

# Integrated multidimensional sustainability assessment of energy system transformation pathways – Supplementary Material

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## 1. List of all analysed studies and scenarios.

Table 1: Overview of all scenario studies taken into account during the scenario selection process

Authors / Institutions	Commissioned by	Title	Year	Scenario Variants
DLR, FhG IWES, IfnE	BMU	Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland	2012	BMU12-A BMU12-B BMU12-C BMU12-THG95
	UBA	Treibhausgasneutrales Deutschland im Jahr 2050	2013	UBA13-THGND
EWI, GWS, Prognos,	BMWi	Entwicklung der Energiemärkte – Energiereferenzprognose	2014	BMWi14-REF BMWi14-ZIEL
J. Nitsch	BEE	GROKO II – Szenarien der deutschen Energieversorgung auf der Basis des EEG-Gesetzesentwurfs	2014	NIT14-GROKO NIT14-100
Öko-Institut, FhG ISI, H.-J. Ziesing	BMUB	Klimaschutzszenario 2050	2015	BMUB14-AMS BMUB14-KSSz80 BMUB14-KSSz95
Wuppertal Institut	SDSN/IDDRI	Pathways to deep decarbonisation in Germany	2015	SDSN/IDDRI15-T SDSN/IDDRI15-E SDSN/IDDRI15-90
FhG IWES, ifeu	BMWi	Interaktion EE-Strom, Wärme und Verkehr	2015	IWES/IFEU15-IntEEStrom
FhG ISE		Was kostet die Energiewende? Wege zur Transformation des deutschen Energiesystems bis 2050	2015	ISE15 - 80-g-k-nb ISE15 - 80-g-CH4-nb ISE15 - 80-g-H2-nb ISE15 - 80-g-el-nb ISE15 - 80-g-mix-nb ISE15 - 80-amb-mix-nb ISE15 - 80-amb-mix-b ISE15 - 85-amb-mix-b ISE15 - 90-amb-mix-b
BET, Hamburg Institut, Greenpeace Deutschland	Greenpeace Deutschland	Klimaschutz: Der Plan - Energiekonzept für Deutschland	2015	GP15-PLAN
J. Nitsch	BEE	Die Energiewende nach COP 21 - Aktuelle Szenarien der deutschen Energieversorgung	2016	NIT16-TREND NIT16-KLIM50 NIT16-KLIM40
J. Nitsch		Erfolgreiche Energiewende nur mit verbesserter Energieeffizienz und einem klimagerechten Energiemarkt - Aktuelle Szenarien 2017 der deutschen Energieversorgung	2017	NIT17-TREND NIT17-MEFF NIT17-HEFF
ifeu, FhG IWES, CONSIDEO, Dr. Karl Schoer SSG	UBA	Den Weg zu einem treibhausgasneutralen Deutschland ressourcenschonend gestalten	2017	UBA17-GreenEe
enervis energy advisors GmbH	INES, BWE	Erneuerbare Gase – ein Systemupdate der Energiewende	2017	INES-ME INES-OS
FhG ISI, ifeu, Consentec	BMWi	Langfristszenarien für die Transformation des Energiesystems in Deutschland	2017	BMWi17-REF BMWi17-Basis BMWi17-gNetz BMWi17-altEE BMWi17-restarm
Jacobson et al.		100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries in the World	2017	JAC17-WWS
DECHEMA et al.	Leopoldina, acatech, UddAdW	„Sektorkopplung“ – Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems	2017	ESYS17
BCG, Prognos	BDI	Klimapfade für Deutschland	2018	BDI18-REF BDI18-80 BDI18-95
dena, ewi Energy Research & Scenarios gGmbH	dena	dena-Leitstudie - Integrierte Energiewende. Impulse für die Gestaltung des Energiesystems bis 2050	2018	dena18-REF dena18-EL80 dena18-EL95 dena18-TM80 dena18-TM85
GWS, Prognos, DIW, FhG ISI, DLR	BMWi	Gesamtwirtschaftliche Effekte der Energiewende	2018	BMWi18-KF BMWi18-EWS

## 2. Documentation of selected harmonised re-modeled scenarios

Here we present some central results of the harmonised re-modeled scenarios. More details (energy balances, installed capacities,...) can be found on the project website: <https://www.innosys-projekt.de>

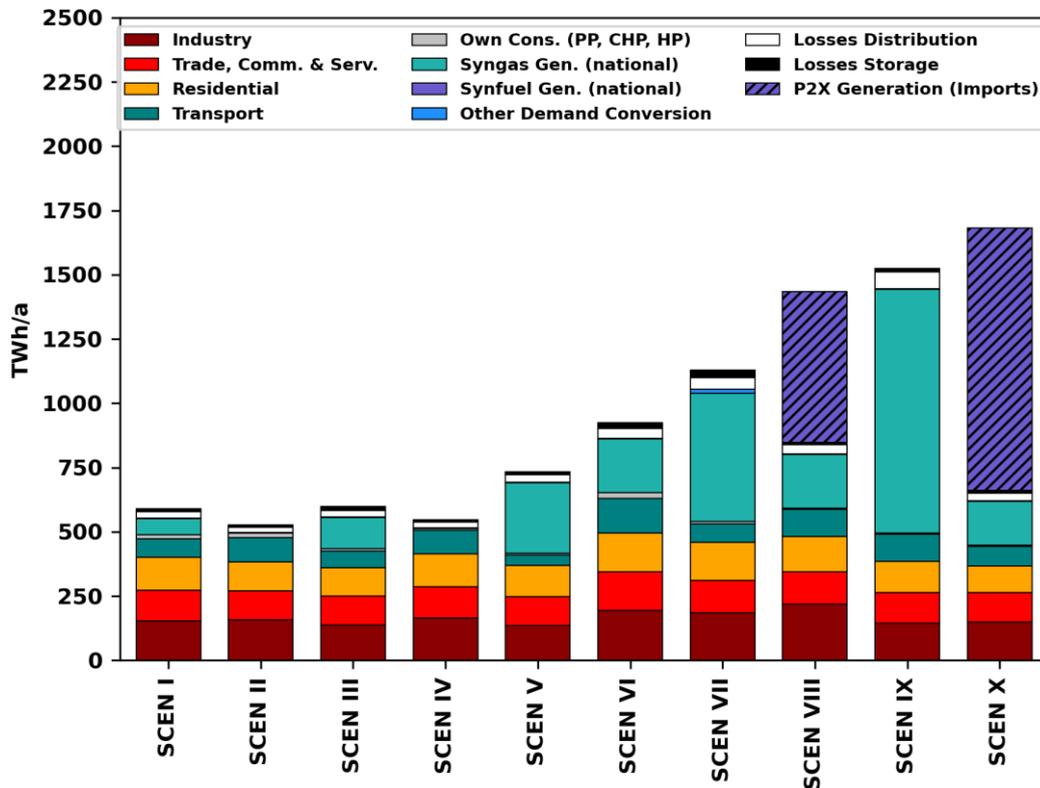


Figure 1: Power demand per sector (including power demand for P2X imports)

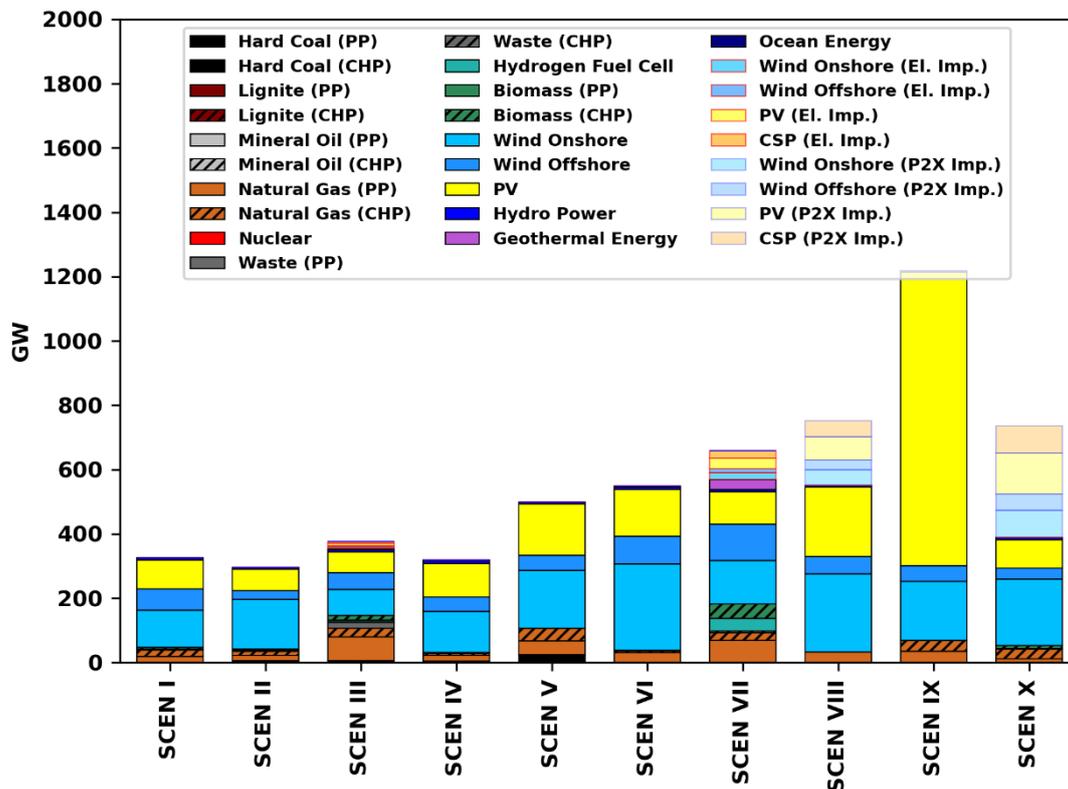


Figure 2: Installed capacity power generation in remodeled scenarios (including installed capacities for P2X imports)

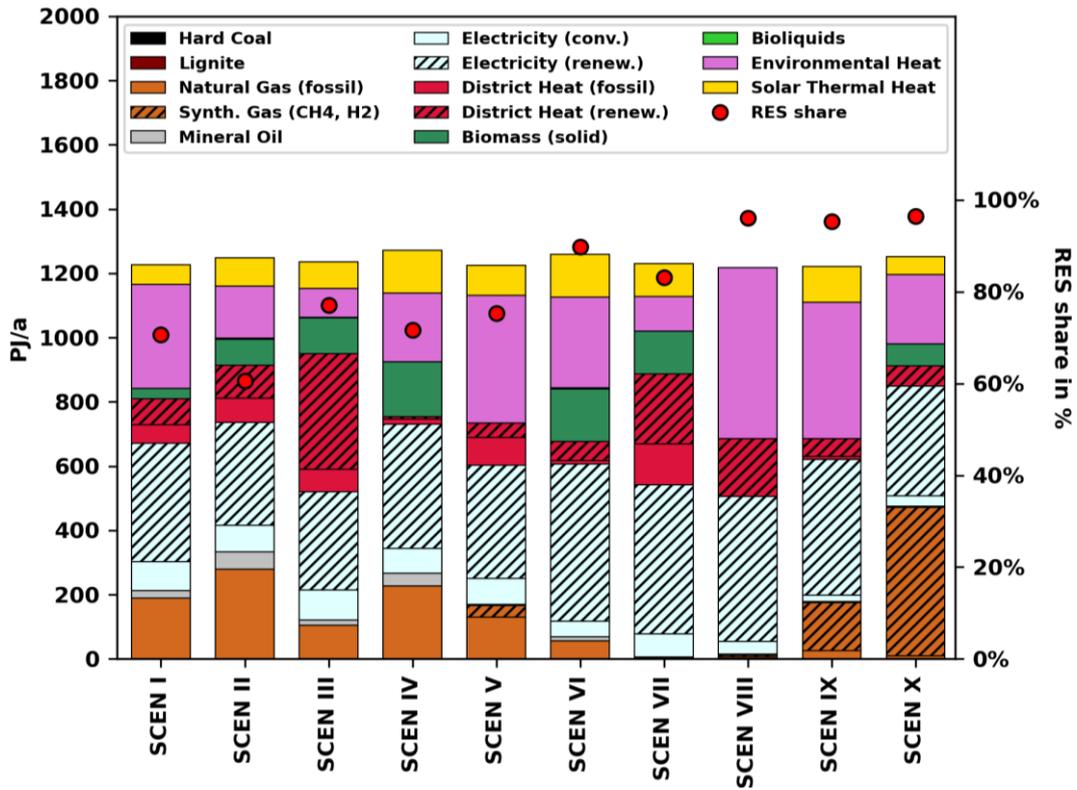


Figure 3: Final energy demand and resulting share in renewable energies in residential sector

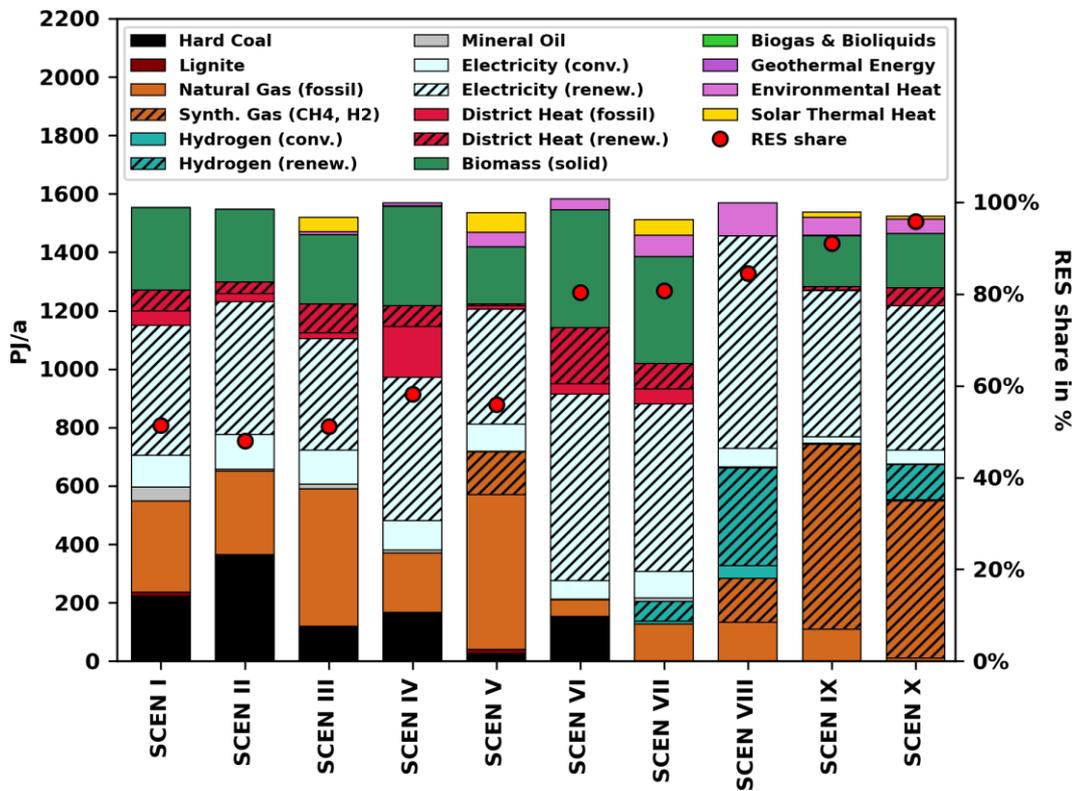


Figure 4: Final energy demand and resulting share in renewable energies in the industry sector

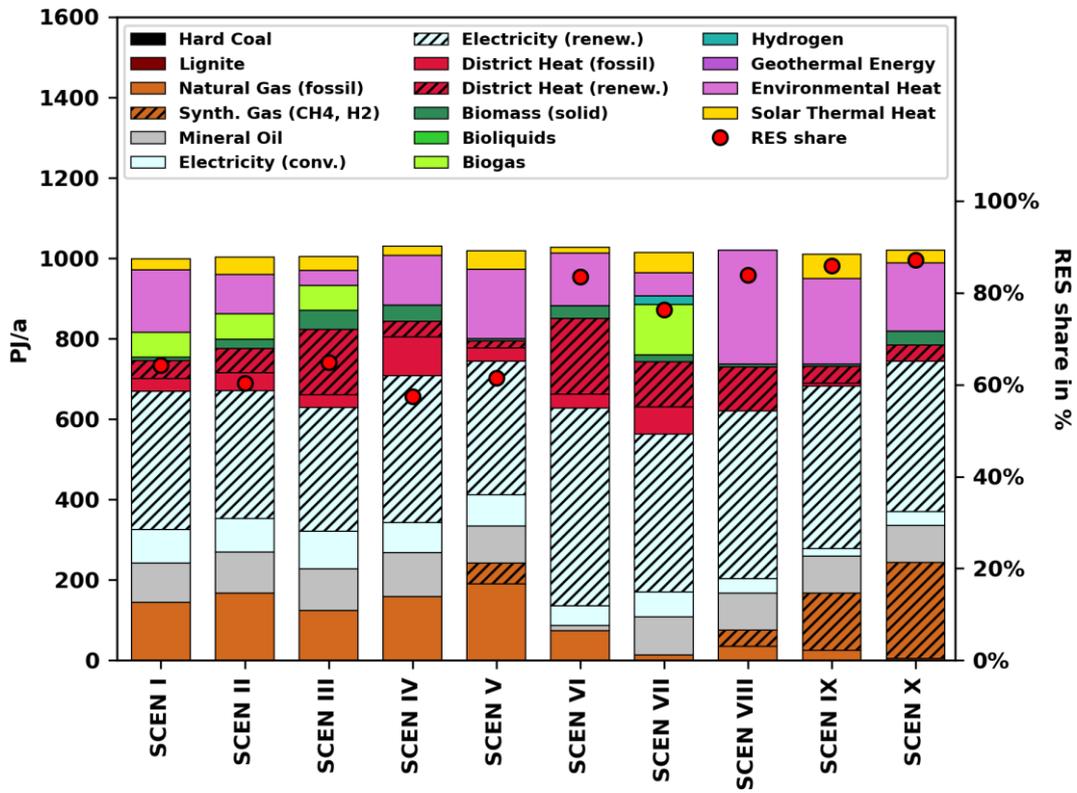


Figure 5: Final energy demand and resulting share in renewable energies in the sector trade, commerce, and services

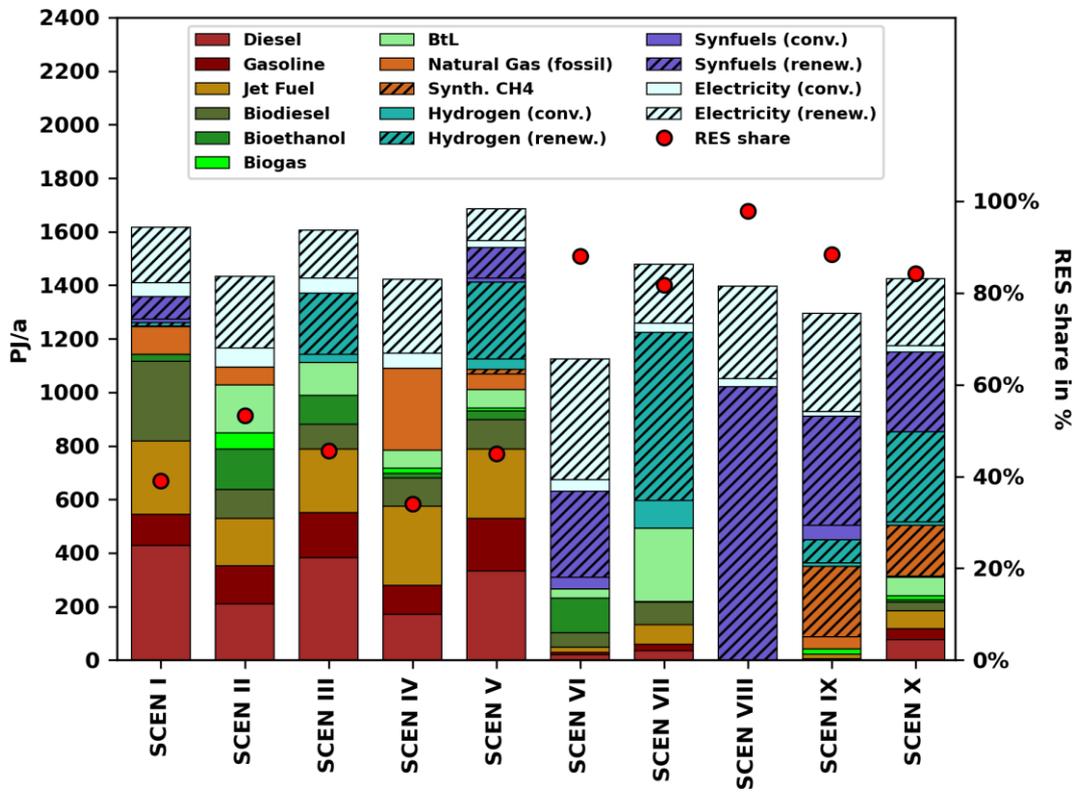


Figure 6: Final energy demand and resulting share in renewable energies in the transport sector

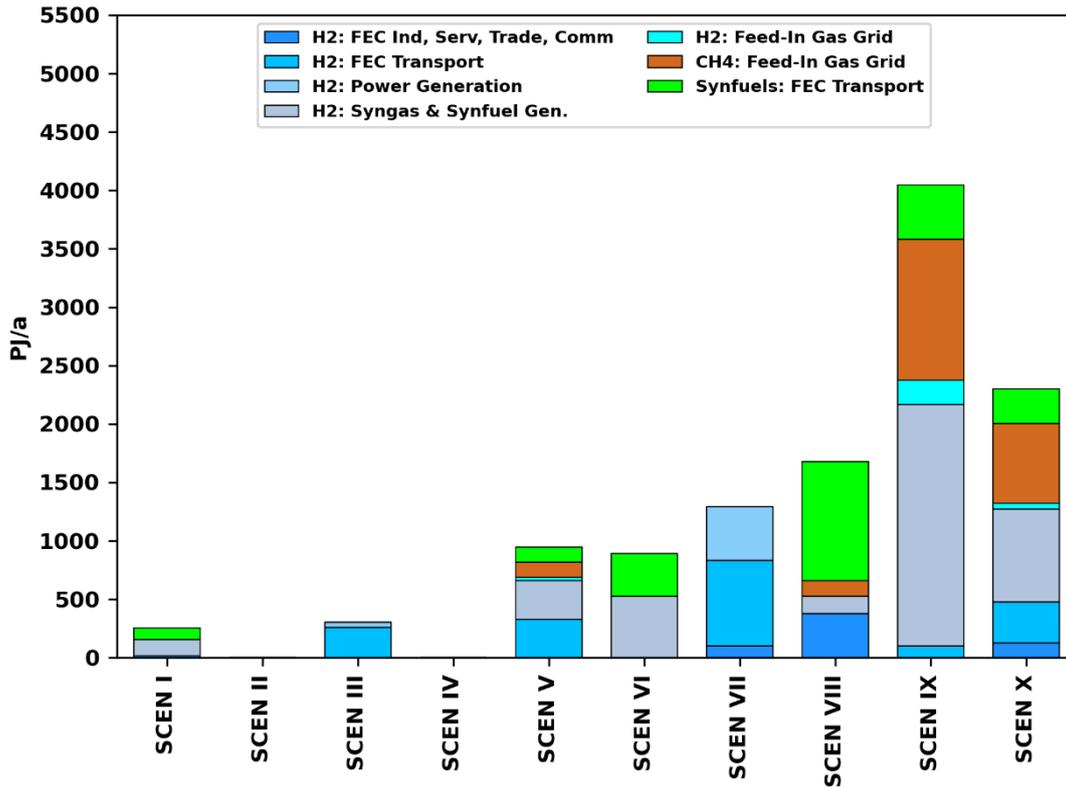


Figure 7: Consumption of synthetic gases (H<sub>2</sub>, CH<sub>4</sub>) and fuels

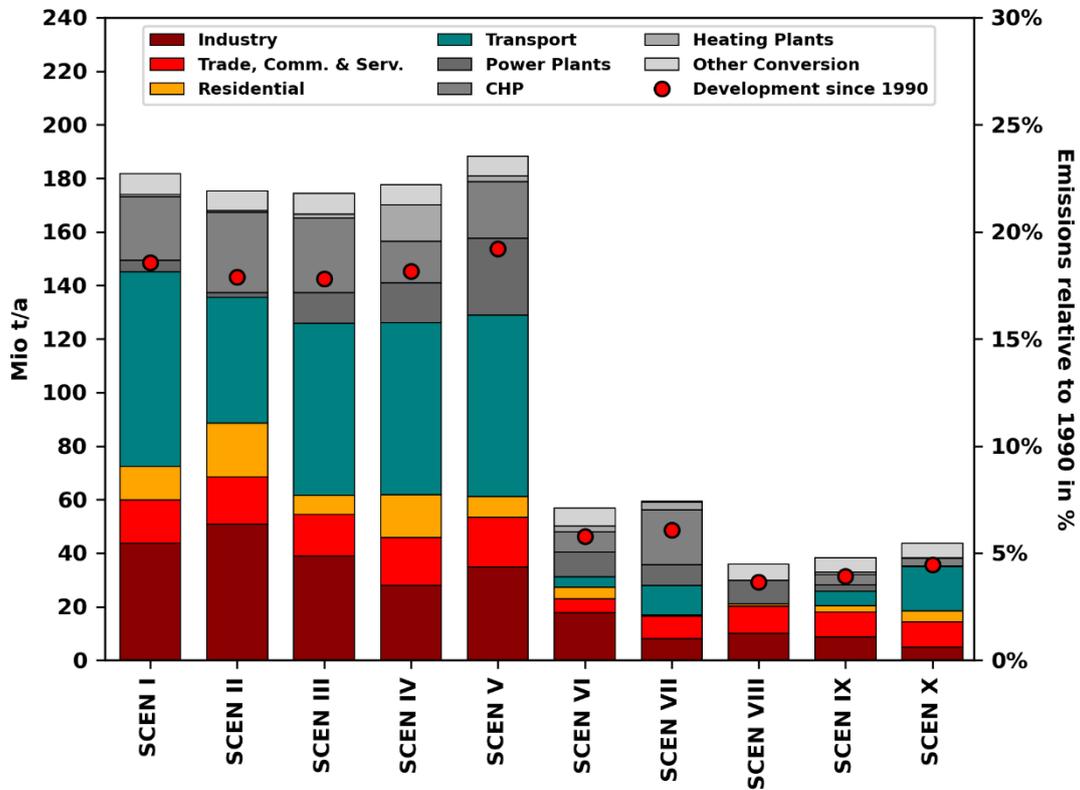


Figure 8: Direct, energy-related CO<sub>2</sub> emissions

### 3. Short description of the models

#### 3.1. MESAP

The harmonized re-modeling of the scenarios was done with the the decision support system Mesap/PlaNet (Modular Energy System Analysis and Planning Environment [1]). The Mesap/PlaNet model is an accounting framework that is used, among others, to develop normative scenarios for energy systems [2-6]. Scenario development with Mesap/PlaNet is based on background knowledge and exogenously defined premises considering detailed studies of issues such as the efficiency of demand sectors, future technologies and their implementation potentials, regulative interventions, and market developments and their effects. Therefore, experience and knowledge of the scenario developer is essential to the scenario building process, as he/she enjoys a certain degree of freedom when selecting model parameters. The model serves as a framework for integrating a wide variety of aspects of energy system transformation. It differs fundamentally from optimization models that apply a cost minimizing objective function. Resulting effects of the scenarios can be estimated, e.g., in terms of energy demand and supply structures, emissions, and energy costs. Energy model calibration was done using available statistical information such as official energy balances.

Because of its flexibility, MESAP is ideally suited to re-model scenarios from other studies.

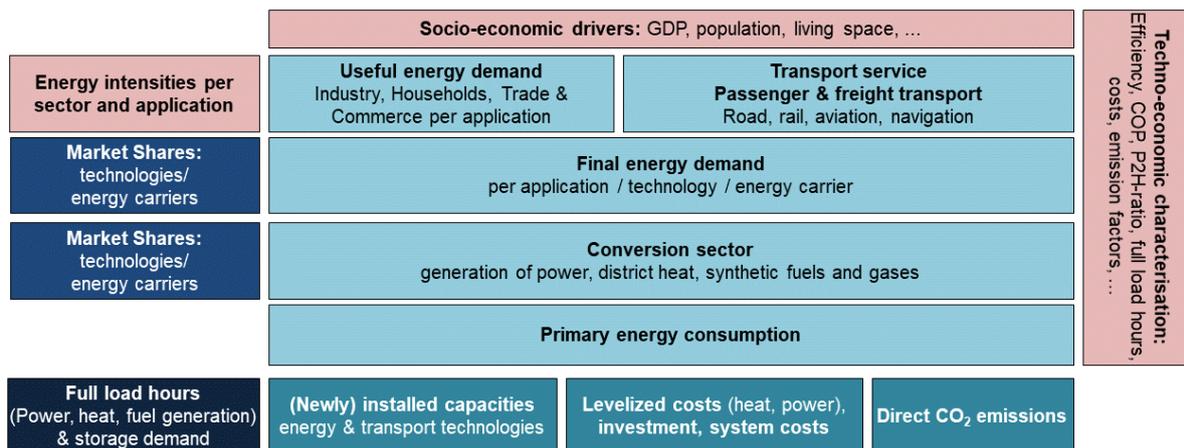


Figure 9: Schematic overview of the structure and workflow of MESAP. For details see main text.

In the InNOSys project, MESAP uses the following quantities as boundary conditions for all the re-modeled scenarios (red fields in Figure 9):

- Database with techno-economic characterization of energy and transport technologies (efficiencies, COP, power-to-heat ratios, invest & O&M costs, technical lifetime, ...)
- Socio-economic drivers (GDP, population) (taken from [7])
- Energy Intensities allow the calculation of useful energy demand for different applications (like space heat or process heat) in the different sectors as well transport services. (intensities: e.g. useful space heat demand per living space, useful process heat demand per gross value added) (based on [7])

The next step in the scenario development process is to set market shares for all relevant technologies in the final energy and conversion sectors (blue fields in Figure 9). This could be for example the market shares of different propulsion technologies in passenger cars, the market shares of wind onshore, wind offshore and PV in total power generation or the market shares of different technologies to provide space heat in the residential sector. These market shares are taken as far as possible from the original studies (see Table 1 in main document). Thus, the technical strategies to fulfill the useful energy demand and the transport services are inspired by the original scenario study.

MESAP then calculates the entire energy balances from useful energy and transport services over final energy demand to the primary energy consumption.

MESAP's temporal resolution is one year. In order to calculate installed capacities & number of cars, assumptions on full load hours and annual mileage of individual plants and vehicle types are required (dark blue field in Figure 9). Furthermore, MESAP is not capable of calculating power storage demand. In order to obtain estimates on full load hours of power generation plants and power storage demand, MESAP is coupled with flexABLE as described in the main manuscript. Full load hours for the generation of space heat and hot water are uniformly set to 1650 h/a. Full load hours for the generation of process heat are uniformly set to 3500 h/a. Full load hours for electrolyzers: 4000h/a, methanation: 8000h/a, P2L: 7900 h/a, biogas generation: 8760h/a, biofuel generation 4000 h/a. The annual mileage of cars is uniformly set to 17,250 pkm/a (on average 1.15 people per car, 15,000 km/a per car). The annual mileage of trucks is set in order to obtain realistic values for the number of trucks in Germany from [8] for the year 2017.

When full load hours and annual mileage are provided, MESAP calculates the installed capacities for power, heat, synfuel and biofuel generation, as well as the number of cars and trucks. Furthermore, annual new installations are calculated based on an age cohort approach.

### 3.2. flexABLE

flexABLE is an agent-based electricity market simulation model. The model follows a bottom-up approach and includes main types of generation assets such as conventional power plants, variable renewable generators, and storage units. These assets, represented by agents, can participate in both an energy exchange market (or energy-only market EOM) and a control reserve market (CRM). Additionally, eligible power plants capable of heat co-generation, such as coal and gas power plants, can participate in the regional district heating market (DHM). In the current implementation, the model operates at a quarter-hour resolution for all markets except for CRM, where the market clearing for the reserve capacity occurs on a four-hour basis.

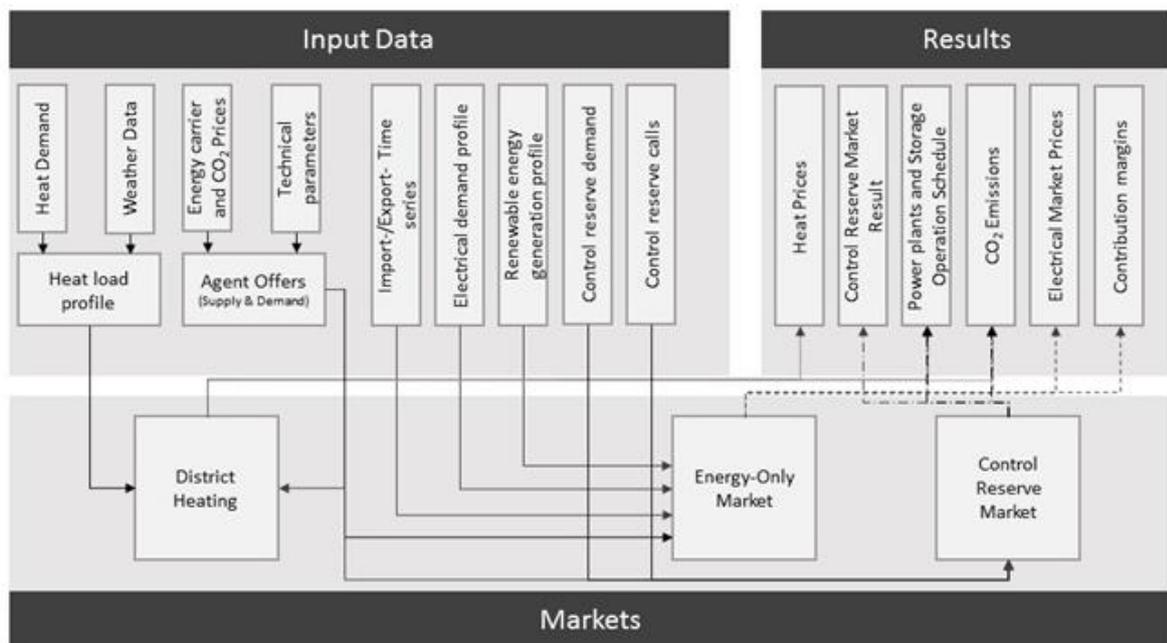


Figure 10: Overview of the Structure of flexABLE

A brief description of the simulation sequence is presented in the following. First, all eligible agents submit their bids on the CRM. In the current implementation, only conventional powerplants and storage units can participate in the CRM. Agents can submit CRM bids for both positive and negative reserve. Each bid includes the capacity, capacity price, and energy price. The submitted capacity price is used for the reserve capacity market clearing, and the energy price is used during the call for energy

market clearing. After the CRM clearing the agents receive feedback from the market. The feedback includes acceptance, partial acceptance, rejection, and call for energy if present. Second, eligible power plants submit their bids on regional district heating market and receive feedback after the market clearing. Third, agents formulate bids for the EOM based on several techno-economic parameters, such as marginal cost, shut-down cost, ramp-up or rump-down speed. After the EOM clearing happens, and the agents receive feedback about the market results. This procedure repeats for each time step during the simulation. As a result, this model allows for detailed simulation of single units' dispatch plans and the markets' outcomes. Details on the model can be found in [9].

### 3.3. PANTA RHEI

PANTA RHEI is an environmentally extended version of macroeconomic simulation and forecasting model INFORGE [10], developed for the macroeconomic evaluation of environmental protection measures and energy economic policy. To quantify these macroeconomic effects, the long-term structural change in economic development and environmental-economic interdependencies are modeled.

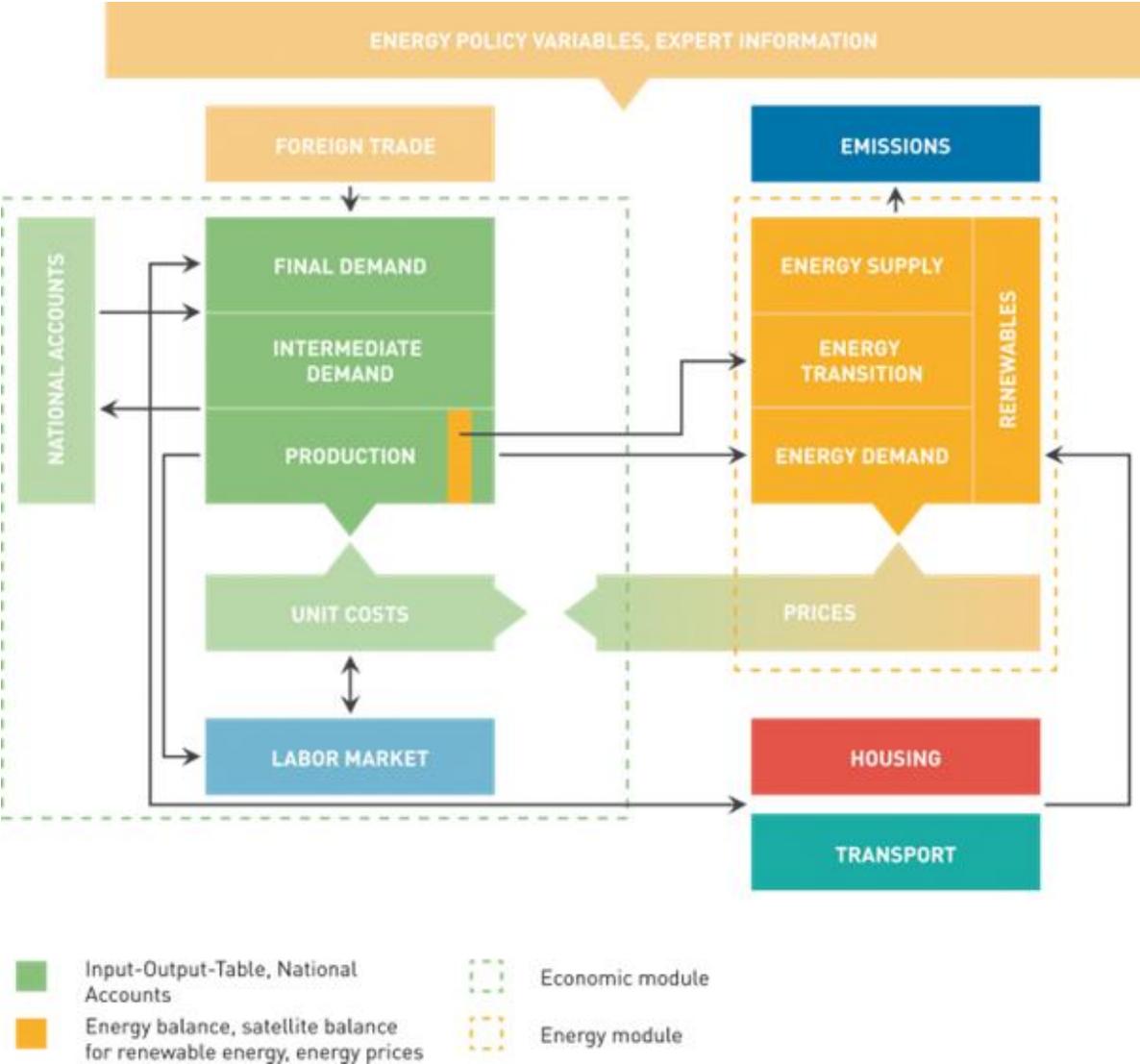


Figure 11: Overview of the PANTA RHEI model

The flow chart shown in Figure 10 provides an overview of the structure of the PANTA RHEI model. In addition to the comprehensive economic modelling, the sections of energy consumption and emissions as well as transport and housing are covered in detail. All model parts are consistently

linked to each other. For example, the transport sector models fuel consumption in litres, which, multiplied by the price per litre, feeds into input demand from the manufacturing sector and demand for consumer goods. Changes to fuel tax rates result in changes to tax receipts and a broad range of economic adaptation processes. However, changes in fuel prices also lead to changes in behaviour, which are also considered in PANTA RHEI. The model is solved with full interdependence, i.e., the impacts between all model variables are captured simultaneously.

The model contains a multitude of macroeconomic variables drawn from official statistics and provides disaggregated information on 63 economic sectors. Energy balances (including satellite balances for renewable energy) are fully integrated into the model. The behavioral parameters are econometrically estimated based on time series data.

The economic core model INFORGE is regularly used, among others, for long-term employment projections and simulations by the Institute for Employment Research and the Federal Institute for Vocational Education and Training [11, 12]. The model linkages are described in detail in [13]. The PANTA RHEI model has been used extensively in recent years, e.g., to evaluate the macroeconomic effects of the energy transition [7, 14] and to develop socio-economic scenarios [15].

### 3.4. Framework for the Assessment of Environmental Impacts of Transformation Scenarios (FRITS)

Figure 12 gives an overview of structure of the FRITS framework. For more explanations please refer to the main manuscript. Details on FRITS can be found in [16].

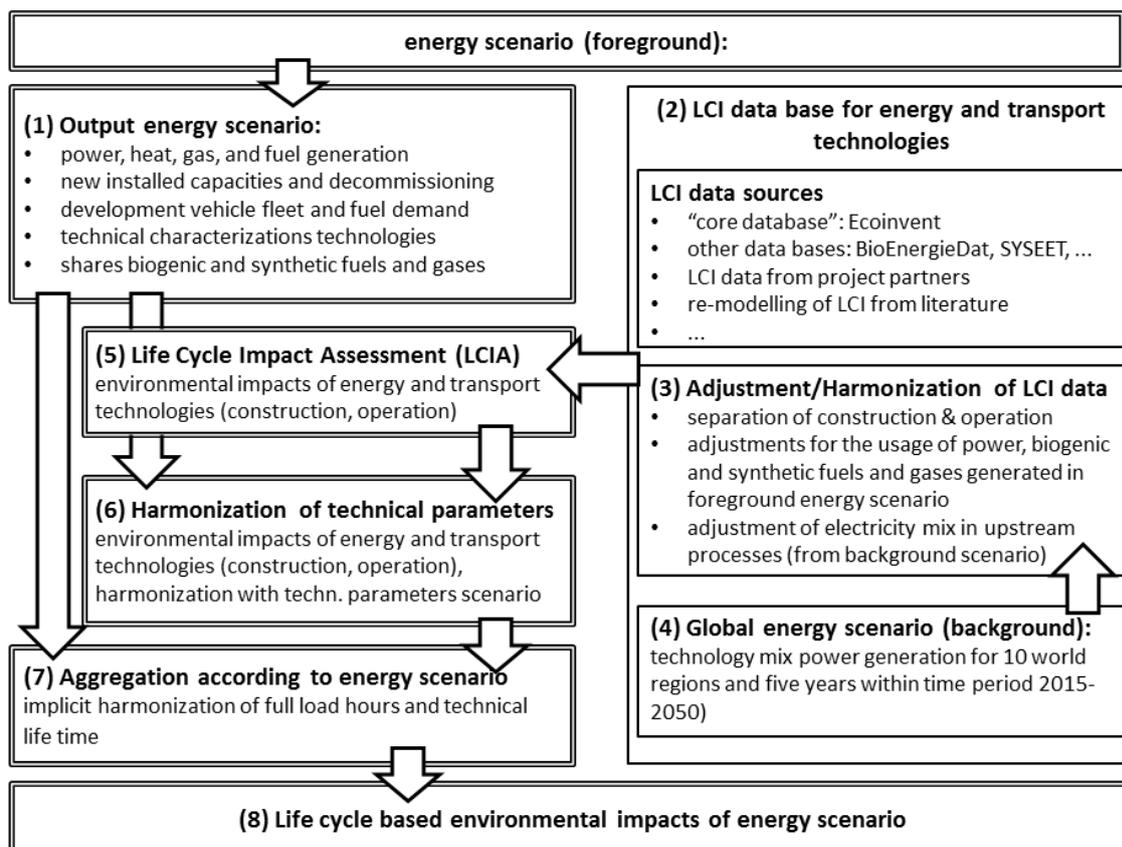


Figure 12: Overview of the workflow in FRITS (from [16])

#### 4. Documentation of approach for focus groups and conjoint analysis

This table shows how the seven basic technologies were bundled to pairs for the paired choice experiment in order to not compare a pair of only power generating technologies with one that generates power and domestic heat. For natural gas, two different sets of indicators were used – one of a typical power generating gas turbine (GAS-S), one of a domestic gas heating (GAS-W).

All Combinations	Conjoint Option A		Versus	Conjoint Option B	
1	WIND	PV		WIND	BATT
2	WIND	PV		WIND	GeoT
3	WIND	PV		PV	BATT
4	WIND	PV		PV	GeoT
5	WIND	PV		GAS - S	GeoT
6	WIND	BATT		WIND	GeoT
7	WIND	BATT		PV	BATT
8	WIND	BATT		PV	GeoT
9	WIND	BATT		GAS - S	GeoT
10	WIND	GeoT		PV	BATT
11	WIND	GeoT		PV	GeoT
12	WIND	GeoT		GAS - S	GeoT
13	PV	BATT		PV	GeoT
14	PV	BATT		GAS - S	GeoT
15	PV	GeoT		GAS - S	GeoT
16	WIND	GAS - W		WIND	W-Pumpe
17	WIND	GAS - W		WIND	P2G
18	WIND	GAS - W		PV	GAS - W
19	WIND	GAS - W		PV	W-Pumpe
20	WIND	GAS - W		PV	P2G
21	WIND	W-Pumpe		WIND	P2G
22	WIND	W-Pumpe		PV	GAS - W
23	WIND	W-Pumpe		PV	W-Pumpe
24	WIND	W-Pumpe		PV	P2G
25	WIND	P2G		PV	GAS - W
26	WIND	P2G		PV	W-Pumpe
27	WIND	P2G		PV	P2G
28	PV	GAS - W		PV	W-Pumpe
29	PV	GAS - W		PV	P2G
30	PV	W-Pumpe		PV	P2G

Figure 13: Technology pairs for paired choice experiment

Every person got one of four different sets of six decisions among decisions numbered 1 to 15 and six from among the decisions numbered 16 to 30. The sets were chosen so that every subsample of the focus groups was presented an evenly distributed technology pairs and decisions to create an even distributed decision table with at least 50 decisions per cell for stability of statistical calculations.

## 5. Workflow for the WSM (weighted sum model)

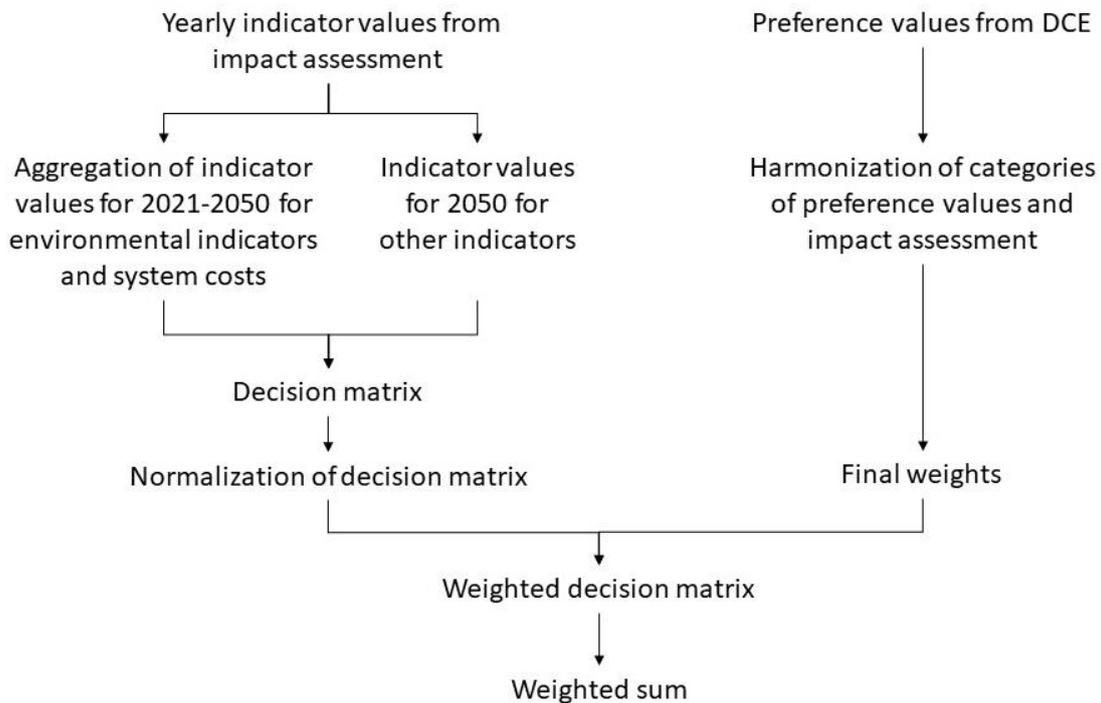


Figure 14: Workflow for the integration of indicator values from impact assessment and preference values from DCE in the MCDA (weighted sum model/WSM)

## 6. Selection of sustainability indicators

For the selection of the relevant and significant sustainability indicators an intensive literature research analysis was conducted. The analysis was systematised on the basis of the following procedure. First, literature was consulted that reflects the international and national discussion in Germany of sustainability or sustainable development in a political and scientific context in order to develop guidelines and frameworks for an sustainability assessment. Then the search was concentrated on literature which handles with energy technologies or a sector of the energy system. In a further step, literature on the assessment of environmental impacts of products, processes and services was evaluated, as the debate on environmental protection in an industrial society was the precursor to the concept of sustainable development. This early debate was about reducing anthropogenically induced material and energy flows through industrial society so that both the limited absorption capacity of the environmental compartments air, water, soil are not exceeded and the use of resources (raw materials, water, land) are not exhausted. In this context, a series of instruments for the quantitative environmental assessment of products and services have been developed, which both pursue a system-analytical approach and evaluate indicators for assessment via environmental modelling, which have been embedded in the concept of sustainable development and represent a part of the environmental-related sustainability indicators.

### 6.1. International and national literature on sustainable development

In the international debate on sustainable development, the UN publishes in the frame of the Programme of Work on the Development of Sustainability Indicators relevant documents, which

provide guidelines for countries. The first two sets of indicators of the UN Commission on Sustainable Development were published in 1996 and 2001 [17]. The UN commission has continued this work continuously over a period of 20 years until they published the 17 sustainable development goals (SDGs), which is a road map to ensure a world-wide progress in balance of social, environmental and economic aspects on sustainable development [18]. On this way to the different 17 SDGs, which including nearly 220 indicators, other organizations like the OECD provided important intermediate results on specific subjects like green growth or green economy within industry societies [19].

The 17 SDGs were agreed upon by developed and developing countries, but for any country they have their different meaning to build the SDGs into their national policies and sustainable strategies. In Germany, the work of the UN has been taken up by both academia and government to make substantial contributions to the extraction of sustainability indicators. The German government's National Strategy for Sustainable Development is largely based on this work [20, 21]. In the scientific context, the theoretically well-founded Integrated Concept of Sustainable Development has been used as a methodological framework for deriving sustainability indicators [22], especially in projects to monitor and navigate the transformation of the energy system in Germany [23-25]. The results of these projects provided not only a large number of indicators but also new approaches that, in the case of higher resilience of systems, gave a country valuable suggestions, especially for the design of energy supply, as to how improved resilience can be mapped by means of quantitative indicators for the entire energy system as well as for subsystems such as electricity supply [26-28].

## **6.2. International and national literature of sustainable indicators for energy supply, technologies and sectors**

Since securing energy supply is of great importance in modern industrial societies with the increase of globalisation, the composition of the mix of energy sources, taking into account both a country's dependence on imports and the technologies to be used, for example, for power generation and their potential accident risks, has triggered a scientific and societal discussion that has led to a number of important international and national publications proposing energy- and technology-related sustainability indicators. First, the applied literature sources are listed that deal with the entire energy supply or deal with subsystems [29-32]. Subsequently, the literature is cited that deals with the topic of sustainability assessment of specific electricity generation technologies. Here, the focus was particularly on the use of nuclear energy [33-35].

Of particular importance is the contribution by [31], which sums up the results of an international partnership initiative on indicators for sustainable energy development, which aims to provide an analytical tool for assessing energy production and consumption patterns at national level. The set of represented indicators was a consensus reached on this issue by five international organisations - two from the United Nations system (the Department of Economic and Social Affairs and the International Atomic Energy Agency), two from the European Union (Eurostat and the European Environment Agency) and one from the Organisation for Economic Cooperation and Development (the International Energy Agency). Building on general guidelines, the proposed national energy indicators can be used to monitor the impact of national energy policies on the social, economic and environmental aspects of sustainable development. Specifically for the environmental assessment of the impacts of energy supply, impact indicators were used for various environmental aspects such as climate change or acidification. These indicators were developed within the framework of the systems

analytical approach of life cycle assessment and reflect the current state of knowledge on the assessment of environmental aspects, which we present in detail in Chapter 5.3.

**6.3. Literature of applied environmental indicator within the framework of Life Cycle Impact Assessment**

The preservation of the natural environment and its productive capital in order to secure its existence for future generations is an important requirement in the concept of sustainable development. The preservation of the natural environment and its productive capital in order to secure its existence for future generations is an important requirement in the concept of sustainable development. The method of life cycle assessment has become established in science for the quantitative assessment of environmental technology or system consequences in the field of energy. The reasons for this are the system-analytical approach of taking into account both the entire life cycle of the object under investigation and quantifying the overall effects on the environment , including humans. In this context, the term environment is composed of four different protected environmental areas [36]. These are

- abiotic and biotic natural resources (e.g. raw materials, water, soil, flora and fauna)
- abiotic and biotic natural environment (e.g. high mountains, environmental media water, soil, air)
- human health
- abiotic and biotic cultural landscape and cultural assets

The general concept structure for environmental assessment by means of impact categories within LCA is shown in the following figure:

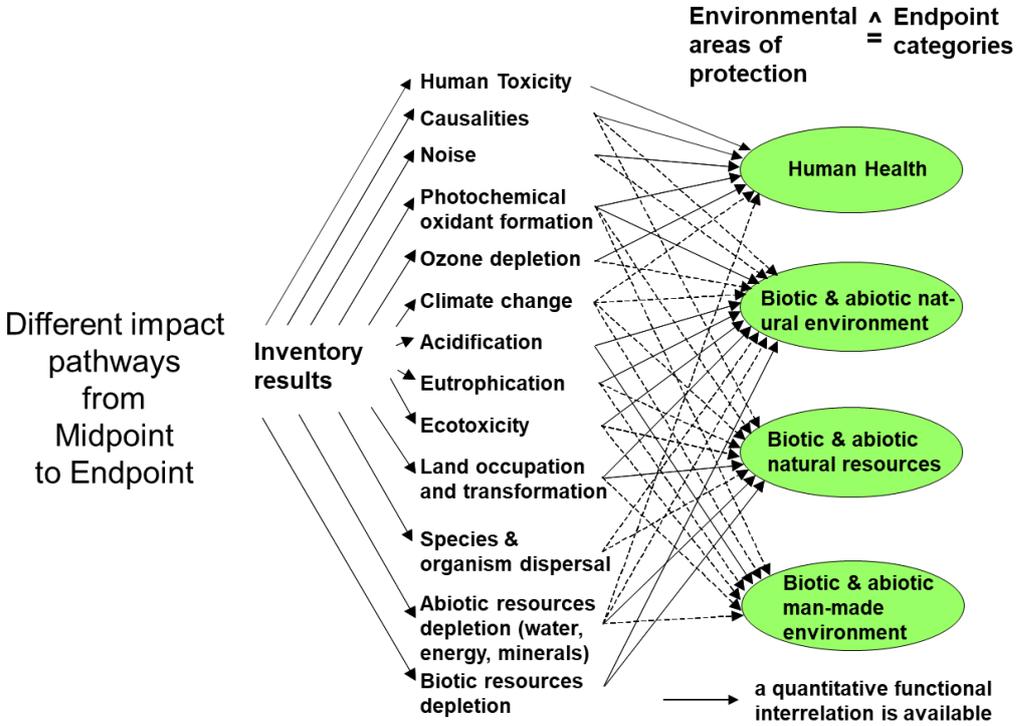


Figure 15: General structure of the Life Cycle Impact Assessment framework [36]

The aim of the concept structure is to delimit both the input- and output-related environmental influences (impact categories) into individual impact pathways, such as climate change, and to enable a functional relationship to describe the change on the basis of the environmental assets defined above. This flexible concept offers the advantage that new environmental impacts or those that could previously only be described qualitatively can be easily integrated into the structure. In addition, it takes into account the increasing knowledge about real impacts on environmental protection areas and the causal interrelationships.

When determining where along the environmental impact pathway the functional relationship for the mathematical description of the impact indicator begins, there are two different approaches, which are referred to in the Anglo-Saxon literature as the midpoint and endpoint approach [36, 37].

In the comparison of the two approaches midpoint and endpoint for quantifying the effect relationship, it remains to be noted that the endpoint approach requires a longer causal chain in the mathematical modelling. Two mechanisms of action must always be functionally linked with each other. This makes a pronounced differentiation of the damage to the individual protected areas, the endpoints, visible, but a longer causal chain is required for the mathematical description, which leads to a higher uncertainty between the causal emissions and the environmental effects to be measured with each additional chain link.

This insight was also taken up by the Joint Research Center in its recommendation of characterisation models to be used for different impact categories, which were developed in a multi-stage process on the basis of scientific criteria with the leading scientists in this field and finally published in a handbook [38]. In light of the discussion on the product environmental footprint (PEF), the characterisation model to be recommended was updated for some impact categories [39]. As a result, the updated ILCD environmental impact assessment method was given the name ILCD Midpoint 2.0. In addition, the characterisation factors for minerals and metals from van Oers were updated for the abiotic resource depletion potential, which were also adopted [40]. The ILCD method considers 16 midpoint impact categories, which cope single environmental aspects. The table 2 lists the impact categories considered, their recommended characterisation models with the associated literature sources, and the physical unit of the impact indicators.

*Table 3: Updated list of impact categories, characterisation models and impact indicators according to the ILCD Midpoint Method 2.0*

<b>Impact category</b>	<b>Recommended characterisation model</b>	<b>Impact indicator and unit</b>
Climate change	Base climate model at 100 years residence time from Intergovernmental Panel of Climate Change (IPCC); Status: 5th IPCC report 2013 [41]	Radiative forcing in W/m <sup>2</sup> as global warming potential (GWP 100) in CO <sub>2</sub> equivalents
Stratospheric ozone depletion	Equilibrium state model of the ozone depletion potential of world meteorological organisation (WMO); Status: WMO 1999 [42]	Reduction of stratospheric ozone concentration as ozone depletion potential (ODP steady state) in CFC-11 equivalents
Human toxicity, cancerogenic effects	USEtox model; Status: Rosenbaum et al 2008 [43]	Comparative toxic units for humans (CTUh)

Human toxicity, non-cancerogenic effects	USEtox model; Status: Rosenbaum et al 2008 [43]	Comparative toxic units for humans (CTUh)
Ecotoxicity (freshwater)	USEtox model; Status: Rosenbaum et al 2008 [43]	Comparative toxic units for ecosystems (CTUe)
Respiratory effects, inorganics/ particulate matters	RiskPoll model; Status: Rabl, A. a. Spadaro, J. 2012 [44], Greco et al 2007 [45] and Humpert 2009 [46]	Human intake of particulate matter in kg PM2.5 equivalents per kg particulate matter emission
Photochemical ozone formation	LOTOS-EUROS model; Status: van Zelm et al, 2008 as implemented in ReCiPe Midpoint [47]	Increase in tropospheric ozone concentration in kg ethene equivalents
Acidification	Accumulated exceedance of the critical acidification load value; Status: Seppälä et al 2006 [48], Posch et al 2008 [49]	Acidification equivalents (mol H <sup>+</sup> equivalents) per year
Eutrophication, terrestrial	Accumulated exceedance of the critical load for terrestrial eutrophication; Status: Seppälä et al 2006 [48], Posch et al 2008 [49]	Eutrophication equivalents (mol N equivalents) per year
Eutrophication, freshwater	EUTREND model; Status: Struijs et al 2009 as implemented in ReCiPe Midpoint [50]	Fraction of nutrients in freshwater (in kg P equivalents)
Eutrophication, marine water	EUTREND model; Status: Struijs et al 2009 as implemented in ReCiPe Midpoint [50]	Proportion of nutrients in marine water (in kg N equivalents)
Ionising radiation, human health	Human health effect model; Status: Frischknecht et al 2000 [51]	Human exposure efficiency relative to kBq U235
Land use	Soil quality index based on LANCA; Status: Bos et al 2016 [52]	Soil quality index in points (Biotic production, erosion resistance, mechanical filtration a. groundwater replenishment)
Resource use, minerals an metals	Abiotic resource scarcity model based on ultimate reserves; Status: van Oers et al 2020 [53]	Abiotic resource depletion of minerals and metals in kg Sb equivalents
Resource use, fossil fuels	Abiotic resource scarcity model based on fossil fuels; Status: van Oers et al 2002 [54]	Abiotic resource depletion of fossil fuels in MJ
Freshwater Scarcity	Available WAtER REMaining (AWARE) model, Boulay et al 2018 [55]	User deprivation weighted water consumption in kg world equivalents deprived

As a result of the literature analysis, more than 300 sustainability indicators were available for selection. Therefore, the number of indicators had to be narrowed down on the basis of selection criteria in order to evaluate the different transformation strategies of the energy system of the examined ten energy scenarios ex-post. Based on the selection criteria listed on the left-hand side in figure 16, a reduction to 23 sustainability indicators was made. This number of 23 indicators is too comprehensive to be practical for discussions with stakeholders or for the results of a MCDA, in particular given limited (time) resources.

- Relevance to the current sust. Discussion
- Full set addresses the ecologic, economic, and social dimension of sust. and additionally takes into account system-related aspects
- All indicators have different impact mechanism of sust. development
- Future development of the indicator can be estimated satisfying with available models FRITS, PANTA RHEI, flexABLE
- It must be directionally safe concerning the measured sustainability aspect
- Depends on the development of the supply side of future technology mix

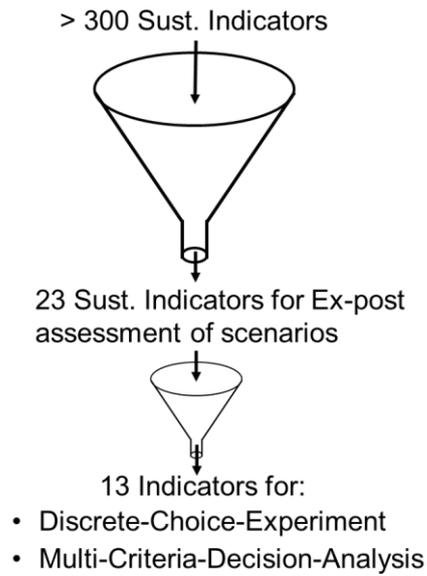


Figure 17: Complete procedure of the selection of sustainability indicators

Therefore, a sub-set of indicators had to be selected which additionally met the following criteria: Number of indicators manageable for discussions with citizens as well as the MCDA results which have to be understandable for non-experts. Additionally, the selected indicators in particular should be relevant for the citizens' daily life as well as the reduced sub-set of indicators still addresses ecologic, economic, technical and social dimension of sustainability.

## 7. Results for life-cycle based environmental impacts

Indicator	unit	2019	Scen I	Scen II	Scen III	Scen IV	Scen V	Scen VI	Scen VII	Scen VIII	Scen IX	Scen X
CC (climate change total)	Mt CO2-Eq	895	306	310	313	285	348	314	199	228	197	357
EQ (freshwater & terrestr. acidification)	1.e6 mol H+-Eq	3.419	1.907	2.313	2.208	1.680	3.934	2.139	1.823	2.447	2.608	3.952
EQ (freshwater ecotoxicity)	1.e9 CTU	965	743	1.039	1.008	810	908	804	1.078	934	786	941
EQ (freshwater eutrophication)	1.e6 kg P-Eq	425	82	99	94	122	273	116	126	128	172	188
EQ (marine eutrophication)	1.e6 kg N-Eq	576	347	369	382	320	509	336	335	403	381	457
EQ (terrestrial eutrophication)	1.e6 mol N-Eq	7.423	4.918	5.459	5.392	3.684	8.161	5.363	3.517	6.198	5.662	7.459
HH (carcinogenic effects)	CTUh	7.685	6.401	5.914	6.714	6.436	13.392	6.853	7.629	13.290	10.637	13.128
HH (non-carcinogenic effects)	CTUh	83.603	62.554	75.656	88.224	77.897	125.902	66.301	78.766	116.817	87.769	110.649
HH (ionising radiation)	1.e6 kg U235-Eq	76.952	9.516	8.108	9.157	8.011	5.894	8.718	4.475	5.542	4.158	6.804
HH (ozone layer depletion)	kg CFC-11-Eq	135.793	85.568	73.191	84.428	68.307	82.749	113.206	72.335	88.572	81.734	86.203
HH (photochemical ozone creation)	1.e6 kg NMVOC-Eq	1.730	1.192	1.269	1.378	1.244	2.125	1.118	1.307	1.471	1.506	1.849
HH (respiratory effects, inorganics)	disease incidence	30.119	19.478	22.575	21.587	19.894	33.429	19.120	21.225	23.563	21.543	33.306
RES (fossils)	1.e9 MJ	14.445	4.433	4.468	4.572	4.339	3.957	4.524	2.773	3.003	2.434	4.100
RES (dissipated water)	1.e9 m3 water-Eq	107	64	90	91	69	105	63	98	95	79	99
RES (land use)	1.e9 points	18.616	18.368	46.155	42.595	27.478	18.360	22.864	28.606	65.453	14.133	30.311
RES (minerals and metals)	1.e6 kg Sb-Eq	65,9	84,1	80,5	135,7	107,1	247,8	159,1	109,8	224,4	157,3	206,7

Figure 18: Summary over all life-cycle based environmental impacts for 2019 and for all scenarios in 2050. CC: climate change, EQ: ecosystem quality, HH: human health, RES: resources

Indicator (cumulated 2020-2050)	unit	Scen I	Scen II	Scen III	Scen IV	Scen V	Scen VI	Scen VII	Scen VIII	Scen IX	Scen X
CC (climate change total)	Mt CO2-Eq	18.005	18.424	18.604	18.403	18.616	18.535	17.447	17.307	17.014	18.605
EQ (freshwater & terrestr. acidification)	1.e6 mol H+-Eq	85.086	92.985	92.861	81.398	99.399	84.034	90.072	93.976	87.791	102.267
EQ (freshwater ecotoxicity)	1.e9 CTU	28.995	35.676	34.548	29.068	29.662	29.648	35.012	31.902	28.451	30.824
EQ (freshwater eutrophication)	1.e6 kg P-Eq	6.261	6.682	6.511	6.776	8.221	6.403	7.152	6.777	7.360	7.124
EQ (marine eutrophication)	1.e6 kg N-Eq	14.094	14.573	14.804	13.882	15.236	13.643	14.702	14.565	14.112	14.795
EQ (terrestrial eutrophication)	1.e6 mol N-Eq	194.684	200.987	203.753	178.411	200.944	177.930	184.165	206.273	183.460	212.303
HH (carcinogenic effects)	CTUh	232.457	234.721	241.684	234.772	300.734	240.545	271.041	295.004	279.857	302.374
HH (non-carcinogenic effects)	CTUh	2.377.776	2.571.669	2.748.772	2.553.821	2.932.732	2.340.779	2.723.663	2.904.470	2.620.740	2.798.402
HH (ionising radiation)	1.e6 kg U235-Eq	749.404	741.774	754.842	742.672	734.518	766.292	728.758	726.978	716.185	743.755
HH (ozone layer depletion)	kg CFC-11-Eq	3.664.432	3.512.506	3.587.731	3.418.644	3.883.709	4.234.069	3.644.773	3.759.579	3.952.557	3.874.548
HH (photochemical ozone creation)	1.e6 kg NMVOC-Eq	45.520	47.246	48.724	46.590	52.029	44.428	49.106	48.250	47.150	49.420
HH (respiratory effects, inorganics)	disease incidence	802.741	860.118	847.090	791.918	863.230	752.504	856.718	840.477	785.001	889.309
RES (fossils)	1.e9 MJ	275.432	281.656	285.472	283.327	278.837	284.965	266.611	264.854	258.138	278.552
RES (dissipated water)	1.e9 m3 water-Eq	2.671	3.264	3.281	2.741	2.936	2.585	3.351	3.117	2.708	3.015
RES (land use)	1.e9 points	618.995	798.092	844.385	674.825	549.621	570.449	759.538	925.216	527.662	670.436
RES (minerals and metals)	1.e6 kg Sb-Eq	2.568	2.659	3.260	2.845	4.501	3.535	3.098	4.508	3.555	4.046

Figure 19: Summary of life cycle based environmental impacts (cumulated 2020-2050) for all ten scenarios. CC: climate change, EQ: ecosystem quality, HH: human health, RES: resources

More details on the life cycle-based environmental impacts can be found on the project website: <https://www.innosys-projekt.de>

## 8. Results for total system costs

Total system costs comprise the following components:

- Annuities for investment in new technologies (calculated with a uniform interest rate of 6%)
- fixed O&M costs
- variable O&M costs (fuel costs, costs for CO<sub>2</sub> emission certificates)

for all power, heat, synfuel and biofuel generation technologies. For the transport sector, only fuel costs are taken into account. An overview of the development of the total system costs is given in Figure 20.

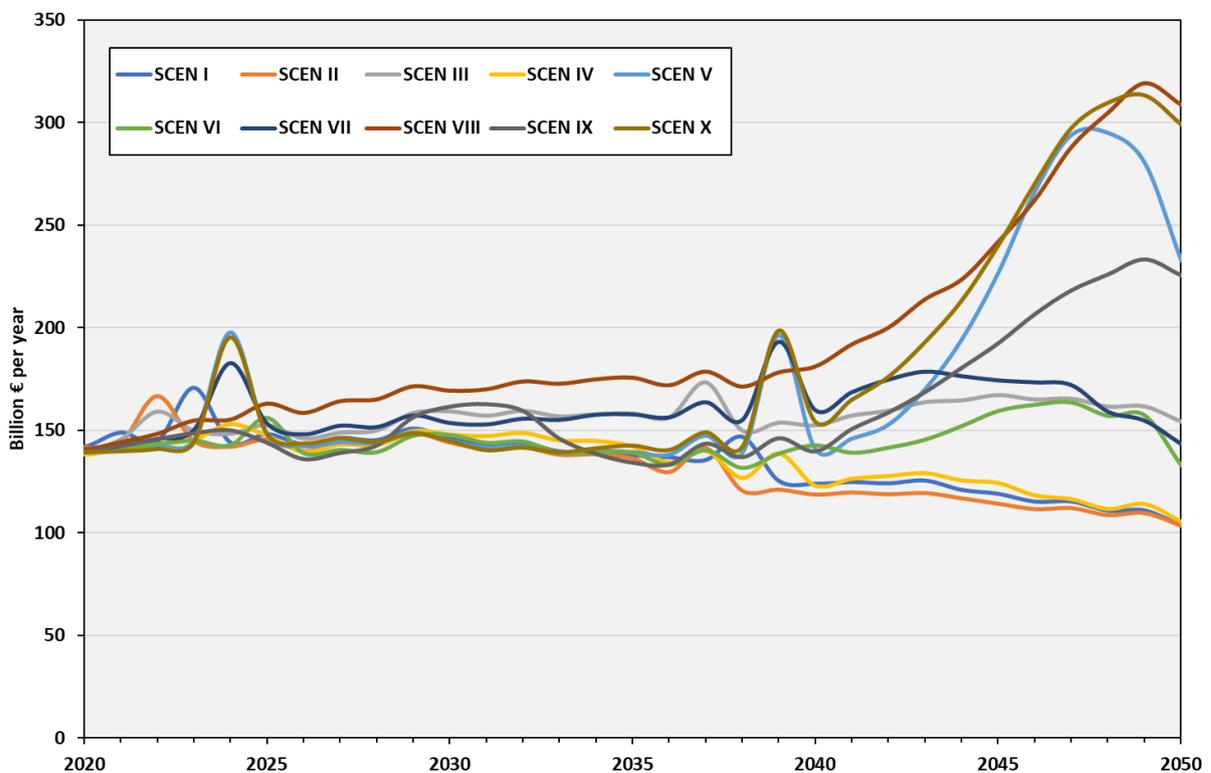


Figure 20: Total system costs in the selected scenarios

## 9. Results for indicator “diversity of power supply”

In order to measure diversity of generation technologies, criteria related to the physical plant, the fuel used, the generation characteristics of the plant, and its environmental and social effects are considered. However, environmental effects, social effects, and some economic effects are considered in the broader MCDA of which the diversity measurement is itself only one criteria, so these were excluded from the diversity measurements.

For the physical plant, the average plant lifetime and average plant capacity (based on [56]) and the average lifetime (derived from [57-63]) were considered. To describe diversity between fuels, its sourcing was measured as the proportion of fuel imported, and nations providing imported fuel [64, 65]. To describe diversity between generation capabilities, we derived seven criteria, sourced . We derived four criteria from empirical generation data for the five years from the SMARD database over the period 2015-2019 [66]. The first criterion was the correlation of the average daily generation curve for each energy source with the average daily demand, with timesteps of 15 minutes. The second criterion was again the correlation of average generation with average demand, but calculated for average cumulative daily generation and demand over the course of the year. These two criteria measure the usability of power generated by each plant. Next, we measured the self-correlation of the generation data, at time offsets of a day and a year. As in the previous criterion, the daily data was calculated with a sample period of 15 minutes, and the annual data was calculated using cumulative daily generation. These two criteria measure the “predictability” or “reliability” of power generation from each source. All four correlations were calculated with the Pearson correlation coefficient. Additionally, some indicators were chosen to describe the plant’s flexibility: ramping ability, or maximum rate of change of power generation; minimum operable load; and capacity factor, or the average percentage of rated capacity generated (based on [67-69]). Together, these seven criteria give a well-rounded, quantified image of the predictability, usability, and flexibility of the energy sources. Finally, we included two economic criteria which were not considered in the larger MCDA. The first was the market concentration of suppliers, which was calculated with the Herfindahl-Hirschman Index from a list of all German power plants (based on [56]). Finally, we incorporated a criterion based on the requirements of each energy source for critical raw materials. The EU lists 30 such critical raw materials, which hold potential supply chain risks in the future [70]. We chose to measure the total number of critical raw materials required for each energy source, blind to quantities, because of the lack of reliable data on the quantities of each material required, and the lack of a simple measure to aggregate a comparison of material requirements which varied by several orders of magnitudes. These material requirements were drawn from a number of studies [71-76].

Each criterion was normalized by dividing it by the maximum value obtained by any energy source. An equal weight was assigned to each criterion, except for the two criteria on correlation of power supply and demand. These were the only criteria with a negative range; therefore, they were assigned a weight half that of the others, to account for the larger range.

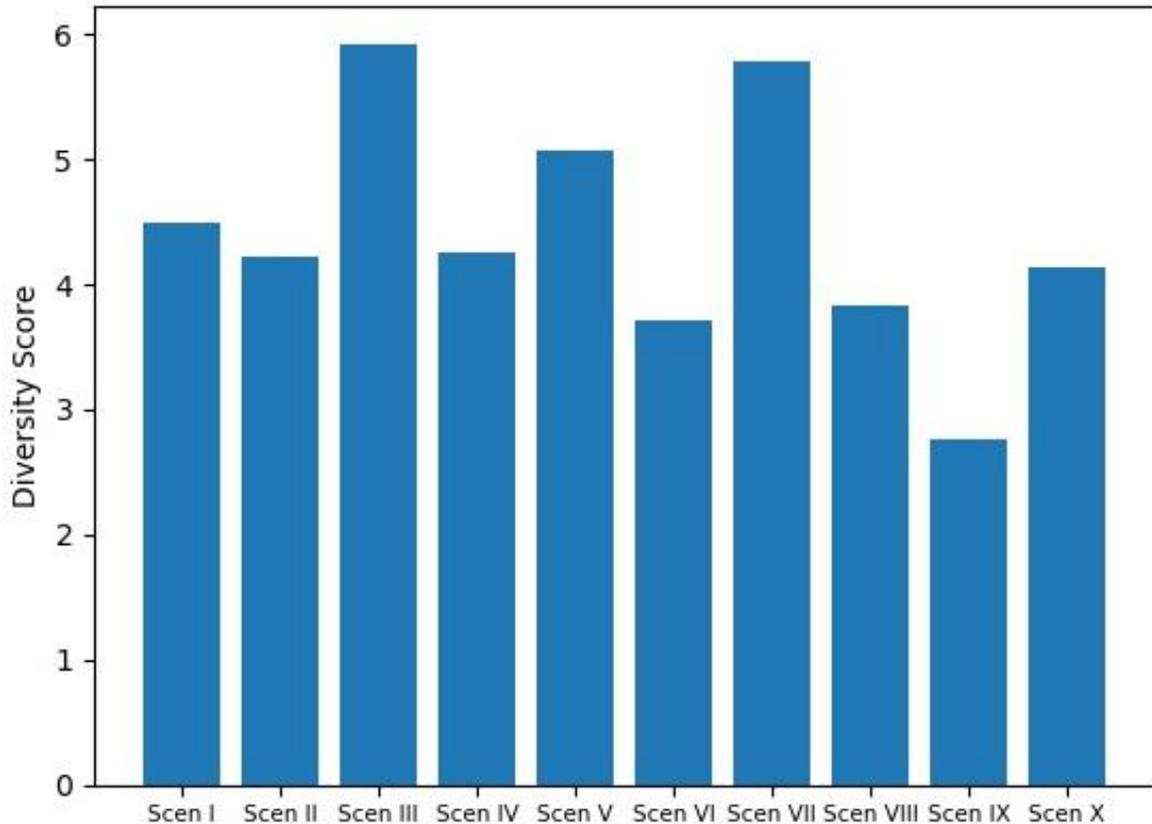


Figure 21: Diversity scores of all scenarios

Most scenarios receive a score of close to 4. There are four outliers: Scenarios 3, 5, and 7 have much higher diversity, and Scenario 9 has much lower diversity. Examination of the composition of those scenarios shows that Scenarios 3, 5, and 7 have higher proportions of conventional power, whereas all others are almost entirely renewable; this results in a higher diversity score. In contrast, Scenario 9 consists of nearly 75% photovoltaic, which explains its low diversity score.

## 10. Original quotations from the focus groups

Original quotations from the focus groups. As the groups were conducted in German, the quotes have been translated. References within transcripts in brackets.

A1: *“That’s why I say on the one hand »security of supply« and on the other hand »affordability«. Because I can’t say we’re all going to be unemployed, but because we’re doing all this with renewable energies, everything is going to be even more expensive. For this we need a concept that society can afford.”* [#01:43:11-2].

A2: *„Hard to assess ... On the one hand I find the other points [speaker refers to ecologic outcomes of energy production] more important than the costs, however, it is true in terms of social justice that if the generation costs are so high ... someone has to bear them and that will have a negative effect.”* [#01:43:42-1].

A3: *“The most important thing for me would be the security of supply and the jobs, because that would create satisfaction among the population and that is a basic building block for establishing something like that [refers to the green energy technologies] and making it available. So, if people realize it works and I’m not out of a job.”* [#01:35:12-9]

A4: *“One important source of energy I have not found here and that is simply the human: The bicycle instead of the car. The renunciation of 25 degrees in the bathroom and floor heating. All the things that you could save by being aware of what you consume, keyword renunciation.”* [#00:43:27-6].

A5: *“It’s only on this point of quality of life that I think our society has often tended to say, »everybody must do this, and everybody must not do that«. And that’s what I find interesting, that every other point-of-view...how do you deal with it? Because one person can do without this and another person can do without that. I haven’t used a TV for two years, I’m fine with it.”* [#01:19:30-4].

A6: *“I’d check all technologies on their effects on human health and climate change and maybe the security of supply. But all the rest...what’s the use if I have few costs but the climate or my health is down the drain? [...].”* [#01:48:07-0].

A7: *„I find it hard to relay on the costs for power generation, because there’s no guarantee that it will stay the same. Will it always be more expensive, or is that only valid for the first few years until maybe innovation kicks in and makes it way cheaper? For me that’s hard to assess.”* [#01:43:11-1].

## **11. Harmonization of indicators and final weighting factors for MCDA**

For MCDA results from impact assessment and discrete choice experiment (DCE) have to be matched since indicator sets differs slightly. For DCE aggregated indicators for human health and resources were applied and preferences were generated. Those preference values must be adapted to be used as weights for MCDA. The following table shows the steps of the applied procedure.

At first, the  $\beta$ -coefficient retrieved from DCE is normalized to 1. Then aggregated  $\beta$ -coefficients for human health and resources are disaggregated applying the weighting scheme provided by [77]. The disaggregated  $\beta$ -coefficients are multiplied with a robustness factor according to [77] to take into account that the methods used to survey (environmental) impacts vary in validity. The robustness of the indicators “unemployment rate”, “resilience”, and “system costs” were assessed by expert judgement within the project team. Those intermediate coefficients are finally again normalized to 1 to get the final weighting factors for MCDA.

Table 4: Harmonization of indicators and final weighting factors for WSM

Discrete-choice indicator	Integrated assessment indicator	$\beta$ -coefficient	$\beta$ -coefficient normalized	weighting factor (public) according to [77]	$\beta$ -coefficient, norm., disaggregated	Robustness factor according to [77]	Intermediate Coefficients	Final weighting factors (incl. Robustness)
			scaled to 1		A	B'	C=A*B	scaled to 1
Climate change		0.0582	0.318		0.318	1	0.318	0.532
Human Health		0.0252	0.138					
	Ozone layer depletion			5.29	0.022	1	0.022	0.037
	Carcinogenic effects			7.24	0.030	0.4	0.012	0.020
	Non-carcinogenic effects			5.74	0.024	0.4	0.010	0.016
	Respiratory effects,			5.18	0.022	1	0.022	0.036
	Ionizing radiation			5.13	0.021	0.6	0.013	0.021
	Photochemical ozone creation			4.44	0.019	0.6	0.011	0.019
Resources, land use		0.0189	0.104		0.104	0.2	0.021	0.035
Resources, mineral, metals, fossils		0.0299	0.164					
	Resources, mineral and metals			5.57	0.074	0.2	0.015	0.025
	Resources, fossils			6.75	0.090	0.2	0.018	0.030
System costs		0.0138	0.076		0.076	0.7*	0.053	0.088
Security of supply	Diversity	0.0229	0.125		0.125	0.25*	0.031	0.052
Employment	Unemployment rate	0.0137	0.075		0.075	0.7*	0.053	0.088
			1		1			1

\* Expert judgement since indicators are not covered by [77]

Table 5: Overview of indicator values used in the MCDA

		SCEN I	SCEN II	SCEN III	SCEN IV	SCEN V	SCEN VI	SCEN VII	SCEN VIII	SCEN IX	SCEN X
Unemployment rate [%]	2050	5.69	5.69	5.71	5.62	5.60	5.51	5.20	5.45	4.97	5.96
Diversity (SI) [-]	2050	4.48	4.22	5.96	4.25	5.01	3.68	5.81	3.82	2.76	4.12
System costs [€]	cum	4.03E+12	3.93E+12	4.71E+12	4.04E+12	4.34E+12	4.82E+12	5.89E+12	4.87E+12	5.22E+12	5.46E+12
Climate change [kg CO <sub>2</sub> -Eq]	cum	1.79E+13	1.84E+13	1.85E+13	1.85E+13	1.85E+13	1.75E+13	1.74E+13	1.69E+13	1.86E+13	1.87E+13
Carcinogenic effects [CTUh]	cum	3.08E+05	3.11E+05	3.15E+05	3.19E+05	3.16E+05	3.51E+05	3.73E+05	3.50E+05	3.80E+05	3.82E+05
Ionizing radiation [kg U235-Eq]	cum	6.83E+11	6.78E+11	6.82E+11	6.86E+11	7.05E+11	6.66E+11	6.55E+11	6.53E+11	6.73E+11	6.85E+11
Non-carcinogenic effects [CTUh]	cum	2.68E+06	2.97E+06	3.06E+06	3.08E+06	2.66E+06	3.16E+06	3.30E+06	2.93E+06	3.31E+06	3.24E+06
Ozone layer depletion [kg CFC-11-Eq]	cum	3.53E+06	3.39E+06	3.79E+06	3.33E+06	4.25E+06	3.53E+06	4.65E+06	3.83E+06	3.92E+06	4.12E+06
Photochemical ozone creation [kg NMVOC-Eq]	cum	4.76E+10	4.98E+10	5.08E+10	4.99E+10	4.67E+10	5.20E+10	5.12E+10	4.91E+10	5.46E+10	5.24E+10
Respiratory effects, inorganics [desease incidence]	cum	8.33E+05	8.98E+05	8.80E+05	8.41E+05	7.85E+05	8.99E+05	8.87E+05	8.14E+05	9.02E+05	9.34E+05
Resources, fossils [MJ]	cum	2.68E+14	2.76E+14	2.77E+14	2.80E+14	2.79E+14	2.61E+14	2.58E+14	2.51E+14	2.74E+14	2.75E+14
Resources, land use [points]	cum	6.08E+14	7.89E+14	8.34E+14	6.68E+14	5.60E+14	7.52E+14	9.17E+14	5.17E+14	5.41E+14	6.63E+14
Resources, minerals and metals [kg Sb-Eq]	cum	3.12E+09	3.51E+09	4.97E+09	4.00E+09	4.53E+09	4.06E+09	8.61E+09	4.16E+09	5.70E+09	6.07E+09

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