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Article

A Pathway for the German Energy Sector Compatible with a 1.5 °C Carbon Budget

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Abstract: We present an energy transition pathway constrained by a total CO₂ budget of 7 Gt allocated to the German energy system after 2020, the Budget Scenario (BS). We apply a normative backcasting approach for scenario building based on historical data and assumptions from existing scenario studies. The modeling approach combines a comprehensive energy system model (ESM) with REMix—a cost optimization model for power and heat that explicitly incorporates sector coupling. To achieve the necessary CO₂ reduction, the scenario focuses on electrifying all end use sectors until 2030, adding 1.5–2 million electric vehicles to the road per year. In buildings, 400,000–500,000 heat pumps would be installed annually by 2030, and the share of district heating would double until 2050. In the scenario, coal needs to be phased out by 2030. Wind and Photovoltaic (PV) capacities would need to more than double to 290 GW by 2030 and reach 500 GW by 2050. The BS results indicate that a significant acceleration of the energy transition is necessary before 2030 and that this higher pace must be maintained thereafter until 2050.

Keywords: net-zero; energy scenario; decarbonization; carbon budget; energy transformation pathway; renewable energy; electrification



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1. Introduction

The Nationally Determined Contributions (NDCs) of the Paris agreement submitted by countries are far from sufficient to prevent temperature increase beyond 1.5 °C [1]. One reason is that even though we are comparatively certain about the limitations of the remaining global carbon budget [2], no agreement has been reached how to share the burden among nations. This is not only due to a large uncertainty of the carbon budget [3], but also due to unsolved issues on equity and responsibility [4,5]. A few things, however, are certain if climate change is to be avoided: Each country will have to face a limited carbon budget and will require resolute and fast mitigation actions in all economic sectors.

The energy system is responsible for 65% of today's total Greenhouse Gas (GHG) emissions [6] and, thus, has to contribute the main share of avoiding emissions. This is even more important in strongly industrialized countries, such as Germany, where the consumption of fossil energy accounts for more than 90% of CO₂ emissions [7]. This is in general acknowledged by society and policy, e.g., in Europe with the Green deal [8] or by China's plan to achieve carbon neutrality before 2060 [9]. It is clear that far-reaching technological transformations are required that will fundamentally change the way we generate and use energy. There are different views on key options and development paths for this, which have been and are being presented in numerous scenario-based studies and modeling (see, e.g., [10]).

The choice of emission reduction strategies determines the requirements of specific infrastructural developments to enable a transition in the next decades. According to [5],

policy plans for net-zero all over the world are lacking in detail and consistency when proposing their net-zero targets. Moreover, [5] claims that, beyond long-term targets, shorter perspectives are necessary to adequately adapt transformation to emission reduction requirements.

While the carbon budget as a reference point has been addressed by climate research for the energy sector for a considerable time [11], energy system research has not adopted this concept as a general guideline yet. Previous energy scenarios for Germany focused on reaching a share of 100% renewable energy (RE) or net-zero by 2050 or 2045; so far, they have not considered cumulative emissions compared to the carbon budget on a national level. The Wuppertal Institute presented a rough sketch of what would be necessary in various sectors including the energy sector to comply with the Paris Agreement. They set a German carbon budget of 4.2 Gt from 2020–2050 [12] with a resulting system configuration for 2035; however, they did not present the necessary steps in between.

Up to now, no study presented a detailed long-term energy scenario for Germany, which consistently linked a transition pathway to a nationally fixed carbon budget. Thus, in our study, we elaborate on what would be necessary to comply with a carbon budget specifically for the energy sector in Germany in line with the 1.5 °C target. This can help overcome the shortcomings of most existing studies that focus only on carbon limits for target years and currently still underestimate the burden of past emissions and the necessary speed with which net-zero technologies must be implemented.

We explore one exemplary transition pathway that stays within this carbon budget and thus represents an upper bound of the required technology switch. We follow a deterministic approach on the one hand and a complementary cost optimization of supply infrastructures on the other without claiming that this leads to an optimal or particularly probable scenario. Our modeling approach particularly addresses interactions between the different energy sectors, which appear to be particularly necessary for an effective transition. In detail, we focus on the following research questions:

What kind of technology transition is necessary to supply German energy demand in transport and heat sectors under a strict carbon budget restraint? How does this translate into installation of new technologies and the transformation of the energy supply? From recent scenarios, it is already clear that electrification will play a major role in the energy transition. Our study, therefore, addresses how fast the power sector has to change to renewables beyond the current political targets to accommodate not only electricity demand but also a transport and heat transition.

In the following Section 2, we focus on scenario development and our approach to couple an energy accounting framework with an economic linear optimization model. We provide details of the underlying technology data, the assumptions and the storyline for the net-zero Budget Scenario in Section 3. In Section 4, we present the results of the scenario quantification with regard to energy supply and CO₂ emissions. The potential implications of the technology transition are given in the discussion and conclusion (Sections 5 and 6).

2. Materials and Methods

We develop a normative scenario by applying a backcasting approach and following the steps proposed by [13]. The target is to achieve a net-zero energy system in Germany by 2050 while also remaining within the carbon budget of a 1.5 °C climate target. With regard to greenhouse gases, we limit our modeling to CO₂ emissions (see Sections 2.1 and 2.2). We first define the current structure of energy consumption and production in Germany within our energy system model approach (Sections 2.3–2.6).

Then, we define the scenario limitations by assumptions about (1) socio-economic developments (see Section 3.1), such as future Gross domestic product (GDP) and population, (2) future energy demand per sector (see Section 3.2), and (3) technological limitations and targets for energy supply in 2050 (see Section 3.3). Based on the system setup for 2050, we identify the necessary technology transitions in the industry, transport, residential, as well

as services and other commercial sectors in order to achieve the target. The outcome is a transition pathway of energy supply for all sectors.

2.1. Target and Storyline: Assessing the Limits of a Carbon Budget for the Energy System

The overall storyline focuses on a society that succeeds in limiting CO₂ emissions as a vital step towards climate neutrality. As elaborated in the introduction, the 1.5 °C target depends on limiting cumulative emissions, not only net-zero emissions in a far future.

Thus, our scenario aims at technology change that is guided by a CO₂ budget for the German energy system, which may not be exceeded in the future. The net-zero Budget Scenario (BS) focuses on additional efficiency improvements and on achieving an almost 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.

We specifically exclude the option of an overshoot scenario, which would have to rely on carbon dioxide removal (CDR) technologies for storage, in order to assess an upper limit of a necessary energy transition and its included costs. This is guided by the premise of the energy sector's own responsibility to avoid existing emissions, reserving CDR options for emissions harder to avoid than in the energy sector. Moreover, many CDR technologies feature additional energy demand and, thus, put an additional burden on the renewable energy potential, which, at least for Germany, faces physical, technical, and societal limits.

2.2. Definition of a Carbon Budget for the German Energy Sector

To date, national carbon budgets have neither been agreed upon nor is there a consensus on how they will be calculated. If the equal per capita or the grandfathering approaches are applied, carbon budgets for Germany range from 3.5–13.3 Gt CO₂ [14].

Here, we assume the contraction and convergence approach (C&C) [15], as it is considered “the best possible solution to the twin problems of climate change and inequity” [16]. Under the C&C approach, the total carbon budget for Germany ranges from 7 to 8 Gt CO₂ for the time period of 2020 to 2050 as calculated by [14]. The C&C approach consists of two phases (see Figure 1) [17]. In the first phase, the convergence phase, current national emissions per capita decrease (or increase) until they reach a globally unified value of equal per capita emissions in 2035.

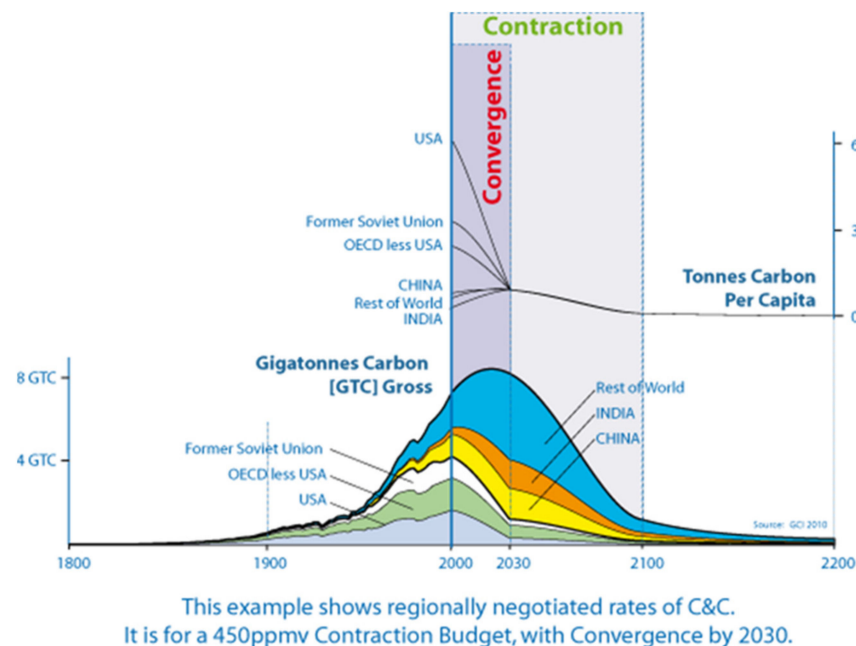


Figure 1. The contraction and convergence approach for deriving fair carbon budgets for nations [17].

This provides time for nations for systemic transformations. Then, all nations are supposed to adhere to this globally unified equal per capita emission rate, which reaches net-zero by 2050. The range of the carbon budget results from different assumptions about the starting year for the C&C approach.

Our Energy System Model (see Section 2.3) accounts for all CO₂ emissions emitted in the energy system, including the industrial emissions in the steel sector. In 2019, this combined system emitted 96% of Germany's CO₂ emissions [7]. Based on these current shares and the total budget from [14], we allocate a range of 6.5 to 7.5 Gt of CO₂ to the extended energy sector, that serves as a constraint to future demand and supply developments.

We start the backcasting approach from 2050 and develop the scenario backward to 2020 in five-year steps. The technical background for the scenario development, i.e., our energy system models and technology data, is described in the next sections. Beyond that, a large variety of underlying assumptions is made, based on statistical data, literature and expert judgement (see Section 3).

2.3. Modeling Approach: Energy System Modeling, Cost Optimization and Model Coupling

In order to identify the transformation pathways for an energy system, while also characterizing fluctuating, variable renewable energy (VRE) sources, we couple the Energy System Model (ESM)—an accounting framework for energy balances on annual basis, and a linear system optimization model (REMix) with hourly resolution.

2.3.1. Energy System Model (ESM)

Our ESM is a framework for balancing energy demand and supply of a given region over a given time period. In this study, it is applied to develop the transformation scenario for the overall energy system, including the residential, industry, transport and services and other sectors, as well as the transformation sector, including power, combined heat and power (CHP), fuel and heat production etc. Figure 2 gives an overview about the sectoral disaggregation and the range of primary energy carriers and supply technologies covered by the ESM.

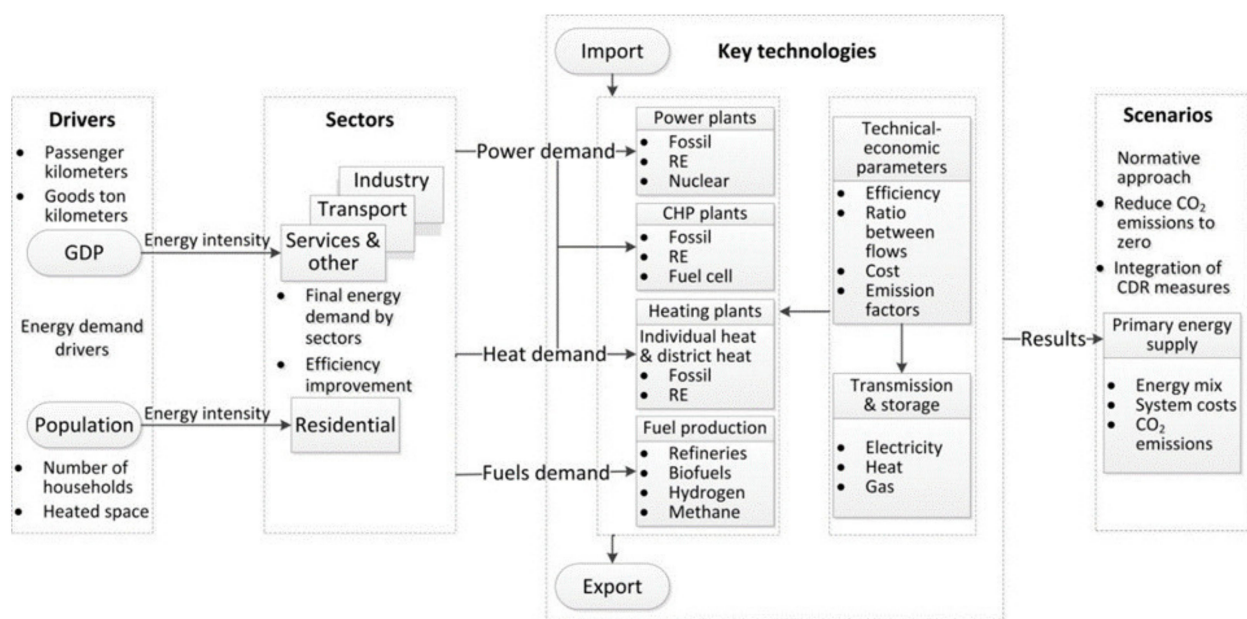


Figure 2. Applied energy system model (ESM) for the energy scenario analysis.

The ESM quantifies energy demand development pathways (see assumptions in Section 3), driven by GDP and population from the below defined framing scenario, assessing and projecting the energy intensity. Additional sectoral drivers are considered for transportation in terms of passenger kilometers and ton kilometers. The model assesses the required energy supply structure: namely, power and heat installed capacities and their costs, as well as CO₂ emissions from a broad range of technologies in the above-mentioned end-use sectors.

The model is calibrated with statistical data for the years 2001–2019. The main inputs are the German energy balances 2019 and previous years [18,19] as well as official energy statistics from the Federal Ministry of Economy and Energy for 2019 [20,21] and previous years. The model represents a time frame up to 2050, divided by five-year intervals. The model calculates annual primary energy, summing up useful energy in each sector disaggregated by technology and multiplied by efficiency factors as represented by the following equations, previously published in [22]:

$$\text{TFD}(s, t) = \sum_s^S \sum_t^{T(s)} \text{UED}(s) \cdot \text{MS}(s, t) \cdot \eta(t) \quad (1)$$

$$\text{TPE}(f) = \sum_f^F \text{FED}(f) \cdot \eta(tt) \quad (2)$$

where

TFD = total final energy demand,

s = a specific energy sector,

t = a specific technology of a sector,

MS = market share of a technology in a sector,

UED = total useful energy demand of a sector,

η = efficiency of a technology,

TPE = total primary energy demand of a country,

f = fuel type, and

tt = transformation technology.

Refer to [22,23] for a more detailed description of the model structure.

The technologies are characterized by efficiencies and ratios that disaggregate energy flows (see Section 2.6) for technologies with more than one energy input or output—e.g., for CHP plants and hybrid vehicles. Additionally, it applies specific CO₂ emission factors for fossil energy carriers.

However, the transmission and storage of electricity, heat, and gas is only roughly represented due to the limitation of the temporal resolution on a yearly basis. This also limits the representation of VRE. For these reasons, we couple the optimization model REMix to allow for a system cost optimized deployment of renewables, specifically VRE, including a detailed assessment of grid and storage infrastructures required for the developed pathway.

2.3.2. REMix

The energy system optimization model REMix combines two models (see Figure 3): EnDAT, which provides the temporal load and the feed-in renewable energy (RE) profiles for each model region; and REMix-Optimo, which optimizes the expansion and operation of the energy system. REMix minimizes the total system cost from a central economic planner's point of view with perfect foresight. The total system cost includes not only operation, fuel and CO₂ certificate costs but also investment costs for model endogenously built capacities. The proportional capital costs of the installed capacities are calculated from technology investment costs and fixed operation and maintenance (O&M) costs, amortization times and interest rates. A detailed model description can be found in [24–26], including all relevant equations of the optimization algorithm.

In our study, we consider the power sector, which is coupled to the heating, transport, industry, and gas sector. The gas sector consists of gas production, usage, storage, imports and transmission. Among these, synthetic gas can be produced through electrolysis and

methanation powered by renewable energy. Additionally, we included two model constraints to the optimization: upper limits for CO₂ emissions, and a minimum of remaining CHP capacities for biomass. Considering the input data for the technological and economical parameters, the weather and load profiles from EnDAT and the additional model constraints, REMix optimizes the energy system and provides the optimized expansion and dispatch of the infrastructures, the total system costs and the annual CO₂ emissions as output.

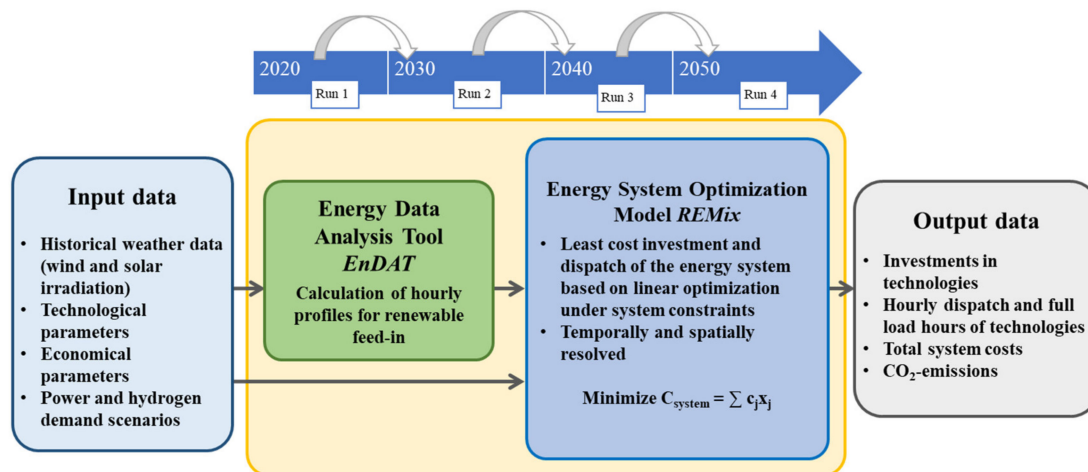


Figure 3. Energy system optimization model REMix adapted from [27].

2.4. System Boundary

For the ESM, we limit our analysis to Germany with an assessment of net imports of synthetic fuels and power. However, for REMix, we adapt the strict system boundaries of Germany due to the requirements of the trans-European power grid. As shown in Figure 4, our REMix modelling focuses on Germany with 10 regional nodes, while 12 additional nodes model its neighboring countries. The power exchange is represented by high-voltage alternating current (HVAC) and high-voltage direct current (HVDC) lines that connect the neighboring model nodes. In our study, REMix comprises 22 regions, about 90 technologies and 8760 h for the scenario years of 2020, 2030, 2040 and 2050.

The optimization with REMix is performed with a myopic approach that optimizes the four scenario years sequentially. The optimized capacities of each model run are passed on to the next scenario year, while technology components that exceed their lifetime are decommissioned. For the sensitivity analysis, we simplified the model to a 3-h resolution, in order to reduce the calculation time.

2.5. Model Coupling

The scenario from the ESM partly serves as the exogenous input for the REMix model (see Figure 5). This applies to the demand of electricity for conventional consumption and electric mobility as well as the total heat demand and the share of electricity envisaged for heat. It also includes the demand of synthetic energy carriers, namely hydrogen and synthetic methane for transport and process heat. Technical assumptions, such as future reduction potentials linked to renewable technology investments, efficiencies or energy losses in the production of synthetic energy carriers, are consistently adhered to between the two models.

The output of REMix in turn serves as an input for the supply side of the ESM, defining the capacities for the power sector and for sector coupling. It primarily involves additionally installed capacities and the utilization in terms of full-load hours (FLH). Furthermore, the additional electrical demand for hydrogen reconversion, e.g., in backup power plants or losses due to electricity storage and long-distance transport via the power

grid, are also included. The parameter exchange between the models is detailed in S1 in the Supplementary Materials.

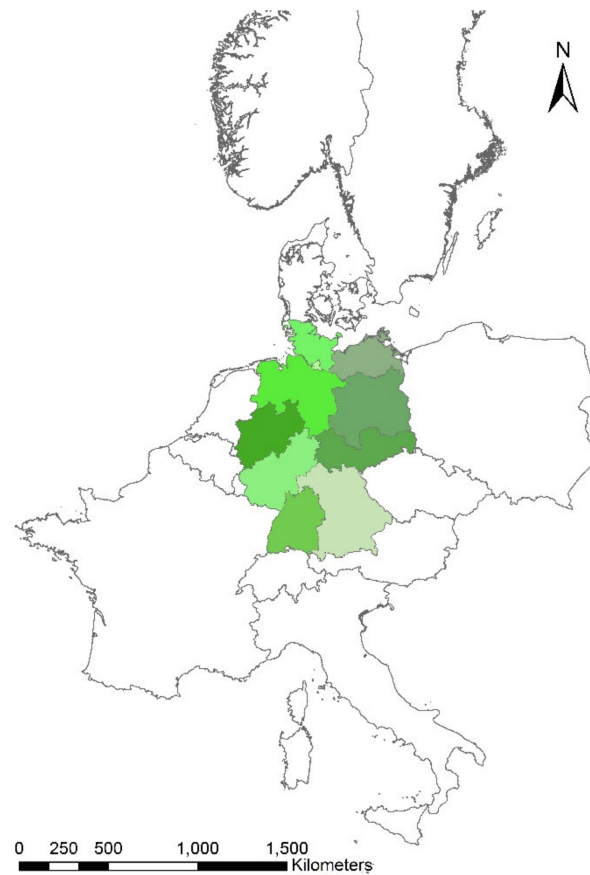


Figure 4. System boundary with modeled regions of Germany and neighboring countries.

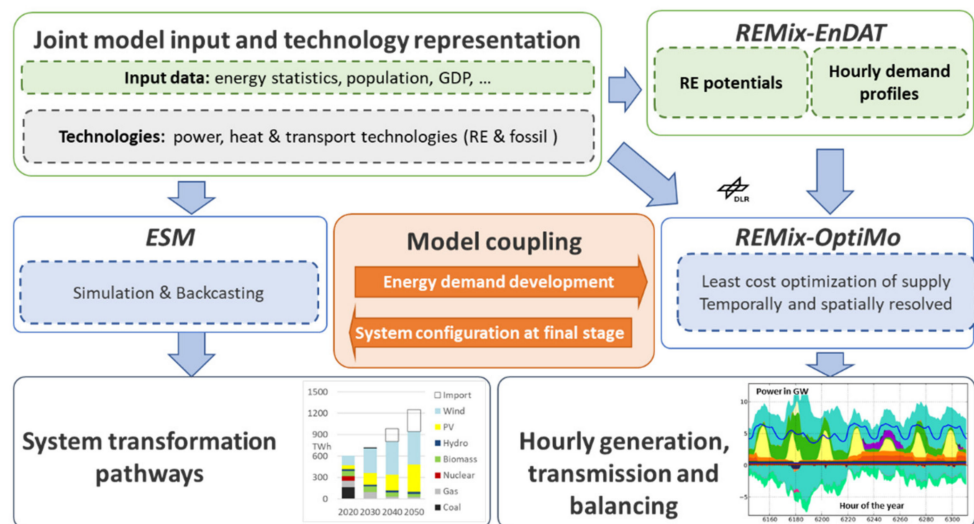


Figure 5. Model coupling of ESM and REMix adapted from [28].

2.6. Technology Data

Both the ESM and REMix rely on the same set of current and future techno-economic assumptions. This technology data set comprises:

1. Technical lifetime.

2. Specific investment costs.
3. Specific fixed operation and maintenance costs.
4. Specific variable operating and maintenance costs.
5. Efficiency.

Specifically, we updated data for technologies to be implemented in large capacities such as PV, wind and balancing capacities, which are crucial for the energy transition. Significant cost reductions would be expected in PV and wind power with an increasing lifetime accordingly. Thus, we adapted existing cost projections from [29] by [30–32] (see Table 1). Especially investment costs are expected to decrease significantly between 2020 and 2050 by 40% for PV and offshore wind and 16% for onshore wind.

Lithium-ion batteries also see significant technology development. Investment costs decline by 50% for both storage and converter units with increasing life time. For gas converting technologies, such as electrolyzers and methanation, a reduction of investment costs is projected, by 61% and 47%, respectively, from 2020 to 2050. Other techno-economic input data for REMix and the ESM refer to [33]. All relevant deviations from the original data set are documented in the SI in S2.

Table 1. Techno-economic parameters of the main technologies in REMix and ESM.

Renewable Power Technology	Scenario Year	Specific Investment Costs	Lifetime	Specific Fixed Operation and Maintenance Cost	Efficiency
		EUR ₂₀₁₆ /kW	Years	EUR ₂₀₁₆ /kW	%
Run of river *	2020–2050	4273	60	214	100
	2020	900	25	15	
Photovoltaic *	2030	700	30	12	100
	2040	600	30	10	
	2050	540	30	9	
	2020	3500	20	110	
Offshore wind *	2030	2250	25	90	100
	2040	2100	30	85	
	2050	2100	30	75	
	2020	1310	20	45	
Onshore wind *	2030	1250	22	45	100
	2040	1180	25	40	
	2050	1100	25	38	
Gas converting technology					
Electrolyzer [34]	2020	900		18	69
	2030	550	25	11	74
	2040	450		9	77
	2050	350		7	80
	2020	1500		37.5	75
2030	1000	25		25	80
Methanation [35]	2040	900	25	22.5	85
	2050	800		20	90
	2020	300		21	2.7
Storage technology					
Lithium-ion battery (storage) [36,37]	2020	300	21	2.7	93
	2030	225	22	1.8	94
	2040	188	23	1.1	95
	2050	150	25	0.8	97

* own assumptions based on [29–32].

3. Scenario Assumptions for the Budget Scenario (BS)

Our approach distinguishes between the general socio-economic frame and the technology-based energy scenario. The framing scenario provides a common background for comparing the net-zero BS with other scenario work and is described in the first section. Assumptions on the development of final energy demand are also derived exogenously from the literature and described in the second section. Beyond that, we provide details on the target-driven technology development in the year 2050 from which we start the backcasting procedure.

3.1. Socio Economic Frame

The socio-economic framing data describe a likely development of the German society in an explorative approach. It is based on the German National Energy and Climate Plan

(NECP) [38,39]. From the NECP, we derive projections for GDP and population until 2050, as well as fuel and CO₂ prices (Table 2).

Table 2. Assumptions on socio-economic development and fuel costs for Germany.

	Unit	2020	2030	2040	2050
GDP	billion EUR ₂₀₁₆	3326	3729	4088	4430
Population	million capita	83.5	82.9	81.3	79.0
CO ₂ price high	EUR ₂₀₁₆ /t	24	140	220	240 *
Fuel prices:					
Crude oil	EUR ₂₀₁₆ /GJ	13.0	17.0	18.0	19.4
Natural gas	EUR ₂₀₁₆ /GJ	8.0	9.0	10.0	10.6
Hard coal	EUR ₂₀₁₆ /GJ	2.5	3.6	4.0	4.3
Syncrude	EUR ₂₀₁₆ /GJ	119	80	65	60
Uranium	EUR ₂₀₁₆ /GJ	0.6	0.7	0.9	1.0
Lignite	EUR ₂₀₁₆ /GJ	5.6	5.1	4.8	4.5

Source: NECP background study [39]; * own assumption.

We supplement these fuel costs with own assumptions on biomass, waste and hydrogen (Table 3), which are not provided by the NECP.

Table 3. Assumptions on biomass, waste and hydrogen costs.

	Unit	2020	2030	2040	2050
Biomass costs					
Waste wood and wood chips	EUR ₂₀₁₆ /GJ	3.2	3.2	3.2	3.2
Pellets, short rotation forestry	EUR ₂₀₁₆ /GJ	13.9	14.8	15.8	16.7
Landfill gas	EUR ₂₀₁₆ /GJ	1.0	1.0	1.0	1.0
Liquid biofuels	EUR ₂₀₁₆ /GJ	21.6	28.3	35.0	41.7
Raw biogas	EUR ₂₀₁₆ /GJ	15.0	14.6	14.3	13.9
Waste cost	EUR ₂₀₁₆ /GJ	0	0	0	0
Hydrogen cost *	EUR ₂₀₁₆ /GJ	24.4	24.4	24.4	24.4

Source: own assumptions based on [40,41]; * based on [42].

3.2. Demand Assumptions by Sector

The demand structure is based on a variety of assumptions on additional efficiency potentials, reaching lower energy intensities for final energy demand. The transport sector relies on an existing transport study and the residential and services/other commercial sectors on a literature review. For industry, we develop an own specific modeling. To adapt these demand projections for the BS, final energy demand was translated to useful energy and “energy services”, such as person or ton kilometers (pkm and tkm) or production of steel.

3.2.1. Residential and Services and Other Sectors

The BS follows the “Klimaschutzplan”-Scenario from the NECP [39] until 2030 for the useful energy demand in the residential and services and other sectors. From 2030 to 2050, our demand assumptions are based on a scenario comparison, evaluating the demand range of 62 scenarios from 21 studies for Germany from [10] (for details see S3 and S4 in the SI). For the BS, we therefore select the median demand projection for 2050. The residential sector achieves an intensity of 0.33 GJ per EUR₂₀₁₆, which means a 53% reduction in energy intensity per GDP and 36% per capita compared to 2016. The aggregated remaining sectors, which subsume all not previously mentioned sectors such as services and commerce, agriculture, forestry etc. reach an intensity of 0.17 GJ per EUR₂₀₁₆ in 2050, which represents a 60% intensity reduction compared to 2016.

3.2.2. Industry

Industry is considered as a hard-to-abate sector [43,44] since many production processes currently depend on fossil fuels as raw material input for chemical reactions or as energy input to achieve high temperatures. Thus, we consider process-specific analyses and develop detailed decarbonization pathways for process heat for iron and steel as well as cement production—the two sectors with the largest energy demand for high temperatures [45,46].

For all other industrial energy demand (power, space heat and hot water etc.) as well as process heat for the remaining industry sectors, we assume a constant production and a decreasing energy intensity of 2% per year until 2050. This reduction is derived from historic trends from before 2018 calculated from [18,20] and adapted to [35].

For steel, we focus on a technology-switch from the current coal-based primary production to hydrogen- and electricity-based primary production by 2050 [47]. This means that the coal-based blast-furnace route is gradually replaced by the novel technologies of hydrogen-based direct reduction [48] and electricity-based electrowinning [49].

Similarly, for cement, our scenario describes a shift to best-available technology [50], which are firstly rotary kilns with precalciners [51] and from 2030 onwards with electrified precalciners. Additionally, we assume an energy efficiency improvement by 3% and a decreasing clinker to cement ratio from 0.75 to 0.57 from 2020 to 2050 [50,51].

3.2.3. Transport

The projection of transport demand is derived from a detailed scenario for road and rail, provided by a dedicated transport scenario study [52]. For national navigation, we use assumptions corresponding to the project work from [53] and the future fuel demand for aviation is derived from a scenario dependent forecast from [54].

We adopt the “regulated shift” road scenario, with stable passenger transport service in terms of passenger km (pkm) but a strong decrease of 25% in vehicle stocks to around 35 million vehicles. For freight transport, the “regulated shift” scenario envisages a 60% increase in ton kilometers (tkm) until 2040. Key features are a reduction of specific fuel demand for various vehicle types with smaller reductions in conventional internal combustion engines (ICE) and significant reductions in electric drive trains and for hydrogen fuel cell vehicles (EV and FCV).

For the BS, we extend the “regulated shift” scenario trends to 2050. This results in a total demand of 1,270,000 million pkm per year and 954,000 million tkm per year and a specific energy consumption reduction of 10–20% for ICE and 30–40% in EV and FCV per pkm and tkm. For aviation and navigation, we assume a reduced specific energy demand of 10–15% per tkm and 30% per pkm.

3.3. Technological Limitations and Targets for Energy Supply in 2050

The renewable energy potential serves as a major technical limit of the BS (Table 4). For wind and PV, we rely on dedicated potential analyses from EnDAT (see Section 2) on an hourly basis [26,35]. The biomass potential in Germany is derived from [55] for residues and allows for a constant agricultural area dedicated to energy crops from [56,57]. Beyond that, the German energy system is not completely restricted to national potentials, as power and biofuel or synfuel imports are considered in the models. For reasons of plausibility, we limit the net power import to Germany, setting a target of at least 90% national power production.

Table 4. Renewable energy potentials in Germany considered in our Budget Scenario.

	Unit	Potential	Sources
PV	GW	566	[26,35]
Wind			
Onshore	GW	217	[58,59]
Offshore	GW	72	[26,35]
Biomass			
Biogas	PJ/a	950	[55]
Solid Biomass	PJ/a	340	[55]
Energy crop area	mil ha	2.7	[56,57]

Additionally, we assume a variety of limitations to the deployment of energy supply technologies, presuming an almost completely renewable energy supply and strong sector coupling. Cooling and mechanical energy are completely electrified by 2050 in the BS. We consider a constant hydropower capacity of 11 GW, including 6 GW of pumped storage [60]. Offshore wind requires a minimum capacity of 20 GW in 2030 and 40 GW in 2040 according to German law [61].

For CHP technologies, we envisage a reduction of fossil applications, phasing out of coal, reduction of gas in favor of dispatchable gas power plants, resulting in a transition to biomass, based on the already existing capacity of solid biomass CHP and biogas plants. For the remaining power sector, we apply the cost optimized expansion and dispatch of power plants under CO₂ limitations with REMix.

For space heat and hot water in buildings, we reinforce our previous technology targets for 95% CO₂ reduction from [35] towards a CO₂-free and balanced energy supply (Table 5). The scenario features a strong focus on district heat and heat pumps and only a marginal residue of gas, but a complete phase out of coal and oil.

Table 5. Targets for market shares of energy carriers in space heat, hot water and process heat for 2050.

Energy Source	Residential Space Heat & Hot Water	Services: Space Heat & Hot Water	Industry: Space Heat & Hot Water	Industry: Process Heat
Power	17%	18%	18%	39%
Gas (Methane, H ₂)	5%	6%	10%	33%
District heat	30%	30%	35%	6%
Solar thermal	10%	10%	8%	5%
Biomass	7%	15%	8%	10%
Heat pumps and geothermal	30%	21%	21%	1%
Hard coal and waste	-	-	-	4%
Oil products	-	-	-	2%
Total	100%	100%	100%	100%

For industrial process heat, the main supply comes from power and gas, including hydrogen, i.e., 39% and 33%. It is assumed that some production processes cannot be completely decarbonized and still rely on residual fossil fuels, e.g., in steel production, and on waste incineration as in cement production (see SI S4). Therefore, small amounts of fossil energy are still implemented for process heat in the Budget Scenario (Table 5).

Market shares for alternative drive trains in the transport sector are based on scenarios developed previously [52] for 2040, extended to 2050 by [35,62]. Due to the necessary acceleration until 2030, the transport transition focuses on electrification, both in passenger and freight transport. In 2050, the BS reaches the following market shares:

1. Individual transport is mostly based on hybrid electric vehicles (EREV: 48%), battery electric vehicles (BEV: 39%) and fuel cell vehicles (FCV: 12%).
2. Light duty traffic has similar shares with EREV (32%), BEV (52%) and FCV (16%).
3. Heavy duty traffic features a higher share of FCV (20%) and a focus on catenary electric and hybrid trucks (78%) with significant residual fuel demand.

4. Rail is assumed to be completely electric in 2050.
5. The residual fuel demand, e.g., for hybrid vehicles, navigation and aviation is assumed to come from synfuels (72%) and biofuels (28%).

We derive car numbers from assumptions on average annual mileage per car and occupancy rate based on [52,63].

4. Scenario Results: How Fast Do We Have to Change the Energy Sector?

The above described assumptions set the limits for our long-term scenario for a carbon limited society. It is clear that current emissions in the German energy sector of around 650 Mt of CO₂ per year would consume the budget of 6.5–7.5 Gt of CO₂ in about a decade. Thus, we focus also on the speed of transition specifically until 2030. While we highlight the most relevant transition aspects in the paper, the complete result data set for all analyzed sectors and technologies can be found in S5 and S6 in the SI.

4.1. CO₂ Emissions from the Energy System

In the BS, the energy system needs to half CO₂ emissions already before 2030 (see Figure 6). With limited time to develop new technologies for CO₂ neutral synthetic fuels within the next years, the focus of the transition is first on electrification. Consequently, a decarbonization of the power sector based on renewable technologies, which are already broadly available on the market before 2030 is a prerequisite, reducing CO₂ emissions from power plants and CHP by 3/4.

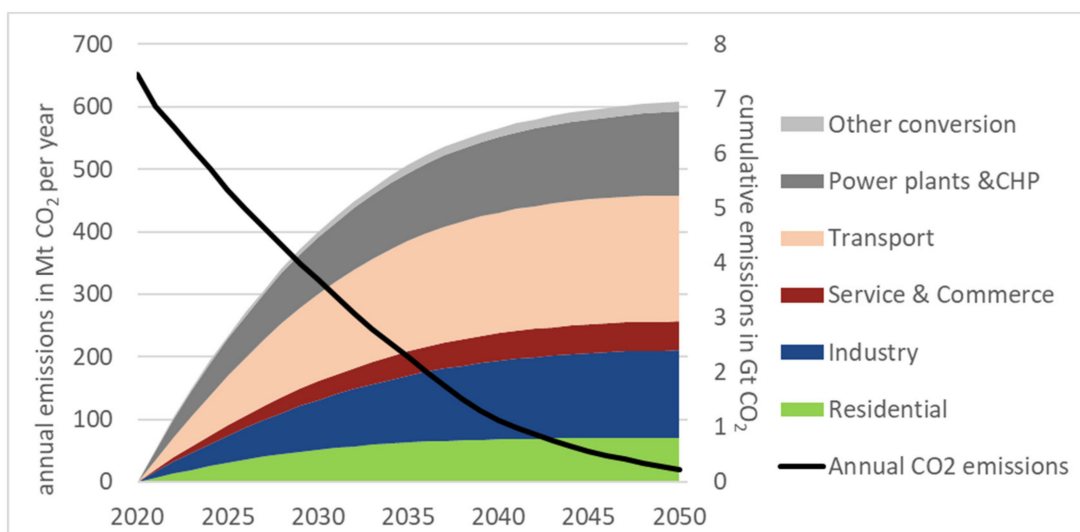


Figure 6. Cumulative CO₂ emissions from 2021–2050 and annual CO₂ emissions from the German energy system under the Budget Scenario.

Specifically, the transport (1/3) and the industry sector (1/4) will consume the largest shares of the budget. From 2030 on, hydrogen and synfuels based on renewable power will help to avoid the harder to abate emissions, leading to an overall reduction of 97% of emissions in 2050 compared to 2020. Residual energy-related CO₂ emissions result from waste incineration both in the industry and transformation sectors. How this CO₂ reduction is implemented over time in the various sectors is shown in the next subsections.

4.2. Energy Demand

Energy statistics show that Germany decreased its final energy demand since 2010 (Figure 7). However, the technology transition in the BS described below requires a significant acceleration in implementing efficiency measures, specifically in the next decade.

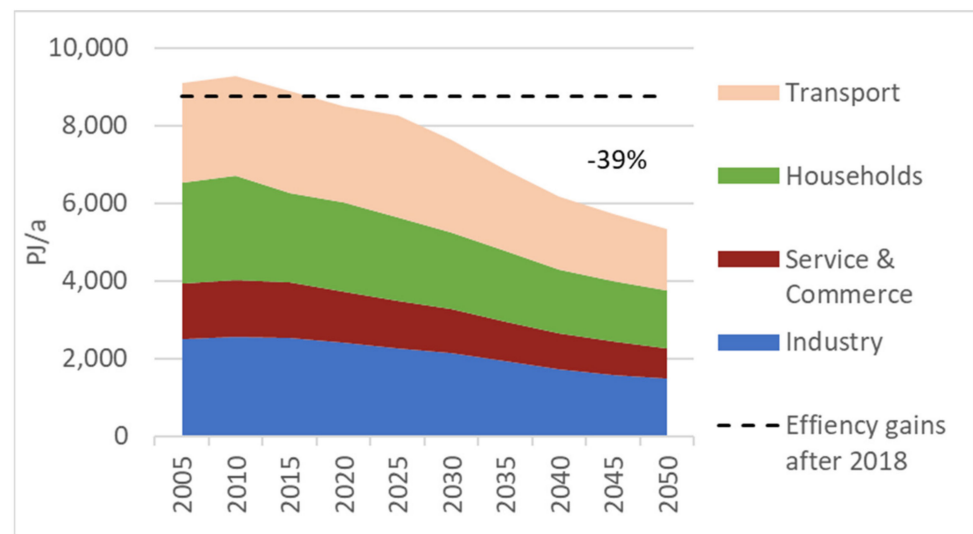


Figure 7. Projection of final energy demand in the BS after 2020 compared with historic development from 2005–2018.

The efficiency gains are on the one hand concentrated in the transport sector due to a technology switch to electric mobility. On the other hand, large efficiency gains can be achieved in the household sector through improvements to the building envelope. The assumed efficiency gains as derived from the scenario comparison lead to an overall reduction of energy demand by 37% between 2020 and 2050. These efficiency improvements are a prerequisite for the transition in the energy supply focusing on direct or indirect electrification.

4.2.1. Heat Supply

Heat supply in the BS would rely on an integration of all available renewable energy sources. In the residential, services and other commercial sectors, ambient heat via heat pumps and solar collectors are deployed for space heat and hot water. By 2030, almost 5 million heat pumps are necessary in the BS for buildings in both sectors, increasing to more than 8 million in 2050. Power to heat is increasing already significantly until 2030 in the BS by 1/5 compared to today (services and other commercial sectors), and 1/2 (residential), also due to the electrification of process heat (Figure 8).

Oil and coal are phased out largely by 2040. Heating networks also need to be expanded and rebuilt to handle lower heat densities in the future and supply more buildings than today with a similar amount of energy. With the phase-out of fossil CHP, the heat grids rely mostly on biomass and integrate solar energy, electricity surpluses and waste heat into heat supply via seasonal storage. Synthetic gas and hydrogen play a minor role for heat in the BS, predominantly in buildings, which are difficult to refurbish.

In the industrial sector, an electrification takes place where possible to phase out fossil gas and coal (Figure 8). However, electrification is limited, and hydrogen and syngas are required especially for very high temperatures or specific chemical reactions [64]. Primary steel production, for example, needs to switch from currently coal-based processes in blast furnaces to hydrogen-based direct-reduction of iron ore starting from 2025 [47]. In the long run, other power-based processes, such as the electrowinning of iron ore, would be implemented as well [47,49].

The remaining fossil energy in industry comes from the incineration of waste. Direct and indirect electricity use (for hydrogen and syngas) will also replace district heat and CHP. Even though efficiency improvements lower the demand of final energy, the electrification will strongly increase power demand in the future even more due to the conversion losses for hydrogen and synfuel production (see Section 4.3 on power supply).

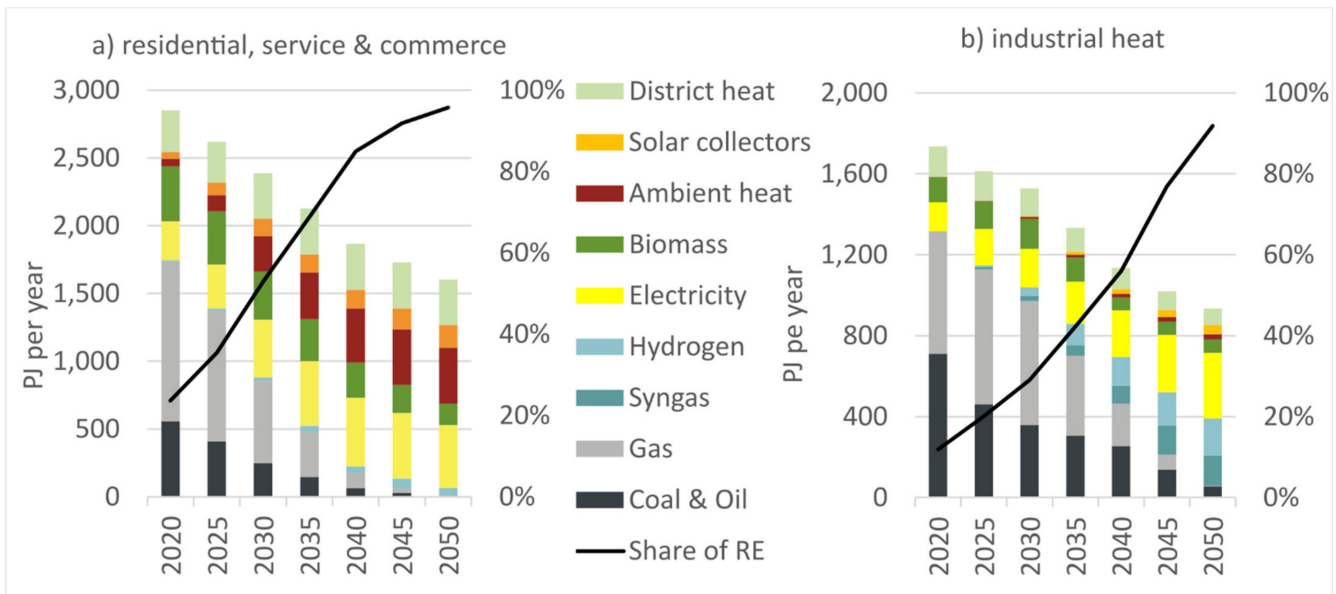


Figure 8. Heat supply for the residential, industrial, services and other sectors in the BS, (a) residential, service & commerce, (b) industrial heat.

4.2.2. Transport Sector

Transport, as the largest CO₂ emitting sector, specifically needs an accelerated emission reduction by 2030. Thus, electrification is also the key strategy in transport, especially for passenger cars. Even though assumptions on modal shift from [35,52] lead to an additional reduction in energy demand (at stable total passenger transport in pkm), the focus must be direct electrification, reserving synfuels and hydrogen, e.g., for trucks and planes (see Figure 9). To reduce CO₂ emissions significantly in the next decade and to avoid an overproportionate increase in power demand (due to conversion losses for hydrogen and synfuels) the BS requires an additional 1.5–2 million electric and hydrogen cars per year until 2035, leading to a total of 17.5 million in 2030. By 2050, more than 2/3 of the energy demand is provided by electricity in the BS.

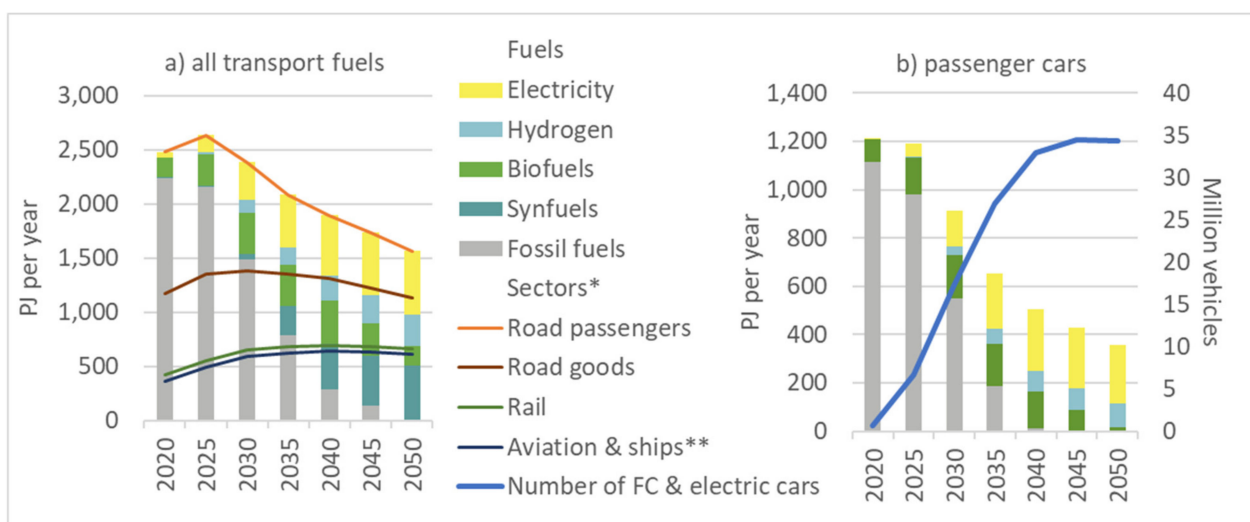


Figure 9. Fuel supply to total transport and specifically passenger cars; * each sectoral energy supply consists of a mix of fuels; ** only domestic, (a) all transport fuels, (b) passenger cars.

For goods transport, more than 50% of light duty vehicles would also be directly electrified in the BS by 2030. For heavy duty vehicles, all emission reduction options need to be integrated: hybrid and catenary electric trucks and fuel cell engines. The BS requires more than 50% of low CO₂ emission fuels by 2030, if the carbon budget is to be met. As an interim solution, it is also essential to provide the remainder of the existing fleet with bio- and synfuels, which provide 1/3 of the energy in 2040. By then, 95% of the fuels are based on renewables in the BS.

As the power sector becomes increasingly coupled with transport and heat, the need for a fast transformation of the power sector to renewable energy is even more pressing.

4.3. Power Supply—Results of the REMix Modelling

Simultaneously considering the carbon budget (see Section 2.1) and additional power demand from the above described heat and transport sectors, the power capacities in the BS almost triples in Germany until 2050 (see Figure 10). About 212 GW PV, 125 GW onshore wind and 50 GW offshore wind are additionally installed in the BS, which serve as the backbone for Germany's power supply system in 2050. Consequently, the share of renewable energy reaches 96% by then. To accelerate the power system transformation, around 310 GW (additional 180 GW) of renewable capacity need to be installed already by 2030 in the BS.

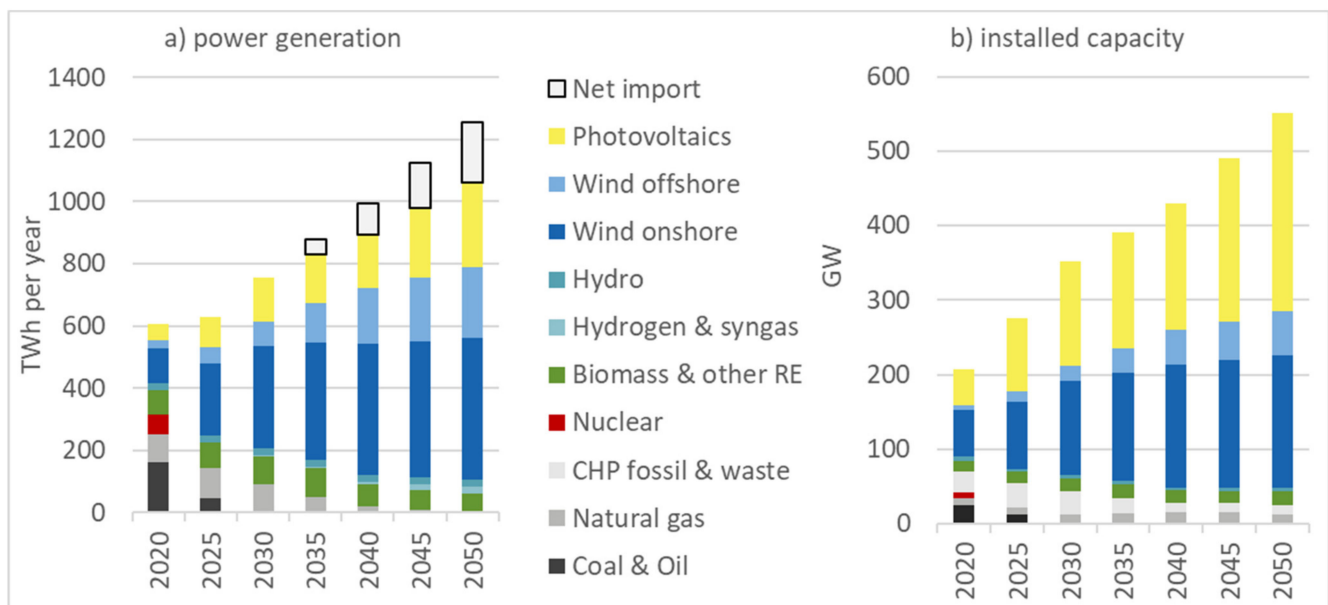


Figure 10. Installed power capacities and generation in the BS in Germany, (a) power generation, (b) installed capacity..

The role of CHP is uncertain in the optimization. District heating gas CHP would still play a role in covering peak loads in 2050. For the optimization algorithm, the reconversion of synthetic CH₄ is preferable to biomass CHP under the given biomass price assumptions. Thus, only the predefined capacity of around 16 GW of existing biogas and waste applications (see Section 3.3) remain in the system. Other studies applying cost optimization suggest no or very low CHP in power systems with very high shares of RE [62,65]. For balancing VRE, sector coupling (e.g., via electric vehicles and electric heat supply) is an important factor in the BS, replacing the back-up gas capacity to a large extent.

However, the installation of solar and wind capacities shows significant regional disparities under the assumption of system cost optimization (see Figure 11). A total of 70% of the offshore wind would be installed along the coast of Lower Saxony (40 GW) due to the local abundant offshore wind resources. In the BS, the installation of PV would be largely distributed in the southwestern and southern part of Germany. The northern and

northeastern regions are mainly supplied by wind energy, which plays a major role in all regions except Bavaria. Bavaria and Baden-Württemberg would expect an installation of the highest RE power capacities (~90 GW) among the 10 modeled regions.

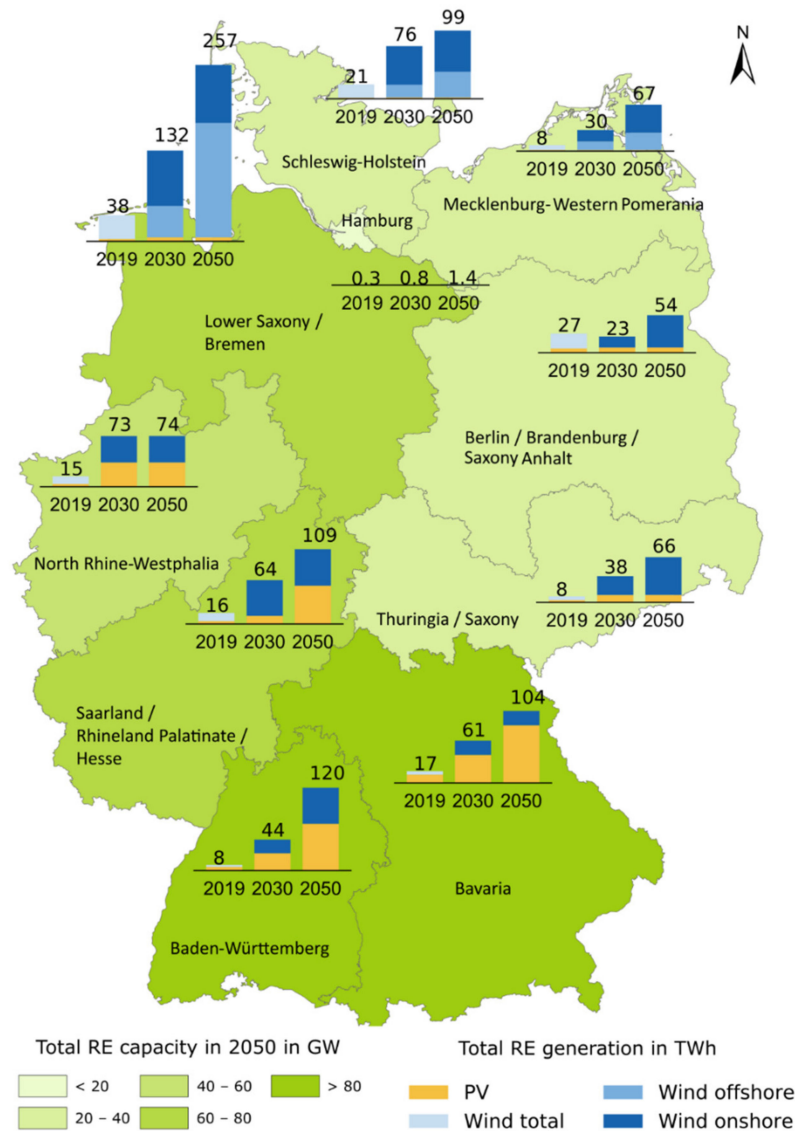


Figure 11. The results of a purely cost-optimizing modeling of regional RE power generation capacities in 2050 (colored area) and electricity production in 2030 and 2050 (column charts). Values for 2019 are derived from statistics.

The above described expansions of VRE capacities with regional heterogeneous characteristics require fundamental infrastructures for power transmission, storage and conversion. Figure 12 shows the necessary grid expansion between 2020 and 2050 with the grid development plan (in German: NEP) 2030 [66] taken into consideration.

Within Germany, total grid transfer capacity in the BS needs to triple from 61 GW in 2020 to 189 GW in 2050. Among them, the connection between Lower-Saxony and North Rhine-Westphalia region requires the strongest grid expansion of 12 GW HVAC and 8 GW HVDC. The BS sees strong grid expansion to neighboring countries, by factor 5 from 29 GW in 2020 to 153 GW in 2050. The North Rhine-Westphalia region shows the highest grid expansion to Belgium with 9 GW HVAC and 5 GW HVDC accordingly.

Other north–south connections also need expansion, each around 10 GW: between Brandenburg/Saxony-Anhalt and Mecklenburg-Western Pomerania, Hamburg and

Schleswig-Holstein additional 10 GW and cross border for Baden-Württemberg and Switzerland, and Schleswig-Holstein to the western part of Denmark. Such an accelerated grid expansion under 1.5 °C carbon budget between Germany and its neighbors alone already illustrates the necessity of a joint power grid development among EU countries to deal with high share of renewable power capacities, which are envisaged for the future in the context of EU green deal [8].

In addition to new infrastructure for power exchange, the BS also requires significant additions of both production and storage capacity for synthetic fuels. Figure 13 shows the required expansion of production, storage and transport of hydrogen in 2030 and 2050 respectively. The BS sees a massive deployment of 26 GW of electrolyzer capacity within the next decade in Germany, increasing to 96 GW in 2050. Hydrogen production is focused in the three modeled northern German regions where electrolysis could be used to balance the offshore wind fluctuations.

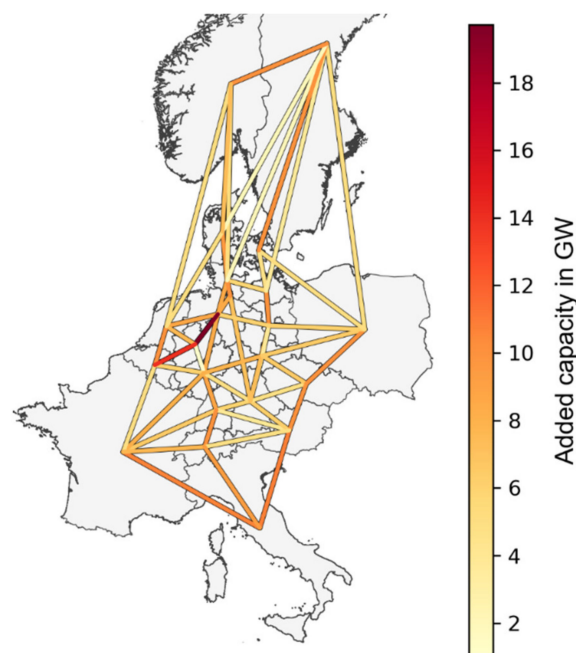


Figure 12. Added power grid capacity between 2020 and 2050 within German regions and to the modeled neighboring countries in the Budget Scenario.

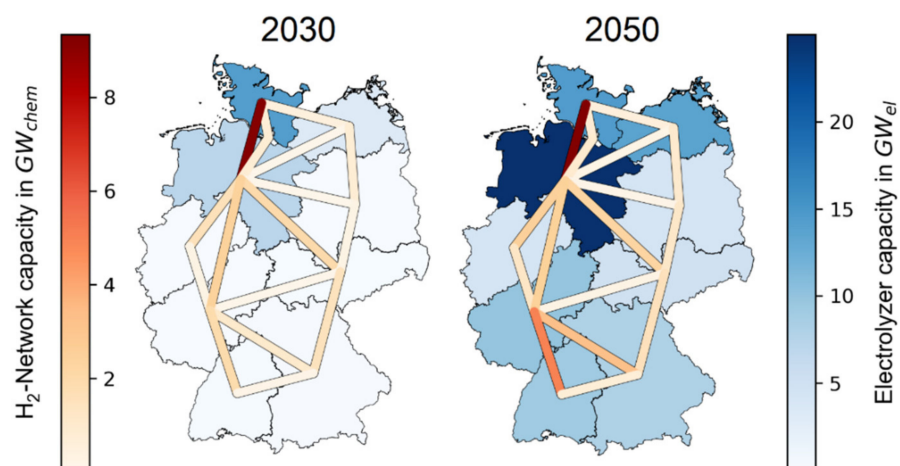


Figure 13. The regional distribution of hydrogen infrastructures in the scenario year of 2030 (left) and 2050 (right).

In contrast, the correlations between the installation of electrolysis and PV are weak. To be on track with the carbon budget, an early construction of hydrogen transport network is required reaching 23 GW in 2030 and 33 GW in 2050 in order to connect the central electrolyzer capacities and cavern storage in the north (50% or 27 GW in Lower-Saxony) to the demand centers in the south and west.

The above discussed energy system requires substantial investment in renewable energy technologies and related infrastructures. Figure 14 shows the total annual system cost components as modeled for Germany, which include the investment costs, fixed and variable O&M costs, fuel costs and CO₂ emissions costs, power import costs and power export revenues for the German nodes. The highest system costs of 65 billion € occur in 2030. They decline to around one third in 2050.

This is accompanied by a shift from fuel costs as the main component in 2020 (64%) to investment costs, which represent the largest share in 2050 (46%). Replacing fossil fuels significantly reduce CO₂ emissions costs, which cover 25% of total modeled costs in 2020, and only 1% in 2050. At the same time, the power import costs would account for up to 26% of system costs in 2050, replacing partially today's fuel imports.

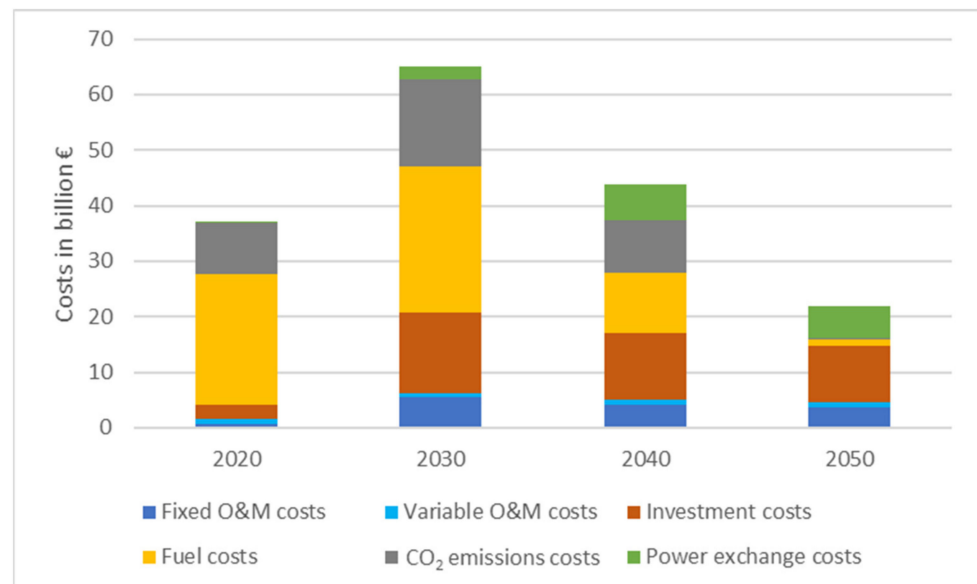


Figure 14. Total system costs (including power import costs) for Germany in the BS.

Sensitivity Analysis of the Power Supply

The above optimized power system highly depends on assumptions on fuels and emerging technologies. Thus, we test four sensitivity cases to illustrate the robustness of our modeled results regarding the power sector (see Table 6). The analysis focuses on variations of maximum power import shares, assumed renewable energy potentials and biomass cost assumptions. The detailed results can be found in S7 in the SI.

Table 6. Sensitivity analysis for the optimization of the power system in Germany with REMix.

Scenario Names	Min. Domestic Power Generation Share	PV Potentials (Germany)	Fuel Price for Solid Biomass	Description
BS	90%	566 GW	High	High PV potentials
HighImport	80%	566 GW	High	Lower minimum domestic power generation share
LowPV	90%	283 GW	High	Half PV potentials
LowFuelBio	90%	566 GW	Low	Low fuel price scenario for solid biomass
LowImport	95%	566 GW	High	Higher minimum domestic power generation share

First, we compare the influence of the changed assumptions in the sensitivity scenarios on the power generation from PV and wind and on the net power imports in Germany relative to the Budget Scenario (see Figure 15). The share between PV and wind installations is highly sensitive to all changing parameters. Limiting power imports leads to an overproportioned increase of the installed PV capacity. However, we find little effect of biomass prices on the system.

Even with lower fuel cost assumptions for the biomass power plant and CHP, its role in the German power system is still quite limited under the cost optimization approach. However, setting a minimum domestic power generation share for the modeled regions significantly affects the power exchange between them. This may result in a maximum annual net power export from Germany of up to 56 TWh (95% domestic generation) or to maximum net power imports to Germany of up to 111 TWh in 2050 (80% domestic generation).

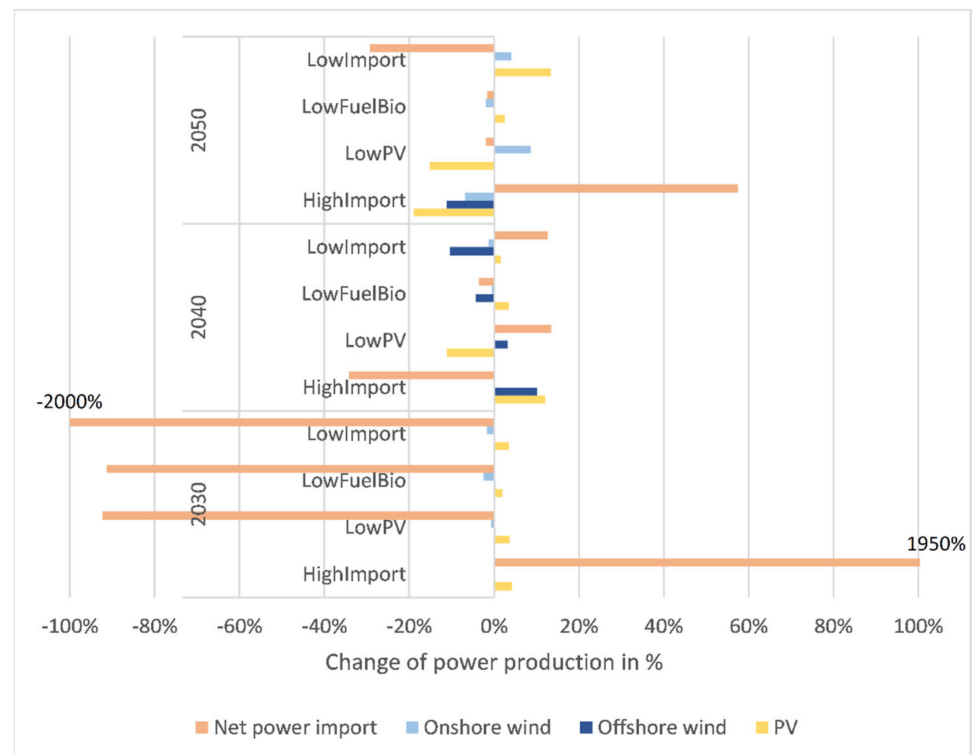


Figure 15. The sensitivity analysis of power generation from PV, wind and net power imports in Germany relative to the BS.

All variants (3-h resolution) increase system costs gradually over time from 50% to 80% in 2050 compared to the BS (see Figure 16). The differences are mainly due to power exchange costs especially in the LowFuelBio and LowPV scenarios. Other than that, the changes from investment costs and fixed O&M costs also play a role in the HighImport and LowImport scenarios. Even though the cost increase is higher with less imports in the beginning of the energy system transition, the LowImport scenario results in significantly higher system costs in the decarbonized energy system in 2050.

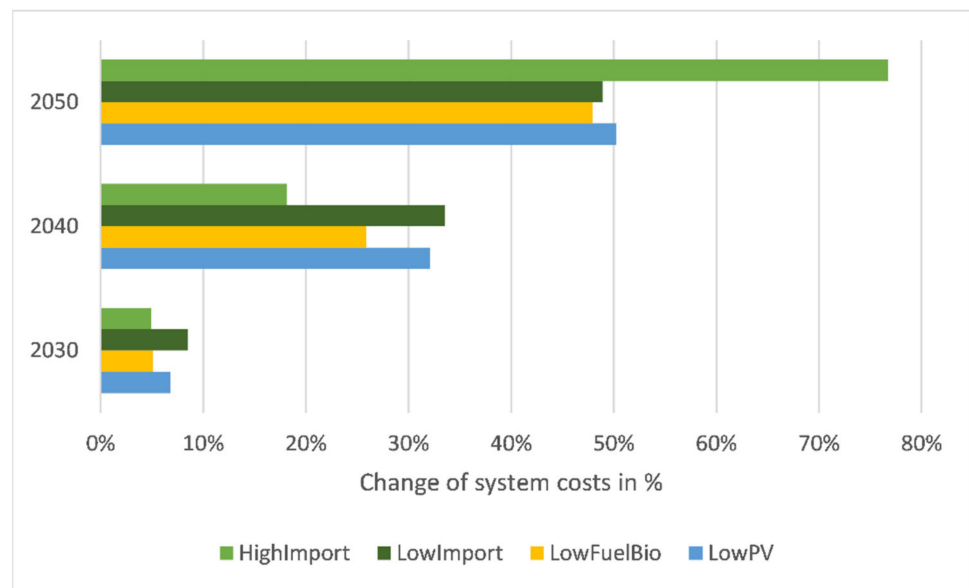


Figure 16. Sensitivity analysis of total system costs for Germany relative to the BS.

4.4. Primary Energy Supply

As electricity becomes the main “fuel” in the BS and power production is increasingly shifted to renewable energy, the primary energy supply consistently changes over time (Figure 17). In order to restrict the German energy sector to the proposed carbon budget, the speed for increasing the renewable energy share in primary energy needs to triple within the next decade; by 2030 the share of renewable energy in primary energy needs to rise to 43%. Imports of oil, gas and coal would be replaced partially by green imports—as electricity or power based synthetic fuels and gases. However, a residual of fossil fuels can still be seen in the BS in 2050, resulting mainly from incineration of “fossil” wastes and non-energy use as feedstocks. Overall, the scenario leads to a total of 95% renewable energy in primary energy in 2050—representing a residual emission of below 20 Mt CO₂ that could be offset via carbon dioxide removal (CDR) measures.

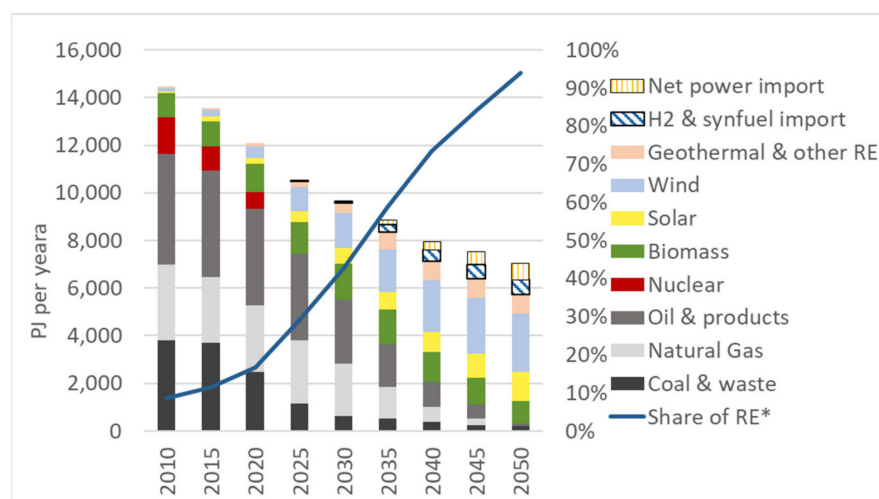


Figure 17. Primary energy supply in the BS for Germany (historic values before 2020 and modeling results from 2020).

5. Discussion

Our normative target scenario explores the scale and limits of developments physically and technically necessary to achieve the climate targets. The goal is to illustrate the

technical challenges beyond what is currently assumed as realistic or possible. We do so by developing a Budget Scenario that shows ONE single exemplary path to energy transition. Hence, we neither claim to show the full range of possible pathways nor to represent an overall optimized system (in terms of e.g., costs, acceptance or feasibility).

The limits and determinants of the transformation, which may result from decisions of the relevant actors from industry and politics as well as from public acceptance, are not explicitly addressed here. These factors are difficult to predict; however, as the context of the scenario, they must enable the decisive impetus for disruptive developments so that the necessary implementation of new technologies in line with the net zero target can happen.

Our Budget Scenario shows that achieving the climate targets of Paris is only possible if a turnaround in the energy system is tackled promptly in all consumption and supply sectors, the remaining emission budget serving as a joint target. The CO₂ budget that could be allocated to Germany is still unclear as the variance of the calculations is high. While our assumption of 6.5–7.5 Gt CO₂ for the energy sector covers a medium range of the existing budget calculations, the authors of [12], for example, aim for much lower limits of 4.2 Gt CO₂ until 2050. In most calculations, the remaining CO₂ budget for Germany will be used up within the next 10 years under current conditions.

In our scenario, the VRE from solar and wind will play the main role in the future, supplying renewable primary energy, especially in the form of electricity. However, they can only become the backbone of the energy system if sector coupling, infrastructure expansion and hydrogen economy are implemented quickly and are already substantial by 2030. Our modeling provides a first hint for the spatial distribution of this infrastructure demand under the objective function of minimum system costs—with a focus on wind and storable energy in the Lower Saxony region and PV all across the south west from Bavaria to North Rhine-Westphalia.

While the modeled grid infrastructures go far beyond the currently planned installations in the TYNDP [66], our results are limited by the spatial resolution of the modeling. For a detailed infrastructure planning, especially of power, hydrogen and gas grid transformation a higher spatial resolution is necessary. Additionally, a detailed modeling of future import and export relations both for power and synthetic fuels will significantly influence the capacities to be installed.

The sensitivity analysis provides hints at the influence of European power exchange; however, this is limited to the neighbor countries, neglecting a trans-European perspective, which has been the focus of various other studies [67–69]. For synthetic fuels and gases, significant potential and cost advantages are envisaged for production overseas [42,70]. While these import aspects might have significant impact on the system optimization with regard to installed capacities and total system costs, our study limits hydrogen and synfuel imports outside the geographical system boundary to external assumptions.

The Budget Scenario has also a strong focus on the final energy demand sectors: efficiency measures play a crucial role in the transformation of the energy system. A reduction of the final energy demand of all sectors in Germany by 30% to 45% compared to 2018 seems to be technically possible. However, the behavioral component included in this is not clearly quantifiable—neither in terms of sufficiency, nor in terms of rebound effects. Demand reduction can already be strongly advanced in the transport sector by 2030 through electric drives [52].

The challenge of long-term investments in the building sector for insulation and the installation of efficient heating systems, such as heat pumps and heat networks, is disproportionately higher. The building sector, therefore, requires a significant increase in transformation incentives ranging from information campaigns and recommendations for building improvement to financial support and the development of reward-penalty systems for net zero buildings [71], specifically accelerating energy saving. However, the modeling approach with regard to demand specifically in buildings and other sectors is clearly limited to findings from literature. Consumer aspects, e.g., in the residential and transport sectors cannot be represented within our supply and technology focused models.

In industry, CO₂ emissions are still considered difficult to avoid today, even though, for example, key technologies, such as direct reduction, are already being intensively developed and promoted in steel production [72]. According to our scenario, 50% to 70% of coal-based blast furnaces should be replaced by new low-emission technologies for primary steel production by 2030. In addition to such specific solutions, the direct electrification of process heat generation and complementary replacement of fossil fuels by synthetic gases are seen as essential elements of transformation in the industrial sector.

However, the scenario analysis in this paper cannot answer the important question of the future role and economics of the gas grid in directly supplying industrial sites (just as it cannot for buildings). The techno-economic limits of direct electrification as well as of energy savings through more efficient solutions cannot be evaluated here in all individual branches but are addressed through assumptions on the average achievable energy intensities according to the best available technologies. More in-depth analyses of possible options and their limits are required, which are beyond the scope of this paper but are also in part already included in transformation studies with varying degrees of detail, which were also used here as a background knowledge for parameterizing the model.

Here, we would like to refer to the complementary analysis by Rhoden, Simon et al. [73], identifying challenges and opportunities for net zero emissions scenarios, such as the BS, focusing on the spatial dimension of impacts, benefits and losses for different stakeholders and technologies. Especially stakeholder perspectives and public acceptance need to be and are addressed increasingly [74–77]. Our scenario can provide a valuable data base for such additional analyses.

Thus, despite all efforts to outline a feasible decarbonized energy system, there are considerable uncertainties in the implementation of available new technologies assumed in the scenario as well as about the remaining residual emissions of CO₂ from energy supply. Whether through unavoidable emissions from industrial processes or from the use of waste to generate energy, there are other obstacles to a completely CO₂-free energy system than “just” the energy transition.

6. Conclusions and Outlook

This paper presents one of the first budget-driven energy scenarios for Germany. We assumed a total of 7 Gt of CO₂ from 2021 to 2050. By coupling a cost optimization model (REMIX) and an accounting framework (ESM), our results show that Germany will have to accelerate its energy transition considerably to stay within this boundary. For this to happen, the necessary reduction in CO₂ emissions must be achieved to a large extent by 2030, and this is only possible through a massive expansion of RE technologies that are already marketable. In particular, the significant increase in tenders for renewable electricity generation plants by at least a factor of 2 to 3 compared to today must be a short-term measure to also ensure the basis for a rapidly increasing supply of renewable energies to the other sectors.

A transition to new and more efficient technologies must be organized and financed in parallel for all consumption sectors. Important directional decisions, e.g., on the expansion or transformation and future use of electricity, gas and district heating networks, must be made in the five to ten years. Moreover, a phase-out of coal use by 2030 is a basic requirement. This has to be complemented by a tripling of power generation from PV and wind, around 16 million electric vehicles and 5 million heat pumps in the same time. In the long run, such shifts require new power transmission capacity in the order of 120 GW and around 100 GW of hydrogen electrolyzers by 2050.

In addition to the mitigation of energy-related emissions, other sources of greenhouse gases must also be increasingly addressed, for example agriculture or further industrial processes. Options for carbon removal via natural and technical means (CDR measures) should also be advanced, even if they will only play a limited and rather long-term role. In the case where politics and the economy are globally too indecisive and react too late,

these options might eventually become important for negative emissions but are expected at significantly higher costs compared to emission mitigation measures.

Finally, adaptation measures will become increasingly important for flood-prone and highly urbanized areas. Care should be taken to ensure that efforts in adaptation do not limit funding and investment for mitigation and are not misused as excuse for avoiding ambitious measures in the energy sector. In the end, the work for this scenario analysis has again shown that there is a broad consensus in the scientific community that political and economic decision-makers must now set the course for climate neutrality decisively and courageously and implement the necessary measures without further delay.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/su14021025/s1>, SI-pdf-file: SI_pathway_German energy sector_1_5_C_budget_03_12_2021.docx Spread sheets: S1_ESM_to_Remix_16_07_2021.xlsm; S1_Remix_to_ESM_04_10_2021.xlsx; S2_Input data Net Zero Budget Scenario.xlsm; S4_heat_supply_for_industrial_process_heat.xlsx; S5_Results ESM Net Zero Budget Scenario_selected.xlsx; S6_Results REMix Net Zero Budget Scenario_selected.xlsx; S7_Results REMix_Sensitivity Analysis.xlsx.

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