HELMHOLTZ
CLIMATE INITIATIVE

SCENARIO DEFINITION AND CONSISTENT PARAMETRIZATION OF ALL MODELS

PROJECT 1.2 | M-P1.2.1

SCENARIO DEFINITION AND CONSISTENT PARAMETRIZATION OF ALL MODELS

PROJECT 1.2 | M-P1.2.1

CONTENT

1 BACKGROUND

The project Net-Zero-2050, Cluster I of the Helmholtz Climate Initiative (HI-CAM) targets net zero CO_2 emissions by the year 2050 for Germany. The energy system is currently the main emitter of CO_2 in Germany and globally (Teske, 2019; UBA, 2019). Therefore, the Net-Zero-2050 specifically focusses on quantifying carbon emissions from the energy system via an integrative scenario modeling project: P1.2 Energy Scenario Quantification. Our approach advances and combines models and methods for integrated scenario analyses with the focus on net zero emissions pathways. This integrates the overall assessment of possible technical options, their contributions to GHG mitigation, and their systemic interactions with a combination of different quantitative and qualitative assessment criteria. This first deliverable provides therefore an overview of methods and approaches applied within the P1.2 project on quantitative scenario analysis.

Our first step in P1.2 was the definition of the scenario approach which was jointly defined in the Net-Zero-2050 cluster and is documented in the project briefing #4 “Scenario Approach”. For defining the system boundaries and a scenario concept, P1.2 contributed to the development of a series of project briefings in the Net-Zero-2050 Cluster: The term “Net Zero emissions” and the system boundaries are defined within the project briefing #1 “Net-Zero-2050 structure”. The specific carbon budget, which will comply with our Net-Zero-2050 storyline is defined in the project briefing #2 “Carbon Budget”, limiting total CO_2 emissions for Germany to a total of 10 Gt from 2018 to 2050.

We summarize the resulting energy scenario approach and definitions in Section 2. This also includes an overview of background studies and scenario literature, both for Europe and Germany, which have been evaluated for the development of a Net-Zero-2050 Germany scenario in P1.2 in Cluster I of the Helmholtz Climate Initiative. Additionally, we document modeling approaches and the relevant interfaces to interlock results between project partners in Section 3 and 4.

2 SCENARIO CONCEPT

The overall storyline of the Net-Zero-2050 project focusses on a society that succeeds in compensating its CO_2 emissions through mitigation measures and carbon sinks by 2050. This storyline also drives the development of the energy scenarios in the project. The approach distinguishes between a socio-economic background (‘framing’) scenario as a common frame for all scenario work in the Net-Zero-2050 cluster and specific scenarios related to the energy system.

2.1 Framing scenario

The German National Energy and Climate Plan (NECP), as provided to the European Commission in 2019 (BMWi, 2019), serves as a reference for the socio-economic background. It describes in an explorative approach a likely development of the society and is based on the NECP background study (Kemmler et al., 2020). It provides projections for GDP and population until 2050. The NECP (BMWi, 2019) also serves as a reference for the overall energy demand under business as usual conditions. Additionally, a working group within P1.2 proposes assumptions on energy carrier prices based on various available studies. Table 1 & Table 2 present these framing input data in 10-year steps.

Table 1: Socio-economic framing data for Germany

	Unit	2020	2030	2040	2050
GDP	Mio. EUR 2016	3,326,396	3,729,306	4,087,767	4,429,732
population	Thousand cap.	83,458	82,868	81,293	79,000
CO_2 price NECP low	EUR 2016/t	24	35	52	92
CO_2 price NECP high	EUR 2016/t	24	140	220	240*

Source: NECP background study (Kemmler et al., 2020); *own assumption

Table 2: Fuel costs assumptions for Germany

Fuel costs	Unit	2020	2030	2040	2050	Source
industry & power plants						
crude oil	Euro 2016/GJ	13.0	17.0	18.0	19.4	NECP Background study (Kemmler et al., 2020)
natural gas	Euro 2016/GJ	8.0	9.0	10.0	10.6	(Kemmler et al., 2020)
hard coal	Euro 2016/GJ	2.5	3.6	4.0	4.3	(Kemmler et al., 2020)
Syncrude	Euro 2016/GJ	119	80	65	60	(Kemmler et al., 2020)
uranium	Euro 2016/GJ	0.6	0.7	0.9	1.0	(Nitsch et al., 2012)
lignite	Euro 2016/GJ	5.6	5.1	4.8	4.5	(Nitsch et al., 2012)
biomass						
waste wood and wood chips	Euro 2016/GJ	3.2	3.2	3.2	3.2	own assumptions*
pellets, short rotation forestry	Euro 2016/GJ	13.9	14.8	15.8	16.7	own assumptions*
landfill gas	Euro 2016/GJ	1.0	1.0	1.0	1.0	own assumptions*
liquid biofuels	Euro 2016/GJ	21.6	28.3	35.0	41.7	own assumptions*
raw biogas	Euro 2016/GJ	15.0	14.6	14.3	13.9	own assumptions*
waste	Euro 2016/GJ	0	0	0	0	own assumptions
hydrogen	Euro 2016/GJ	24.4	24.4	24.4	24.4	(Liebich et al., 2020)

* based on (FNR, 2018; Thrän et al., 2019)

2.2 Energy scenarios within Net-Zero-2050

The scenario quantification aims for providing several consistent techno-economic energy transition pathways, which achieve different climate protection trajectories and represent various roles of technological and regulative options. These scenarios are target driven normative scenarios, describing energy pathways towards an energy system with minimal CO_2 emissions. So far, we developed a concept of consecutive scenarios, including a variety of possible energy technologies, their contributions to CO_2 emission mitigation, and their systemic interactions.

Starting with a Base scenario, we first explore what is necessary in the energy system comply with the carbon budget without CDR measures. The speed of the development towards this target is defined by the overall carbon budget allocated to the energy sector. However, such a pathway demands an immediate “turn around” regarding all investment priorities in the energy sector. There also exists a high uncertainty on the carbon budget already on global level, moreover for the potential carbon budget of a German energy system (see project briefing #2 “Carbon Budget”). Starting from this base scenario we develop a variety of scenarios, including information on other mitigation options and challenges and barriers for technology development, that limit the energy transition process. The development of these additional scenarios will also strongly rely on intermediate results from Project 2-4 and the technology assessment matrix with regard to deployment potential, additional energy demand and CO_2 mitigation costs, forming the parameters of the Carbon Dioxide Removal (CDR) scenarios (see also project briefing #4 “Scenario Approach”). Integration of these results will be implemented in 3-4 scenario variants of the Base scenario, e.g. considering different carbon budget limits and the deployment of CDR/CCU/CCS measures as well as their related additional energy demand.

The quantification of this set of energy scenarios will be complemented by an extended assessment of the scenarios both on system level (including an ex-post LCA-assessment) and on stakeholder level in work page 1.2.3.

2.3 Base scenario for Net-Zero-2050

We develop normative energy system scenarios targeting a more sustainable energy supply and a reduction of CO_2 emissions to zero by 2050. Our storyline for the Base scenario focusses on additional efficiency improvements and on achieving a 100% renewable energy system by 2050 for Germany, by replacing all fossil fuels in the power, heat and transport sector either by renewable electricity, heat or green synthetic fuels. Starting with the 2050 target we apply a backcasting approach for the time range between 2020 and 2050 in five-year steps.

The development of the demand and supply structure will be limited by the energy sector’s share of the 10 Gt CO_2 budget for Germany (see project briefing #2 “Carbon Budget”). Based on the current share of the energy system (UNFCCC, 2020), 85% of this budget will be allocated to the energy system. For the development of the demand structure we use the NECP background study as a reference for a business as usual development (Kemmler et al., 2020). The demand development in the Base scenario will cover additional efficiency potentials and therefore lower energy intensities, based on a broad literature research as presented below in Section 0 as well as assumptions derived from the “Klimaschutzplan”-Scenario from the NECP background study.

This will set the scene for the development of the supply structure in the Base scenario: In a myopic approach we assess the necessary changes in the supply structure for the residential, industry and transport sectors and especially the power supply structure for such an ambitious target. However, such an immediate “turn around” might not be feasible or appropriate. Suitable regulatory framework conditions and their effects in the form of investment incentives and implementation of new technologies have to be considered. We therefore will develop a set of scenario variants, addressing limitations in the deployment of renewable energy technologies on the basis of plausible assumptions and the available background knowledge as derived from our extensive scenario literature database (see Section 2.3.1). These scenario variants will also address potential time lags in the energy transition in the transport or buildings sectors as well as variations in the technical setup of supply and infrastructure. They will also include various technological options for the transport or the heating sector, e.g. implementing an electricity, hydrogen or a biomass strategy.

The model structure for the basic scenario is developed consistently with the other scenario variants, so that individual assumptions can be explicitly documented and differentiated with high technological resolution. The related decisions of actors, such as investors, cannot be examined in detail in this scenario development process, therefore these aspects will be addressed in work package 1.2.3.

2.3.1 Background Studies and Scenarios

Reduction of CO_2 emissions has been targeted by a variety of studies for the energy sector during the last decade, predominantly focusing on 80-95% emission reduction from energy by 2050. Even though climate neutrality has only scarcely been targeted, these studies provide the scientific background from which the Net-Zero-2050 scenarios start. Evaluating this broad range of energy scenario studies, both for Germany and Europe serves as a basis for our scenario development. Naturally we rely both on our own previous work as well as external studies, as described below.

2.3.1.1 Previous DLR studies

DLR has developed a series of scenario studies, targeting the energy transition in Germany with high CO_2 reduction targets and focusing on a variety of technologies. Most recently we analyzed the integration of renewable energy into an integrated gas-heat-power-transport system, which included a 95% CO_2 reduction scenario for Germany.

In the 'lead studies' (Leitstudien) and long-term scenarios for the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), DLR developed a systematic storyline and modelling approach to scenario building, which aims to develop plausible and in detail comprehensible transformation paths as a basis for societal discussion (see Nitsch et al. 2012). This scenario building approach was further developed in the Helmholtz-funded project EnergyTrans (www.energy-trans.de) with regard to the consistency of socio-technical assumptions (see Pregger et al., 2019).

From the normative long-term scenarios developed in these projects, updated 80% and 95% reduction paths were derived as framework scenarios in the BMWi-funded project MuSeKo . These scenarios were further investigated with the temporally and spatially resolved energy system model REMix (see Section 3.1.2) developed at DLR with regard to infrastructure requirements (in particular back-up power plants, electricity storage, and power and gas grid expansion) and the utilization of installed capacity. The results were used to check the plausibility and improve the techno-economic development paths assumed in the scenario model.

In recent years, integrated energy-transport scenarios have been developed in close cooperation with DLR transport systems analysis to provide detailed and well-founded transformation paths of the transportation sector (see, e.g., the methodology of the VEU project (Henning et al., 2015)). On this basis, the BEniVer project commissioned by the BMWi is developing new bottom-up scenarios for various ambitious storylines in transportation. The results of these ongoing simulations of the transport sector are also to be used in the project Net-Zero-2050. BEniVer will provide scenario data for rather extreme narratives regarding electric mobility, hydrogen use and the use of synthetic liquid fuels. However, more balanced scenarios will also be derived, which represent a combination of green technologies, primarily subject to the requirement of cost optimisation from the user's point of view. Important background studies for the industrial sector have so far been evaluated and used to identify plausible technical substitution potentials and to integrate their results in the scenario building. In ongoing work at DLR, the potentials of electrification and the industrial use of synthetic energy carriers such as hydrogen are being investigated in own analyses. First results are to be integrated into the Net-Zero scenarios in order to make them more robust regarding the description of transformation processes in the industry sector.

2.3.1.2 External Energy scenarios

Above our own studies we reviewed a broad variety of available external energy scenarios, both for Germany as well as the European Union. The next two tables (3 & 4) give an overview of the analyzed studies. The scenario studies are used to identify diverging potentials and views on future developments and to anchor the Net-Zero-2050 energy scenarios in the scientific landscape and community. The value of these studies, however, depends strongly on the transparency and documentation of assumptions, methods and results, which is often not satisfactorily reflected in the publications. Therefore, additional expert knowledge is necessary to understand and interpret scenario data.

Table 3: Literature review over deep carbonization scenarios for Germany

Author	**Institution/ sponsor**	**Titel**	**Source**
	UBA	Treibhausgasneutrales Deutschland im Jahr 2050	(UBA, 2014)
EWI, GWS, Prognos	BMWi	Entwicklung der Energiemärkte – Energiereferenzprognose	(Schlesinger et al., 2014)
Öko-Institut, FhG ISI et al.	BMUB	Klimaschutzszenario 2050	(Öko-Institut & FhG ISI, 2015)
WI	SDSN/IDDRI	Pathways to deep decarbonisation in Germany	(Hillebrandt et al., 2015)
FhG ISE		Was kostet die Energiewende? Wege zur Transformation des deutschen Energiesystems bis 2050	(Henning & Palzer, 2015)
ifeu, FhG IWES, et al.	UBA	Den Weg zu einem treibhausgasneutralen Deutschland ressourcenschonend gestalten	(Günther et al., 2017)
enervis energy advisors GmbH	INES, BWE	Erneuerbare Gase – ein Systemupdate der Energiewende	(Klein et al., 2017)
BCG, Prognos	BDI	Klimapfade für Deutschland	(Gerbert et al., 2018)
dena, ewi	dena	dena-Leitstudie – Integrierte Energiewende. Impulse für die Gestaltung des Energiesystems bis 2050	(Bründlinger et al., 2018)
GWS, Prognos, DIW, FhG ISI, DLR	BMWi	Gesamtwirtschaftliche Effekte der Energiewende	(Lutz et al., 2018)
FZJ IEK3		Wege für die Energiewende	(Robinius et al., 2019)

Table 4: Literature review over deep carbonization scenarios for Europe

Author	Institution/ sponsor	Titel	source
ENTSO-E; ENTSO-G		TYNDP 2020 Scenario Report	(McGowan et al., 2019)
EURELECTRIC	Union of the Electricity Industry	Decarbonisation Pathways	(Eurelectric, 2018)
IEA	International Energy Agency	Energy Technology Perspectives 2017	(IEA, 2017)
IRENA	International Renewable Energy Agency	GLOBAL ENERGY TRANSFORMATION – The REmap Transition Pathway	(IRENA, 2019)
CLIMACT	European Climate Foundation	Net Zero by 2050: From whether to how-Zero emission pathways to the Europe we want	(Pestiaux et al., 2018)
E3MLab & IIASA	European Commission	EUCO policy scenarios	(Capros et al., 2016)
	Navigant	Gas for Climate. The optimal role for gas in a net zero emissions energy system	(Terlouw et al., 2019)
Brown, T. et al		Sectoral Interactions as Carbon Dioxide Emissions Approach Zero in a Highly-Renewable European Energy System	(Brown et al., 2019)
Zappa et al.		Is a 100% renewable European power system feasible by 2050?	(Zappa et al., 2019)
Child et al.		Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe	(Child et al., 2019)
Grubler et al.	IIASA	A low energy demand scenario for meeting the1.5 °C target and sustainable development goals without negative emission technologies	(Grubler et al., 2018)
Teske et al.	Leonardo Di Caprio Foundation	Achieving the Paris Climate Agreement Goals	(Teske et al., 2019a; Teske et al., 2019b)
Sgobbi et al.		How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system	(Ruiz et al., 2015)
Ram et al.	Energy Watch Group	Global Energy System based on 100% Renewable Energy – Power, Heat, Transport and Desalination Sectors	(Ram et al., 2019)
Jacobson, M. et al		100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World	(Jacobson et al., 2017)

3 INTEGRATIVE MODELING APPROACH: MODEL DESCRIPTION

We quantify the development of the entire energy system within scenarios until 2050. The energy system scenarios apply an integrative approach, which combines different models and methods as well as interdisciplinary perspectives. Figure 1 gives an overview of the model integration.

An accounting framework, the "Energy System Model" is used for the quantitative mapping of storylines and technology implementation in accordance with the higher-level socio-economic narratives. In this model, all technological options and energy system components are mapped on the demand and supply side in the context of entire energy systems. With an additional module, the total Green House Gas (GHG) emissions for each transition path can be estimated on the basis of the expertise available in the initiative. This accounting framework is directly coupled with a detailed cost optimizing energy system model "REMix", which examines in depth the infrastructure requirements on the power system side and the interaction of different sectors (e.g. gas and heat) and technology options (e.g. heat pumps and hydrogen storage). Both models directly interact, to provide a consistent output on the relevant system indicators: Demand and supply structure, CO_2 emission and economic effects.

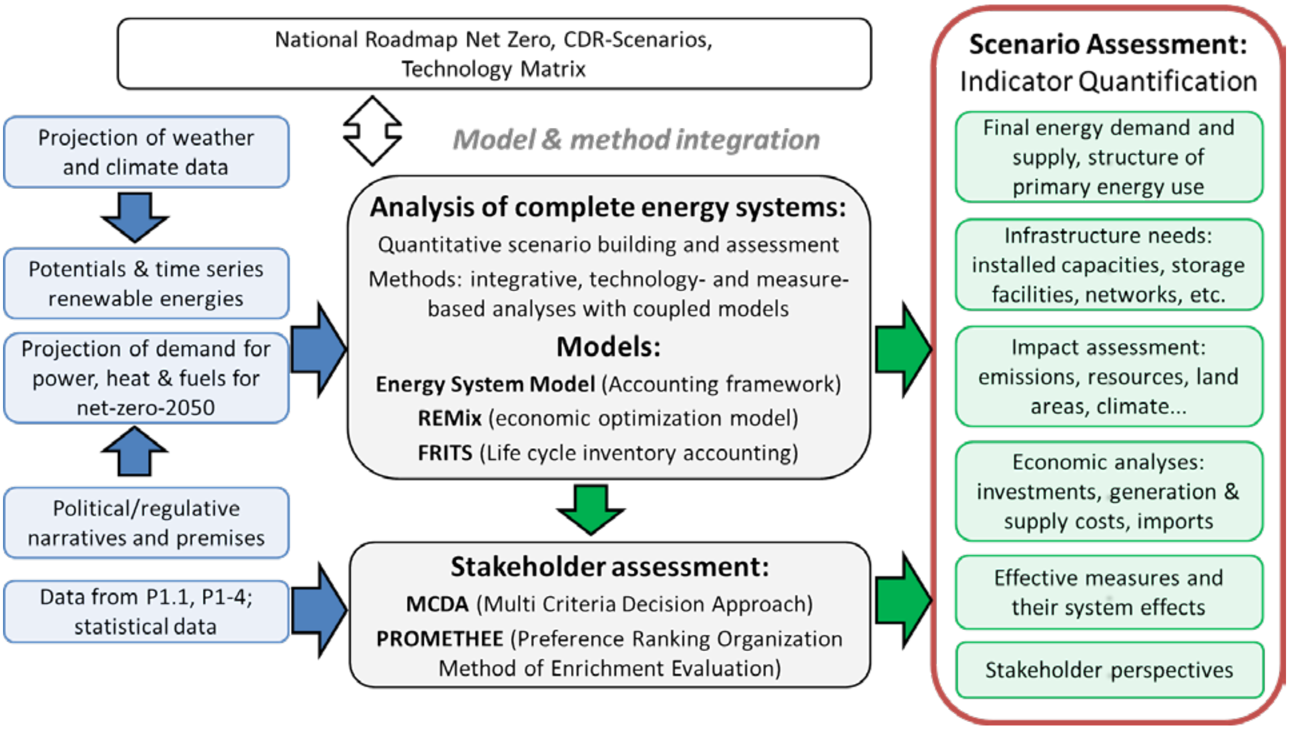

Figure 1: Content and structure of the quantitative energy scenario analysis in Project 1.2 including applied models and assessment approach

This model output serves as input to an ex-post environmental impact assessment, using the methodology of Life Cycle Assessment (LCA). The latter is carried out with "FRITS", the Framework for the assessment of environmental Impacts of Transformation Scenarios (FRITS) developed at DLR. The complete model suite of DLR will provide a sustainability assessment, covering technical, economic and ecologic aspects.

For further analysis of stakeholder perspectives, results will be handed over to the Scenario Assessment model of FZJ. Indicators to be used in the stakeholder assessment of the transformation scenarios are then developed from the results in the Energy System Model. Stakeholder-specific weightings, reflecting the importance of indicators, are combined with the results for these indicators to reveal which scenarios are preferred by which stakeholder for the three decades to 2050.

Model interfaces ensure a consistent parametrization of models and transfer of input and output of the models. A methodology for knowledge integration summarizes all quantitative and qualitative indicators and assigns them to a multi-dimensional evaluation. One of the next steps to be defined for the Deliverable 2 is the definition of assessment indicators as a basis for the systematic evaluation.

3.1 Integrated Energy system modelling

3.1.1 Energy system model (DLR)

The energy system model (ESM) is an accounting framework, which is currently implemented in the Mesap/PlaNet framework (EnergyPLAN, 2020; Schlenzig, 1998). The model represents a time frame until 2050 divided in five years steps. Its setup is presented in Figure 2.

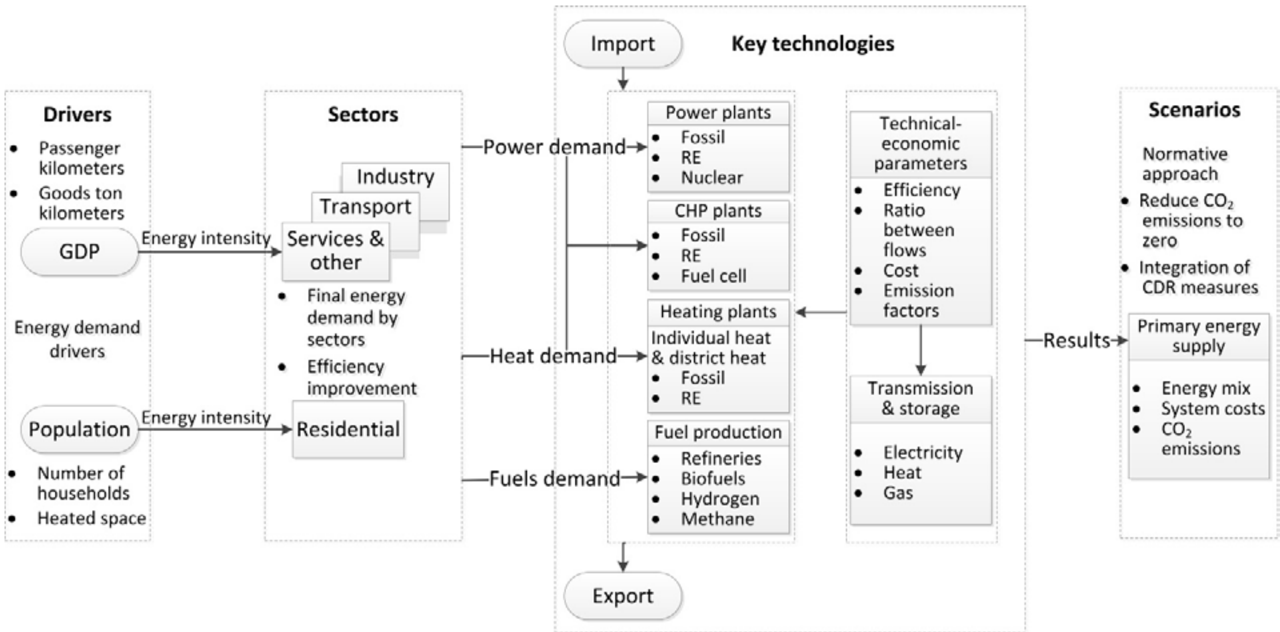

Figure 2: Structure of the applied energy system model developed at DLR.

It starts with energy demand development, driven by GDP and population from the above defined framing scenario and additional sectoral drivers, such as passenger kilometers or ton kilometers in transport and number of households and heated space in the residential sector as well as corresponding energy intensities. With a broad representation of technologies in the sectors of industry, residential, transport, services & others, the model assesses the required energy supply, as well as capacities for electricity and heat supply, CO_2 emissions and costs for heat and power production both from renewables and fossil fuels. A detailed description of the basic layout of the model can be found in (Simon et al., 2018; Teske et al., 2019b).

The technologies for power, heat and fuels supply are represented by efficiencies and ratios between flows to deal with sector coupling (e.g. defined for Combined Heat and Power (CHP) plants and hybrid vehicles), as well as specific costs and emission factors. The energy demand for the production of biofuels, hydrogen and other synthetic fuels with renewable energies are also taken into consideration. The transmission and storage of electricity, heat and gas are roughly represented due to the limitation of temporal resolution on a yearly basis. However, the coupling to the power optimization model REMix (see 3.1.2) allows for well-founded estimates of the corresponding infrastructure requirements to be considered for the scenario assessment.

3.1.2 REMix: Renewable Energy system optimization (DLR)

The model framework REMix developed at DLR consists of two model parts: REMix-EnDat for providing the temporal load and feed-in data for the model regions and REMix-OptiMo for solving a linear minimization problem. The objective function represents the system costs from the point of view of a central economic planner and includes not only the operation, fuel and certificate costs but also investment costs for model endogenously built plants. Considering the installable capacities and the hourly availability of renewable energies, an evaluation of the cost-minimum design and operation of the supply system is made. In order to examine the infrastructure requirements in detail, the optimization is carried out within one year in an hourly resolution. The time horizon up to 2050 is represented by a myopic approach in 10 year steps (Fichter, 2017), see Figure 3.

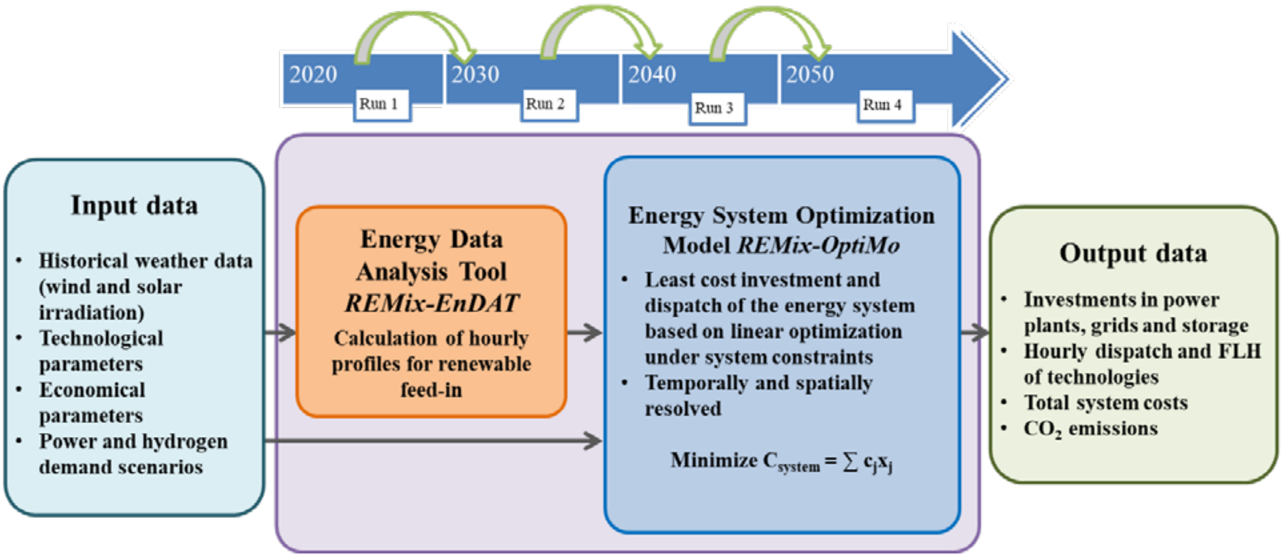

Figure 3: Renewable Energy Mix (REMix) energy system model (Gils et al. 2017)

Investments in new capacities consider technology cost, amortization time and interest rate, allowing the calculation of proportional capital costs for the chosen optimization periods. Due to its modular structure, REMix-OptiMo can be adapted to different scenarios and can model both the power supply system and a coupling to other sectors in the energy system. This includes a consideration of the heat sector, battery electric mobility, industrial load management and processes with synthetic fuels. In principle, an optimization of additional capacities can be carried out for all modelled technologies within the given system constraints such as upper limits for CO_2 emissions and imported electricity as well as minimum shares of renewable energies. A detailed model description can be found in (Gils et al., 2017).

The regional focus of our analysis is on Germany within Europe; therefore, we consider all neighboring countries to Germany and additionally Italy, Norway and Sweden each as one node. Denmark is represented by two nodes with data for east and west Denmark. The resolution of Germany is on Federal state level. Between all nodes with connecting lines there is the possibility of electricity imports and exports. The used model representation of REMix features a detailed representation of sector coupling technologies. This includes a representation of the gas system as well as the heating and transport sector. The gas sector consists of gas imports and transmission as well as gas storage and usage. Synthetic gas can be produced using electrolysis and methanisation.

For the Net-Zero-2050 project, REMix comprises 22 regions, about 90 technologies and 8760 time steps for the four scenario years 2020, 2030, 2040 and 2050. Germany is represented by 10 data nodes; 12 nodes are used to map the surrounding neighboring countries (Figure 4).

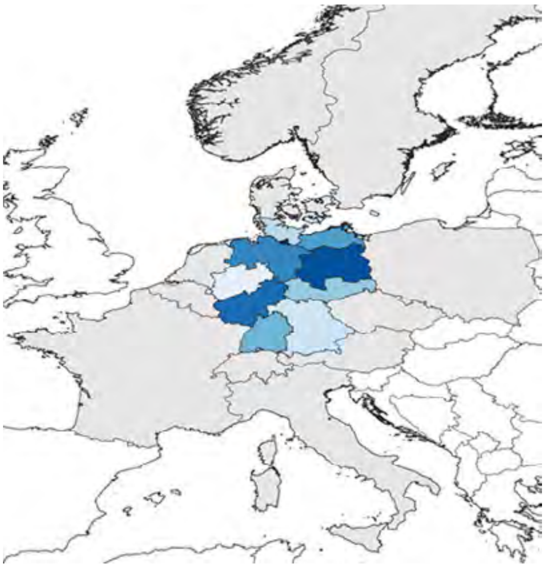

Figure 4: : German regions (blue) and neighboring countries under consideration in REMix according to the MuSeKo project

ESM-REMix Interfaces

The scenario output of the ESM partly serves as the exogenous input for REMix. This applies above all to the demand for electricity for conventional/classical consumption and electric mobility as well as the electricity required to generate the synthetic energy carriers hydrogen and hydrocarbons, which are used as final energy especially in an ambitious transformation scenario. Similarly, the demand for heat in all sectors and the respective share of the total heat covered by an electricity input (electric boilers and heat pumps) is provided by the ESM. Technical assumptions e.g. regarding the efficiencies or energy losses of the production of synthetic energy carriers are kept consistent between both models. REMix results in turn are fed back to the ESM to improve the scenarios. This concerns primarily the power generation structure (annual quantities produced, full-load hours and installed capacities), but also additional electricity demand for hydrogen reconversion e.g. in backup power plants or losses due to electricity storage and long-distance transport via the power grid. Electricity use in the heat sector for e-boilers or heat pumps is endogenously modelled in REMix (including the use of heat storage) and transferred as a result to the ESM. REMix then also provides the relevant values for the electricity-side system costs of the scenarios.

Interface tables in Excel were developed for the transfer of results between the models, with which also the partly different technology categories and resolutions can be tackled.

3.1.3 FRITS: Framework for assessing environmental impacts (DLR)

FRITS, a Framework for the assessment of environmental Impacts of Transformation Scenarios, allows to conduct Life Cycle Assessment of energy scenarios resulting from the ESM (Junne et al., 2020). It links bottom-up ESMs with life cycle inventories to quantify the environmental impacts of entire energy systems accounting for the whole life cycle of the assumed energy technologies for power, heat, and transport. It is particularly suitable for energy scenarios with a high degree of sector coupling.

While the ESM calculates CO_2 emissions during operations, it does not consider any other type of impacts, e.g., caused by construction. FRITS accounts for impacts along the whole life cycle of the modeled energy technologies. This allows not only investigating the role of construction and operation impacts, but also considering life times and full load hours of energy generation technologies.

Hereby, not only carbon footprints but a whole range of diverse impact categories can be analyzed, such as, human toxicity, land use, or resource depletion. Hence, it provides a comprehensive picture of environmental performance of energy scenarios beyond CO_2 emissions. It thereby enables a comparison of different energy transformation scenarios based on a detailed impact assessment. Thus, it is a useful tool to investigate possible side-effects of energy scenarios which are modelled with the goal of carbon reduction.

3.2 Scenario Assessment Model (FZJ)

The transformation paths for the achievement of Germany's Net-Zero Strategy affect different stakeholders in different ways. It is necessary, therefore, to analyze the benefits and costs associated with each path from the perspective of these stakeholders. In our study, we analyze four different scenarios (paths) for the transformation of Germany's energy system from the perspective of four stakeholders, namely: (i) utilities, (ii) energy-intensive industry, (iii) households and (iv) government. In the following we will describe our approach. After some comments on ancillary cost and benefits we will introduce the concept of Multi-Actor-Multi-Criteria analysis as well as the Promethee approach and our extensions of the approach.

3.2.1 Ancillary Costs & Benefits

To capture the implications of each energy transformation path for each stakeholder, we take into account both the primary benefits of emissions reductions and the ancillary effects associated with each path. These ancillary effects are private benefits and costs which emerge from the transformation path for each stakeholder in the energy system which are not related to climate mitigation (Pittel & Rübbelke, 2008). Such effects could include local reductions in air pollution (Buchholz et al., 2020) or increased costs for consumers (Vögele et al., 2020). Both the primary benefits and the ancillary effects determine stakeholder preferences in relation to the transformation paths. Moreover, as the ancillary benefits are realized much earlier than primary benefits, these are less affected by discount rates and, hence, easier to analyze.

3.2.2 MAMCA

Multi Criteria Decision Approach (MCDA) is a well-established technique to analyze complex decision making problems. Given several alternatives, MCDA ranks these alternatives from best to worst based on multiple, sometimes conflicting criteria (Behzadian et al., 2010). Multi Actor Multi Criteria Analysis (MAMCA) is an extension of MCDA and deals with decision making problems where the decision making involves or affects more than one stakeholder who have different objectives. At a very high level, the MAMCA process can be divided into five steps as represented in Figure 5 below.

The MAMCA approach starts with the decision makers defining the problem and the relevant stakeholders. These steps establish the framework in which the decision problem will be studied. Criteria relevant to the stakeholders and within the scope of the problem are fixed; these criteria provide a basis to analyze the alternatives. As different stakeholders assign different priorities to these criteria, weights are introduced to reflect this. There are different ways to operationalize MAMCA – in this case, the PROMETHEE method is used.

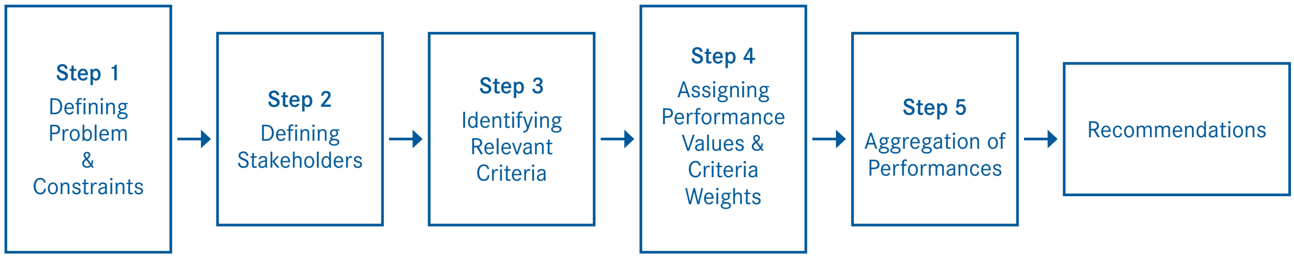

Figure 5: MAMCA Steps

3.2.3 PROMETHEE

The PROMETHEE (Preference Ranking Organization Method of Enrichment Evaluation) approach is based on an outranking technique. One alternative outranks another alternative if its performance is superior on a sufficient number of criteria of enough importance to a stakeholder, but not substantially inferior compared to the other alternative on any one criterion (Dodgson et al., 2009). Alternatives are compared in pairs to evaluate them based on the performance with respect to each criterion. As a result of the pairwise comparison, a preference value is calculated for each criterion.

Based on the weighted average of these preference values for each alternative on each criterion, a positive and negative outranking flow are established. The positive outranking flow represents the outranking character of an alternative, i.e. how preferred it is compared to other alternatives and the magnitude of this difference. The *negative outranking flow* measures the outranked character of an alternative, i.e. the extent to which other alternatives are preferred and the magnitude of these preferences. The net flow is then calculated and the alternative with highest net flow is considered the best alternative for the particular stakeholder.

While working with this approach, the criteria can be either quantitative or qualitative (Brans & De Smet, 2016). This is an advantage as decision making problems in the field of environment/energy management have many qualitative criteria. Unlike other outranking techniques, the decision maker does not have to define several variables. While this is so, PROMETHEE has its own share of disadvantages too. This approach is susceptible to the phenomenon of rank reversal, i.e. the ranking of the alternatives might get disrupted if an additional alternative is added to the decision problem (De Keyser & Peeters, 1996). It also does not specify any standard to set the weights and assumes that the decision maker is equipped with the knowledge to assign appropriate weights and this process of weighting can often be very subjective (Miller & Mattes, 2014). However, this problem can be tackled with pairing another MCDA technique such as AHP to decide the weights.

3.2.4 Integration of Externalities

The positions taken by one stakeholder in preference of a particular transformation path may impact the decisions of the other stakeholders – these effects are known as “externalities” (see Vögele et al. (2020)). In the context of the climate change policies, for example, the preference of government for a particular path may have an impact on the preferences of industry, as government sets the policies and market framework in which the industry operates. By integrating these so-called externalities, the model can further improve and made more robust.

4 COOPERATION

The first year within the Net-Zero-2050 was characterized by a strong cooperation between the involved centers, resulting in a set of project briefings. Specifically, P1.2 – "Integrated Scenario analyses" also focused on an extensive exchange on methods and data with regard to energy scenario and technology assessment.

DLR focused its cooperation on the project briefings, specifically leading briefing #4 "Scenario structure" in close exchange with UFZ, Geomar and GERICS. DLR also contributed to #1 "Structure of Project 1" and #2 "Carbon budget" and #5 "Data sets". Additionally, in P1.2 a joint data set for socio economic and fuel cost data were provided and agreed on between DLR, FJZ, UFZ and GERICS. Ongoing cooperation activities will target a joint technology data set as well as further exchange on indicators for scenario assessment with UFZ and FZJ.

FZJ implemented a multi-actor-multi-criteria approach to assess stakeholder preferences towards energy system transformation pathways, based on the indicators provided by DLR and UFZ. FZJ continues to work closely with DLR and UFZ to develop indicators to assess issues around risk and acceptance of biomass and CDR technologies.

UFZ have been in cooperation with DLR and FZJ to discuss the selection of indicators for the Technology Assessment Matrix (TAM) (P1.1). Within this exchange, indicators used within P1.1 and P1.2 have been compared to identify overlapping areas.

The Climate Service Center Germany (GERICS) established and maintained an exchange with P1.1 "National Roadmap Net Zero“. For this purpose, a joint P1.1 and P1.2 workshop was organized on February 17, 2020, as well as on September 09, 2020. These workshops aimed at fostering a fruitful information exchange within P1 as well as the preparation of joint material for the workshops with the entire team of Net-Zero-2050. Along with this task, P1.2's possible contributions to the national web-atlas, developed in WP1.1.3, was elicited.

Furthermore, GERICS guided the development of project briefing #5 „Data Sets“ which provides a detailed overview on the most relevant data sets used in Net-Zero-2050. Its structure is oriented on the indicators that were selected for the TAM (see above). This supports consistency and coherency across different work packages of Net-Zero-2050.

5 REFERENCES

Behzadian, M., Kazemzadeh, R. B., Albadvi, A., & Aghdasi, M. (2010). PROMETHEE: A comprehensive literature review on methodologies and applications. *European Journal of Operational Research, 200*(1), 198-215. doi:https://doi.org/10.1016/j.ejor.2009.01.021

BMWi. (2019). Entwurf des integrierten nationalen Energie- und Klimaplans. Bundesministerium für Wirtschaft und Energie.

Brans, J.-P., & De Smet, Y. (2016). PROMETHEE methods. In *Multiple criteria decision analysis* (pp. 187-219): Springer.

Brown, T., Schäfer, M., & Greiner, M. (2019). Sectoral interactions as carbon dioxide emissions approach zero in a highly-renewable European energy system. *Energies, 12*(6), 1032. doi:ARTN 1032 10.3390/en12061032

Bründlinger, T., König, J. E., Frank, O., Gründig, D., Jugel, C., Kraft, P., . . . Seidl, H. (2018). *dena-Leitstudie Integrierte Energiewende: Impulse für die Gestaltung des Energiesystems bis 2050.* Retrieved from Berlin/Köln, Germany: https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9262_dena-Leitstudie_Integrierte_Energiewende_Ergebnisbericht.pdf

Buchholz, W., Markandya, A., Rübbelke, D., & Vögele, S. (2020). Analysis of Ancillary Benefits of Climate Policy. In *Ancillary Benefits of Climate Policy* (pp. 1-11): Springer.

Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., . . . Nakos, C. (2016). EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050.

Child, M., Kemfert, C., Bogdanov, D., & Breyer, C. (2019). Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renewable Energy, 139*, 80-101. doi:10.1016/j.renene.2019.02.077

De Keyser, W., & Peeters, P. (1996). A note on the use of PROMETHEE multicriteria methods. *European journal of operational research, 89*(3), 457-461.

Dodgson, J. S., Spackman, M., Pearman, A., & Phillips, L. D. (2009). Multi-criteria analysis: a manual.

EnergyPLAN. (2020). Mesap PlaNet. Retrieved from https://www.energyplan.eu/othertools/national/mesap-planet/

Eurelectric. (2018). *Decarbonisation pathways*. Retrieved from https://www.eurelectric.org/decarbonisation-pathways/

Fichter, T. (2017). *Long-term capacity expansion planning with variable renewable energies : enhancement of the REMix energy system modelling framework.* Stuttgart,

FNR. (2018). *Basisdaten Bioenergie Deutschland*. Gülzow: Fachagentur Nachwachsende Rohstoffe.

Gils, H. C., Scholz, Y., Pregger, T., Luca de Tena, D., & Heide, D. (2017). Integrated modelling of variable renewable energy-based power supply in Europe. *Energy, 123*, 173-188. doi:http://dx.doi.org/10.1016/j.energy.2017.01.115

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., . . . Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy, 3*(6), 515-527. doi:10.1038/s41560-018-0172-6

Günther, J., Lehmann, H., Lorenz, U., Purr, K., & Grimm, F. (2017). *Den Weg zu einem treibhausgasneutralen Deutschland ressourcenschonend gestalten:* Umweltbundesamt.

Henning, A., Plohr, M., Özdemir, E. D., Hepting, M., Keimel, H., Sanok, S., . . . Vogel, B. (2015). *The DLR transport and the environment project - Building competency for a sustainable mobility future. DLR Deutsches*

Zentrum fur Luft- und Raumfahrt e.V. - Forschungsberichte. Retrieved from https://elib.dlr.de/109326/1/Seum_et_al%20DLR-FB-2016-38_p192-198.pdf

Henning, H.-M., & Palzer, A. (2015). *Was kostet die Energiewende? Wege zur Transformation des deutschen Energiesystems bis 2050.* Retrieved from https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Fraunhofer-ISE-Studie-Was-kostet-die-Energiewende.pdf

Hillebrandt, K., Samadi, S., & Fischedick, M. (2015). *Pathways to deep decarbonization in Germany.* Retrieved from https://epub.wupperinst.org/frontdoor/index/index/docId/6079

IEA. (2017). *Energy technology perspectives 2017*. Retrieved from

IRENA. (2019). *Global energy transformation: The REmap transition pathway (Background report to 2019 edition)*.

Jacobson, M. Z., Delucchi, M. A., Bauer, Z. A. F., Goodman, S. C., Chapman, W. E., Cameron, M. A., . . . Yachanin, A. S. (2017). 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule, 1*(1), 108-121. doi:https://doi.org/10.1016/j.joule.2017.07.005

Junne, T., Simon, S., Buchgeister, J., Saiger, M., Baumann, M., Haase, M., . . . Naegler, T. (2020). Environmental sustainability assessment of multi-sectoral energy transformation pathways: Methodological approach and case study for Germany. *in preparation*.

Kemmler, A., Kirchner, A., Maur, A. A. d., Ess, F., Kreidelmeyer, S., Piégsa, A., . . . Ziegenhagen, I. (2020). *Energiewirtschaftliche Projektionen und Folgeabschätzungen 2030/2050, Dokumentation von Referenzszenario und Szenario mit Klimaschutzprogramm 2030*. Retrieved from

Klein, S., Klein, S., Steinert, T., Fricke, A., & Peschel, D. (2017). *Erneuerbare Gase-Ein Systemupdate der Energiewende.* Retrieved from Berlin: https://www.wind-energie.de/fileadmin/redaktion/dokumente/publikationen-oeffentlich/themen/03-sektorenkopplung/20171212_studie_erneuerbare_gase.pdf

Lutz, C., Flaute, M., Lehr, U., Kemmler, A., Kirchner, A., Auf der Maur, A., . . . Piégsa, A. (2018). *Gesamtwirtschaftliche Effekte der Energiewende.* Retrieved from https://www.econstor.eu/bitstream/10419/206679/1/1043732926.pdf

McGowan, D., Rzepczyk, T., Sönmez, C., Powell, D., Fernandez, M., Bogucka, M., . . . Groups;, R. (2019). *TYNDP 2020 Scenario Report.* Retrieved from

Miller, M., & Mattes, K. (2014). *Demonstration of a multi-criteria based decision support framework for selecting PSS to increase resource efficiency*. Karlsruhe: Fraunhofer ISI

Nitsch, J., Pregger, T., Naegler, T., Dominik Heide, Tena, D. L. d., Trieb, F., . . . Wenzel, B. (2012). *Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global*. Retrieved from Stuttgart, Kassel, Teltow: http://www.fvee.de/fileadmin/publikationen/Politische_Papiere_anderer/12.03.29.BMU_Leitstudie2011/BMU_Leitstudie2011.pdf

Öko-Institut, & FhG ISI. (2015). *Klimaschutzszenario 2050.* Retrieved from https://www.oeko.de/oekodoc/2451/2015-608-de.pdf

Pestiaux, J., Cornet, M., Jossen, Q., Martin, B., Matton, V., Meessen, J., . . . Vermeulen, P. (2018). *Net Zero by 2050: From whether to how-Zero emission pathways to the Europe we want.* Retrieved from https://europeanclimate.org/content/uploads/2019/12/09-19-net-zero-by-2050-from-whether-to-how-executive-summary.pdf

Pittel, K., & Rübbelke, D. T. (2008). Climate policy and ancillary benefits: A survey and integration into the modelling of international negotiations on climate change. *Ecological Economics, 68*(1-2), 210-220.

Pregger, T., Naegler, T., Weimer-Jehle, W., Prehofer, S., & Hauser, W. (2019). Moving towards socio-technical scenarios of the German energy transition—lessons learned from integrated energy scenario building. *Climatic*

Change. doi:10.1007/s10584-019-02598-0

Ram, M., Bogdanov, D., Aghahosseini, A., Gulagi, A., Oyewo, A., Child, M., . . . Energy Watch Group, L., Berlin. (2019). Global energy system based on 100% renewable energy–power, heat, transport and desalination sectors.

Robinius, M., Markewitz, P., Lopion, P., Kullmann, F., Heuser, P., Syranidis, K., . . . Ryberg, S. (2019). *Wege für die Energiewende: Kosteneffiziente und klimagerechte Transformations-strategien für das deutsche Energiesystem bis zum Jahr 2050.* Retrieved from https://www.researchgate.net/profile/Martin_Robinius/publication/343601046_WEGE_FUR_DIE_ENERGIEWENDE_Kosteneffiziente_und_klimagerechte_Transformationsstrategien_fur_das_deutsche_Energiesystem_bis_zum_Jahr_2050/links/5f3392fba6fdcccc43c20d90/WEGE-FUeR-DIE-ENERGIEWENDE-Kosteneffiziente-und-klimagerechte-Transformationsstrategien-fuer-das-deutsche-Energiesystem-bis-zum-Jahr-2050.pdf

Ruiz, P., Sgobbi, A., Nijs, W., Thiel, C., Dalla Longa, F., Kober, T., . . . Hengeveld, G. (2015). The JRC-EU-TIMES model. Bioenergy potentials for EU and neighbouring countries. *European Commission Joint Research Centre*.

Schlenzig, C. (1998). PlaNet: ein entscheidungsunterstützendes System für die Energie-und Umweltplanung.

Schlesinger, M., Hofer, P., Kemmler, A., Kirchner, A., Koziel, S., Ley, A., & Ulrich, P. (2014). *Entwicklung der Energiemärkte-Energiereferenzprognose.* Retrieved from

Simon, S., Naegler, T., & Gils, H. (2018). Transformation towards a Renewable Energy System in Brazil and Mexico—Technological and Structural Options for Latin America. *Energies, 11*(4), 907.

Terlouw, W., Peters, D., van Tilburg, J., Schimmel, M., Berg, T., Cihlar, J., . . . Buseman, M. J. N. N. B., März. (2019). „Gas for climate: The optimal role for gas in a net-zero emissions energy system “.

Teske, S. (Ed.) (2019). *Achieving the Paris Climate Agreement Goals*: Springer.

Teske, S., Pregger, T., Naegler, T., Simon, S., Pagenkopf, J., van den Adel, B., & Deniz, Ö. (2019). Energy Scenario Results. In S. Teske (Ed.), *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5 °C and +2 °C* (pp. 175-401). Cham: Springer International Publishing.

Teske, S., Pregger, T., Simon, S., Naegler, T., Pagenkopf, J., van den Adel, B., . . . Nagrath, K. (2019). Methodology. In S. Teske (Ed.)*, Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5 °C and +2 °C* (pp. 25-78). Cham: Springer International Publishing.

Thrän, D., Lauer, M., Dotzauer, M., Kalcher, J., Oehmichen, K., Majer, S., . . . Jordan, M. (2019). *Technoökonomische Analyse und Transformationspfade des energetischen Biomassepotentials (TATBIO)*. Retrieved from https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/technooekonomische-analyse-und-transformationspfade-des-energetischen-biomassepotentials.html

UBA. (2014). *Treibhausgasneutrales Deutschland im Jahr 2050.*

UBA. (2019). Nationale Trendtabellen für die deutsche Berichterstattung atmosphärischer Emissionen seit 1990, Emissionsentwicklung 1990 bis 2017 (Stand 01/2019). Retrieved from https://www.umweltbundesamt.de/daten/klima/treibhausgas-emissionen-in-deutschland#treibhausgas-emissionen-nach-kategorien

UNFCCC. (2020). GHG Data Interface, Report produced on Tuesday, 12 May 2020. Retrieved from https://unfccc.int/

Vögele, S., Ball, C., & Kuckshinrichs, W. (2020). Multi-criteria approaches to ancillary effects: the example of e-mobility. In *Ancillary Benefits of Climate Policy* (pp. 157-178): Springer.

Zappa, W., Junginger, M., & van den Broek, M. (2019). Is a 100% renewable European power system feasible by 2050? *Applied Energy, 233-234*, 1027-1050. doi:https://doi.org/10.1016/j.apenergy.2018.08.109

AUTHORS

DLR: Sonja Simon, Mengzhu Xiao, Thomas Pregger, Judith Riehm, Carina Harpprecht
FZJ: Stefan Vögele, Christopher Ball
UFZ: Malgorzata Borchers
GERICS: Bettina Steuri

CONTACT PERSON

Dr. Sonja Simon (DLR) | sonja.simon@dlr.de

The Helmholtz Climate Initiative (HI-CAM) is funded by the Helmholtz Association‘s Initiative and Networking Fund. The authors are responsible for the content of this publication.

More results from the project Net-Zero-2050 are available here:

www.netto-null.org
www.helmholtz-klima.de/en/press/media-library

September 2020