 TWh) in 2045.

While all studies emphasize that the domestic hydrogen and synfuel production would be preferable, it is mostly assumed that Germany will continue to be an energy import country. To meet the GHG emission reduction goals and ensure the financial feasibility, significant imports will be needed: for hydrogen between 60 and 90% (130-400 TWh/yr), for PtX ca. 77-90% (320-600 TWh/yr). Only the UBA GreenSupreme scenario considers hydrogen to be fully produced domestically by 2045. This needs to be related to the overall lower energy demand that the UBA GreenSupreme scenario assumes, according to which the domestic green power potentials would be sufficient to cover the green hydrogen production. Samadi/Lechtenböhmer (2022) underline, however, that the energy imports in 2045 will be 70 percent lower than today´s imports of fossil energy sources.

Figure 14: Hydrogen and PtX-Synfuels demand in Germany

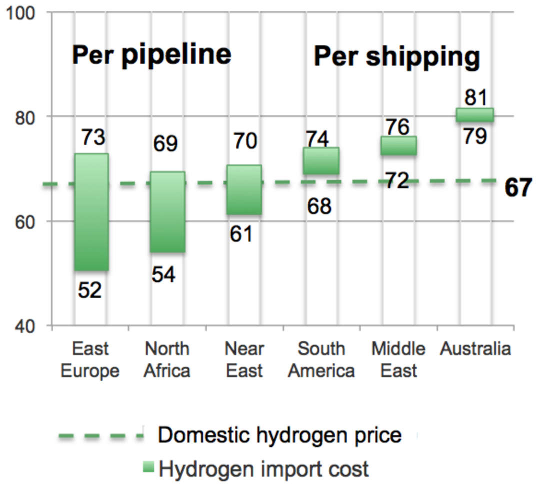


Since hydrogen for the time being will be mostly imported, the price will depend on the region of origin and the means of transport. Figure 15, extracted from the dena study, illustrates the respective price differences arising for imported hydrogen: Countries outside Europe often have better conditions for renewable electricity production. However, the more favorable production conditions are countered by longer distances for hydrogen transport. Especially for distant countries, from where hydrogen will need to be transported to Germany by ship, transportation costs account for a large share of the total hydrogen import costs. The import via pipelines from Eastern Europe, North Africa, Middle East appears cheaper than by ship from South America, Middle East and Australia. Accordingly, the price range fluctuates. Finally, geopolitical considerations must be taken into account as well, as the current situation in Eastern Europe painfully shows.

It is commonly agreed in all studies that *green* hydrogen production has to be pursued. Natural gas will drop to almost zero in 2045. Accordingly, in 2045/2050, almost all gas for power plants has to be green hydrogen to reach carbon neutrality. This implies that power plants that may still be fed by natural gas in the period 2030 to 2045 must already be constructed "hydrogen-ready" to convert them gradually to hydrogen.

In addition to the optimized use of biogenic energy sources, the studies project a need for further engagement in the national and international market development of hydrogen and PtX synfuels.

Figure 15: Hydrogen import costs to Germany by region in 2045 (dena 2021)



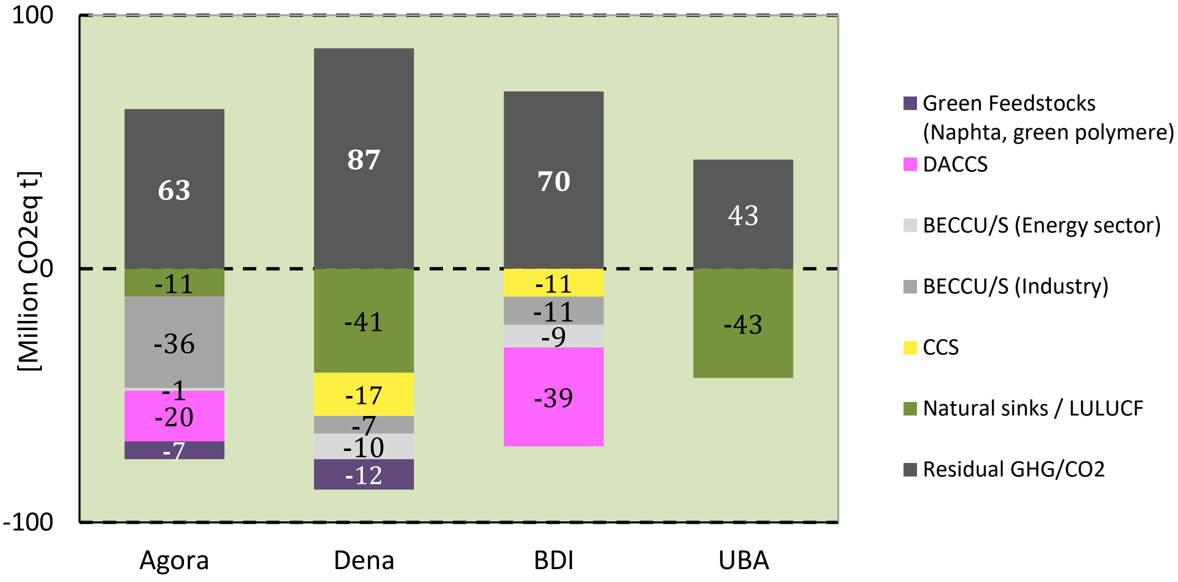
5.2.4 Removing residual greenhouse gas emissions

It is expected that despite all measures and efforts, some greenhouse gas emissions particularly in the agriculture, industry and waste sectors, will remain inevitable. For 2045, the analyzed scenarios expect residual emissions of about 43 to 87 billion tCO_2eq

(cf. Figure 16). These amounts range from about 5 to 10% of the emissions in 1990, and compensation appears feasible. But the relevance of technical and/or natural sinks is considered quite differently across scenarios. Especially the authors of the Agora and BDI study claim that the use of direct and indirect carbon capture technologies needs to be practiced earlier and with more emphasis. Most of the scenarios emphasize BECCS as a main strategy. Dena and BDI also assume some CCS for natural gas, and BDI considers DACCS as the most important option.

The GreenSupreme Scenario does not focus on technical measures for carbon dioxide storage (CCS), because CCU is considered to be required for the provision of electricity-based hydrocarbons (in PtG/PtL technologies). But since national priority is given to the production of hydrogen for industry, the nationally produced PtG quantities are limited and thus also the need for CO_2 sources. Instead, the GreenSupreme focuses solely on natural sinks. Also, the dena study states natural sinks as a major option.

Figure 16: Technical and natural negative emissions 2045 (in million tCO_{2eq})



6. Japanese-German Comparison

Authors: The Institute of Energy Economics, Japan and Wuppertal Institute for Climate, Environment and Energy

The selected scenarios in both countries follow a back-casting approach, seek to reach economic solutions with a focus on cost efficiency and are assuming similar framework conditions. Identified common strategies to reach climate neutrality are the reduction of energy demand through improved energy efficiency, the shift in the energy mix towards climate neutral energy carriers, the electrification of energy end uses, and the compensation of residual GHG emissions through technical sinks. However, details, characteristics and targeted shares differ, as shown below.

6.1 Improving energy efficiency

Japan: The primary energy demand on average decreases about 33%, only REI is more ambitious with a reduction of 50% until 2050 (from ca. 5,100 TWh in 2020 to a range of 4,700 (NIES) to 2,000 TWh (REI)). The final energy demand decreases by 30% (from 3,361 TWh to approximately 2,500 TWh). The analyses of the demand side are not sufficiently shown by current studies. In the future, it is recommended to assess the impact/potential on the demand side in more detail.

Germany: Improving energy efficiency is a key point to reduce CO_2. In the analyzed scenarios, the primary energy demand between 2019 and 2045 decreases on average by 50% (from 3,557 TWh to a range of 1,883 to 1,794 TWh), with the BDI scenario achieving a slightly lower reduction of 44% (2,003 TWh). The final energy demand in the analyzed scenarios decreases between 2019 and 2045 by 36% (from 2,484 TWh to a range of 1,604 to 1,572 TWh), whereas for the UBA scenario that has a special focus on energy efficiency and sufficiency, it even reaches a decrease of 57% (down to 1,056 TWh in 2050). Potentials must be fully exploited according to the

UBA scenario, even if this may exceed the current targets and strategies of the government.

6.2 Energy mix

Japan: Concerning the primary energy mix, the Japanese scenarios differ. The share of fossil energy decreases from 85% (2020) to 0-10% (REI, NIES) or 40-50% (RITE, IEEJ scenarios with CCS) in 2050. The share of renewable energies in the generated electricity mix rises from 20% in 2020 to 100%–(REI) or 40-70% for the other scenarios. The installation of renewable energies is limited because of land use restriction. If a massive expansion of renewable energies should be adopted, renewable energy sources would have to be installed in restricted areas such as forests or farmland.

In contrast to Germany, nuclear energy is also considered as a supporting energy carrier towards climate neutrality by most scenarios. In addition, final energy consumption from gas and oil remains for transportation or industries, including steel or chemical. The residual greenhouse gas emissions are compensated by using DAC and CCUS.

In many Japanese scenarios, electrification is determined as a model result while some scenarios may consider electrification as an assumption. If marginal electricity costs are lower than the costs for other technology combinations such as gas + DAC or gasoline + DAC, electrification will tend to increase. Many scenarios show the share of electricity in final energy demand also increasing up to 40–50%, since the total final energy consumption is reduced by 2050.

Germany: In German scenarios, the share of renewable energies in primary energy rises to 95%, and to 100% in electricity production by 2045. Thus, compared to Japan, the installation of renewable energies is significantly higher. In order to achieve this, massive additional capacities of on- and offshore wind power (174-250 GW) and PV (119-385 GW) are needed. The higher numbers consider the available potential for wind energy in Germany, but not the complete PV potential, because it does not fully include e.g. building-integrated and agri-PV.

The electricity supply-demand balance can be assured by all kinds of flexibility options and some 5-7% of gas-fired power generation (including H_2). Hydrogen from other countries and from electricity by offshore wind is a key option to reduce CO_2 in industry and transportation. Nuclear energy is not included in the model assumptions, because the German government decided on the nuclear phase-out to be completed by 2022. In most scenarios, coal power would be phased out by ca. 2030.

6.3 Key technologies to fully reduce CO_2 emissions

This section first relates to options used in the scenarios for fully reducing the *energy-related* GHG emissions. Afterwards, options for emissions from other sectors are discussed.

Japan: DAC (approximately 100-200 Mt CO_2 per year) and CCS are considered key options to reduce CO_2 from e.g. gas power plants or furnaces in those scenarios that still see a considerable share of fossil fuels in 2050. However, it is uncertain how much CO_2 can be stored by CCS (see also chapter 7.1.2). Other scenarios, such as REI, rely on hydrogen imports instead of fossil fuels.

Germany: The import of zero-carbon fuels, such as green hydrogen and derived PtX fuels, is a key option to meet the overall final energy demand. Maintaining the electricity supply-demand balance depends on domestic flexibilities, domestic green hydrogen, and in some scenarios, limited net electricity imports. Nuclear power plants are generally assumed in the models to be phased out by 2022.

While the Japanese scenarios stress the need to consider various technologies (including nuclear energy) so as to ensure cost-efficiency and energy security, the German scenarios underscore that energy security can go along with positive economic effects and the impact of innovations, while phasing out nuclear and coal energy.

In addition to energy-related emissions, particularly in the sectors agriculture, waste treatment, and some industrial processes it appears difficult, if not impossible, to fully reduce GHG emissions, and the remaining emissions will need to be removed from the atmosphere through various technologies, such as those discussed in chapter 5.2.4. All German scenarios, therefore, consider technical sinks as an inevitable strategy. However, the envisaged quantities are relatively low. For about 5% of remaining GHG emissions, mostly from the non-energy sectors, natural sinks, BECCS and DACCS are the most important options considered. Remarkably, the BDI puts emphasis on DACCS.

7. Shortcomings to achieving the net zero carbon target for 2050 in Japanese scenarios and enhanced or new strategies

Author: The Institute of Energy Economics, Japan

7.1 Gaps

All Japanese scenarios assume achieving carbon neutrality in Japan by 2050. And all models focus only on Japan. Hence, none of the models shows any implication of the 1.5-degree-reduction-target that must be achieved worldwide. In order to discuss the possibility to reach the 1.5-degree, it is necessary to develop a worldwide model assessment. Although it is difficult to discuss the worldwide potential to meet the 1.5-degree-target based exclusively on this scenario comparison, to achieve the results predicted by the models, it is important to analyze the gap between ideal scenario results and reality.

7.1.1. Social acceptance for installation of nuclear and renewable energies

All Japanese scenarios consider either nuclear power plants or renewable energy as important power sources to achieve carbon neutrality. As for nuclear power plants, almost all scenarios model only with existing nuclear power plants or those that are already in the planning. Only RITE and IEEJ develop scenarios allowing new constructions. Although the scenarios show that new constructions potentially contribute to a reduction of total integration costs based on model analysis, cost-analysis considering safety measures should be carefully evaluated, as German studies argue that the construction of new nuclear power plants in Germany is not cost-effective (DIW 2019). In addition to this, social acceptance regarding restarting or constructing nuclear power plants is a key issue to implementing these scenarios. Following the Fukushima accident in 2011, many residents are opposed to restart nuclear power plants because of safety concerns.

The issue is raised not only for nuclear power but also for renewable energies. Many scenarios show a massive installation of renewable energies to achieve carbon neutrality. As a result, the percentage of renewable energies in generated electricity in 2050 is approximately 40-100%. However, for achieving this capacity, PV systems or wind turbines must be installed in restricted areas such as forests or farmland. Even for offshore wind energy systems, wind turbines must be installed in the near shore area which has a negative effect on the coastal landscape or is restricted by the fishery rights in that area. In Japan, fishers have a strong legal basis to refuse developments in areas covered by fishery rights based on the Fishery Act. For example, they have the right to claim losses caused by development changes and seek injunctions. Therefore, developing offshore wind energy in areas covered by fishery rights is impossible without the consent from the fishers.

7.1.2. Potential of CO_2 storage

Many Japanese scenarios assume utilizing CCS or DAC to capture CO_2 from power plants or industry plants such as furnaces. The scenarios set the upper limit of CO_2 capture capacity at approximately > 1000 million t / year. The CO_2 storage requires large areas of land, but it is not clear, how big the CO_2 storage potential on the Japanese territorial land or oversea is. If CCS or DAC could not be fully utilized as the scenarios show, more electricity from renewable energy or electrification is required and total energy system costs will increase. Thus, it should be noted that the feasibility of scenarios using CCS or DAC depends on the potential of CO_2 storage capacity.

7.1.3. Feasibility of massive installation of storage systems

The Japanese scenarios show that a massive installation of storage systems is required as renewable energies increase (>1000 GWh). Even if 10 kWh storage systems were installed in currently existing residential homes (290 GWh), the capacity cannot be satisfied with the required capacity to maintain hourly energy supply-demand balance. Moreover, materials shortages are also a concern in regards to lithium. Hence, not only economic feasibility but also the material supply risks of storage systems should be taken into account.

7.2 Enhanced or new strategies to close the gap

Although many Japanese scenarios draw pictures of carbon neutrality by 2050 using back-casting models, there is no scenario that convincingly proves the feasibility of climate neutrality by 2050. As described above, all scenarios have some kind of critical issue such as social acceptance or the potential of CO_2 storage. If a specific technology is excluded in the scenario assumption, the number of possible strategies to achieve carbon neutrality is also limited. Hence, it is important to seek various low emission technologies, not only renewable energies, but also to include nuclear power, CCS, DAC and ammonia power plants. To come closer to the pictures drawn by the scenarios, the following strategies are considered important.

7.2.1 Establishing a process to gain consensus from stakeholders

Given the estimated increase of nuclear power plants or massive installations of renewable energies in order to reach carbon neutrality, the need of social consensus will increase respectively. However, a concrete process to gain consensus from stakeholders or local residents has not been sufficiently established. Especially for PV systems or onshore wind, there are no specific rules on how to take the opinions of stakeholders or local residents into consideration. Hence, it is important for the feasibility of scenarios to consider the question of how to reach consensus among stakeholders and/or local residents to enable the massive installation of renewable energies or nuclear power plants.

7.2.2 Consistency between local spatial planning and carbon neutrality

Up to now, some of the PV systems or onshore wind turbines — for instance, those in forests — proved to have negative effects on the local environment and wildlife / biodiversity. According to a report by the Japanese Forestry Agency, the total area of deforestation attributable to the installation of PV systems is more than 90 km^2, which is equivalent to an installed PV power capacity of 6 GW (Japanese Forestry Agency, 2019). In the case of onshore wind energy systems, 56% of systems installed after 2004 were in forests or wilderness areas (MoE 2011). Given these facts, the Japanese government now considers spatial planning called “positive zoning” to determine those areas where only few or no negative effects on nature through the installations of photovoltaic (PV) systems and wind turbines are to be expected. Therefore, the expansion of renewable energies to the end of reaching carbon neutrality and the spatial planning that regulates the installation are in a trade-off relationship. For example, many scenarios implying renewable energy may have to be installed in restricted areas such as forests, but these areas are possibly excluded from positive zoning areas. Hence, it is essential for decision-makers who determine renewable energy targets to also take spatial planning into consideration. Moreover, it is also important to develop agri-PV by ensuring crop production and reducing the impact on the landscape.

7.2.3 Assessing the impact of non-power sectors for carbon neutrality

Many current Japanese scenarios focus on the power sector. However, non-power sectors such as the industry sector and the transportation sector account for approximately 50% of total CO_2 emissions. It is thus important to also consider the non-power sector when aiming at carbon neutrality. Hence, future scenario analysis should also include key strategies for non-power sectors to approach carbon neutrality.

8. Shortcomings to achieving the net zero carbon target for 2045 in German scenarios and enhanced or new strategies

Author: Wuppertal Institute for Climate, Environment and Energy

The German scenarios presented in Chapter 5 all underscore the technical feasibility of achieving carbon neutrality by 2045 while presenting somewhat different pathways with varying degrees of energy demand reduction, electrification, renewable energies, the use of hydrogen and hydrogen-based synthetic fuels, and carbon sinks.

The basic strategies in the German representative scenarios are comparable and can be summarized as follows.

- the nuclear phase-out will be completed in 2022;
- coal-fired power generation must be phased out well ahead of 2038, ideally by 2030;
- the expansion of renewable energies and, above all, renewable power generation is massively accelerated;
- the rate of energetic refurbishment of the building stock is increased considerably, and *deep renovation* must be achieved during retrofit processes; energy efficiency is also increased in the industry sector, and some potentials of sustainable transport are harnessed;
- decarbonization of the transport, building and industry sectors takes place as far as technically and economically possible through direct (green) electrification
- the expansion of the hydrogen economy – with increasing proportions of imports (hydrogen and PtX) – plays an important role mainly after 2030.

Indeed, numerous scenarios also from other institutes, even with different technical and energy policy positions, nevertheless reflect *a broad scientific consensus on the technical feasibility* of climate neutrality in Germany by 2045 with regard to the basic strategies. In all scenarios, the phase out of nuclear energy in 2022 is assumed to be safely manageable. The basic availability of less risky climate protection technologies to achieve climate neutrality by 2045 is no longer in question in any scenario. Instead, the discussion focuses on fundamental questions about the socio-economic relevance of the strategies and scenarios as well as on the tension between scenarios, levels of ambition and implementation, which will be addressed below.

In this respect, various shortcomings can be identified that could be resolved by a number of additional strategies that should be considered in prospective studies. Through a stronger analysis of the necessary policies and these additional strategies, the reliability of the scenarios and the confidence that carbon neutrality will be achieved in practice by 2045 can be enhanced. They will make the rationale of highly ambitious climate mitigation policies more understandable and acceptable for the public. On this background and backed with additional analysis, it might be possible to achieve carbon neutrality even faster than by 2045, eventually by around 2035.

8.1 Shortcomings of technology-focused German scenarios

The selected German scenarios are strongly focused on *energy-related strategies* and the associated *technical feasibility* of decarbonization. A special focus is on the electricity market and on the differentiated analysis of a renewable electricity supply. This is undoubtedly a crucial pillar of ambitious climate protection policy, but the essential socio-economic aspects are only addressed in the BDI study, while the behavioral aspects (e.g. rebound and growth effects or the opposite, more sustainable consumption patterns) of an energy transition are not touched upon at all or only marginally in all scenarios, with the exception of the UBA study.

8.1.1. Energy efficiency first

Energy efficiency plays an important role in all scenarios to reduce the overall demand. Still, in most scenarios, the existing potentials, particularly in the transportation and building sectors, but also in the industry sector, are not fully exploited. Hence, the principle of ‘energy efficiency first’ is not fully considered. Only the GreenSupreme scenario of the UBA takes a larger potential into consideration. The combination of

material efficiency and circular economy strategies is also only partially pursued, e.g. by the UBA study and to a certain degree by the BDI study. Without a policy integration of climate and resource protection, the strategy is biased towards supply-focused electrification strategies.

8.1.2 Socio-economic aspects

While technical feasibility is a crucial prerequisite of transformative paths to decarbonization, economic optimization of possible pathways is also important. However, in the selected studies, the simulation of **macroeconomic effects** is missing or only carried out in the first steps. Moreover, challenges such as area restrictions related to the estimated intensive installation of renewable power plants and the importance of **social acceptance** are not fully anticipated in most studies. The same holds true for material restrictions related to PV and wind power (silicon, rare earths). With regard to social acceptance, **distributional effects** for households, companies and regions also deserve closer attention in order to devise the necessary narratives of a just transition; they are only analyzed to some degree in the BDI study. In this context, rebound and lifestyle effects (values, behavior), sufficiency policies and issues of change management (innovation/exnovation) also need to be shed light on. To date, only the UBA study includes some of these aspects.

8.1.3 Policies for the actual implementation of the strategies

Most scenario studies conclude with a list of policies that are perceived as being able to reach the calculated scenario results. However, usually the studies do not directly model the impact of concrete policy instruments and packages, which are needed to enable and incentivize both the technical and behavioral actions needed for the transition.

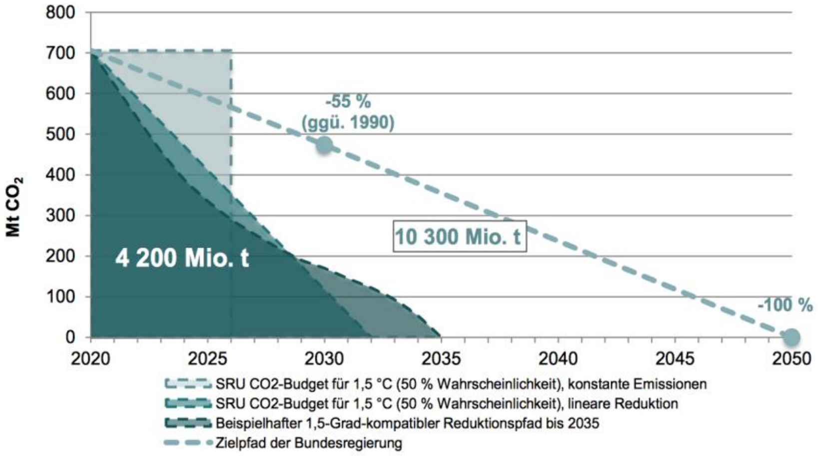
8.1.4 The ambiguous role of hydrogen

While the importance of including significant amounts of hydrogen and hydrogen-based synthetic fuels is common ground among the studies, only little is said about the challenges that come along with it: Neither do the scenarios present detailed concepts on the necessary infrastructure, nor do they thoroughly discuss possible target conflicts concerning (domestic and) imported hydrogen (e.g. perspectives of exporting countries/global competition/international standards for certifying green hydrogen/synfuels).

8.1.5 Compliance with international commitments: how to reach the 1,5°C-target

Finally, the scenarios fail to explicitly discuss whether the ambition level and the strategies they provide suffice to achieve the internationally agreed 1,5°C-target. The studies by Agora, dena, and BDI only focus on the analysis of if and how the carbon neutrality target for 2045 could be achieved. Applying the aforementioned budget approach (cf. chapter 5), the Wuppertal Institute showed that the global CO_2 budget compatible with the targets of the Paris agreement demands for even more ambitious targets: As the graphic below illustrates, Germany would have to reach climate-neutrality as early as 2035, because the remaining CO_2 budget of 4,200 tons would have been consumed by then.

Figure 17: Exemplary Emission Reduction path according to a German 1.5°C budget



Source: Wuppertal Institute 2020; based on SRU 2020

It must be emphasized that the study of the Wuppertal Institute (2020) as of today (March 2022) still is an initial illustration for Germany that has not yet been backed-up by a complete scenario analysis. However, it highlights that Germany's contribution to a global strategy “keeping 1.5 degrees within reach” requires a tremendous additional effort. Nevertheless, the authors of the study sum up: “A climate-neutral energy system by 2035 is very ambitious, but fundamentally feasible if all strategies that are possible from today's perspective are joined together" (Wuppertal Institute 2020[15]).

Thus, the key challenge remains how the technology-focused strategies in the existing highly ambitious scenarios must and can be combined with stronger policies or other policy integration options, e.g. with sufficiency, circular economy/material efficiency, and stronger energy efficiency policies, to reach carbon neutrality ideally in 2035.[16] It should therefore be examined whether and to what extent the existing energy-related scenarios can be linked and supplemented with corresponding quantified sub-scenarios, in order to establish robust strategies for policy advice (see chapter 9).

8.2 Enhanced or new strategies to close the gaps

Corresponding to the aforementioned shortcomings, the following strategies are suggested to be included in future scenarios and connected analyses: (1) the integration of circular economy strategies, (2) the consideration of sufficiency policies, lifestyle changes, (3) just transition and public/social acceptance, and (4) the inclusion of policies and policy integration in the modelling.

8.2.1 Integration of circular economy (CE) strategies

The integration of circular economy strategies into climate protection policies unfolds significant synergies related to material and energy efficiency: Including the use of raw materials into the scenario analysis would also help to avoid problem shifting to critical metals and unsustainable extraction facilities. The technical potentials do exist, but every kilowatt hour avoided through energy and material efficiency would facilitate the

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[15] https://wupperinst.org/a/wi/a/s/ad/5169

[16] A so called global „Societal Transformation Scenario (STS)"has been published recently: „The...results for the STS show a large decline in energy demand in the Global North and a reduction of global GHG emissions of roughly 50% from 2020 to 2030 and a further 22% (12.7 Gt CO_2eq) by 2050. The cumulative CO_2 emissions remain within the carbon budget that gives us a 2/3 chance to staying within the temperatur increase of 1.5° C." (p.10). The assumed redistribution of wealth, power, consumption and production might be utopian but it presents food for thought to analyze opportunities and risks of including sufficiency policies into technically focussed scenarios. https://www.boell.de/sites/default/files/2020-12/A Societal Transformation Scenario for Staying Below 1.5C.pdf?dimension1=division_iup

expansion of renewable energy generation and particularly help to reduce the immense implementation problems (e.g. space requirements, network expansion, resource consumption, import requirements, acceptance).[17]

8.2.2 Consideration of sufficiency policies, lifestyle changes

To ensure a comprehensive analysis of the pathway towards climate-neutrality, socio-economic aspects need to be considered. This includes values, change-management, innovation and exnovation strategies. Most important societal topics of socio-economic transformation (e.g. behavior shifts, societal tipping points, mobility patterns, floor space, living comfort, eating habits, reducing meat/dairy products, food waste, etc.) sometimes cannot easily be included into existing modelling approaches. Also, a transformation of the agricultural sector with fewer livestock, more organic farming, an increase of non-productive areas and biodiversity should be considered. The risk that a scenario-based “proof“ of the technical feasibility leads to wishful thinking and unrealistic target-setting should be avoided. For example, rebound effects, the inertia of lifestyles, or growth effects are a reality and they should be anticipated into scenario assumptions and procedures as much as possible.

8.2.3 “Just transition” and citizen participation

The socio-economic transformation and enormous economic structural change on the way to carbon neutrality makes it imperative to anticipate possible detrimental or supporting distribution and welfare effects. For example, carbon pricing will have a regressive impact on households and can induce carbon-leakage if not supported by compensation measures. Also, wind power and huge ground-mounted PV might face strong local opposition. But refunding a part of the revenues from carbon pricing, citizens participation, financing and local benefit sharing can increase public acceptance for the transformation. Thus, *just transition* should be a basic focus of scenario-related analysis and it should be directly included into scenario assumptions and strategies.

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[17] Compare Acatech (2021), Circular Economy Roadmap for Germany; acatech/Circular Economy Initiative Deutschland/SYSTEMIQ (Eds.) Update December 2021.

In Germany, for example, the coal regions and – foreseeable – the automotive sectors are focal points of structural change. Thus, macro-economic analyses are of utmost importance, but they should be combined with calculating net effects, e.g., for jobs, added value, income and budgets referring to regional hotspots of economic structural change.

8.2.4 Analysis of policies and policy integration, and their inclusion in the modelling

Finally, the analysis of policies, which are needed to implement both, the technical and behavioral actions needed for the transition, need to be included in the models to offer a more realistic view on whether and how targets can be achieved. In addition, policy integration (e.g. heading for a sustainable and just mobility not only relying on electrification or integrating the housing and the overall city planning) allows for a comprehensive view on the endeavor of reaching climate-neutrality. For example, through the integration of comprehensive policies in the scenario strategies, the potential of technical (e.g. prefabricated buildings), economic (e.g. overcoming split incentives), institutional innovation (e.g. one-stop-shops for targeted advice and support, decentralized heat networks) and social goals (e.g. affordable housing for low income families) can be addressed in comprehensive policy packages.

As mentioned above, probably the most ambitious targets of the scenario-based policies in Germany refer to the heating sector and the retrofit of the existing building stock. Achieving a doubling or even a tripling of the retrofit rate and a rapidly growing share of renewable energy for heating systems implies a comprehensive policy mix to drive complex system changes, not only in single buildings, but also in neighborhoods and districts.

9. Overall conclusions

In this study, a comparative analysis of recent long-term scenarios to reach climate-neutrality in Germany by 2045 and Japan by 2050, respectively, was conducted. The objective was to identify, which strategic technological options are being considered and what transferable lessons can be learned. The analysis revealed some similarities in the approaches as well as divergent assessments (cf. chapter 6). Also, shortcomings of prevailing scenarios and opportunities to use scenario comparisons as an instrument for social learning were identified. Following are some general conclusions which can be derived:

9.1 Strategic technological options

For both countries, the scenarios underscored the importance of energy efficiency and of a forced market introduction of renewable energies. The shift towards a more climate-neutral energy mix is supported by expanded electrification of the building and transport sector and the increased use of ‘green’ or at least low-carbon hydrogen and synthetic fuels. Finally, both countries also consider technical carbon sinks to compensate residual (“hard to abate”) greenhouse gas emissions. Comparing the strategic *technology options* of German and Japanese scenarios, three important differences can be summarized:

(1) The amount of energy reduction

The reduction of primary and final energy by 2045/2050 in German scenarios seems to be more pronounced than in Japanese scenarios. These differences should be further explained, e.g., how far this impact is related to more ambitious energy efficiency improvements or pronounced acceleration of renewable energy sources or different patterns of structural change. As the UBA GreenSupreme scenario demonstrates, also within the selected range of German scenarios there are apparent differences concerning the implementation of the “Energy Efficiency First” principle of the IEA.

(2) Energy mix: Interpretation of the term *climate-neutral* technology

While Germany aims at a share of renewable energies of almost 100%, including the use of 100% green hydrogen/synfuels by 2045, the renewable energy share in Japanese scenarios varies from only 40 to 100% in Japan (until 2050). Although hydrogen in Japan is also considered as an important strategic pillar of decarbonization, the focus is not necessarily on green hydrogen, due to a lower share of electricity from renewable sources. Another reason might be that international pipelines for hydrogen supply are not easily available in Japan. Additionally, almost all of the selected Japanese scenarios also include nuclear energy and the continued use of fossil energy with CCS technology. The feasibility of these technologies depends on how much potentials for CCS is available, how far renewable energy costs and storage costs will decrease and whether social acceptance of nuclear power plants and CCS can be achieved.

(3) Residual emissions and removals:

The German scenarios target at full decarbonization of the energy sector, fewer residual emissions from the non-energy sectors and relying both on technical and natural sinks. The majority of Japanese scenarios – due to a larger residual share of fossil fuels – result in higher remaining greenhouse gas emissions, including those from the energy sector, and therefore need to strongly rely on CCS, including DACCS (cf Chapters 4, 5, 6).

9.2 Improved scenario approaches

But there are also shortcomings in both countries regarding the methodology and the use of scenario analyses as well as in policy mixes to effectively guide the fundamental structural changes and the transition strategies elaborated by the scenarios.

It seems to be worthwhile to address them by future research cooperation on scenarios.

In brief the recommendations can be summarized as follows:

- Operationalize the principle “Energy Efficiency First” (IEA) and conduct a comprehensive assessment of energy efficiency potentials, costs and co-benefits in all sectors
- Prioritize direct electrification (where feasible) instead of gas-based pathways, due to the higher energy efficiency, by a factor 3 to 5, and hence lower needs to expand low-carbon power supply
- Develop integrated energy and material efficiency approaches by combining climate protection and Circular Economy (CE) strategies
- Combine technically focused strategies with elements of sufficiency strategies, including enabling strategies towards sustainable production and consumption
- Consider barriers and policies to achieve social acceptance, by reflecting also area restrictions, possible problem shifting (e.g. concerning critical metals) and nature conservation
- Integrate socio-economic distributional aspects dealing with just transition, reflecting regional structural change, resilience, citizen participation and citizen financing
- Focus on sector coupling and policy integration, e.g. concerning transportation (e.g. e-mobility) and buildings (e.g. heat pumps, district heating/cooling)
- Continue efforts towards the market introduction of risk-minimizing, low-carbon technologies to avoid lock-in effects into high-risk technological pathways (e.g. coal or nuclear energy)

It is evident that the uptake of these recommendations must be considered and evaluated in an international and geostrategic setting. This setting might currently be perceived predominantly as a threat (see outlook), but it would be wise to recognize the long-term opportunities as well. This general recommendation can be summarized as follows: Assess the opportunities of long-term global dynamics, innovations and competition of transformative strategies and technologies to carbon neutrality. Global technical and market developments might change the optimum energy mix in the direction of rapid climate neutrality, more energy security, further cost degression of low-risk technologies and less resource conflicts on fossil fuels.

9.3 Interlinkages between scenario modelling and policies

In both countries there is a close exchange between the scenario community (e.g., think tanks) and politics. In the past, e.g. in Germany, political targets regarding GHG emissions reductions were often justified by scenario-based back-casting approaches. Accordingly, the GHG reduction targets (2050/2045) defined by the governments appeared more based on a prevailing perception of the current government what might be *"feasible"*[18] than on the internationally agreed GHG reduction targets that are deemed *necessary*: limiting global warming to well below 2°C, if possible to 1.5°C. Thus, in order to develop comprehensive, independent and research-based climate policy approaches, two prerequisites need to be taken into account: 1) global necessities and 2) national possibilities.

9.3.1 Global necessities

IPCC in particular, represents a benchmark for national climate mitigation policies based on the latest international scientific insights. According to the budget approach, "what is necessary" requires a normatively based answer to the question of an appropriate and responsible national contribution to global climate protection. Thus, the ambition level of national climate policies and the back-casting target year of decarbonization scenarios should ideally be in line with global targets and agreements, such as the Paris Agreement 2015.

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[18] E.g. the Agora study, the only available scenario prospecting climate-neutrality until 2045 at the time of the revision of the German climate protection law in 2021, can be said to have strongly influenced the political decisions.

9.3.2 National possibilities

While taking into account the global necessities, it is also indispensable to consider the national possibilities of ambitious GHG emissions reduction targets. The question on national possibilities cannot solely be answered by emphasizing the technological feasibility. Instead, scientific knowledge, political majorities, social acceptance and economic interests are key factors that need to be reflected in national climate policies. To this end, it is of utmost importance that the scenarios provide an analysis of socio-economic aspects as well. Yet, scenarios also need to consider that policy is able to shape national possibilities, e.g. by accelerating technology implementation and learning, and by measures to increase acceptance. Only if the important role of science is acknowledged, scenarios can significantly contribute to promising climate policies.

9.3.3 Strengthening the supporting role of science – scenario-based stakeholder dialogues

The future is uncertain and the uncertainty increases when decisions on decarbonization strategies for the target year 2045/2050 have to be taken today by majority votes and consensus. Scenarios can be a powerful instrument of consensus building not only within the research community or between research and policy, but also related to the interests of different stakeholders and the broad public.

In Germany, there are some successful processes showing how scenarios contributed to consensus building on climate protection targets and a consensus-oriented formulation of the climate law in the state of North-Rhine Westfalia (NRW). [19] Furthermore, there are first positive experiences by establishing citizens assemblies[20] on climate policy in Germany, which were supported by scenario-based research. The integration of civil society actors that is enabled in such formats and processes can be evaluated as an important prerequisite of broader social acceptance.

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[19] e.g. Schepelmann (2018)

[20] https://www.buergerrat.de/en/news/climate-assembly-in-germany/

9.3.4 International cooperation

Against the background of international competitiveness, a pivotal role can also be attributed to international cooperation, e.g. bilaterally between Japan and Germany or in a multinational context like the EU, the G7 or the G20. Synchronous and mutually reinforcing activities worldwide can help to increase the public support for even more vigorous climate policies at the national level.

Substantial and coordinated steps forward towards climate neutrality in Japan and Germany could induce important impulses to stimulate modernization, innovation and investment dynamics worldwide, putting the “well below two degrees” statement of the Paris declaration into reach.

9.4 A bright or a frightening outlook?

At the time of writing and finalizing this study (March 2022), the invasion of Ukraine by the Russian army has already caused endless human suffering and victims. The current expectation is that the end of the war and its catastrophic consequences are not yet in sight. It is likely that not only the entire geopolitical structure and the balance of power will change, but that the global energy system and climate policy will also be massively affected. So, does this war of aggression change everything for the energy world and the energy futures outlined above for Germany and Japan? One thing is certain: the perception of energy import dependency will change fundamentally, not only in Europe and Germany, but worldwide. Too much dependence on fossil fuels obviously affects peace and freedom, so it must be reduced as quickly as possible and, in the future, reduced to zero, not just because of climate protection, but for minimizing geostrategic conflicts. Kilowatt-hours saved or gained from sun and wind do not cause or finance wars. For example, Germany's dependence on Russia for imports of 55% for natural gas, 45% for coal and 34% for oil is extremely dangerous for Germany and indispensable for Russia's military apparatus. But the 15 nuclear power plants and the 55% share of nuclear power in the Ukraine are a recognizable high risk as well, which should be reduced as quickly as possible after the end of the war, hopefully soon. Minimizing all risks connected with the domestic use of energy sources and the interdependent risks of all imported energy for the exporting and the importing countries should be taken much more into the research focus of long-term scenario approaches than in the past.

So, is everything changing? It is possible that climate protection will be pushed into the background again by the war. But it is also possible that there will be a growing recognition that energy efficiency and renewable energies are possible "freedom technologies" (as the German Minister of Finance called them), because they reduce conflicts about fossil fuels and other risky energy technologies, thereby minimizing potentially catastrophic life risks. In this respect, many options such as energy efficiency and renewable energies will be solutions for both climate action and improving energy security – a win-win situation. Nevertheless, a general risk check is required for the key energy transition and climate protection strategies and paths (Fischedick 2022). This also applies to conceivable new import dependencies in a globalized hydrogen economy or for PV panels.

It seems that bilateral research between Japan and Germany and within the GJETC is confronted with many new research topics, which should be addressed by intensified cooperation.

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