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Assessment of transformation strategies for the German power sector under the uncertainty of demand development and technology availability

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Abstract

The long-term energy strategy issued by the German government in 2010 and 2011 embraces a substantial reduction of CO_2 emissions and high shares of renewable energy in electricity production, along with energy efficiency improvements and an accelerated nuclear phase-out. While several studies illustrate scenarios reaching these targets, there are substantial uncertainties pertaining to key assumptions, particularly long-term electricity demand and the large-scale availability of offshore wind and carbon capture and storage (CCS). This paper explores conditions under which model-based scenarios for the German electricity sector comply with the official targets for CO_2 emission reductions and renewable shares. We apply the energy system model LIMES-D, which allows for a joint optimization of generation and transmission capacities. The results indicate that reducing electricity demand plays a crucial role for attaining the government's targets. Scenarios for which either offshore wind or CCS is not available show an even stronger need for a decreasing electricity demand to reach the targets and a different pattern of transmission capacity expansion than is the case with full technology availability. Hence, a broad technology portfolio could in turn hedge against future power demand increases that may challenge the joint attainment of the German decarbonization and renewable energy targets.

Keywords: Decarbonisation, CCS, Renewable Energy, Demand uncertainty

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1. Introduction

The German government set ambitious long-term targets for CO_2 emission reductions, energy generation from renewable energy technologies and energy efficiency improvements in its energy concept [1]. In the year 2011 it was amended so as to include the accelerated phase out of nuclear power decided upon in the aftermath of the events in Fukushima Daiichi [2]. The energy concept embraces a profound restructuring of the German energy system, known internationally as the German "Energiewende" (energy transition). Until the year 2050, CO_2 emissions are intended to decrease by 80-95 % relative to 2005, the share of renewables in electricity production shall increase gradually to at least 80%, and total electricity demand is meant to decrease by 20%.

Even though the "Energiewende" addresses all sectors of the energy system, the plans for the electricity sector are most concrete and it has developed most dynamically in the recent years: over the last decade, the share of renewables in electricity generation increased by more than 15 percentage points to 23.5% in 2012 [3]). Also, the renewable energy target in the electricity sector is the only one that is legally binding, as it is explicitly specified in §1 of the Renewable Energy Act [4]. Considering that the climate and energy policy targets for CO_2 mitigation, high shares of renewables and electricity demand reduction are not independent of each other, the following questions arise: What are the conditions under which these interacting targets can be reached jointly? Which low carbon technologies are particularly important in this context?

While there are many sources of uncertainty in the development of long-term scenarios for the German power sector, two issues are particularly important in the present context: the future development of electricity demand and the large-scale availability of innovative low-carbon technologies, particularly offshore wind and Carbon Capture and Storage (CCS). When taking into account statistics for the last ten years, electricity demand has been constant or rising and strongly connected to economic developments [5, 6]. While extensive energy efficiency measures could lead to significant reductions in aggregate demand, current trends do not indicate that a rapid acceleration of energy efficiency measures will occur in the near-term future. Also, it is unclear whether postulated energy efficiency potentials can after all be leveraged in Germany [7]. Furthermore, since future electricity demand might increase e.g. due to extensive electrification of other sectors such as transport, no unambiguous projection for electricity demand is available.

Regarding the second issue, technology availability, it is widely acknowledged that technologies drawing on solar and wind energy will play a substantial role in the future German power generation mix [see e.g. 7]. In the past decade many gigawatts of solar photovoltaic (PV) and wind onshore capacities have been installed and these technologies have proven their large-scale viability. However, in the case of offshore wind the development has been very sluggish, owing to numerous engineering, legal, and logistical challenges [8]. Also, the availability of CCS on a commercial scale in Germany is highly uncertain [see e.g. 9] and is subject to decisive opposition by local communities and only limited political support. Yet, the various available long-term scenarios for the German power sector postulate the large-scale availability of offshore wind and CCS [e.g. 10, 11] in the near-term future.

This paper explores the impacts of different conceivable assumptions regarding the development of electricity demand and technology availability in the German electricity sector on the compliance of model-based mitigation scenarios with the German government's long-term climate and energy policy targets and the system-cost optimal technology portfolios. We thereby apply a German version of the Long-term Investment Model for the Electricity Sector LIMES [12, 13, 14], referred to as LIMES-D hereafter. It allows not only for a joint inter-temporal optimization of long-term generation and transmission capacity deployment while accounting for effects of investments with perfect foresight, but also takes into account the impacts of short-term fluctuations arising from wind and solar utilization. This paper contributes to the existing literature by revealing important interdependencies of generation and transmission capacity planning for the German electricity sector that, due to the absence of a suitable energy system model for Germany, have not been made explicit in scenario analyses to date.

The remainder of this article is structured as follows: Section 2 discusses the setup of models used for previous scenarios of the German power sector, showing that to date no integrated analysis that jointly optimizes transmission and generation capacity deployment has been pursued. Section 3 presents relevant features of the model LIMES-D (Section 3.1) and the setup of the different scenarios for this analysis (Section 3.2). While Section 4 illustrates the scenario results, Section 5 briefly compares them to other studies. Finally, Section 6 discusses the findings of this research and concludes.

2. Literature Review

So far, integrated assessments of the combined requirements for an adequate grid in Germany together with the necessary expansion of generation capacities have received only little attention. Several analyses have been published recently, but none of the studies is developed with a model that is capable of taking into account the interplay between generation and transmission capacity planning endogenously. The common practice is to either focus on generation capacity planning and postulating Germany was a copper plate, or to adopt a clear focus on transmission grids and take generation capacity development as an exogenous assumption over the entire time horizon of analysis.

Table 1 illustrates this observation. It presents a review of recent studies and different models used for investigating the German power system and its transformation and checks temporal and spatial resolution, power grid representation and the development of power generation and transmission capacities within the respective model or study. Literature summarized in Table 1 can be subdivided into four categories (visualized by horizontal lines). First, studies commissioned by the German policymaker or other political actors that present scenarios illustrating how Germany can successfully achieve the "Energiewende". Second, integrated assessment and energy system models for Germany that have a clear focus on the intertemporal dynamics and economic impacts of generation capacity deployment. Third, models that have a very fine resolution of the power grid enabling dedicated analysis of transmission capacity planning for Germany. A fourth category covers recent integrated energy system models investigating both transmission and generation for Germany or Europe, to which the model applied in this study - LIMES-D - also belongs to.

The comprehensive scenario studies investigating the development of the German power sector mainly cover generation technologies and treat infrastructure network issues only briefly [11, 10, 15, 16, 17]. Several models have been used in the past for the investigation of energy scenarios for Germany [18, 19, 20, 21]; however, most of them focus on the energy system as a whole and either omit spatial consideration of power transmission or use rough approximations. Others, such as German Energy Agency [23], Leuthold et al. [24], Weigt et al. [28], Leuthold et al. [29], Weigt [30], use more detailed representations of the German power grid but treat power generation capacity development only exogenously. In 2012, German transmission system opera-

Table 1: Comparison of studies on the integration of renewables and related transmission grid expansion Germany (D) and Europe (- indicates absence of a feature, + its availability, (+) its availability in partial or stylized form or as exogenous consideration).

	Intertemporal endogenous capacity	Transition 2010–2050	Grid		Temporal Resolution
			Within D	To others	
Schlesinger et al. [10]	(+)	+	-	+	+
Nitsch et al. [11]	-	+	-	(+)	(+)
SRU [15]	-	-	(+)	+	+
Klaus et al. [16]	-	-	-	-	+
Kirchner and Matthes [17]	(+)	+	-	-	+
REMIND-D [18]	+	+	-	-	(+)
TIMES-D [19]	+	+	-	-	-
IKARUS [20]	+	+	-	-	-
PERSEUS [21, 22]	+	+	-	+	(+)
German Energy Agency [23]	-	-	+	-	-
ELMOD [24]	-	-	+	+	-
URBS-D [25]	-	-	+	+	+
URBS-EU [26]	-	-	+	+	+
DIMENSION [27]	unclear	+	-	+	+
LIMES-EU$^+$ [13]	+	+	-	+	+
LIMES-D (this study)	+	+	+	-	+

tors (TSOs) presented a plan for transmission network development based on previously defined scenarios [31]. This report uses scenarios from Schlesinger et al. [10] and Nitsch et al. [11] for the development of generation capacities in Germany to investigate necessary power grid extensions via a heuristic, iterative process. In the two updated versions of 2013 [32] and 2014 [33] hese endogenously defined scenarios were adapted but the general method remained the same. In sum, none of these studies combine long-term development with temporal and spatial detail to cover the complete transition process.

There are only a few models capable of providing an integrated investigation of the transformation of the electricity system alongside the necessary expansion of the electricity grid endogenously. Heitmann and Hamacher [25] and Schaber et al. [26] use the model URBS to compute scenarios for electricity generation and transmission in Germany and Europe, respectively. While URBS provides information on necessary generation capacities, it does not ensure refinancing of investments and does not take existing capacities into account. Furthermore, no inter-temporal optimization is performed to ensure a coherent development of capacities. The model DIMENSION, presented by Fürsch et al. [27], allows for assessments of power generation and transmission transformations for Europe through an iterative process between a market model and a network model. Haller et al. [13] present scenarios for Europe, the Mediterranean region and north Africa with the multi-scale power system model LIMES-EU$^+$, which endogenously optimizes capacities for generation, transmission and storage over time, including a analysis of results for Germany. However, in LIMES-EU$^+$, Germany is represented as a single region. Since inadequate domestic transmission could be an important inhibitor to a successful transformation, due to e.g. problems with transporting wind power from the north to demand centers in the south, it deems necessary to use a more detailed setup for Germany. We aim to fill this gap with the model LIMES-D, which is described in the following.

3. Model and Scenarios

For this analysis, the modeling framework LIMES [12, 13, 14] has been adapted to a five-region-setup along the lines of the TSO areas for Germany (LIMES-D) and includes both temporal and spatial resolution as well as a time horizon until 2050 to allow the investigation of scenarios with high shares of renewables. LIMES-D thus enables the assessment of German electricity generation and transmission capacity expansion in the context of climate and energy policy in an integrated manner. Section 3.1 provides information on the main features of the model LIMES-D with an emphasis on the implementation of regional detail and temporal variability. Section 3.2 presents the definition of scenarios that are subject to analysis in this paper.

3.1. Model Setup

LIMES-D is a partial, multi-regional electricity sector model that performs an intertemporal minimization of total discounted power system costs for the time frame 2010-2050. These consist of investment costs, operation and maintenance costs, fuel costs, and costs resulting from the transport of captured CO_2 to remote reservoirs. We use an interest rate of 5% p.a.. The salient parameters describing technologies for generation, storage and transmission of electricity implemented in LIMES-D are reported in Appendix AppendixA. For an in-depth description of the model including a detailed presentation of model equations, see Ludig et al. [12], Haller et al. [14, 13].

An important asset of the LIMES modeling framework is that it features two time scales. On the one hand, time steps of 5 years that are relevant for long-term investment decisions into capacities for generation, storage and transmission. On the other hand, time slices that represent characteristic hours of the day to warrant a representation of short-term variability of renewable energy sources wind and solar (see Section 3.1.2). Both capacity investments and dispatch are an endogenous model result for each time step, time slice and region. Depreciation for installed capacities is represented through vintages evolving over time. The optimization algorithm ensures that all investments are refinanced from revenues. Power demand is inelastic[1] and set exogenously for each time slice. 2010 values are based on TSO data[2] time series and Länderarbeitskreis Energiebilanzen [38] to ensure correct demand shares for each region. Load shedding is not possible, i.e. demand has to be met by either generation within the respective region, by imports from another region or through storage charge and discharge. An initial model calibration ensures that demand is met by generation in each region for the first time step.

[1] No demand side measures are implemented in this version of the model.

[2] 50Hertz Transmission GmbH [34], Amprion GmbH [35], TenneT TSO GmbH [36], TransnetBW GmbH [37]

3.1.1. Regional Structure

In order to represent regional differences for the potential of renewable energy sources and power demand within Germany as well as to capture the main features of electricity transmission LIMES-D is endowed with five model regions. They are designed along the four control areas of the German Transmission System Operators (TSOs) *50Hertz Transmission GmbH*, *TenneT TSO GmbH*, *Amprion GmbH* and *EnBW Transportnetze AG*[3]. The *TenneT TSO* region has been subdivided to further represent the north-south spread of the country. Figure 1 shows the regional setup of LIMES-D. Model regions are connected by stylized long distance high voltage alternating current transmission lines.

Initial capacities for transmission lines are based on own calculations derived from Net Transfer Capacity (NTC) values by Hohmeyer et al. [39]. Table A.6 in the Appendix lists initial NTC for LIMES-D. Detailed information on transmission capacities between TSO areas in Germany is not publicly available for comparison. While NTC values of a current system are strongly dependent on its setup, they are deemed an adequate as initial values for this analysis. An in-depth presentation of the implementation of transmission in LIMES, including a discussion on load flow constraints can be found in Haller et al. [14] and Haller et al. [13]. By applying NTCs, LIMES-D reduces the transmission of electricity to a transport problem, which is a strongly simplified assumption. However, it is numerically impossible to solve a model that considers the line-sharp representation of power flows and an endogenous optimization of generation and transmission capacities at the same time. As the aim of LIMES-D is the latter, we opt for a stylized representation of transmission. Nevertheless, this needs to be kept in mind when interpreting the model results.

The numerical complexity arising from the integrated optimization of the long-term transformation pathways and short-term dispatch of the model also limits the number of regions that can be included. However, despite only covering an aggregated view of the German grid within LIMES-D, the most important aspects of discussion are included: first, there is a limited connection of the *50Hertz* region to the rest of the grid for historical reasons.

[3] *EnBW Transportnetze AG* has become *TransnetBW GmbH* in March 2012 http://www.transnetbw.com/press/press-release-enbw-transportnetze-ag-becomes-transnetbw-gmbh.

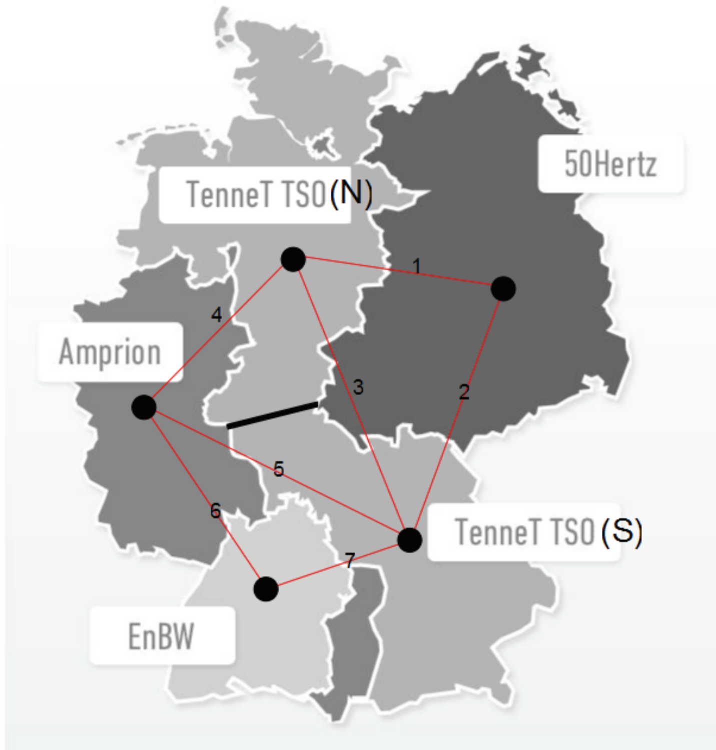


Figure 1: Model regions and long-distance transmission corridors in LIMES-D based on the control areas of the German Transmission System Operators (TSOs). (Map source: [40])

Second, offshore wind, when available, will be connected to the northernmost regions[4], creating a necessity for electricity transmission to the southern demand centers. These main issues, represented by the aggregated transmission capacities in LIMES-D, match important transmission corridors and ongoing projects as listed by the German Federal Network Agency[5].

Model regions differ by (i) magnitude and temporal pattern of electricity

[4]Offshore wind turbines are assumed to be connected directly to the *50Hertz* and *TenneT (N)* regions, connections of wind parks to the shore are not represented in LIMES-D.

[5]http://www.netzausbau.de/SharedDocs/Downloads/DE/EnLAG/EnLAG-Monitoring-A4_2012_Q2.pdf?__blob=publicationFile, accessed on , in German.

Table 2: Overview of important parameters that are different in each model region.

		50Hertz	*Tennet (N)*	*Tennet (S)*	*Amprion*	*EnBW*
Demand[a,b,c,d,e]	[TWh/a]	126.12	115.44	99.84	225.62	73.24
Wind Onshore Potential[f]	[TWh/a]	50.10	59.32	29.66	39.97	22.50
Wind Offshore Potential[g]	[TWh/a]	40	80	-	-	-
Solar PV Potential[h,i]	[TWh/a]	33.28	14.56	43.68	8.32	49.92
Lignite Resources[k]	[TWh]	$1.18 \cdot 10^4$	-	-	$1.70 \cdot 10^4$	-
CCS storage potential[l]	[GtC]	1.2	1.0	0.2	0.1	0.025

[a] [38] [b] [34] [c] [36] [d] [35] [e] [37] [f] [44] [g] [45] [h] [46] [i] [47] [k] [48] [l] [49]

demand, (ii) potential for renewable electricity generation, (iii) lignite resources, and (iv) potential for storage of CO_2. CO_2 transport infrastructure between regions is proxied by costs. Table 2 gives an overview on regionalized data such as demand, potential for wind and solar energy as well as carbon storage capacities and lignite resources. Lignite open cast mines are limited to the areas of *50Hertz* and *Amprion* and while offshore wind is naturally restricted to coastal areas, also potentials for onshore wind is highest in the northern regions *50Hertz* and *Tennet (N)*. The solar potential, on the other hand, is higher in the south (mainly *EnBW* and *Tennet (S)* where the main demand centers are located. The biomass potential is considered to be available nationwide since biomass crops can be transported within Germany incurring low additional costs. Only lignocellulosic biomass is considered for combustion in biomass fueled power plants. Its potential is 450 PJ/a in 2010 increasing to 700 PJ/a in 2050 ([41][6], Scenario "Naturschutz Plus") with increasing fuel costs.

It is important to note that LIMES-D does not consider electricity imports from neighboring countries. This autarky assumption is especially relevant when considering reaching the renewables targets over time. Their current formulation in the plans laid out by Federal Government [1] implies that imports of power generated by renewable energy sources are a possible means to cover the domestic renewables target. Currently, however, Germany is a

[6]Even though this potential estimate dates back to 2004, the numbers were used in the so-called lead studies published by the German Ministry of Environment issued since 2007 [42]. The most recent one [43] uses similar potential estimates for biomass.

net exporter of electricity [50] and while most sources expect this to change around 2030 [10], it can not be assumed that all power imported from abroad is generated from renewable sources. LIMES-D thus uses a conservative approach with a domestic renewables target as presented e.g. in SRU [15]. To prevent an underestimation of the possibility to reach the German renewables target, potentials for renewables implemented in LIMES-D are aligned with higher assumptions, e.g. Bofinger et al. [44] for onshore wind energy. The impact of the autarky assumption on model results is discussed in Section 6.

3.1.2. Consideration of Short-term Variability

The representation of temporal variability of wind and solar constitutes a severe modeling challenge when investigating scenarios with high shares of renewables. One possible solution used in several studies [12, 51] is the introduction of time slices subdividing each model year. Temporal resolution within LIMES-D is thus represented using two dimensions: While long-term investment decisions are made in five-year time steps, time slices are used to represent short-term fluctuations in the demand and supply of power.

The year is subdivided into four seasons each being represented by three days that cover low, medium and high wind supply. Every characteristic day is subdivided into four time slices with a length of six hours each. Thus, each season is represented by 12 time slices based on TSO data[7]. This setup, leading to 48 time slices (each representing 6h of a day), ensures a higher coverage of wind variability than without the differentiation by wind supply. As an illustration, Figure 2 shows the coverage of the variability within the initial data sets for wind, solar PV and demand by the chosen time slice setup[8] and compares it to a setup without the wind supply differentiation. This comparison shows that the consideration of different wind supply situations significantly improves the coverage of variability by the chosen time slices.

However, as discussed in Ludig et al. [12], even high numbers of time slices are not fully adequate in covering the complete variability from wind energy. Thus, LIMES-D includes additional constraints for backup capacities and generation, ensuring that sudden drops in output from variable renewables

[7]50Hertz Transmission GmbH [52, 53, 34], Amprion GmbH [54, 55, 35], TenneT TSO GmbH [56, 57, 36], TransnetBW GmbH [58, 59, 37]

[8]Ludig et al. [12] provides a detailed explanation of the determination of variability coverage by different time slice setups.

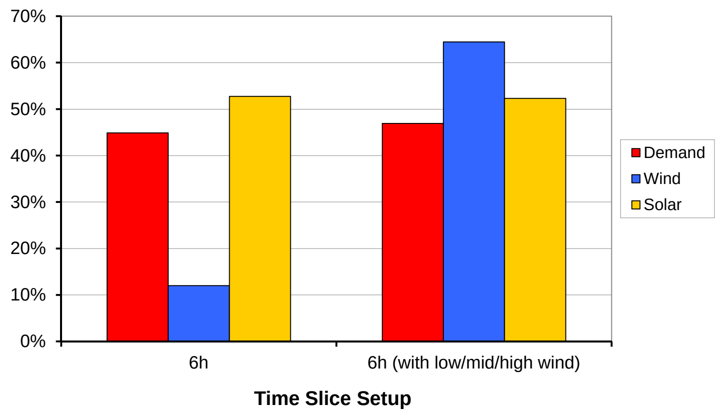


Figure 2: Comparison of variability covered (in %) by a setup with time slices representing 6h of each characteristic day with and without differentiation of low, medium and high wind feed-in.

can be balanced as well as coverage of longer still wind periods. Backup and balancing capacity requirements are linked to the installed amount of variable renewables to account for their increasing impact on power system operation. The technologies providing this backup and balancing are gas and diesel turbines as well as biomass combustion plants. Furthermore, a *superpeak* time slice is introduced to account for longer periods with low wind energy feed-in and high demand which typically occur during the winter period in Germany. This constraint enforces the installation of sufficient reserve capacities to ensure system reliability[9].

3.2. Scenario Definition

In order to explores the impacts of different conceivable assumptions regarding the development of electricity demand and technology availability in the German electricity sector on the compliance of model-based mitigation scenarios with the German government's long-term climate and energy policy

[9]The *superpeak* constraint is comparable to a stylized capacity market assumption.

targets and the system-cost optimal technology portfolios, the scenarios are defined as follows.

All scenarios are subject to three exogenously imposed policy targets. First, the CO_2 emission reduction in the year 2050 needs to be at least 98% in 2050, compared to 0.35 $GtCO_2$ in 1990. We motivate this strict mitigation target by considering that the German government aims at 80-95% CO_2 emission reduction for the energy system as a whole [1]and given that currently the technology options for the electricity sector are much more abundant and economically viable than for the heat and transport sectors this seems adequate. The particular number is furthermore motivated by European Commission [60]. As the mitigation target is after all only given for the year 2050 we assume a linear decrease of CO_2 emissions between 2010 and 2050. The second policy target imposed in all scenarios is the nuclear phase-out until 2022 as specified in the energy concept [2]. Finally, the renewables target is implemented as defined in the Renewable Energy Act [4]: the share of renewable electricity generation needs to amount to at least 35% in 2020, 50% in 2030, 65% in 2040 and 80% in 2050.

Electricity demand projections for Germany in different publications differ substantially, as illustrated by the impressive spread in Figure 3. In fact, most existing projections do not comply with the energy efficiency targets set by the energy concept Federal Government [1], which foresee energy efficiency measures to reduce power demand by 25% (compared to 2008 values) by 2050. The models PRIMES [61] and POLES [62] assume rising demand, Nitsch et al. [11] expect demand to be decreasing and subsequently increasing while Schlesinger et al. [10] and Kirchner and Matthes [17] preview demand to drop until 2050. Interestingly, the latter two are the only two projections that are derived with dedicated bottom-up demand models that appear to be rather optimistic regarding the potential to leverage energy efficiency potentials [cp. 7].

In order to take this spread into account, the scenario formulation in this analysis considers three different projection paths for demand that are set exogenously in LIMES-D: a near constant pathway with a 0.2% annual increase within the reference scenario, a projection based on the scenario PRIMES Baseline and a demand path based on the efficiency assumptions in Federal Government [1]. Initially, the even higher demand scenario from the POLES model was chosen as an upper limit. However, since no feasible solution for the targets discussed in this paper was found using this demand path because reaching the renewables target and the CO_2 emission reduction

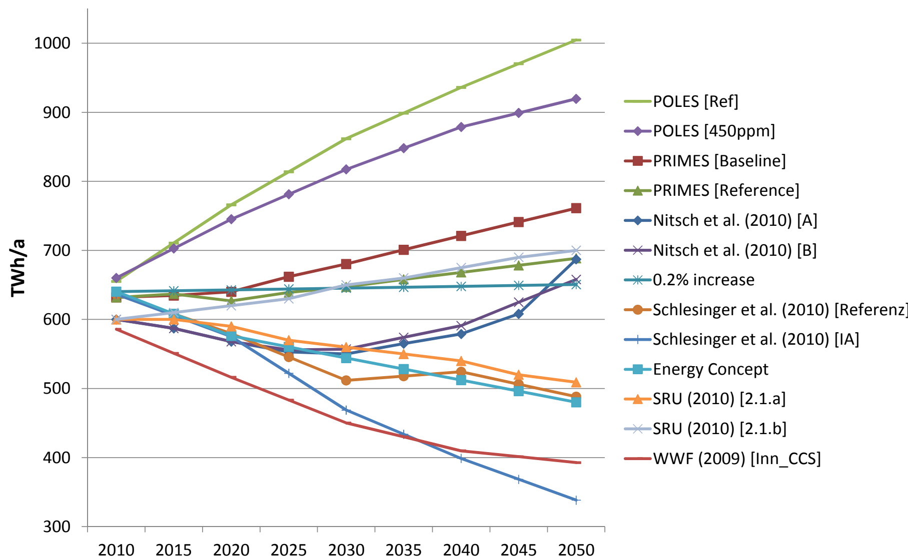


Figure 3: Different existing projections for total annual gross electricity generation in Germany.

target is impossible due to residual emissions from balancing constraints (see Section 3.1.2), the PRIMES Baseline scenario was selected. Lower demand scenarios than the one based on Federal Government [1] were not analyzed since targets would constitute even less of a constraint with further decreasing power demand. Medium, high and low electricity demand scenarios are labeled *Med*, *High* and *Low* in the remainder of this paper.

The second dimension for the scenario definition regards the large-scale availability of CCS and offshore wind, which may not necessarily be the case in the next decades due to political, public as well as technical considerations. Scenarios for which all technical options are available will be denoted by *All Opt* while scenarios without CCS are marked *No CCS* and the unavailability of offshore wind is labeled *No Off* (see Table 3).

We consider the scenario with a moderate power demand and no constraints on technological availability as the reference scenario. A comparison of the different scenarios along the lines of the two dimensions for the scenario definition, electricity demand and technology availability, with the reference scenario allows for an assessment of their impact on the resulting system-cost optimal technology portfolios. Here, the main variables of interest are the technology mix and the capacity deployment of transmission lines as well as

Table 3: Overview of scenarios considered in this study differentiated by technology availability (rows) and demand projections (columns).

	0.2% increase	PRIMES BASELINE	Energy Concept
All Options	*All Opt Med*	*All Opt High*	*All Opt Low*
No CCS	*No CCS Med*	*No CCS High*	*No CCS Low*
No Offshore Wind	*No Off Med*	*No Off High*	*No Off Low*

the total power system costs. The question of whether the scenarios comply with the German government targets can be answered by investigating whether the model finds a feasible solution. If that is not the case, one can conclude that such a scenario does not comply with the targets and look into which model equations are after all infeasible.

4. Results

The following starts with a description of the reference scenario in Section 4.1. A comparison of capacity and resulting generation for each technology within the reference case *All Opt Med* allows to assess which technologies are installed and analyze their utilization ratio. Furthermore, transmission grid expansions and electricity mixes for each region show the impact of regional differences on developments of power generation and transmission. Section 4.2 then presents the impact of different assumptions for electricity demand. Section 4.3 turns to the impact of non-availability of CCS or offshore wind energy on the feasibility of government targets, technology portfolios and grid expansion corridors. Section 4.4 compares the scenarios' total power system costs.

4.1. Reference Case (All Opt Med)

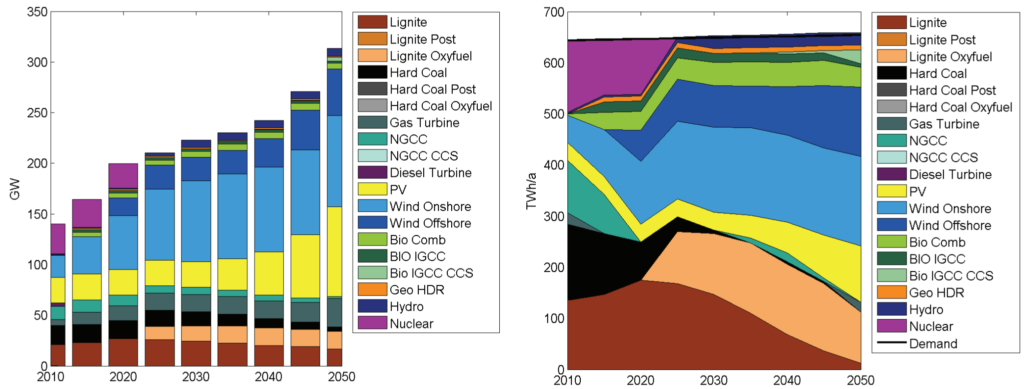
For the reference case *All Opt Med* with a moderate power demand and no constraints on technological availability the model results show a significant transformation of the power generation technology mix for Germany from 2010 to 2050 (see Figure 4). As expected, due to the renewable and CO_2 emission reduction targets, capacity developments shown in Figure 4a include high increases in renewable energy capacities, mainly for wind (onshore and later offshore) and solar PV. Contrary to recent trends [3], installations of solar PV are only minor for the coming decades until their capacity sees stronger increases after 2030. This might seem counter intuitive, but it has to be noted that current PV installations in Germany have strongly been fueled by guaranteed feed-in tariffs while no policy measures supporting renewables are implemented in LIMES-D. Gas turbines are installed mainly due to backup and balancing requirements (see also Section 3.1) and lignite power plants with oxyfuel capture enter the technology mix. Conventional hard coal and lignite capacities, on the other hand, decrease since, as one could expect, very little new capacities are installed while old power plants go offline.

Until 2020, when the nuclear phase out[10] will be almost completed, nuclear energy still plays a fairly important role in the power mix. In the initial phase, electricity generation from natural gas, lignite and hard coal takes up substantial shares. While capacities of wind energy and other renewables are increasing even in this early phase, the most substantial changes occur from 2020 onwards when offshore wind energy and then lignite capacities with CCS take up increasing shares. This closely coincides with the final steps of the nuclear phase out which triggers substantial changes in the power system and leads the way from large shares of electricity generation based on fossil fuels to a renewables-dominated mix. However, despite the high share of renewables in power generation in 2050 (80% are set as target share), lignite still plays an important role, mainly in oxyfuel capture plants.

While the respective generation shares of natural gas technologies vary throughout time, their capacity stays fairly constant as less efficient but more flexible gas turbines are installed in favor of the less flexible Natural Gas Combined Cycle (NGCC) technology. For balancing and backup purposes, a certain amount of natural gas and biomass capacities needs to be installed (relative to the share of renewables) to cover for sudden power drops by fluctuating renewables (see Section 3.1.2 for details on the LIMES-D implementation for backup generation). Furthermore, some generation by these backup capacities is required to make up for still wind periods not accounted for by the model time slices. Since a large share of this requirement is covered by power generation from biomass combustion plants, only small amounts of electricity are really generated from the installed natural gas capacities.

Overall, the analysis of capacities and power generation for Germany shows a strong switch to renewables with a decreasing but still important

[10] All German nuclear power plants will go out of operation until 2022 [see 2].



(a) Capacity (b) Generation

Figure 4: Germany-wide installed capacities (a) and power generation (b) by technology in the *All Opt Med* scenario for the years 2010-2050. Abbreviations: Natural Gas Combined Cycle (NGCC), Carbon Capture and Storage (CCS), Photovoltaic (PV), Integrated Gasification Combined Cycle (IGCC), Hot-Dry-Rock (HDR) technology.

residual share of fossil fuel based technologies. These changes raise the question about power transport within the country and the necessary changes to the transmission grid.

A corresponding transition to the shift in the generation mix can also be observed for changes in transmission capacities. Figure 5 shows the evolution of capacity additions for the regional interconnections that are introduced in Figure 1. Until 2020, transmission capacities are not extended while substantial changes happen in the following years. Similar to the transition in the power generation mix, the nuclear phase out in 2022 coincides with major expansions of the transmission infrastructure. The changes in the electricity mix, from largely centralized fossil fuel based generation to renewables with regionally differing potential, increases the need for power transmission within Germany since demand centers and generation sites do not match anymore, as it has been the case historically.

The first connection for which the model increases the capacity is the interconnection between the *50Hertz* and *Tennet TSO (S)* regions. This north-south connection is important for transporting electricity generated using wind and lignite from the less densely populated areas in the north-eastern parts of Germany to the demand centers located mostly in southern and south-western areas. This is in line with reports by 50Hertz Transmission

GmbH et al. [31, 32, 33], German Energy Agency [63, 23] which stress the importance of the expansion of the so-called “Rennsteig” connection which runs across this region border. For historical reasons, the connection of the *50Hertz* region to the rest of the country is limited which also explains that the connection between *50Hertz* and *Tennet TSO (N)* is extended. Besides the connection of the eastern part to the other regions, the lines interconnecting *Tennet TSO (N)* to *Amprion* see the most substantial capacity increase to connect the demand centers within the *Amprion* region to wind-based power generation in the North Sea area. This expansion is also important for the transport of wind energy further to the South. Figure 6 presents the corresponding regional electricity mixes in 2025 and 2050. Exports of wind energy from the northern regions play an important role. In the *50Hertz* region, wind energy is expanded early together with lignite-based power generation, followed by substantial amounts of mainly offshore wind power in the North Sea connected to *TenneT (N)*. Lignite based generation in the *Amprion* region is phased out until 2050 and the region developes into a net importer. Investments into lignite oxyfuel plants occur only in the *50Hertz* region. The *TenneT (S)* region in the south switches almost completely to renewable energy sources with a large share of solar PV. Overall, there is a strong increase in renewable generation with remaining shares of lignite in the north and large increases of north-south transmission capacities. Changes in regions further south consist in a stronger interconnection of regions with a near complete switch to renewable energy technologies.

4.2. The Impact of Electricity Demand Development

The comparison of power generation in 2050 for the three different demand scenarios in Figure 7 shows similar technologies for all cases but some notable differences occur in their respective shares. Large amounts of renewables dominate the installed capacities with some additional natural gas and lignite-based generation, the latter being equipped with CCS. While the high demand scenarios employ lignite in combination with oxyfuel capture, the *All Opt Low* scenario shows lignite with post-combustion capture. This can be attributed to the lower required generation from gas turbines since most of the required backup and balancing generation can be provided by biomass combustion plants. Since this allows to “save” CO_2 emissions in the budget, the higher remaining emissions from post-combustion capture (compared to oxyfuel) do not prevent reaching the CO_2 emissions target and allow for the use of the less expensive post-combustion CCS technology.

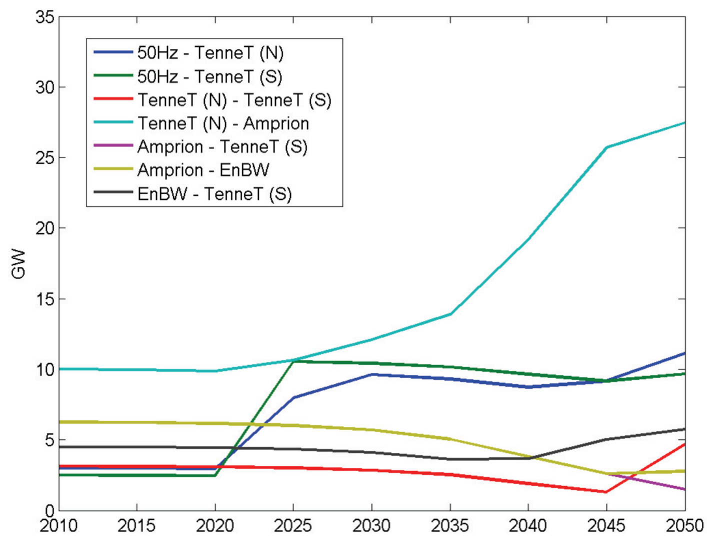
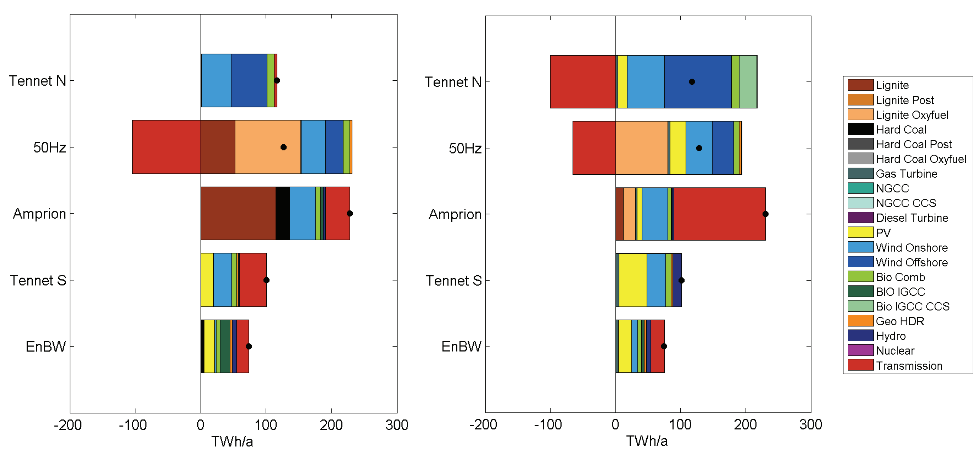


Figure 5: Transmission capacities between regions in the *All Opt Med* scenario.



(a) 2025 (b) 2050

Figure 6: Regional electricity mixes in the *All Opt Med* scenario in the years 2025 and 2050. The black marker indicates the demand for each region. Abbreviations see Figure 4.

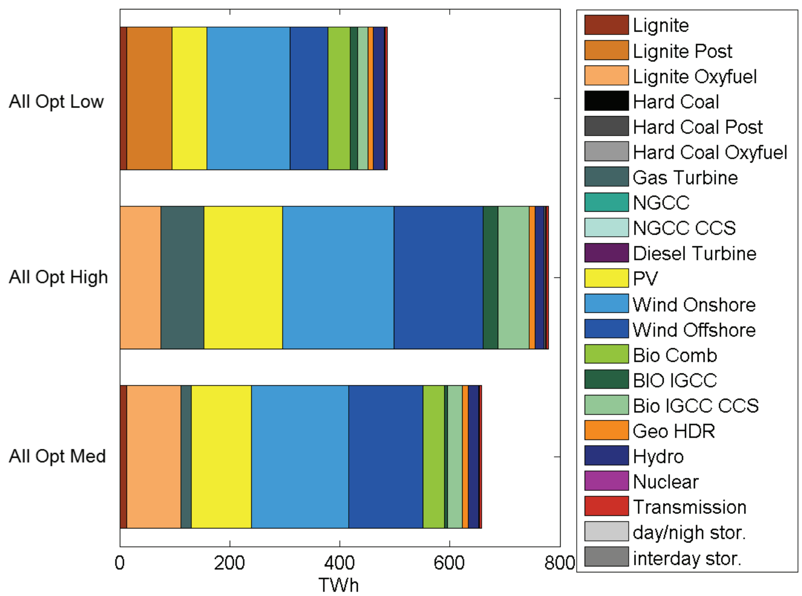
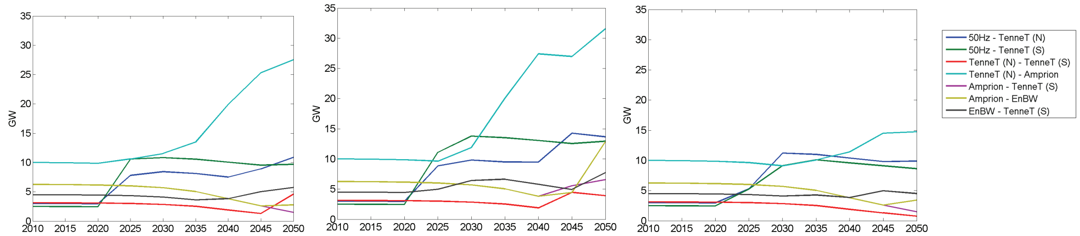


Figure 7: Comparison of the generation mix for Germany for the *All Opt* scenarios in 2050. Abbreviations see 4.

As differences in power generation also affect requirements for transmission, transmission capacity expansion pathways for the different *All Opt* cases are illustrated in Figure 8. The general trend is similar for all demand cases: lines connecting the *50Hertz* region to the western and southern regions are extended first and overall the expansion of north-south transmission capacities plays an important role. However, the timing and the relative importance of single connections varies between scenarios. The higher demand in *All Opt High* leads to an earlier and stronger expansion of the connection between *Tennet (N)* and *Amprion* as well as high capacity expansions of connections from *Amprion* to regions further south stressing the importance of this north-south connection. Results for *All Opt Low* show that even in cases with lower power demand, there is still a substantial need for transmission capacity expansions and confirm the trends found for *All Opt Med*.

To conclude the comparison of demand scenarios, three major findings can be determined:

- Generation mixes show similar shares of renewables but differ in the chosen CCS technologies due to CO_2 emission constraints.



(a) All Opt Med (b) All Opt High (c) All Opt Low

Figure 8: Transmission capacity expansion comparison for the *All Opt* scenarios.

- While the overall trend is robust for all cases with strong extensions of mainly north-south interconnections, higher demand growth entails higher grid capacity expansion, particularly between the *Tennet (N)* and *Amprion* regions.

- No feasible solution for reaching all targets can be found for very high demand scenarios (see discussion in Section 3.2).

4.3. The Impact of Technology Availability

The main finding for this part of the analysis is that no feasible solution can be achieved under the current CO_2 emission and renewable targets when either CCS or offshore wind are not available for both the near constant as well as the higher power demand scenarios (*No CCS Med*, *No CCS High* and *No Off Med*, *No Off High* cases). Residual CO_2 emissions from gas turbines required for balancing make it impossible to find a solution that meets both the targets for CO_2 emissions and renewables, since fluctuating renewables entail a certain amount of CO_2 emissions through gas turbine balancing. Higher biomass availability or the usage of other CO_2-free balancing options, e.g. demand-side management, could change this result.

However, when a reduction of power demand as planned by Federal Government [1] is achieved, both the absence of CCS or of offshore wind can be compensated. Other options besides demand reduction would be to increase demand flexibility by implementing demand side measures or to import electricity generated from renewables or other low CO_2 options from neighboring countries which are not considered in LIMES-D[11]. If both technology options

[11] For a discussion on imports, see Section 3.1.1

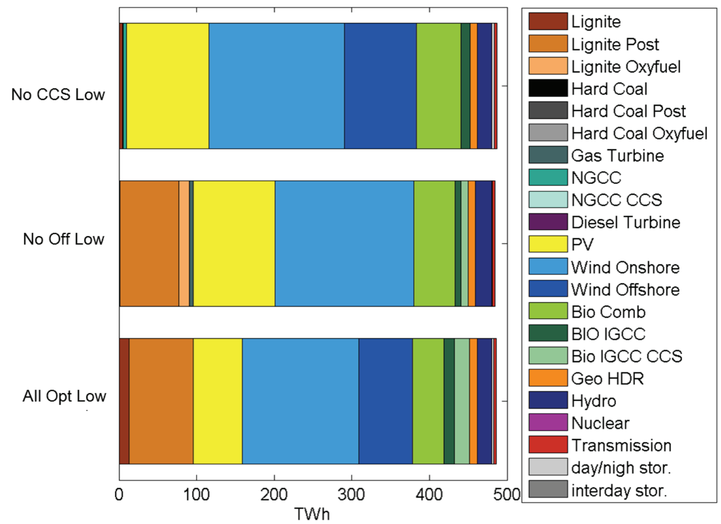
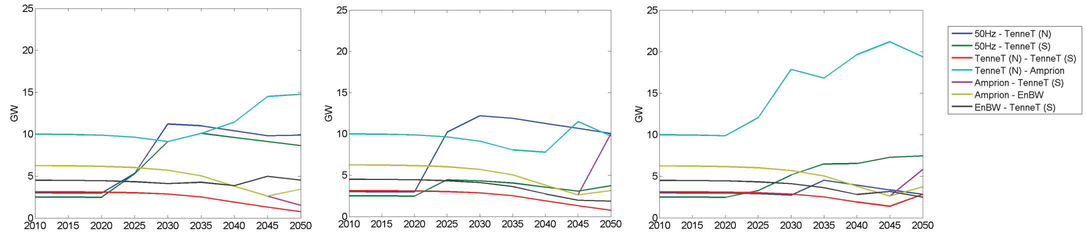


Figure 9: Generation mixes for Germany in 2050 (*Low* demand scenario). Abbreviations see Figure 4.)

are unavailable though, there is again no solution to the optimization problem - even under reduced electricity demand.

Considering the large spread of power demand projections for Germany as well as current uncertainty about the large-scale availability of CCS and offshore wind, these scenarios indicate that a successful implementation of current German government targets is challenging. Even if successful efficiency measures would lead to a decreasing power demand of the residential, commercial and industrial sector, an accelerated electrification of other sectors such as transport could limit overall power demand reductions. For reaching the decarbonization and renewable targets, it is thus important to develop a broad technology portfolio to hedge against future power demand increases.

In the following, an analysis of the *Low* cases investigates the substantial impact of the non-availability of CCS or offshore wind on the power mix and on transmission capacity expansions. Figure 9 compares power generation for 2050 for both cases to the corresponding *All Options* case. In both cases for which either CCS or offshore wind are unavailable (*No CCS Low* and *No Off Low*), they are compensated by generation from solar PV and, to a lesser extent, from onshore wind and biomass combustion. This entails significantly higher capacities of these renewable technologies, indeed reaching the limits



(a) All Opt Low (b) No Off Low (c) No CCS Low

Figure 10: Transmission capacity expansion for *Low* scenarios.

of their respective potential (see Section 3.1.1 for details on their values).

Figure 10 shows transmission capacity expansions for the *No CCS Low* and *No Off Low* cases in comparison to *All Opt Low*. In absence of offshore wind (Figure 10b), the need for strong north-south connections is reduced, leading to lower expansions of the connections of the regions *50Hertz* to *Tennet (S)* and *Tennet (N)* to *Amprion*. Increased use of local-fossil based and renewables generation reduces the overall need for transmission capacity expansions. In the *No CCS Low* case, displayed in Figure 10c, a different pattern emerges. As lignite usage is reduced by the non-availability of CCS, the importance of the connection between the *50Hertz* region (where the most important lignite resources are located) and the other regions is diminished. The high share of offshore wind energy increases the need for north-south connections, especially from the *Tennet (N)* region, bordering the North Sea, to the South. Thus, technology availability, in particular of offshore wind and CCS, determines transmission capacity requirements.

In addition to the scenarios for which one technological option is unavailable, an experiment without both CCS and offshore wind was performed for the *Low* demand case. A feasible model solution was not possible in LIMES-D for this case, underlining the relevance of offshore wind energy and CCS for meeting the CO_2 emission and renewable targets.

To conclude the comparison of demand scenarios, four major findings can be determined:

- No feasible solution for reaching the CO_2 and renewable targets can be found for scenarios with constant or increasing demand when either CCS or offshore wind (or both) are not available.
- Even for low demand scenarios, no feasible solution is possible when

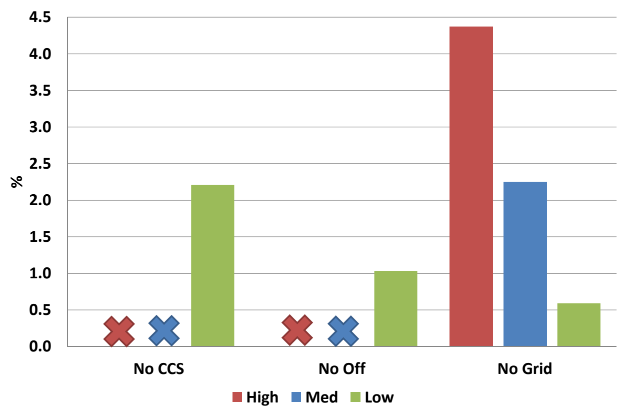


Figure 11: Comparison of total discounted power system costs for the different technology availabilities, inhibiting the use of carbon capture and storage (No CCS), offshore wind (No Off) or transmission capacity expansion (No Grid). Percentages indicate the difference between the case with constraints and the respective *All Opt* case for each of the demand scenarios, a cross indicates that there was no feasible solution for the respective scenario.

both CCS and offshore wind energy are not available.

- The non-availability of either offshore wind or CCS is compensated by solar PV as well as onshore wind and biomass combustion.
- The availability of offshore wind and CCS strongly determines transmission requirements, leading to different corridors depending on the available technology portfolio.

4.4. Power System Cost Comparison

Beyond questions of technical feasibility, it is instructive to compare the overall electricity system costs incurred in the different scenarios. Figure 11 shows total discounted power system costs over the period 2010-2050, in terms of the percentage difference between the cases with technology constraints and the respective *All Opt* case for each of the demand scenarios. As outlined above, the unavailability of CCS leads to a significantly different generation mix and also strongly influences transmission line expansions while solar PV and onshore wind compensate the absence of offshore wind. This is mirrored in Figure 11 where the *No CCS Low* case entails 2.2% higher

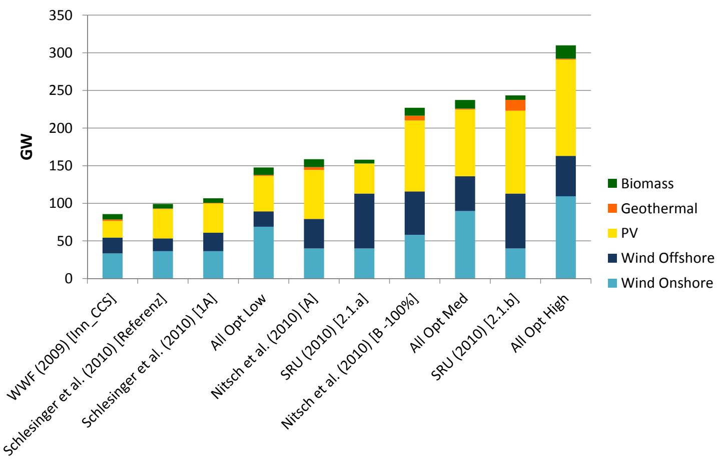


Figure 12: Installed capacities of renewable technologies in 2050 for different studies compared to LIMES-D scenarios (bracket indicates scenario name within the respective study).

power system costs than *All Opt Low* whereas the difference for *No Off Low* amounts to only 1%.

In order to set these cost differences into context, power system costs for scenarios without grid extensions above is presented. In these scenarios (*No Grid*), the transmission grid is not extended above today's capacities to investigate the impact of political and public impediments to power grid expansions. In contrast to scenarios without CCS or offshore wind energy, scenarios *No Grid High* and *No Grid Med* are feasible in LIMES-D and show fairly strong differences in power system costs to the respective *All Opt* cases. A comparison of power system cost differences for all three *Low* scenarios shows that the impact of technology unavailability is higher than that of grid expansion restrictions since costs for *No grid Low* are only 0.6% higher than for *All Opt Low*. This shows that regional renewable potentials and CCS, in combination with the current power grid, are sufficient to allow for a successful energy transformation but go along with overall cost increases.

5. Comparison to Other Studies

To provide an evaluation of LIMES-D model scenarios, this section presents a comparison of installed capacities of renewables for different studies presented in Section 1. While these studies rely on different methods to generate their scenarios and the underlying assumptions vary, it is nonetheless illustrative to compare results for the year 2050.

As shown in Figure 3 in Section 3.2, projections for electricity demand in Germany vary significantly. Demand obviously has a strong influence on necessary capacities, which is one of the main reasons for the large spread of installed capacities for 2050 which is shown in Figure 12. Assumptions range from 400 TWh [17] to 761 TWh (*PRIMES Baseline* [61]). This is reflected in Figure 12 where total installed capacities of renewables reach a low of 82.20 GW in Kirchner and Matthes [17] while capacities are significantly higher in other studies. Power demand in 2050 is similar for Nitsch et al. [11] *B* and the LIMES-D *All Opt Med* scenario which is reflected in comparable overall installed renewable capacities for 2050. These scenarios additionally assume similar target shares for renewables, which also contributes to the similarity of installed capacities. The effect of different underlying political assumptions is reflected in different values for LIMES-D *All Opt Low* and Schlesinger et al. [10] *[Referenz]* which both have similar power demand in 2050 but fairly different capacities of renewable energy technologies.

Relative shares of renewables vary throughout scenarios but most show high shares of solar PV and onshore wind followed by offshore while biomass and geothermal energy only play marginal roles. Differences between studies are most likely based on different estimations of the potentials of renewables. These can vary strongly based on underlying assumptions on technologies, available space, etc.. Even though potential assumptions for offshore wind are similar throughout these studies, its relative capacity share within LIMES-D is lower than in most others with similar demand projections. This can be attributed to the representation of transmission requirements which are not explicitly included in other assessments. Higher shares of onshore wind are on the other hand likely influenced by newer potential assessments with higher regional detail (based on Bofinger et al. [44] for LIMES-D). These appear more optimistic than earlier figures due to the more positive consideration of onshore wind potential in southern regions of Germany. Results for PV for LIMES-D lie within the range for those of other studies. Comparisons for geothermal energy and biomass based electricity generation are difficult since

LIMES-D does not consider combined heat and power plants, predominant for these energy sources.

Since most of the above studies do not provide a discussion of required transmission capacity extensions, it is not possible to compare this part of the results. Two other publications, namely German Energy Agency [23] and 50Hertz Transmission GmbH et al. [31] as well as its successors 50Hertz Transmission GmbH et al. [32] and 50Hertz Transmission GmbH et al. [33] provide an overview on important transmission corridors for Germany. Both studies stress the importance of the north-to-south connection within Germany which can also be witnessed in LIMES-D. However, the time horizon in these studies is limited to 2010-2020 which makes a direct comparison of capacity values for 2050 impossible since most changes to transmission line capacities in LIMES-D happen only after 2020.

6. Discussion and Conclusion

This paper presented an analysis of different scenarios for electricity generation in Germany and resulting transmission pathways. For all scenarios, the German government's plans for a reduction of electricity-related CO_2 emissions and the legally binding target of 80% renewables in the power mix in 2050 are imposed on the model LIMES-D. The scenarios are differentiated along the lines of two key uncertainties, electricity demand projections and technology availability, to assess their impact on the system-cost optimal generation technology mix and transmission capacity deployment as well as the overall target compliance.

The level of power demand strongly influences necessary capacities for generation and transmission and a general trend for reinforcing north-south connections can be determined. Very high demand scenarios are infeasible because reaching the CO_2 emission reduction target is impossible due to residual emissions from balancing constraints. This is important since even though household and industry electricity demand might decrease, this effect could be mitigated by increasing shares of electric vehicles or other technological developments. Imports of electricity from other countries, especially when generated from renewables, could alleviate this constraint and allow for a successful attainment of targets even when power demand is higher than projected. Since this analysis is only considering an isolated German power system, it provides a conservative assessment of Germany's potential to reach its climate and energy targets. To further investigate this aspect, future analyses with LIMES-D shall include connections to other countries, e.g. via the integration of LIMES-D into LIMES-EU$^+$ [13].

An analysis of technology availability shows that under moderate to high power demand, offshore wind and CCS both play an important role for the feasibility of decarbonization in LIMES-D. When electricity demand is decreasing, the lack of either technological option can be compensated by higher shares of other technologies, mostly solar PV, wind and biomass combustion. Without both offshore wind and CCS, however, even low demand scenarios are infeasible in LIMES-D. Since variable renewables require some amount of balancing by gas turbines in the model, achieving CO_2 emission reduction targets is more difficult when their overall share increases. For scenarios with constant or increasing power demand, both offshore wind energy and CCS are thus necessary to successfully reach the decarbonization target. It is thus important to develop a broad technology portfolio to hedge against future power demand increases while still reaching the decarbonization and renewable targets, more so since recent discussions have stressed that demand reductions as planned by the German government might be unlikely [64].

These findings, however, do not imply that meeting both the German decarbonization and renewable target is impossible if CCS and offshore wind are not available. Rather, they indicate that diversification beyond the flexibility options considered in this modeling exercise is required. Such options have not been considered because they are in a very early stage of innovation or regulatory mechanisms are not fully available yet. The power-to-gas technology for example is an important supply-side option to provide long-term storage of electricity in the gas grid while at the same time enabling flexible generation based on renewable gas. This technology is a promising option for Germany [65], however, significant improvements in efficiency, reliability, lifetime and costs are required for a mainstream application [66]. Another option on the supply side is to improve the integration of the electricity and heat sector by increasing the deployment of demand-driven combined heat and power plants, e.g. based on biogas [67]. In order to foster such a development an appropriate regulatory framework for their successful market introduction is required first [68]. The demand side also offers a variety of flexibility options if appropriate market frameworks are installed: Demand response [69], smart grids [70] or smart control including the transport sector [71]. Each of these options has their specific advantages and disadvantages and can add flexibility to the system.

Low electricity demand scenarios without either CCS or offshore wind show differing requirements for grid expansion. This is due to strong changes in the choice of generation technologies in either case: the absence of CCS leads to increased shares of renewables, especially offshore wind and thus to stronger north-south transmission connections. Without offshore wind energy, more power is generated locally from wind turbines, solar energy as well as lignite-fuelled CCS plants, and thus creating less need for transmission line expansion. The only exception is the remaining demand for east-western connections to transport power generated by lignite CCS plants to other regions. The difference between these two cases is also reflected when considering costs: total discounted power system costs display a stronger increase when CCS is not available. Other possible obstacles such as the unavailability of biomass or a ban on new lignite plants where found not to have a large impact for feasibility or power system costs within LIMES-D scenarios and are not discussed win this paper. While storage technologies are important for the integration of renewables, analyses with LIMES-D have shown that their availability is not crucial for the decarbonization and renewable targets discussed here.

One additional conclusion from this analysis is that all scenarios show substantial needs for transmission grid expansion in Germany, particularly in order to keep mitigation costs low. The connection of north-eastern Germany to the other regions as well as general north-south linking of regions are common to all cases. However, an important finding is that the extent of the necessary grid capacity increases depend on technology availability and underlying power demand. This is currently not reflected in the transmission capacity planning process in Germany, as the generation capacity mix is not substantially varied in the scenarios used for grid planning [72, 73, 31, 32, 33]. Adequate grid extensions will require a close cooperation between the TSOs and local as well as national authorities to ensure timely and coordinated planning processes.

Moreover, limited technology availability leads to varying requirements on grid extensions and can prove to be an obstacle to the full transformation of the power system when power demand increases compared to today's values. The overall conclusions are thus that a broad technology portfolio could hedge against future power demand increases to enable reaching decarbonization and renewable targets and, more importantly, transmission line expansions should be planned with a careful consideration of the available generation technologies now and in the future. Generalizing these findings to other countries is difficult as the role of different technologies in the overall endeavor towards a low-carbon electricity system greatly depends on the specific conditions of the country, particularly the characteristics of local renewable energy potentials.

AppendixA. Model Data

The model includes a total of 19 different technologies for producing electricity and two storage technologies (intraday and day-to-day storage). This choice is based on the power plant fleet currently installed in the area considered plus additional options such as Carbon Capture and Sequestration (CCS). Table A.4 displays the salient techno-economic parameters and the initially installed capacities for all electricity generation technologies considered and storage characteristics can be found in Table A.5. Investment cost evolution for learning technologies is shown in Figure A.13.

The investment costs indicated for wind energy (onshore and offshore) and solar PV are costs for 2005 and are assumed to decrease due to learning effects. The values used in LIMES are derived from model runs with REMIND-D [18] and are presented in Figure A.13.

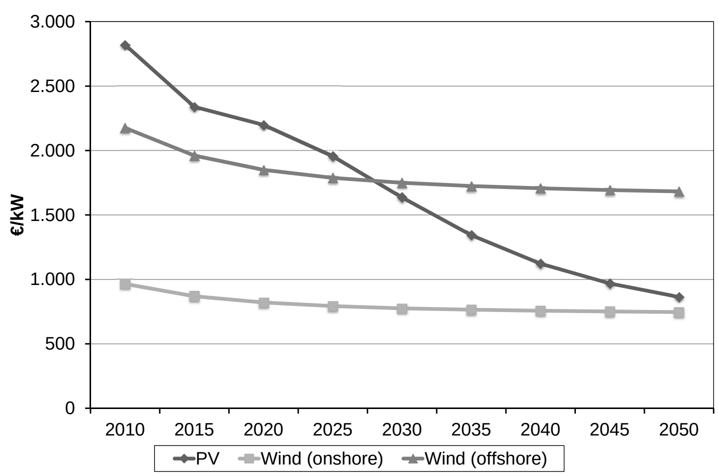


Figure A.13: Investment cost decrease for renewable technologies based on learning effects. Source: Schmid et al. [18].

Fixed Operation and Maintenance (O&M) costs contain labor costs and yearly overhead maintenance while variable O&M include all costs related to auxiliary material as well as wear and tear maintenance. Please note that

Table A.4: Techno-economic parameters of generation technologies (see sources indicated in the table for mapping to technology)

Technology[a]	Investment Costs [€/kW][b]	Fixed O&M Costs [% Inv. Cost]	Variable O&M Costs [€/GJ]	Technical Lifetime [a]
PC[c,d,e,f]	1100	2	2.11	60
PC+Post[c,d,e]	1800	2	3.52	60
PC+Oxy[c,d,e]	1900	2	4.23	60
Lignite[c,d,f]	1300	2	2.82	60
Lignite+Post[c,d]	2100	1	4.58	60
Lignite+Oxy[c,d]	2200	2	5.28	60
DOT[f,g]	322	3	0.28	35
NGT[f,h]	300	3	0.57	35
NGCC[f,h]	500	6	0.16	45
NGCC+CCS[h]	850	4	0.58	45
Geo HDR[g]	4427	4	0	40
Biomass Combustion[g]	1875	2	0.89	45
Biomass IGCC[g]	1500	4	0.89	45
Biomass IGCC+CCS[g]	2061	4	1.43	45
Hydro[g]	3000	2	0	80
TNR[i]	-	3	0.87	45

[a] Abbreviations: Pulverized Coal power plant(PC), Post-combustion Capture (Post), Oxyfuel Capture (Oxy), Lignite power plant (Lignite), Diesel Oil Turbine (DOT), open cycle Natural Gas Turbine (NGT), Natural Gas Combined Cycle (NGCC), Geothermal Hot Dry Rock (Geo HDR), Integrated Gasification Combined Cycle (IGCC), Hydroelectric Power Plant (Hydro), Thermonuclear Reactor (TNR).
[b] All investment costs are overnight costs. All €-values are 2005 values.
[c] Hake et al. [74] [d] Schlesinger et al. [10] [e] Massachusetts Institute of Technology [75] [f] German Energy Agency [76] [g] Schmid et al. [18]
[h] Krey [77] [i] Bauer et al. [78]

Table A.5: Parameters of storage technologies [based on 13]

Technology	Investment costs [€/kW]	Fixed O&M Costs [%/a]	Variable O&M Costs [ct/kW]	Round trip efficiency [%]	Technical lifetime [a]
Intraday storage	1500	0.5	0.24	80	80
Day-to-day storage	2500	1	0.00	70	10

variable O&M costs do not include fuel costs. Fuel costs are parameterized on the basis of Nitsch [79] (path B)[12] for fossil fuels and Bauer et al. [78] for uranium and biomass. Figure A.14 shows fuel prices paths for LIMES-D.

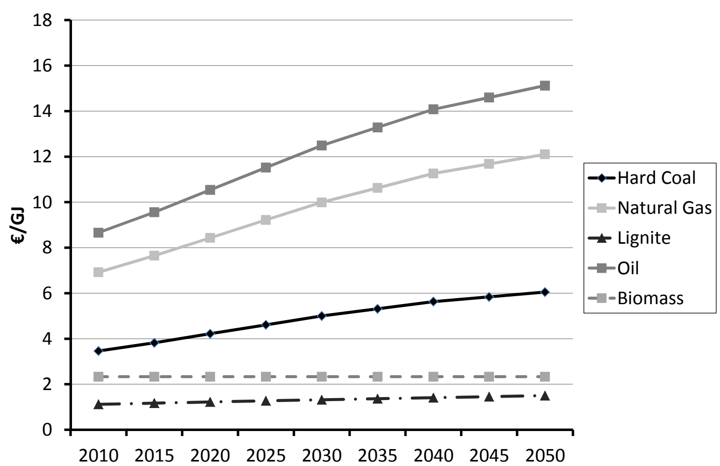


Figure A.14: Fuel prices in LIMES-D

Investment costs for overland cables in LIMES-D are 0.38 €/kW km and losses are assumed to be 7 %/1000 km [14, 13]. Initial capacities for transmission lines are based on NTC values from Hohmeyer et al. [39]. Table A.6 provides an overview of initial net transfer capacities (NTCs) in LIMES-D.

[12]There are two main assessments of fuel prices for Germany, namely Nitsch et al. [11] and Schlesinger et al. [10]. We found that while some details of resulting power mixes might vary, the overall results for this paper are independent of the chosen fuel cost assumption.

Table A.6: Initial Net Transfer Capacities in LIMES-D

Connection	Initial Transmission Capacity [GW]
50Hertz–Tennet (N)	3.00
50Hertz–Tennet (S)	2.50
Tennet (N)–Tennet (S)	3.13
Tennet (N)–Amprion	10.00
Amprion–Tennet (S)	6.25
Amprion–EnBW	6.25
EnBW–Tennet (S)	4.50

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