Renewable energy and CCS in German and European power sector decarbonization scenarios

vorgelegt von
Diplom-Ingenieurin
Sylvie Ludig
geboren in Luxemburg

von der Fakultät VI – Planen Bauen Umwelt
der Technischen Universität Berlin
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Gutachter:

Prof. Dr. Ottmar Edenhofer
Prof. Dr. Thomas Bruckner

Promotionsausschuss:

Prof. Dr. Johann Köppel (Vorsitz)
Prof. Dr. Ottmar Edenhofer
Prof. Dr. Thomas Bruckner

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Summary

In order to avoid unmanageable impacts of anthropogenic climate change, it is necessary to achieve substantial CO_2 emission reductions in all energy sectors. Due to salient decarbonization options such as renewable energy technologies and carbon capture and storage (CCS), the power sector plays a major role in climate change mitigation strategies. However, these options come with a set of challenges: the output of wind and solar energy varies in time and space and CCS faces technical challenges and public acceptance problems.

This thesis develops power sector decarbonization scenarios for the EU and Germany while taking into account both the interplay of renewable energy technologies and CCS as mitigation options as well as the technical challenges of renewable energy integration. More specifically, a series of model based studies address the respective roles of CCS and renewable energy technologies in emission reduction strategies while evaluating technical integration options such as transmission, storage and balancing technologies.

Results show that large-scale expansion of renewable energies will play the main role in power sector decarbonization scenarios, but the availability of CCS could lead to lower total costs and easier reaching of emission reduction targets through compensation of emissions generated by balancing technologies. Long-distance transmission enables better siting of renewable energy and thus higher achievable renewable shares in power generation and higher capacity factors. These indirect effects of delayed expansions induce additional power system costs, which are high relative to investment costs for new transmission lines. Results also reveal a preference for flexible technologies in combination with high shares of renewables for balancing purposes rather than inflexible baseload plants.

A case study for the EU shows that a near-complete decarbonization is possible both with and without transmission expansions, but total power system costs are lower when transmission and storage are available. Restrictions on transmission expansion induce high amounts of storage since high local shares of solar PV lead to large output variations. In contrast, a highly interconnected European power grid allows for optimized renewable power generation siting in regions with highest potentials, which requires large-scale transmission expansions but limits total power system costs.

Results of a detailed study of renewable energy integration in Germany show that the level of power demand is strongly relevant for the realization of high renewable shares and ambitious decarbonization targets. A broad technology portfolio allows to hedge

against the failure to meet efficiency goals for electricity demand. CCS is necessary to reach ambitious government targets if power demand is not sufficiently decreased by efficiency measures, as is offshore wind energy. Even in case of decreasing demand, at least one of both technologies needs to be available. The choice of transmission expansion corridors is strongly influenced by technology availability: in scenarios without offshore wind energy, north-south interconnections, which are crucial in all other scenarios, only play a minor role.

The studies in this thesis show that a large-scale decarbonization of the German and European power sectors is achievable through large shares of renewable energy technologies for electricity generation. CCS is not a prerequisite for successful CO_2 emission strategies, but allows to reach mitigation targets at a lower cost. A portfolio of renewable energy integration options is essential to manage temporal and spatial fluctuations; the optimal technology mix is determined by the underlying power system.

Zusammenfassung

Zur Vermeidung eines ungebremsten Klimawandels ist es wichtig, Emissionen aus allen Bereichen der Energieversorgung zu reduzieren. Der Stromsektor spielt dabei eine herausragende Rolle, da die Alternativen an CO_2-armen Technologien hier besonders groß ist. Erneuerbare Energien und CO_2-Abscheidung und -Speicherung (CCS) können einen wichtigen Beitrag leisten, bringen jedoch auch Nachteile mit: fluktuierende Technologien wie Windkraft und Solarenergie schwanken zeitlich und räumlich, CCS ist politischem und öffentlichen Widerstand ausgesetzt. Letzterer erstreckt sich vermehrt auch auf erneuerbare Energien und reduziert dadurch ihr verfügbares Potential.

Diese Arbeit entwickelt und vergleicht Szenarien für die Dekarbonisierung des Stromsektors unter Berücksichtigung der Konkurrenz von CCS und erneuerbaren Energien sowie von technischen Fragestellungen der Integration fluktuierender erneuerbarer Energien. Mehrere modellbasierte Studien erkunden die Rollen von erneuerbaren Energien und CCS in Szenarien für CO_2-Reduzierung in Deutschland und Europa im Zusammenspiel der Entwicklung von Kapazitäten zur Erzeugung, Speicherung und Übertragung von Strom.

Die Ergebnisse zeigen, dass ein starker Ausbau erneuerbarer Energien die wichtigste Rolle in Szenarien für die Stromerzeugung bis 2050 spielt. Die Verfügbarkeit von CCS führt allerdings zu geringeren Gesamtkosten. Die Erweiterung von Kapazitäten zur Stromübertragung erlaubt eine optimierte Installation von erneuerbaren Energien in Gebieten mit hohen Potenzialen und ermöglicht damit höhere Anteile erneuerbarer Energien an der Stromerzeugung und bessere Ausnutzungsgrade. Die entstehenden Kosten solcher indirekten Effekte im Falle einer Begrenzung von Stromleitungsausbau sind sehr hoch im Vergleich zu den reinen Installationskosten. Desweiteren unterstreichen die Modellergebnisse die Notwendigkeit flexibler Kraftwerke in Kombination mit fluktuierenden erneuerbaren Energien.

Eine modellbasierte Fallstudie zur Europäischen Union und den angrenzenden Regionen zeigt, dass eine nahezu CO_2-freie Stromerzeugung in 2050 auch ohne einen weitreichenden Ausbau der Stromnetze möglich ist, die Gesamtkosten lassen sich jedoch mit länderübergreifenden Netzerweiterungen deutlich senken. Ein eingeschränkter Netzausbau führt zu einem sehr starken Bedarf an Stromspeichern, da hohe lokale Anteile von beispielsweise Photovoltaik zu starken Schwankungen in der Stromerzeugung führen, besonders in zentraleuropäischen Ländern wie Deutschland. Im Gegensatz dazu erlaubt ein optimierter europäischer Netzausbau einen Ausbau von erneuerbaren Energien in Regionen mit den höchsten Potentialen und führt zu ge-

ringeren Gesamtkosten der europäischen Stromerzeugung.

Ergebnisse einer Studie zur Integration erneuerbarer Energien in Deutschland zeigen, dass die Höhe der Stromnachfrage eine große Relevanz für das Erreichen von Zielen zum Ausbau erneuerbaren Energien und zum Klimaschutz hat. Ein breites Technologieportfolio erlaubt jedoch eine Absicherung gegen das Scheitern von Effizienzzielen für die Stromversorgung: die Verfügbarkeit von CCS und einem breiten Spektrum erneuerbarer Energien, vor allem offshore Windenergie, ermöglicht das Erreichen von Emissions- und erneuerbare Energien-Zielen auch bei hoher Stromnachfrage. Außerdem wird festgestellt, dass der Stromnetzausbau stark von der Technologiewahl beeinflusst wird: in Szenarien ohne offshore Windenergie spielen Nord-Süd-Verbindungen eine untergeordnete Rolle im Vergleich zu allen anderen Szenarien. Die Anbindung der windreichen Regionen im Osten des Landes an die stärker bevölkerten Bundesländer im Westen ist in allen Szenarien von großer Bedeutung.

Die in dieser Dissertation diskutierten Studien zeigen, dass eine umfangreiche Emissionsminderung in Deutschland und der europäischen Union durch hohe Anteile von erneuerbaren Energien ermöglicht wird. Die Verfügbarkeit von CCS ist keine notwendige Voraussetzung, erlaubt jedoch das Erreichen von Klimaschutzzielen zu niedrigeren Kosten. Ein breites Portfolio an Technologien ermöglicht die erfolgreiche Integration erneuerbarer Energien während die Gewichtung der einzelnen Optionen vom jeweiligen System abhängt.

Chapter 1

Introduction

1.1 Decarbonization options in global climate change mitigation strategies

There is a broad consensus in the scientific community on the need to reduce anthropogenic CO_2 emissions in order to mitigate dangerous interference with the climate system (IPCC 2007). International pledges for emission reduction efforts after the 2009 Copenhagen Summit are ambitious, yet still insufficient to limit global warming in such a way as to avoid unmanageable climate impacts (UNEP 2012). However, even though no international agreement on emission reductions has been reached, several regions and countries, including Europe and Germany, have mapped out their own plans to achieve a substantial decarbonization of their energy systems. Today's energy generation, still largely relying on fossil fuels in most part of the world, is thus already starting to undergo a transition.

While there is no consensus in international policy how substantial global CO_2 reductions will be achieved, several studies have analyzed possible pathways to reach climate mitigation goals and found renewable energy technologies (RET) and carbon capture and storage (CCS) to play an important role in their scenarios (Edenhofer et al. 2009; Vuuren et al. 2009; Luderer et al. 2012). Nuclear energy, while discussed as a possible mitigation options, was not found to play a significant role. Figure 1.1 shows results from the Recipe-Project (Edenhofer et al. 2009) from three different models where RET and biomass account for at least half of the global primary energy consumption in 2050 and beyond. Luderer et al. (2012) also show that RET can play an important role especially in power generation (see Figure 1.2). Furthermore, all scenarios contain significant amounts of CCS, either in combination with fossil fuels (mainly coal) or biomass. Figure 1.2 also underlines that today's energy generation relies heavily on fossil fuels. To reach ambitious climate change mitigation goals, there is thus need for a significant transformation[1] of the energy sector and especially of power generation to reach decarbonization targets and mitigate climate change.

[1]Questions have been raised about the extent of the power system transformation and the associated ramp-up of capacities. Wilson et al. (2012) have compared historical capacity extensions with scenario results and found that the projected installation rates are within limits of historical rates.

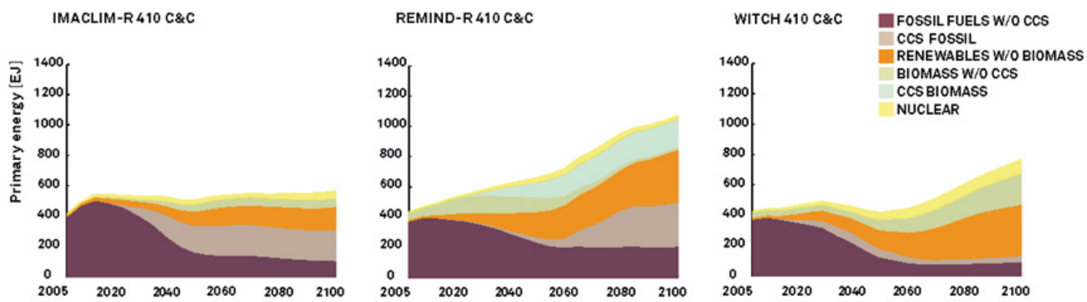

Figure 1.1: Global primary energy supply for the *410 C&C* policy scenario from the RECIPE project (Edenhofer et al. 2009)

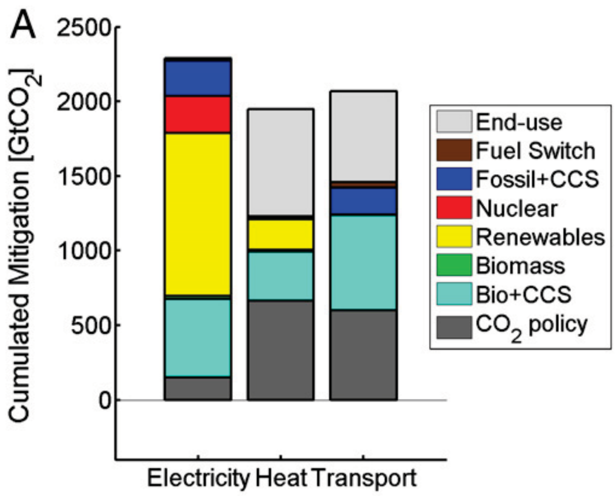

Figure 1.2: Cumulated mitigation contribution of technologies for different sectors. Results from the REMIND model from Luderer et al. (2012)

The intrinsic properties of renewable energy technologies such as wind energy, photovoltaics (PV) and biomass differ from those of conventional energy carriers. Their availability varies in space and time: potential of renewable energy sources is not equally distributed throughout countries and regions and does not necessarily correspond with load centers. Additionally, output of renewable energy technologies is influenced by the varying temporal availability of the resources. Since the nature of electricity is such that demand and supply have to be balanced at any time, temporal and spatial variations of RET, raise questions about their integration into existing power systems. Section 1.2 provides an overview on issues arising through the natural variability of RET and presents options to enable their integration.

Alongside RET, most decarbonization scenarios discussed above contain CCS as another important mitigation option. Fossil fuel or biomass based power plants could be equipped by facilities for CO_2 capture, thereby reducing the amount of emissions at the respective plant. So far, however, large-scale implementations are still limited, mostly owing to missing public acceptance and, more importantly, limited financial incentives (Hirschhausen et al. 2012; Scott et al. 2012). Nonetheless, since many projections for future energy use assume the availability of this technology, it is important to investigate the impact of CCS on the integration of RET as their respective characteristics could be in opposition to one another.

Installed RET capacity and yearly investments are among the highest worldwide in Germany (BMU 2012b). Starting from an energy system heavily relying on fossil fuels, renewable energy shares have increased rapidly over the last two decades. High amounts of wind and solar energy are increasingly raising questions about RET integration in the German power system, especially in relation to large installed capacities of lignite. Plans for up to 80% RET in the German electricity mix in 2050, and a substantial decarbonization including CCS installations (Federal Government 2011) require a substantial transformation of the power sector. This process, together with similar plans in the European Union (European Commission 2011a,b,c), will provide important insights on the interplay of RET integration options and could aid similar transformations in other parts of the world.

This thesis investigates the role of renewable energy technologies in decarbonization strategies for the electricity sector with a regional focus on the German and European power systems. The scope of the analysis is twofold: compare integration options for high shares of RET in the LIMES modeling framework and investigate the interplay of RET and CCS in decarbonization scenarios for the power sector. Ambitious plans for decarbonization and RET development in Germany and Europe will be investigated along these questions to provide a discussion on prerequisites for their successful implementation.

1.2 RET integration issues and solution portfolio

This section first provides an account of problems arising around the integration of RET (Section 1.2.1). Then, Section 1.2.2 presents technical options for enabling large-scale RET integration and finally, several studies are analyzed in Section 1.2.3 and their ability to address critical points from Section 1.2.1 are discussed.

1.2.1 Aspects of system integration of renewable energy technologies

Power system integration of RET is a multi-dimensional problem. RET potential varies in time and space and long investment time-frames in power systems induce additional problems for RET integration into existing networks. These aspects are discussed in the following.

Spatial Variability Potential for generating electricity from RET is varying from region to region, mostly limiting usage of the respective technology to areas where expected output is sufficiently high for installations to be profitable. Biomass is the only resource which can be transported after being harvested, but while fossil energy carriers such as hard coal or oil can be transported fairly easily from their source to power plants in other regions, the lower energy density of biomass constraints usage to a limited area range for economic reasons (Dornburg and Faaij 2001; McKeough et al. 2005)[2]. Electricity from wind or solar energy is usually generated in areas where the respective resource is abundant. Since areas with high renewable energy potential do not necessarily match demand centers, electricity has to be transported over long distances, requiring adequate infrastructure for interregional transmission capacity to be in place.

Temporal Variability Since generation from most renewable energy sources is closely linked to certain weather conditions, their output varies in time relative to those conditions. Wind turbines show an increasing generation with increasing wind velocity up to their rated output speed and have to be shut down in case of storms for security reasons. Power generation from most photovoltaic plants is possible, yet less effective, under cloudy skies whereas Concentrated Solar Power (CSP) facilities need direct sunlight so generate electricity. An overview on the different scales of temporal variability of RET can be found in Figure 1.3. Additional problems arise through the nature of electricity, which is such that supply and demand have to be balanced at all times. Conventional fossil-fuel-based power plants are designed to generate electricity when needed. While there are differences between plant and fuel types concerning their load-following ability, conventional power plants are generally dispatchable. Since the output of variable RET such as wind and solar PV is directly linked to wind speed or irradiation, respectively, it can only be varied by reducing output. An increase on demand is impossible, leading to a limited dispatchability. These aspects require that measures are taken to integrate RET into the power sector under consideration of their specific characteristics.

Long-term power system development Most of the integration options described in the following Section 1.2.2 are relevant to RET integration on more than

[2]Limiting biomass to areas close to harvest regions is a conservative assumption since global bioenergy trade is developing (Junginger et al. 2008; Peksa-Blanchard et al. 2007). The assumption of non-tradeability underestimates biomass potentials in countries with limited potential (compared to energy demand).

Technology		Plant size range (MW)	Variability: Characteristic time scales for power system operation (Time scale)	Dispatchability	Geographical diversity potential	Predictability
Bioenergy		0.1–100	Seasons (depending on biomass availability)	+++	+	++
Direct solar energy	PV	0.004–100 modular	Minutes to years	+	++	+
	CSP with thermal storage*	50–250	Hours to years	++	+**	++
Geothermal Energy		2–100	Years	+++	N/A	++
Hydropower	Run of river	0.1–1,500	Hours to years	++	+	++
	Reservoir	1–20,000	Days to years	+++	+	++
Ocean energy	Tidal range	0.1–300	Hours to days	+	+	++
	Tidal current	1–200	Hours to days	+	+	++
	Wave	1–200	Minutes to years	+	++	+
Wind energy		5–300	Minutes to years	+	++	+

Figure 1.3: Integration characteristics, adapted from IPCC (2011).

one scale. Variability of RET takes place both in time and in space as output of e.g. wind turbines and solar PV plants vary both during the day and over the time of a year as well as across regions where potentials for RET-based generation can differ strongly. It is thus necessary to combine these aspects when investigating power system integration of RET. Additionally, a third dimension needs to be included: development of power systems happens on long time scales, requiring extensive planning processes over several years. This aspect is relevant to the analysis of RET integration since power systems show strong path dependencies. Cost-intensive investments into power plants or transmission capacities have long refinancing time-frames, requiring the installed capacities to run over a longer period to ensure their profitability. Since this can create lock-ins into power systems whose characteristics are inadequate to integrate large shares of RET, it is necessary to use a coordinated expansion strategy which includes variability management. Therefore, investments into flexible power plants needed for balancing or storage technologies also need to be planned in time to be available when required.

It is thus important to combine the investigation of long-term power system development with short-term fluctuation issues and regional differences in demand and supply to obtain an integrated view on the optimal portfolio of RET technologies and integration options. This way, high shares of RET within the resulting electricity system can successfully lead to a strong decarbonization of power generation and thus support climate change mitigation in this sector.

1.2.2 Technical RET integration options

As stated in Section 1.1, the nature of electricity is such that demand and supply have to be balanced at any time. Temporal and spatial variability of RET lead to conflicts as increasingly large shares of renewable energy technologies enter the power system. In addition to the need to transport electricity from remote areas to demand centers and the dependency of output on time-varying natural energy flows, high shares of RET might induce stability problems in the power system due to the insufficient provision of frequency control by older installations.

Several technical options are available to facilitate the integration of renewable energy technologies into the electricity market (IPCC 2011): for example improved forecasts lead to easier scheduling of flexible balancing technologies, storage technologies allow for the bridging of times with low supply, long-distance transmission connects power demand and RES supply and lastly, demand side measures can adapt electricity demand to varying supply. This section provides an overview on these options and discusses possible benefits and drawbacks.

Flexible balancing technologies The first technical option to facilitate the integration of RET into the existing power system is the utilization and update of existing thermal generation capacities (Carraretto 2006). The existing power plant fleet already shows a certain level of flexibility necessary to provide following of load changes. Since increasing levels of RET induce higher variability in certain systems, new installations or upgrades of old conventional thermal power plants are necessary. Biomass combustion plants or hydropower can also play a role in providing operational flexibility, but their potentials are limited which constraints their possible role in power system balancing. Some studies discuss flexible operation of CCS power plants as an additional flexibility option (Chalmers and Gibbins 2007; Cohen et al. 2008), which would include switching off capture to temporarily increase power output. Furthermore, it could be possible to limit the rate at which RET are allowed change their output to prevent sudden needs for backup generation. However, since RET are dependent on natural energy flows, complete control of output change rates is impossible, except for the curtailment of RET output.

Some challenges for the conventional power plant fleet arise through increasing shares of RET: to prevent electricity generation costs and emissions from rising too high, it is necessary to prevent efficiency of conventional power plants from being lowered too much by generation at low output levels. Furthermore, RET displacing conventional fossil generation might lead to less dispatchable generation available, reducing overall system flexibility. Climate change mitigation strategies could lead to higher shares of nuclear power or new technologies such as CCS or IGCC which are less flexible than for example gas turbines (Q. Chen et al. 2012). It is thus necessary to consider the complete electricity sector when planning future power generation. Besides the installation of technologies, flexibility options are available for the operation of the power market. Shorter gate-closure times, making decisions closer to real time, allow for a more efficient commitment of power plants (Frans Van Hulle et al. 2009; EWIS 2010). As mentioned above, long-term planning should include variability to ensure a power plant fleet adequate for flexible operation, facilitating the integration of RET. Furthermore, larger balancing areas could help reduce stress in each region by pooling flexible generation and evening out variability of RET (Milligan and Kirby 2010).

Transmission infrastructure Despite hitherto slowly increasing capacities which indicate acceptance problems and political challenges, there are several benefits of an expansion of transmission infrastructure: First, power can be transported from remote areas with high RET generation potential to demand centers. Second, stronger interconnections allow larger regions to be balanced, reducing RET integration costs by distributing balancing requirements among more generators. Last, the interconnection of larger regions allows to exploit geographical diversity and imperfect correlations among RET resources, thereby reducing the need for additional balancing by conventional technologies. Net variability and uncertainty are thus decreased (ENTSO-E 2010).

Increasing installations of RET in the distribution grid raise the necessity for stronger supervision and control in this part of the network by inducing power flows in two directions (i.e. from the distribution grid back to the transmission grid) instead of the previous one-directional power delivery (Sebastian et al. 2008). The transmission grid in general also profits from increased communication and surveillance since better information on possible stress allows a more efficient use of the existing grid. Institutional challenges might pose the biggest obstacles to a successful expansion of the power grid: public opposition often prevents or delay building of new transmission lines and long administrative processes increase construction time

(Buijs et al. 2011). One example of grid expansions impeded by political discussions is presented in Section 1.4.1: there are several studies (e.g. Frans Van Hulle et al. 2009; SRU 2010) underlining the importance of an expansion of the interconnections between EU member states, yet differences between single countries have so far constrained concrete plans for a coordinated expansion of the European transmission grid. Intensifying public information and streamlining of administrative procedures could mitigate these delays as well as financial incentives to grid operators to increase transmission capacities ahead of time.

Electricity storage A seemingly obvious integration option for renewables is the usage of electricity storage. However, there are important obstacles to a large-scale implementation of storage technologies: so far, most options have very high upfront investment costs and mostly still a low round-trip efficiency. Pumped Hydro Storage (PHS) and Compressed Air Energy Storage (CAES) are the only technologies implemented on a large scale in power systems up to date. Both PHS and CAES are highly site-specific and while their efficiency is high, installation is very expensive. General assumptions for most developed countries believe remaining potential for PHS to be limited. However, recent research (Steffen 2012) shows that plans for increasing shares of RET could improve prospects for PHS, e.g. in Germany. Recent developments have shown that methanation from biomass using wind energy could be an interesting option (Sterner 2009) but most other technologies such as Lead-Acid or Lithium-Ion batteries, fuel cells or flow batteries are still either in early-stage research or probably not useable in large-scale applications (H. Chen et al. 2009).

Providing that further developments allow for successful large-scale implementations, storage technologies could help reduce RET curtailment and enable a more efficient use of base-load by reducing variability peaks and reduce or delay need for new transmission. Furthermore, storage could provide ancillary services through very fast power injections and provide short-term inertia to smaller or isolated systems, as well as increase system flexiblity. Studies have shown that it is usually not cost-effective to implement storage as a dedicated balancing capacity for a RET installation, but rather for system-wide balancing (IPCC 2011).

Demand side measures While not widely implemented yet, demand side measures could prove to be an important integration option since demand that can be quickly curtailed could provide short term reserves and intra-day balancing. A large potential for flexible demand adaptation can be found in domestic as well as industrial applications, especially heating and cooling. Cooling appliances can be switched off for certain periods of time without compromising refrigerated goods, for example, and intrinsic energy storage allows for water heating or heat pumps to generate heat to be used later (Stadler 2008). Large industrial facilities for aluminium production or water pumping, for example are able to provide a similar flexibility (Milligan and Kirby 2010). In the future, assuming a significant increase in electric vehicles, battery charging could also represent a controllable load which could aid system operation by taking up peaks from RET generation (Kempton and Tomić 2005). As these examples show, more research is needed before demand side measures can play a relevant role in aiding RET integration. Implementation of a market for demand response or an incentive system are most likely needed and could increase the willingness of residential, service and industrial consumers to adapt their demand to the needs of the power system.

This overview of integration options shows that there is no single silver bullet for renewable energy integration into the electricity market but a portfolio of different options needs to be determined. Different studies that have tried so far to investigate one or more aspects of RET integration will be presented in Section 1.2.3.

1.2.3 Literature review on integration studies

There are a number of studies discussing technical options for the integration of RET into power systems. Chapter 8 of IPCC (2011) provides a comprehensive overview of RET integration studies showing that the scope of RET integration studies range from larger systems (EU, parts of the US) to small islands and mostly focus on wind energy and some solar PV. Most of these studies have a limited focus in terms of renewable technologies and integration options and thus consider only part of the technology portfolio available for large-scale RET installations in highly decarbonized power systems. This literature review presents results from several studies for the EU, for Germany and for different parts of the US and discusses findings on RET integration options and limitations of the chosen analysis methods. While this thesis focuses on the integration of RET in Germany and Europe, the reviewed studies were chosen to show the bandwidth of goals for RET and different possible model assumptions. An overview on different investigations on concrete German RET targets can be found in Section 6.1 in Chapter 6 in this thesis. Since findings in the following are strongly related to the underlying system, results are not comparable by numbers alone, but allow to analyze the bandwidth of different aspects relevant for RET integration issues. The following literature review thus provides an overview on RET integration challenges and options in different power systems and indicates requirements for further research.

TradeWind Study (Frans Van Hulle et al. 2009) The TradeWind study, the final report of a project funded under the EU's *Intelligent Energy-Europe* program, focuses on the integration of wind energy into the European power system. It uses an exogenous setting of wind installations and conventional generations which are analyzed in a detailed model for cost efficient capacity dispatch and transmission allocation. Maximum 300 GW wind energy in the EU are assumed for the year 2035, which constitute 28% of total power generation for that year in the studied scenarios. The target value of 300 GW in 2035 is set exogenously, the study does not consider the capacity build-up in the European power system leading to this goal. Simulations are performed for different snapshot years to determine the most congested transmission lines and give recommendations for their update. Study results show that overall system costs decrease when grid extensions are implemented as recommended. The TradeWind study provides a very detailed description and investigation of infrastructure but does not give any information on long-term planning aspects. Furthermore, only integration aspects of wind energy are being investigated. However, as discussed in Section 1.1, most climate change mitigation strategies include a portfolio of different decarbonization options, including different types of RET. Thus, while Frans Van Hulle et al. 2009 provide insights on possible transmission grid expansion requirements, the analysis does neither provide information on possible power generation capacity extension needs over a longer time-frame, nor a pathway to large-scale RET integration and decarbonization for Europe.

Eastern Wind Integration and Transmission Study (EnerNex Corporation 2010) and Western Wind and Solar Integration Study (GE Energy 2010) The Eastern Wind Integration and Transmission Study (EWITS) investigates the integration of 20-39% of wind energy into large parts of the Eastern Interconnect in the USA. The study focuses on the calendar year 2024 and uses an extensive data set for wind energy with a high level of spatial and temporal detail. Model calculations are conducted using the commercial tools PROMOD IV for dispatch modelling, EGEAS for system development planning and GE-MARS for system reliability investigation. The EGEAS model determines capacity extensions through a long-term cost-minimization of investment and generation costs. It provides only five alternatives for power generation: hard coal power plants, natural gas turbines and NGCC, nuclear power and wind energy. Other technologies such as biomass combustion or hydropower are considered being not economically competitive under the assumptions of the analysis. Results show that wind penetrations of 20-30% can be realized when significant expansions of transmission capacities take place leading to the recommendation that planning for transmission should start early since it usually involves longer processes than installations of wind energy. For cases where transmission expansions are not available, significant curtailments of wind energy are necessary as transmission helps reduce impact of wind variability, thus also lowering integration costs.

A similar study is conducted for the western part of the US. However, the Western Wind and Solar Integration Study (WWSIS) has a smaller scope, using a target year of 2017 and focusing on investigating system adequacy. A site selection and transmission expansion determination algorithm is used to find adequate sites for 30% wind and 5% solar energy that constitute the goal figures for the WWSIS study. Model results include reductions of 40% in annual operating costs and 25-45% CO_2 emissions. Assuming an extensive balancing area cooperation, the study finds transmission not as important in the short run.

Both studies, while relying on extensive data for wind and solar energy potentials and fluctuations, do not consider long-term evolution of the respective power systems but only considers a target year. It is thus neither possible to assess the feasibility of a transformation from the existing to the target power system, nor the required evolution beyond this system.

Renewable Electricity Futures Study (Hand et al. 2012) The Renewable Electricity Futures (RE Futures) Study explores different scenarios for 30%-90% RET in the US power sector, including several sensitivity analyses for the 80% RET case. The study does neither consider new installations of nuclear energy plants nor of CCS for fossil fuel plants. The scenarios are designed around specific renewable generation share levels and thus do not explore which level of RET might be economically optimal for the US. Two models are used in the investigation, NREL's Regional Energy Deployment System (ReEDS) model (Short et al. 2011) and a commercial model from ABB, GridView (ABB 2005). ReEDS is a power system development model for the US which determines a cost-optimal mix of electricity generation and transmission technologies under constraints of system security and resource constraints for fossil fuels and RET. The optimization is performed in two-year periods for the time-frame of 2006-2050. The model includes time slices for the representation of demand and RET supply variations and a high level of regional detail. GridView is a commercial software for hourly power market simulation which is applied in the RE Futures study to determine whether the technology mix and transmission expansions determined by the ReEDS model provide adequate system stability.

Main results of the study include a power system with 48% variable RET in 2050 for the 80% RET scenario and significant increases of storage technologies and transmission grid capacities. Furthermore, Hand et al. (2012) determine the need for increased system flexibility via higher reserve capacities, demand-side management, larger balancing areas interconnected by long-distance transmission and an increase of dispatchable RET technologies such as CSP. The level of power demand has a strong influence on the expansion velocity for RET and other technologies but does not limit the inhibit high RET share targets.

The combination of a long-term power system development model with a system simulation provides important insights for the integration of large shares of RET into the electricity grid. However, both models are limited in regional focus and do not provide versions for Europe or other regions outside the U.S.. Furthermore, the recursive optimization method does not ensure a consistent expansion over the time period in consideration. While the ReEDS model would be suitable to determine a cost-optimal share of RET for the power sector, the focus of the RE Futures study limits the investigation to a set of predetermined targets.

Energy Target 2050 Study (UBA 2010) The Energy Target 2050 study was conducted by the German Federal Agency for the Environment (UBA) and the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) to investigate a transformation of the German energy system leading to emission reductions of 80-90% and including up to 100% renewable energy sources. Capacities for RET for 2050 are set exogenously through a "story-and-simulation method" based on assumptions for economic and demographic parameters presented in the study. The model SIMEE developed by IWES (Saint-Drenan et al. 2009) is employed to perform a simulation of the resulting power system for the year 2050 to analyze technical feasibility and system adequacy. The simulation includes PHS storage and novel technologies such as methanation. Reserves and balancing are provided through gas turbines using gas generated from methanation and, to a lesser extent, imports from neighboring countries. Power transport is not modeled explicitly but expansions of the transmission grid are presumed to take place until the target year of this study. Thus, while providing extensive investigations of power storage and system adequacy, the Energy Target 2050 study neither considers the development of transmission nor that of generation capacities from the present until 2050.

SRU (SRU 2010; Scholz 2010) In 2010, the German Advisory Council on the Environment published a study for a power mix made up of 100% RET for Germany. While the study focus lies on the German electricity sector, interconnections to the rest of Europe and Northern Africa are also considered. Three different transmission grid scenarios are analyzed using the REMix model developed by the German Aerospace Center (DLR): (i) autarky, (ii) a strong connection of Germany to Scandinavian countries or (iii) extensive imports of electricity generated from CSP . REMix has 36 regions and performs a minimization of total system costs for the year 2050, when investments in generation, transmission and storage capacities are determined endogenously and enter the objective function as annualized costs. Capacity dispatch is optimized at a hourly resolution. While all scenarios consider imports of electricity from neighboring countries, national transmission of electricity is not included. In contrast to Frans Van Hulle et al. (2009), EnerNex Corporation (2010), and GE Energy (2010) and UBA (2010), the SRU study performs an endogenous optimization of investments and power plant dispatch. However, the optimization is only performed for the year 2050 while the development of capacities for the period 2010-2050 is not considered. Furthermore, electricity transmission within the region of scope is expected to be adequate for the power system in place.

The models URBS (Schaber et al. 2012) and DIMENSION (Fürsch et al. 2012) Recent publications on RET integration in Europe include studies based on the models URBS and DIMENSION. While URBS is also limited to the investigation of one target year, it contains an optimization of investments and dispatch for that year and combines capacities for storage and generation with transmission between regions[3] in Europe. DIMENSION goes one step further and includes an investigation of the transition from 2010 to 2050. It remains unclear from the information given in Fürsch et al. (2012) whether capacities are optimized intertemporally for this period. DIMENSION includes an optimization of investments into generation and dispatch of capacities which is combined with a simulation of transmission to determine possible grid inadequacies and ensure security of supply. Investments into transmission are thus not included in the original optimization of investments.

The models and studies included in this literature review address different aspects of RET integration into existing power systems. However, none completely combines all three aspects discussed in Section 1.2.1. The LIMES modeling framework, which is presented in the following Section 1.3, includes an intertemporal optimization of capacities for generation, storage and transmission while distinguishing power demand and RET potential for different regions and at different times during the year. It thus allows to conduct an integrated analysis of issues investigating the

[3]Regions in URBS are represented on a sub-country scale, e.g. containing 4 regions to describe Germany.

integration of RET into the electricity system. The social planner perspective allows to determine an optimal combination of integration options for RET, presenting a portfolio of solutions rather than considering RET integration options separately.

1.3 The LIMES modeling framework

As discussed in Section 1.2, the investigation of the integration of RET into the power system is a multi-level issue: It is necessary to combine the consideration of long-term planning horizons with short-term and regional variability issues. The LIMES (Long-term Investment Model for the Electricity Sector) model framework takes into account these three dimensions. This section gives a brief description of the most important features of the model framework, which has been developed to analyze different aspects of RET integration into the electricity sector.

LIMES is a multi-region modeling framework that performs an intertemporal minimization of total power system costs subject to policy constraints for CO_2 emissions, RET deployment and technology availability. Costs considered in the model are investment costs, fuel costs, operation and maintenance (O&M) costs and, optionally, CO_2 transport costs. The optimization within the model is performed over an adjustable time-frame, usually 2010-2050. This allows to consider changes in fuel prices as well as the technical depreciation of generation capacities over time. Investments into capacities for electricity generation, storage or transmission are decided in 5 year time-steps, taking long planning and construction times into account. Power plants and transmission lines are not considered on a per-unit basis but as aggregated capacities for each technology.

In addition to long time-frames for capacity expansion, LIMES also includes time-slices for the representation of short-term variability of demand. Each model year is subdivided by a varying number of time-slices, which can be adapted according to requirements of numerical accuracy on one hand and computational demand on the other hand. Fluctuations of RET supply and electricity demand are considered on seasonal, diurnal and intra-day scales and represented by time-slices with a resolution between 24h and 1h. A more detailed description of the implementation of temporal variability within LIMES and a discussion of problems and limitations can be found in Chapter 3.

The multi-level approach of this thesis led to the implementation of a varying number of regions, depending on the regional scopes of the analyses in Chapters 2 to 6. The one region version of eastern Germany (Chapters 3 and 4) is included in a five region version of Germany in Chapter 6. Germany, while with less regional resolution is also represented the multi-region model version in Chapter 5. Regions are interconnected by long-distance transmission lines and calibrated to data from the respective regions for the starting year 2010.

Cost-efficient dispatch of capacities for generation, transmission and storage of electricity is determined endogenously for each time-slice and region, ensuring that supply and demand are matched for each. The endogenous price for electricity is set at the marginal costs of the most expensive technology necessary for power gen-

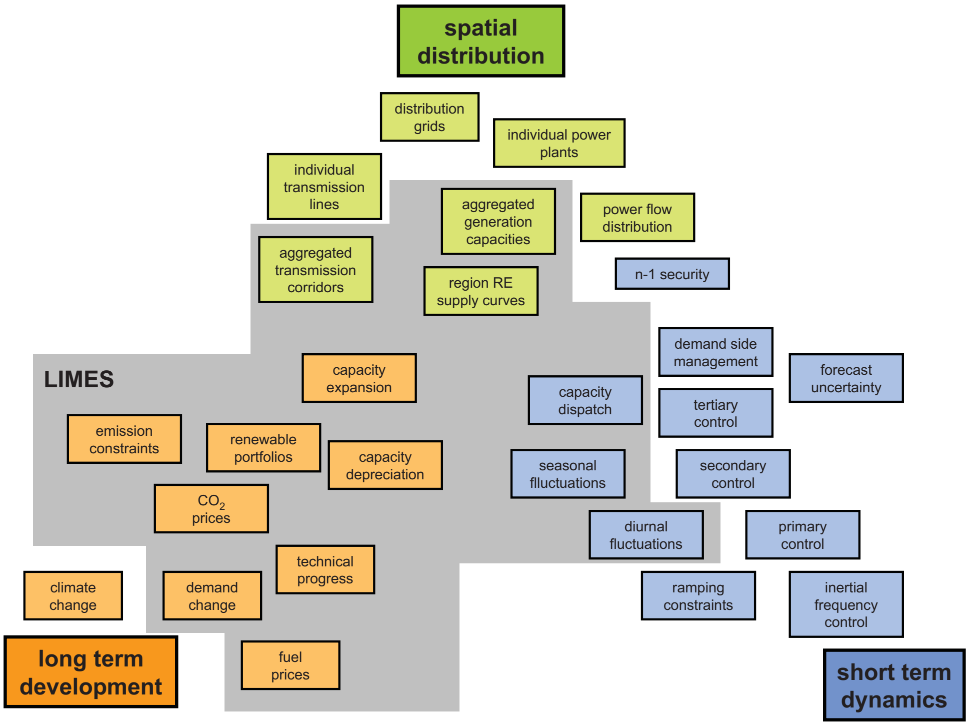

Figure 1.4: Overview on power system characteristics and their representation in LIMES. Figure source: Haller (2012)

eration in the respective time slice[4]. Storage allows to transfer electricity between time-slices. LIMES thus combines long-term investment decisions with short-term dispatch, ensuring that all installed capacities are refinanced through rents generated over time. Long-term climate change mitigation strategies can be accounted for by CO_2 prices or emission budgets. Figure 1.4 provides an overview on characteristics of LIMES relevant to long-term planning, short-term dispatch and regional distribution.

As discussed in Section 1.2.2, the integration of RET requires different options to mitigate the effects of temporal and spatial variability. Backup and balancing requirements through conventional technologies or dispatchable RET, transmission and storage technologies are implemented in LIMES. Demand side measures are not considered thus far due to the limited experience with this option and the high requirements of resolution detail. Nonetheless, LIMES allows to determine a portfolio of RET technologies and necessary integration options in long-term scenarios for the power system, which can be used to investigate the role of RET in climate change mitigation strategies.

[4]Generation technologies with marginal costs exceeding the electricity price can be shut down temporarily.

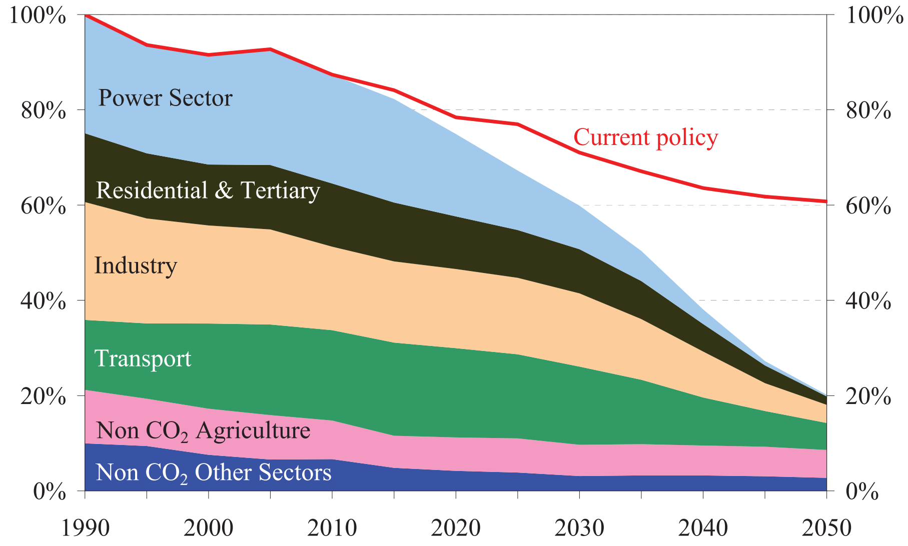

Figure 1.5: EU Greenhouse Gas Emission Projection towards a reduction by 80% compared to 1990. Figure Source: European Commission (2011a)

1.4 Renewable energy in Germany and Europe

In both the recently published energy strategies of the European Union (EU) (European Commission 2011a,b) and Germany (Federal Government 2011), RET play an important role in the efforts to reduce Greenhouse Gases (GHG) from the energy sector. Several challenges, including questions of RET integration, could impede a successful realization of the goals both for the EU as a whole and for Germany itself. This section lays out the main points of the respective plans for future power generation and provides an overview on the RET integration issues.

1.4.1 The EU energy roadmap

The European Union has plans to reduce its GHG emissions by 80-95% compared to 1990 values by 2050 (European Commission 2011b). Figure 1.5 shows a road-map scenario (from European Commission 2011a) including all energy sectors and their contributions to this reduction where the power sector undergoes a near-complete decarbonization. European Commission (2011c) presents RET as the main technology choice in this transformation with a share of 37% in electricity generation in 2020 and increasing thereafter. Since other power sector decarbonization options, such as nuclear energy and CCS, face issues of public acceptance, safety regulations or technical implementation, their contribution to the mitigation effort remains limited, enforcing the role of RET.

RET potentials in the EU are abundant, albeit distributed very unevenly. While countries in southern Europe have large potentials for both PV and CSP, wind energy dominates all coastal regions, with strong potentials in northern and central Europe. Hydropower plays an important role in the Alps and in Scandinavia. To combine these resources, it would be necessary to interlink all regions by transmission capacities sufficiently strong to simultaneously sustain high RET supply situations in one area and high demand in another (ENTSO-E 2012a). However, historically, connections of the different national transmission grids are only dimensioned to provide balancing and system stability support and need significant extensions to enable long-distance transmission of electricity (ENTSO-E 2012b).

Despite increasing efforts to harmonize European electricity markets, interconnections between neighboring countries have not been expanded significantly in the past. The European Network of Transmission System Operators for Electricity (ENTSO-E) has published a *Ten-Year Network Development Plan* for the period until 2020 (ENTSO-E 2012b) wherein they identify more than 40 000 km of transmission lines in need of upgrade or expansion, both within countries and cross-border. Due to long planning times for transmission lines made even more complex by the necessary coordination among neighboring countries, it remains unclear whether expansions of cross-border interconnections will occur in due time for the realization of plans for high shares of RET throughout Europe. In Chapter 5, scenarios for a coordinated expansion of capacities for generation, storage and transmission of RET within Europe are analyzed. Results including substantial transmission grid expansions between countries are compared to cases where cross-border interconnections remain at today's capacity, allowing to identify possible impacts on costs for electricity and the feasibility of climate change mitigation plans.

1.4.2 The German *Energy Concept*

In 2010, the German federal government published an energy concept (Federal Government 2011) containing several goals: reduce energy-related GHG emissions by 80-95%[5] in 2050, achieve a share of 80% RET in electricity generation in 2050 and realize a decrease of power demand by 25%[6] in 2050. In addition to RET, conventional power plants with CCS and nuclear energy were planned to play an important role in power generation. In a follow-up to the events in Fukushima in March 2011, the energy concept was amended to include a nuclear phase out until 2022 (Bundestag 2011).

Potentials for RET are distributed very unevenly throughout Germany. While northern and eastern regions show large potential for wind energy (both onshore and offshore in the North Sea and the Baltic Sea), southern parts of the country have favorable conditions for solar energy, especially PV. Since the main demand centers are located in western and southern Germany, large shares of wind energy increase the need for long-distance transmission of electricity. Additionally, the connection of the eastern part of the country to the west and south is weak for historic reasons, impeding transport of electricity from areas with large potentials for wind energy and substantial lignite reserves to larger demand centers.

Germany's ambitious plans for decarbonization include fossil fuel plants equipped with CCS, despite unclear perspectives for a large scale implementation of this technology (Hirschhausen et al. 2012; Scott et al. 2012). Since large shares of RET in power generation might require some amount of balancing by gas turbines or other

[5] compared to 1990 values
[6] compared to 2008 values

fossil-fuel-powered plants, very low emission levels might not be possible without CCS. According to e.g. UBA (2010) and SRU (2010), power generation based on 100% renewable ressources could be possible, however these studies do not include a representation of the power grid in Germany, possibly overestimating the potential of RET for power generation[7]. It is thus necessary to discuss scenarios for electricity generation in Germany both with and without CCS while considering the transmission network to account for electricity transport from RET generation sites to demand centers.

Another large uncertainty within the energy concept is the target to reduce electricity demand by 25% until 2050 (compared to 2008 values). While technological improvements and energy saving measures might enable substantial power demand reductions, the increasing electrification in other sectors such as transport are bound to countervail these efforts. Higher demand entails more power generation, increasing requirements for RET installations and other technologies. Failure to reach efficiency goals for the electricity sector might thus jeopardize RET share and decarbonization targets.

Recent studies (Schlesinger et al. 2010; Nitsch et al. 2010; Scholz 2010; UBA 2010; WWF 2009; German Energy Agency 2010a; Fürsch et al. 2012; Weigt 2009) have investigated one or more aspects of these challenges. However, no study has combined the necessary spatial and temporal resolution with long-term capacity developments to allow for an integrated analysis of all uncertainties while representing RET integration issues. In Chapter 6 in this thesis, the LIMES framework is applied to Germany to conduct a sensitivity analysis of German plans for the power sector and compare scenarios with high shares of RET under different uncertainties.

1.5 Thesis objective and outline

The aim of this thesis is to investigate the role of renewable energy technologies and CCS in decarbonization strategies for the electricity sector. The scope of the analysis is twofold: (i) compare integration options for high shares of RET in the LIMES modeling framework and (ii) investigate the interplay of RET and CCS in decarbonization scenarios for the power sector. LIMES allows to derive long-term scenarios for the electricity sector while taking account of the temporal and spatial variability of RET. A regional focus is set on the development of the European and German power systems to investigate how large shares of RET can be integrated into different systems to reach ambitious emission reduction targets.

The first part of the analysis investigates the impact of investments into technical options for RET integration and GHG emission reduction. Three model studies analyze technology choices for system flexibility and consequences of delayed investments into long-distance transmission. In the second part, two case studies for Europe and Germany discuss long-term decarbonization scenarios with high shares of RET. Transmission grid expansions between European countries are investigated

[7]Additionally, imports of RET-based electricity from neighboring countries are included, thus facilitating the achievement of RET share objectives.

to determine RET integration limits under CO_2 emission reduction targets. Furthermore, competition between CCS and RET is analyzed with a focus on the German power grid.

These analyses have been carried out in five articles, which are included in Chapters 2 to 6. Each chapter covers a specific part of the topic characterized by a specific research question. These questions are listed below, together with a short overview on the respective chapter. Chapter 7 presents a synthesis of the main results of this thesis and provides an outlook on further research.

What is the impact of delayed investments into infrastructure for transmission and storage of electricity on the expansion of renewable energy technologies under an emission tax? (Chapter 2)

Increasing the share of renewable energy in the power system leads to rising requirements for integration technologies that mitigate the effects of spatial and temporal variability of RET. Chapter 2 investigates the effect of investments into transmission and storage infrastructure on achievable RET generation shares, RET siting and realized capacity factors. These two options play an important role for the integration of RET into the power sector, however long planning times for power grid expansions and high investments into storage technologies might delay necessary investments. A conceptual 3-region version of the LIMES model is used to combine long-term investment decisions with short-term fluctuation management for variable RET to determine the effects of the availability of storage and large-scale transmission on RET deployment.

Does increased temporal resolution influence results for investment decisions into RET and other low carbon generation options? (Chapter 3)

This chapter investigates the impact of introducing higher temporal resolution into energy system models to allow for the representation of short-term fluctuations. Integrated Assessment models are widely applied in the area of long-term decarbonization scenarios, however, their focus on long time scales usually limits temporal resolution within these models. Chapter 3 presents the implementation of time-slices into the LIMES model and investigates the impact of increasing temporal resolution on results for technology choices and power system costs. The model is calibrated to represent the power sector of the eastern part of Germany (area of the TSO[8] *50Hertz Transmission GmbH*) which historically has only a weak interconnection to the rest of the country. The region has large potentials for wind energy (both onshore and offshore) as well as large lignite reserves, raising the question about the optimal low carbon technology mix including RET, CCS and balancing technologies. Different temporal resolutions between 24h and 1h are implemented to assess the influence of fluctuation representation in long-term scenarios.

[8]Transmission System Operator

Can additional flexibility of Post-Combustion CCS be a RET integration option and does it change the relevance of CCS for electricity generation under climate change mitigation strategies? (Chapter 4)

The region covered by the TSO *50Hertz Transmission GmbH* in eastern Germany has large reserves of lignite, which contribute significantly to present electricity generation. Scenarios for long-term power sector development, as developed in Chapter 3, show that lignite usage in plants equipped with CCS might be a relevant decarbonization option. Since wind energy also plays a major role for power generation in this region, it is necessary that the electricity system is sufficiently flexible to accommodate the fluctuating output by wind turbines. Recent research has shown that flexible usage of CO_2 capture in plants equipped with Post-Combustion CCS could contribute to system balancing. Chapter 4 presents an implementation of flexible Post-Combustion CCS as a RET integration option in the LIMES model. A sensitivity analysis including variation of gas prices, storage availability and wind curtailment shows situations where flexible usage of CCS plants could become an addition to the system balancing options listed in Section 1.2.2.

Which decarbonization scenarios for the European Union with high shares of renewable energy can be realized with and without increases of transmission capacity between countries? (Chapter 5)

As described in Section 1.4.1, long-term plans for the European power sector include a significant decarbonization and high shares of RET. Chapter 5 presents an analysis of different scenarios for power generation in this area with the LIMES-EU$^+$, a multi-region model that covers the EU-27, Norway, Switzerland, and the countries surrounding the Mediterranean Sea. The role of long-distance transmission is investigated in scenarios with and without expansion of country interconnections to determine limits for the integration of spatially and temporally fluctuating RET power generation in Europe.

Which expansion strategies for power generation technologies and transmission corridors should be at the core of future network development plans within Germany? (Chapter 6)

The long-term energy strategy by the German government in 2010 and 2011 contains plans for a substantial CO_2 emission reduction and high shares of renewable energy in electricity generation along with an accelerated nuclear phase-out. Significant improvements in energy efficiency, leading to a reduction in power demand, are at the basis of these scenarios. Projections for power demand in Germany, however, vary from strong increases to significant decreases, the government plans being at the lower end of this spread. Furthermore, the large-scale availability of core technologies such as offshore wind energy and CCS remains unclear. In the light of these uncertainties, Chapter 6 presents a sensitivity analysis using the five-region LIMES-D model including different demand projections and technology availabilities to determine their impact on the feasibility of plans for a significant decarbonization and high RET shares. Furthermore, LIMES-D is applied to determine robust transmission expansion strategies permitting the transport of electricity from remote areas with large potential to demand centers.

Chapter 2

The impact of delayed investments into infrastructure on the expansion of renewable energy technologies*

Markus Haller
Sylvie Ludig
Nico Bauer

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Bridging the scales: A conceptual model for coordinated expansion of renewable power generation, transmission and storage

Markus Haller*, Sylvie Ludig, Nico Bauer

Potsdam Institute for Climate Impact Research (PIK), Postfach 601203, 14412 Potsdam, Germany

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To analyze the challenge of large-scale integration of renewables during the next decades, we present a conceptual power system model that bridges the gap between long term investment allocation and short-term system operation decisions. It integrates dynamic investments in generation, transmission and storage capacities as well as short-term variability and spatial distribution of supply and demand in a single intertemporal optimization framework. Large-scale grid topology, power flow distributions and storage requirements are determined endogenously. Results obtained with a three region model application indicate that adequate and timely investments in transmission and storage capacities are of great importance. Delaying these investments, which are less costly than investments in generation capacities, leads to system-wide indirect effects, such as non-optimal siting of renewable generation capacities, decreasing generation shares of renewables, increasing residual emissions and hence higher overall costs.

Contents

* Corresponding author. Tel.: +49 331 288 2639; fax: +49 331 288 2642.
E-mail addresses: haller@pik-potsdam.de, markus.haller@gmail.com (M. Haller).

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1. Introduction

Due to decreasing costs of renewable energy technologies, increasing scarcity of fossil fuels, changing demand patterns and, most importantly, efforts to mitigate climate change, power systems are facing substantial structural changes during the next decades. Long-term modeling exercises with Integrated Assessment Models (IAMs) (e.g. [1,2]) show that the power sector plays an important role in ambitious climate change scenarios, because in this sector a large number of mitigation technologies are available at comparably low costs. Renewable energy (RE) sources play a decisive role in the majority of these scenarios.

1.1. A challenge to power system design and operation

The integration of large shares of RE sources into existing power systems, however, is a demanding task. Theoretical annual RE potentials, if aggregated over large areas, are very large, but temporal variability and uneven spatial distribution of RE supply require the provision of reserve and storage capacities, demand side management, and the expansion of transmission grid infrastructure for large area pooling. Investments are needed to provide these flexibility options, and these investments must be timed and placed adequately to complement the shift towards renewable energy sources on the generation side. Investment decisions and capital stocks on both generation and network side are obviously tightly interconnected and it can be expected that coordinated long-term planning for both sides would significantly ease the large-scale integration of RE generation. The IPCC, in its *Special Report on Renewable Energy Sources and Climate Change Mitigation* [3], emphasizes that there are significant knowledge gaps regarding quantitative assessments of system integration costs and requirements for integration measures.

1.2. A challenge to power system modeling

This, however, poses a challenge to power system modeling: the transformation process towards a carbon free power system is likely to span several decades, and plant lifetimes are typically in the order of 40–50 years. This calls for a long-term examination. Investment decisions over the next decades, however, will be affected by the technological and economical implications of fluctuating RE integration – and these effects occur on very small temporal and spatial scales.

Connolly et al. [4] review models that analyze the integration of RE sources into energy systems. Pina et al. [5] and Ludig et al. [6] compare approaches for reconciling different temporal scales in power system modeling. Pina et al. [5] suggest to divide models into two generic groups. The tools from the first group are typically used to analyze how energy systems are affected by long-term economic or technical transition processes. They operate on large time scales, and assess changes of system characteristics with a temporal resolution of several years. These models often cover several sectors of the energy system and either do not consider integration of fluctuating RE generation at all, or they use highly aggregated representations. IAMs typically fall into this category. Examples are REMIND [7], WITCH [8], MESSAGE-MACRO [9] and POLES [10].

The second group consists of models that focus on representing technological details of the power system. They usually treat system infrastructure as static, or consider capacity changes in a simplified manner, and analyze system operation and reliability on small temporal and spatial scales. Examples for the European power system are ELMOD [11] and ReMIX [12] which calculate hourly dispatch and power flow distributions in the high voltage transmission grid.

Recent publications show that a third group of models is emerging. These models, to a certain extent, combine features of the first two categories – which shows that integrating short-term system dynamics and transmission requirements into long-term investment models has become an increasingly important issue in the power system modeling community. The ReEDS [13–15] and the US-REGEN [16] models follow this approach. ReEDS has a time horizon of 50 years and a high spatial resolution. It follows a recursive dynamic approach to determine capacity expansions. US-REGEN determines capacity expansions and system operation in an intertemporal optimization framework. The model is currently under construction, and the only renewable generation option considered is wind energy. A TIMES application with an improved representation of short-term fluctuations is presented in [5], but the model is calibrated to an isolated island system and has a time horizon of only four years. Fürsch et al. [17] and Möst and Fichtner [18] present studies where separate investment and dispatch models are utilized in a coordinated manner to analyze consistent expansion scenarios, but there is no hard link between the different models.

1.3. Bridging the scales

As a way to complement the existing modeling strategies, and to bridge the gap between them, we propose a hybrid model that integrates these issues into a single intertemporal optimization framework. In this partial, multi-regional model of the power sector, temporal variability and spatial distribution of supply and demand are modeled explicitly while maintaining a long time horizon. Investments in aggregated transmission capacities between large geographical regions and power flow distributions across the resulting network are determined endogenously. Refinancing of these investments is assured by optimizing under the constraint of short term variability which leads to varying degrees of capacity utilization. In this framework, coordinated expansion scenarios for both generation capacities and flexibility options (transmission and storage capacities) can be developed. Furthermore, the benefits of optimal (i.e. cost efficient) timing of investments, as well as the indirect system-wide effects of constrained expansion of transmission and storage capacities, can be assessed.

Our model determines intertemporally optimal investment paths for generation, transmission and storage capacities over a time horizon of 100 years by minimizing total discounted energy system costs. Long-term transition processes are driven by CO_2 prices, endogenous technological learning and increasing fuel costs. Characteristic time slices are used to represent short-term temporal fluctuations of supply and demand, and the geographical distribution of resources and demand centers is modeled explicitly. Power flow distribution constraints are taken into account following the Direct Current Load Flow (DCLF) approach [19].

Nomenclature

Nomenclature

c, i, r, t, τ	indices for connection, technology, region, time step, and time slice (–)
C^{tot}	total aggregated energy system cost (objective function) ($)
C^E	emission costs (due to CO_2 prices) ($)
C^F	fuel costs ($)
C^G, C^S, C^T	capital costs (generation, storage, transmission) ($)
D	power demand (W)
E	stored energy (Wh)
G	generated power (W)
I	current (A)
K, K^S, K^T	installed capacity (generation, storage, transmission) (W)
$K^{T,max,s}$	max. active power transmission capacity (single line) (W)
L	transmission losses (W)
S^{in}, S^{out}	storage charge/discharge (W)
T	transmitted power (W)
U	voltage (V)
X	line reactance (per unit length) (Ω/km)
α	time slice length (h)
β	transmission line length (km)
η	storage round trip efficiency (–)
λ	loss coefficient (per unit length) (km^{-1})
ν, ν'	capacity factor coefficients for RE generation (–)
ρ	interest rate (–)
θ	voltage angle (rad)

1.4. Structure of this article

The modeling framework and the parameterization are presented in Section 2. In Section 3 we discuss results obtained with a conceptual application of the model, featuring three regions, low temporal resolution, and a small number of representative generation technologies. We analyze the effects of limiting transmission and storage investments under stringent climate policy constraints and perform a sensitivity analysis with respect CO_2 prices, storage potentials and power flow constraints. Section 4 concludes with a summary of the main findings, and an outlook on further developments.

1.5. Limitations

The conceptual mode configuration presented here can only provide qualitative results. It is well suited to demonstrate the capabilities of the modeling framework and to identify robust findings and sensitive parameters, which is of interest for the power system modeler's community. For quantitative assessments, which will then be of interest for stakeholders and policy makers, a fully calibrated model with a higher level of technological detail as well as an increased temporal and spatial resolution will be required.

It is important to note that our model takes on a single actor, partial equilibrium, perfect foresight perspective. It provides insights in economy wide costs and benefits of certain scenarios and constraints, but it cannot attribute investments or any kind of decision to specific actors.

2. Methodology

This section describes the modeling framework (Section 2.1) and parameterization (Section 2.2).

2.1. Modeling framework

2.1.1. Objective function

The model minimizes total discounted energy system costs C^{tot} (1), aggregated over all time steps t. Energy system costs are the sum (over all regions r, connections c, technologies i and time slices τ) of capital costs for generation, storage and transmission capacity (C^G, C^S and C^T, respectively), fuel costs C^F associated with the operation of fossil fuel power plants, and emission costs C^E due to CO_2 prices. The interest rate ρ is 5%/a.

$$C^{tot} = \sum_t e^{-\rho t} \left(\sum_{r,i} C^G_{r,t,i} + \sum_r C^S_{r,t} + \sum_c C^T_{c,t} + \sum_{r,\tau,i} (C^F_{r,t,\tau,i} + C^E_{r,t,\tau,i}) \right) \quad (1)$$

2.1.2. Technologies and transformation pathways

The model features two fossil generation technologies, coal and natural gas combined cycle power plants, and two renewable generation technologies, wind turbines and solar photovoltaics (PV). Transformation processes are linear. Consumption of fossil fuels is associated with fuel costs and CO_2 emissions. Specific fuel costs are given exogenously[1] and increase over time to reflect the scarcity of fossil fuels. Renewable energy resources are divided into grades to reflect different site categories. Each grade is characterized by an upper limit of installable nameplate capacity and a capacity factor to reflect resource quality. Generated power can either be consumed, stored or transmitted to neighboring regions via transmission lines. The only transmission technology that is represented as high voltage AC overland transmission lines. Distribution grid infrastructure substations, and all remaining capital assets other than the transmission lines themselves are not taken into account. The only storage technology that is represented is pumped hydro storage.

2.1.3. Spatial and temporal scales

The geographic area represented by the model is divided into several regions. Each region features a set of transformation technologies and is characterized by a specific electricity demand and specific renewable energy potentials.

The model features two different time scales: investment decisions in grid and generation capacities occur on a long-term time horizon (2005–2100, in five year time steps t). Short-term economic dispatch of available capacities is calculated for a set of time slices τ.[2] Electricity demand as well as capacity factors for renewable energy sources differ across regions and time slices. Electricity demand is exogenous and price inelastic.

2.1.4. Balancing supply and demand

Regional demand can be met either by generation in the respective region, by transmitting power between regions, or by providing previously stored power. For each region r, time step t and time slice τ, generation G, load D, net transmission flows T (aggregated over all incoming and outgoing transmission lines c_{in} and c_{out}) as well as storage charge and discharge S^{in} and S^{out} need to be balanced. Transmission flows T are diminished by dissipative transmission

[1] It is assumed that global fuel costs are not affected by extraction patterns inside the model region (i.e. the model region acts as a price taker).

[2] See Section 2.2 for details on the concept of time slices.

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losses which are assumed to be linear with respect to transmission flow and line length.[3]

$$0 = \sum_{i} G_{r,t,\tau,i} - D_{r,t,\tau} + S^{\text{out}}_{r,t,\tau} - S^{\text{in}}_{r,t,\tau} + \sum_{c_{\text{in}}} ((1 - \lambda_{c_{\text{in}}} \beta_{c_{\text{in}}}) T_{c_{\text{in}},t,\tau}) - \sum_{c_{\text{out}}} T_{c_{\text{out}},t,\tau} \qquad \forall t, r, \tau \tag{2}$$

Non-negativity constraints apply for generation, demand and storage ((3)–(6)). Transmission flows can be positive or negative, depending on flow direction.

$$G_{r,t,\tau,i} \geq 0 \qquad \forall r, t, \tau, i \tag{3}$$

$$D_{r,t,\tau} \geq 0 \qquad \forall r, t, \tau \tag{4}$$

$$S^{\text{in}}_{r,t,\tau} \geq 0 \qquad \forall r, t, \tau \tag{5}$$

$$S^{\text{out}}_{r,t,\tau} \geq 0 \qquad \forall r, t, \tau \tag{6}$$

2.1.5. *Capacity constraints*

Electricity generation by fossil (dispatchable) technologies ($i \in i_{\text{fos}}$), transmission, storage charge and discharge flows G, T, S^{in}, S^{out} are constrained by installed generation, transmission and storage capacities K, K^T, K^S:

$$G_{r,t,\tau,i} \leq K_{r,t,i} \qquad \forall r, t, \tau, i \in i_{\text{fos}} \tag{7}$$

$$T_{c,t,\tau} \leq K^T_{c,t} \qquad \forall c, t, \tau \tag{8}$$

$$S^{\text{in}}_{r,t,\tau} \leq K^S_{r,t} \qquad \forall r, t, \tau \tag{9}$$

$$S^{\text{out}}_{r,t,\tau} \leq K^S_{r,t} \qquad \forall r, t, \tau \tag{10}$$

The (region and time slice specific) relationship between installed capacity and max. output for renewable energy technologies ($i \in i_{\text{ren}}$) is represented by Eq. (11), where ν represents the maximum capacity factor achieved at the regions's best generation sites, and ν' accounts for decreasing average capacity factors as generation sites of lesser qualities are occupied.

$$G_{r,t,\tau,i} \leq \nu_{r,t,\tau,i} K_{r,t,i} - \nu'_{r,t,\tau,i} K^2_{r,t,i} \qquad \forall r, t, \tau, i \in i_{\text{ren}} \tag{11}$$

Investments in generation, storage, and transmission capacities and the technological depreciation of these capacities are modeled explicitly. Capacity additions for each region and connection are continuous, i.e. single cables and power plants are represented by regionally aggregated capacities.[4] Capacities have a limited lifetime and are put out of operation following technology specific depreciation curves. Initial capacity endowments (i.e. capacities that are already in place in the first time step) and their age distribution are also taken into account.

2.1.6. *Power flow distribution*

Our model includes a simplified power flow distribution module, following the DCLF approach [19]. DCLF has been widely used to analyze active power flow distributions in meshed grids (e.g. [20,11]). It assumes a flat voltage profile, loss less transmission ($R \ll X$), and small voltage angle differences throughout the network. [5] Under these assumptions, the model is reduced to a system of linear equations. The power T transmitted along a line depends on the line's reactance X (per unit length), line length lg, voltage level U and the voltage angles θ at the two ends of the line r_1 and r_2:

$$T = \frac{U^2}{Xl} (\theta_{r_1} - \theta_{r_2}) \tag{12}$$

In our model, not only voltage angles θ, but also line reactances X are control variables, as transmission capacities change over time. Reactance $X_{c,t}$ of line c at time step t is expressed as a function of aggregated transmission capacity $K^T_{c,t}$ by representing each connection c as an aggregate of n identical single transmission lines that are connected in parallel. Each of them features a reactance X^s_c and a nameplate transmission capacity of $K^{\text{T,max,s}}_c$, and the aggregate reactance can be calculated as:

$$\frac{1}{X_{c,t}} = n \frac{1}{X^s_c} = \frac{K^T_{c,t}}{K^{\text{T,max,s}}_c} \frac{1}{X^s_c} \tag{13}$$

Inserting this into (12) yields:

$$T_{c,t,\tau} = \frac{K^T_{c,t} U^2}{K^{\text{T,max,s}}_c X^s_c \beta_c} \left(\theta_{r_1,t,\tau} - \theta_{r_2,t,\tau}\right) \qquad \forall c, t, \tau \tag{14}$$

Note that, although the DCLF approach is a linear approximation of power flow distributions, (14) acts as a nonlinear constraint in our model, as both K^T and θ are decision variables.

2.1.7. *Storage balance*

To distinguish between seasonal and diurnal storage applications, storage can be employed to shift power between time slices if these time slices belong to the same storage group g_τ. Inside each storage group, time slices are ordered sequentially. The energy stored in the reservoir E at any given time slice τ is

$$E_{r,t,\tau_i} = E_{r,t,\tau_{i-1}} + \frac{\alpha_{\tau_i}}{n_{g_{\tau_i}}} \left(\eta S^{\text{in}}_{r,t,\tau_i} - S^{\text{out}}_{r,t,\tau_i}\right) \qquad \forall r, t, \tau, \tag{15}$$

where $n_{g_{\tau_i}}$ states how often a sequence of time slices (e.g. one characteristic day) is repeated per storage group. For each region r, time step t and storage group g_τ storage charge and discharge flows need to be balanced (15). A round trip efficiency η of 85% is assumed [22].

$$0 = \sum_{\tau \in g_\tau} \alpha_\tau \left(\eta S^{\text{in}}_{r,t,\tau} - S^{\text{out}}_{r,t,\tau}\right) \qquad \forall r, t, g_\tau \tag{16}$$

No costs are associated with expanding reservoir size, but upper limits on reservoir size can be implemented to reflect geographical limitations of storage potential.

2.1.8. *Learning effects*

One factor learning curves (e.g. [23]) are implemented to represent specific investment costs as a function of cumulated installed capacity. Cost reductions achieved by learning are limited by fixed floor costs. Learning effects are taken into account for wind turbines and solar PV.

2.1.9. *Emissions and CO_2 prices*

CO_2 prices are applied to represent climate policy constraints. For the scenarios presented in Section 3 a price of 10\$/tCO_2 is applied.[6] This corresponds to the average carbon price profile used in [2].

[3] Global trade balances are not required as the consistency of bilateral transmission flows is completely taken into account by the set of regional balance equations.

[4] See below for a discussion of how aggregated transmission capacities are treated in the DCLF constraints.

[5] [21] analyzes the validity of these assumptions and states that, although errors on single lines can be significant, the DCLF approach gives a good approximation of active power flows in most networks.

[6] CO_2 prices are given in present value (2005) prices. Current value CO_2 prices increase exponentially over time with the interest rate of 5%/a.

Table 1
Parameters of generation technologies [1,22]. For fuel costs, the two numbers indicate the specific extraction costs in 2005 and 2100. For investment costs of learning technologies, they denote initial costs and floor costs.

	Inv. costs [$/kW]	Learn. rate [%]	$K_{t0,cum}$ [GW]	Fuel costs [$/GJ]
Coal PP	1400	–	–	2.0 → 3.4
Gas CC PP	650	–	–	5.5 → 7.1
Wind turbine	1200 → 883	12	60	–
Solar PV	4900 → 600	20	5	–
Pumped hydro storage	1500	–	–	–

Table 2
Parameters of transmission technologies [26,27].

Parameter	Unit	Value
Voltage U	kV	345
Reactance X per unit length	Ω/km	0.371
Loss coefficient λ per unit length	%/km	0.012
Active power transmission capacity $K^{T,max,s}$	MW	747
Investment costs	$/kW km	0.5

Table 3
Regional distribution of demand and RE resources. $\overline{D}$: avg. annual demand. $\overline{\nu}$: avg. annual capacity factor for the best resource location.

	$\overline{D}$ (TWh)	Wind $\overline{\nu}$ (–)	Solar $\overline{\nu}$ (–)
Wind res. region	220	0.2	0.1
Solar res. region	220	0.1	0.2
Demand region	880	0.125	0.125

2.1.10. Implementation

The resulting optimization problem is of the NLP type. Nonlinear equations are related to learning curves, DCLF constraints (14) and capacity factor constraints for renewables (11). The model is implemented in GAMS [24] and solved using the CONOPT solver. It is based on the code of the REMIND model [7]. The model has been coupled to the multi-run environment SimEnv [25] and various post processing tools. This makes it possible to perform extensive sensitivity studies, which is valuable to explore the model behavior over a wide range of parameters.

2.2. Parameterization

This section describes the model parameters used in this study. Techno-economic parameters of generation and transmission technologies are given in Tables 1 and 2.

2.2.1. Regional parameterization

The model features two *resource regions* with low demand and high potentials for the two renewable energy sources, and a *demand region* with high power demand and low renewable potentials. Table 3 shows regional distribution of demand and RE resources. Demand and renewable resources, although being unevenly distributed, are larger than zero in all three regions. This creates the two options of either generating renewable based electricity at high quality resource locations and transmitting it via the grid, or relying on domestic renewable resources with lower quality to reduce grid requirements. If not stated otherwise, there are no regional constraints on maximum storage capacities.

Transmission lines can be built between all neighboring regions. Geographical distances between all regions are equal; the length of each grid connection is 500 km. Initial RE generation capacities as well as initial grid and storage capacities are zero. Initial coal and gas power plant capacities in all regions are sufficiently large to meet initial domestic demand.

2.2.2. Temporal parameterization

Long-term addition and depreciation of capacities occurs in 5 year time steps t between 2005 and 2100. Short-term variability is expressed by dividing each time step into a set of time slices τ. These time slices (which can have different lengths) capture various characteristic combinations of supply and load.

In the current parameterization, we distinguish two characteristic days (summer and winter), each with six time slices to represent low, average, and high RE supply at daytime and nighttime. Storage is possible between time slice that belong to the same season; seasonal storage is not available. Table 4 shows the fluctuation of demand and RE capacity factors around their regional averages across these twelve time slices.

Over the long time horizon, an annual demand growth of 0.3%/a is assumed. Fluctuation patterns do not change over the long time horizon. It is assumed that fluctuation patterns for each RE type are perfectly correlated across regions, and the fluctuations of wind and solar resources are positively correlated. This might lead to an overestimation of the overall fluctuations of renewable supply and an underestimation of the benefits of long-distance transmission to pool statistically uncorrelated resources across large areas. On the other hand, stochastic fluctuations are not taken into account at all.

It should be kept in mind that this parameterization is conceptual. It intends to capture characteristic features of a stylized power system in a qualitative way. A proper calibration using empirical data will be reserved for future model versions.

3. Results and discussion

We present a set of different scenarios that all share a stringent CO_2 price path (as discussed in Section 2.1.9). These CO_2 prices represent ambitious climate mitigation policies and induce – in the long-term – a complete (or nearly complete) decarbonization of the power sector. We examine how this transformation process is affected by the availability of storage and long-distance transmission capacities. We first present a reference scenario (Section 3.1), in which investments in both options are possible without timing constraints. In Section 3.2 the system-wide effects of disabling transmission and storage completely and of limiting transmission capacity expansion to 1 GW/a per connection are discussed (see Table 5 for a scenario list). Section 3.3 presents a sensitivity

Table 4
Fluctuations of demand and RE capacity factors across time slices (around their average values given in Table 3).

Storage group		Summer						Winter					
Time of day		Day			Night			Day			Night		
RE supply		Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
$D_\tau/\overline{D}$	[–]	1.2	1.2	1.2	0.8	0.8	0.8	1.2	1.2	1.2	0.8	0.8	0.8
$\nu_\tau/\overline{\nu}$ (solar)	[–]	1.5	3.0	4.5	0.0	0.0	0.0	0.5	1.0	1.5	0.0	0.0	0.0
$\nu_\tau/\overline{\nu}$ (wind)	[–]	0.0	0.6	1.1	0.0	0.9	1.9	0.0	0.9	1.9	0.0	1.6	3.1
Length	[h]	438	1314	438	438	1314	438	438	1314	438	438	1314	438

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Table 5
Scenarios overview. For the reference scenario (bold), both flexibility options are available without timing constraints.

	With storage	Without storage
With transmission	**tON-sON**	tON-sOFF
Without transmission	tOFF-sON	tOFF-sOFF
Limited transm. expansion rate (1 GW/a)	tLIM-sON	tLIM-sOFF

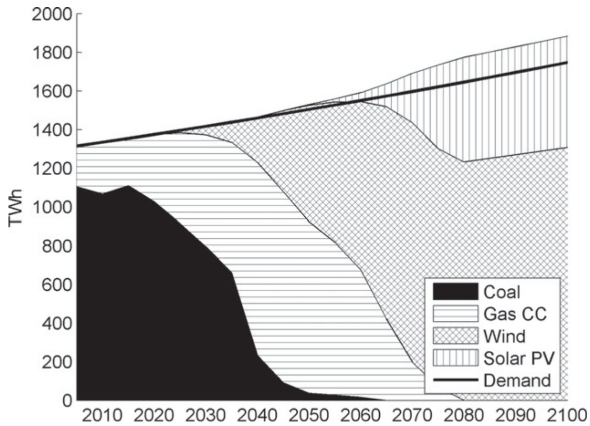

Fig. 1. Generation mix and demand over time for the reference scenario. The differences between total generation and demand is due to transmission and storage losses. Curtailed power from RE sources is not shown.

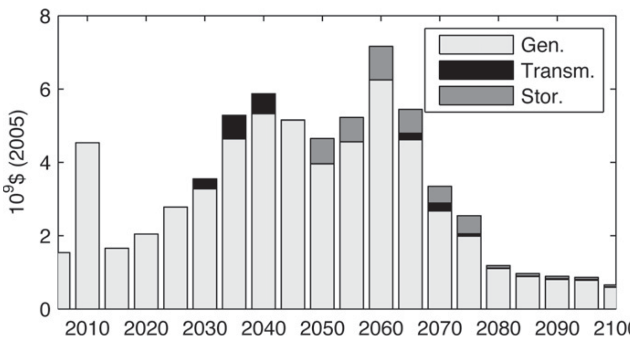

Fig. 2. Investments over time for the reference scenario. Investments decrease over time as they are discounted to net present values.

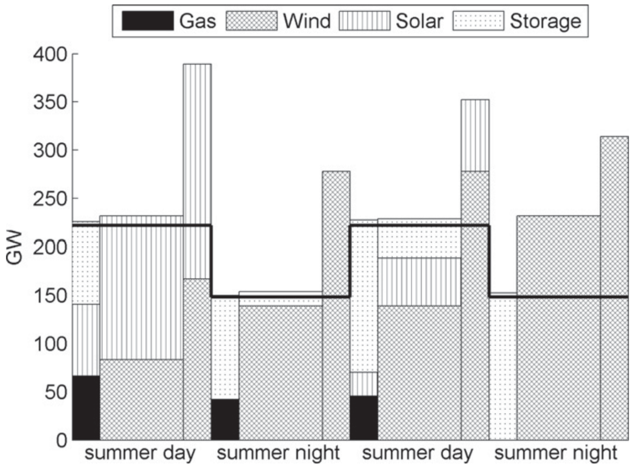

Fig. 3. Global generation and storage discharge across time slices (in 2075). The black line denotes demand; surplus generation is used to charge storage reservoirs. RE curtailments are not shown.

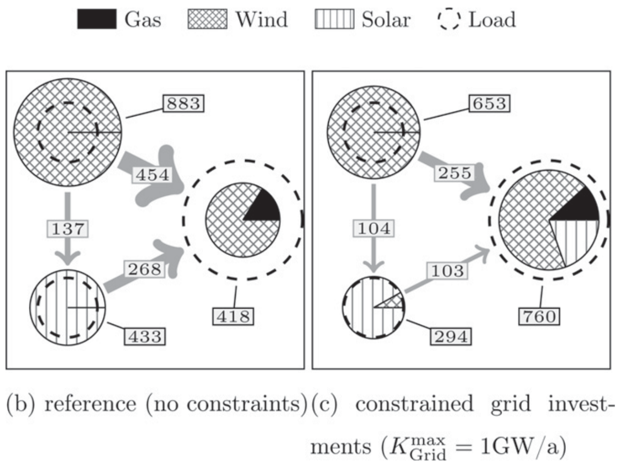

Fig. 4. Generation and net flows in 2075, aggregated over all time slices. The area of the pie diagrams and the numbers next to them show regional generation; the dashed circles show regional demand. The numbers show net transmission and regional demand (TWh).

analysis of model results with respect to storage potential, CO_2 prices and power flow constraints.

3.1. The reference case

Figs. 1 and 2 show generation mix and discounted investment costs time series (both calculated endogenously) for the reference scenario, without restrictions of investments in grid or storage capacities. Investments in new coal and gas power plants decline to zero in 2015 and 2030, respectively. Coal based generation is phased out during the first half of the century. It is being gradually replaced, first by natural gas power plants, then by wind and solar capacities. The power sector is decarbonized completely by 2080. The order in which wind and solar energy enter the system (wind first) is determined by the lower initial specific investment costs for wind turbines (see Table 1). Investments in grid and storage capacities are small compared to investments in generation capacities.

Fig. 3 gives a more detailed view of the power system for the year 2075. It shows how generation and storage are dispatched across time slices to meet demand. Storage is mainly used to shift RE generation from high to low supply time slices, complemented by a small share of gas based generation. Storage capacities are high – for this scenario, the ratio of storage discharge capacity to average load reaches up to 80%, and reservoir capacities could provide average load for up to 5 h.[7]

3.2. Limited availability of transmission and storage

Fig. 4 examines how power system characteristics are affected if the transmission capacity expansion rate is constrained. The figures show generation, demand and transmission flows in 2075, aggregated over all time slices. With grid expansion constraints (in this case, 1 GW/a per connection) in place, the realized transmission flows between resource and demand regions are reduced substantially. A significant share of RE generation capacity is shifted from the resource regions to the demand region, although this region is endowed with renewable potentials of lower quality.

[7] Not shown in figures.

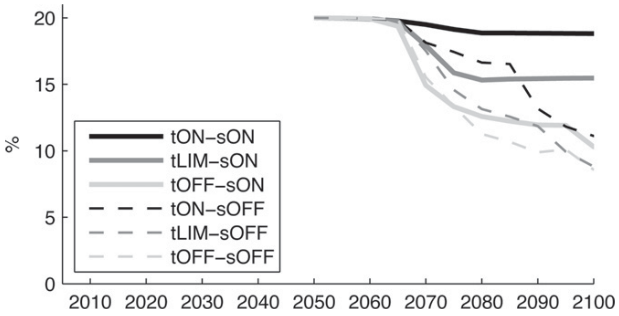

Fig. 5. Average realized capacity factor for solar PV.

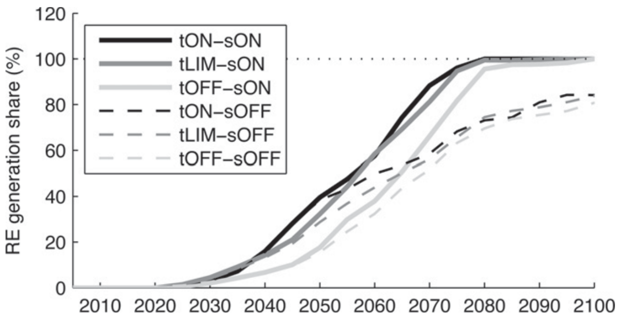

Fig. 6. Generation share of RE over time. Both RE share and penetration rate depend on the availability of grid and storage options.

To further evaluate this effect, Fig. 5 compares the development of the average realized capacity factor[8] of solar PV,[9] for six different scenarios: with and without storage and transmission available, and with transmission expansion rates constrained to 1 GW/a per connection.

For all scenarios, realized capacity factors decrease over time, as resource grades are utilized in order of decreasing quality. Applying constraints on grid expansion significantly decreases the overall capacity factor in later time periods, caused by the suboptimal siting of new generation capacities. Storage, if available, increases realized capacity factors by shifting renewable power supply between time slices and thus reducing curtailments.

The timing of investments does not only affect location choices for RE generation capacities. It also has an influence on how fast RE generation penetrates the market. This is shown in Fig. 6, which presents RE shares of total power generation for the six scenarios discussed above. The figure also shows that availability of storage affects the maximum achievable RE share – complete decarbonization is only reached if storage is available.[10]

Fig. 7 displays discounted cost differences between the six scenarios, cumulated over the complete time horizon. If transmission and storage options are constrained, the higher residual emissions by fossil generation lead to higher emission costs and, consequently, to increasing overall costs. It is interesting to note that investments in storage actually increase if transmission is available – in these scenarios, both flexibility options do not act as substitutes, but as complements.

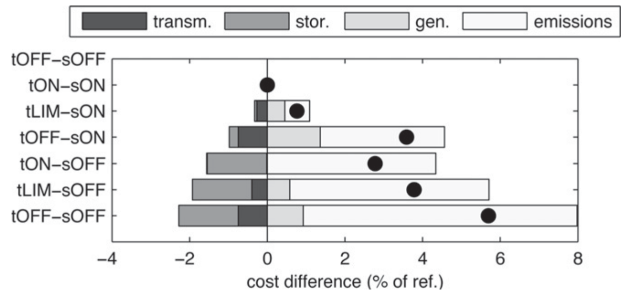

Fig. 7. Decomposition of cumulated system costs, relative to the reference scenario (tON-sON). Total costs are denoted by the black dots.

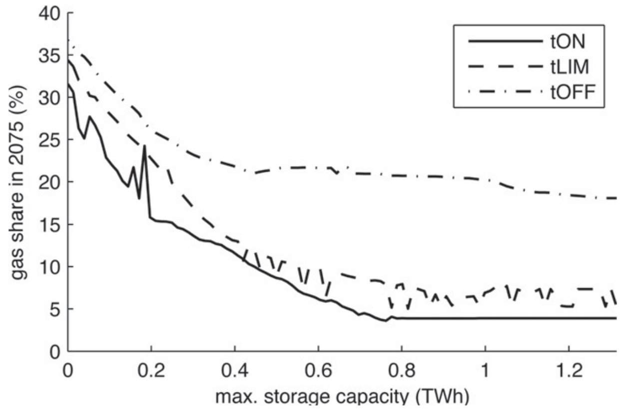

Fig. 8. Sensitivity analysis for maximum storage reservoir size. Generation share of gas (shown for 2075) is reduced if the available storage potential increases.

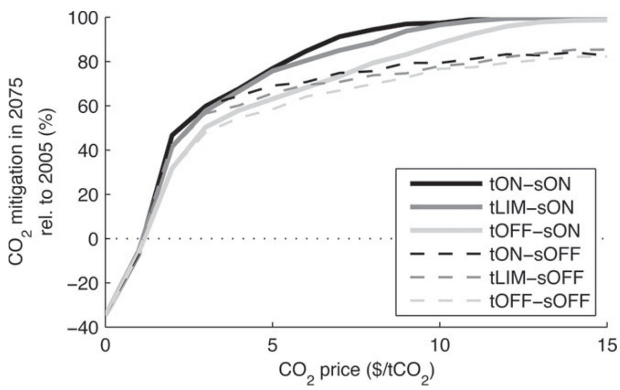

Fig. 9. Sensitivity analysis for CO_2 prices. Mitigation levels (the figure shows emission reductions in 2075, relative to emissions in 2005) are highly sensitive towards price variations. Low CO_2 prices lead to negative mitigation levels, i.e. an increase in emissions relative to 2005. CO_2 prices are given in present value (2005) terms; current values prices increase over time at 5%/a.

3.3. Sensitivity analysis

Fig. 8 presents the effects of constraining storage potential (modeled as a regionally uniform constraint on storage reservoir size). The figure shows gas power plant generation shares in 2075. The importance of gas as balancing option increases significantly if storage potentials are limited. Again, the availability of transmission leads to an increased usage of storage and decreased requirements of gas capacities for balancing purposes.

[8] Generated power divided by installed nameplate capacity, aggregated over all regions and time slices. This parameter is affected by resource quality as well as by curtailments. It is only defined if installed capacities are larger than zero.

[9] Results for wind turbines, which are not shown here, are similar.

[10] This can be attributed to the assumption that fluctuation patterns of supply and demand are perfectly correlated across regions, which means that low supply/high demand situations cannot be mitigated by large area pooling.

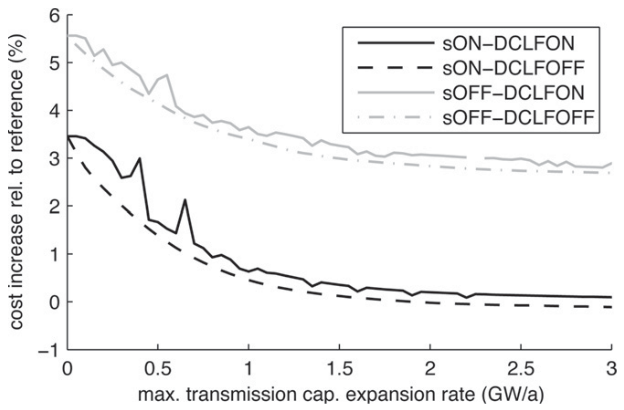

Fig. 10. Sensitivity analysis for max. transmission expansion rate and DCLF constraints. Overall costs are affected by power flow distribution modeling, but the effect is smaller than that constraining transmission and storage availability.

Fig. 9 shows how mitigation levels (emission reduction between 2005 and 2075, relative to 2005 levels) depend on CO_2 prices.[11] CO_2 prices below 2\$/tCO_2 lead to an increase in emissions (negative mitigation levels). Prices between 2 and 3.5\$/tCO_2 trigger a fuel switch from coal to gas[12] and mitigation levels are unaffected by the availability of transmission and storage. At prices above 3.5\$/tCO_2 RE play an increasingly important role. Complete decarbonization is reached if storage is available; without storage, even prices of 15\$/tCO_2 have little effect on the residual emissions caused by gas powerplants required for balancing purposes.

Fig. 10 displays total system costs relative to the reference scenario, for different maximum grid expansion rate constraints, and it compares model runs with and without DCLF constraints. Due to their non-linearity, omitting DCLF constraints has beneficial effects on model complexity – Fig. 10 shows that without DCLF constraints model results are much smoother throughout the parameter space. As expected, power flow constraints increase total costs (as any additional binding constraints should do). This effect, however, is much smaller than the effect of constraining grid expansion rates or storage availability. This result may be specific for the symmetric regional layout used in the present study, and needs to be checked for robustness with calibrated and more complex model versions. Nevertheless, it indicates that – although DCLF constraints certainly do affect actual power flow distributions at certain points in time – their effect on long-term developments of system costs may be rather small.

4. Conclusions and outlook

We present a modeling framework of intermediate complexity that integrates long term investment decisions in generation, transmission and storage capacities as well as the effects of short term fluctuation of renewable supply. It fills the gap between highly aggregated Integrated Assessment Models and bottom-up dispatch models and is well suited to assess cost efficient power system decarbonization pathways.

Results obtained with the conceptual three region model indicate that long-distance transmission and electricity storage play an important role for the large-scale integration of fluctuating RE into the power system. Although the direct investment costs that are required to put transmission and storage capacities in place are small compared to the investments required on the generation side, the *indirect* system-wide effects of delaying investments in these options can be substantial. Achievable RE generation shares, market penetration rates as well as total system costs depend on the availability of these flexibility options. Delayed investments in transmission and storage capacities lead to suboptimal siting of RE generation capacities, reduced realized capacity factors, lower overall RE generation, higher emissions by fossil based generation, and subsequently to higher overall costs.

An interesting finding is that in our model both flexibility options do not to act as substitutes, but as complements: investments in storage are actually highest if the transmission option is available (and vice versa), and achievable cost savings are highest if both technologies are available at the same time. This result, however, may depend on the fluctuation and spatial distribution patterns of supply and load, and their robustness needs to be checked with a calibrated model.

Representing power flow distributions constraints endogenously by means of the DCLF model has relatively small effects on model results. This finding, as well, may depend on the simplified and symmetrical network topology and should be checked for robustness in future model versions.

To manage and coordinate the transition processes that present power systems are facing during the next decades, it will be crucial to gain a better understanding of how single elements of these systems (e.g. generation, transmission, and storage facilities) interact with each other on different time scales. The presented model provides valuable qualitative insights in the characteristics of these interactions.

The modeling framework is flexible enough to create real world applications for different regions, given that the required data is available. It is currently being calibrated to represent the German and European power system. This also includes the implementation of all major generation technologies (CCS, nuclear energy, biomass, offshore wind, CSP), HVDC transmission, and different types of storage. Further interesting applications would be geographically large power systems with rapid growth and diverse RE resources (e.g. India, China).

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[11] CO_2 prices are given in present value terms.
[12] Not shown in figure.

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Chapter 3

How does temporal resolution influence model results?*

Sylvie Ludig
Markus Haller
Eva Schmid
Nico Bauer

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Fluctuating renewables in a long-term climate change mitigation strategy

Sylvie Ludig*, Markus Haller, Eva Schmid, Nico Bauer

Potsdam Institute for Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany

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ABSTRACT

Integrated Assessment models, widely applied in climate change mitigation research, show that renewable energy sources (RES) play an important role in the decarbonization of the electricity sector. However, the representation of relevant technologies in those models is highly stylized, thereby omitting important information about the variability of electricity demand and renewables supply. We present a power system model combining long time scales of climate change mitigation and power system investments with short-term fluctuations of RES. Investigating the influence of increasingly high temporal resolution on the optimal technology mix yields two major findings: the amount of flexible natural gas technologies for electricity generation rises while the share of wind energy only depends on climate policy constraints. Furthermore, overall power system costs increase as temporal resolution is refined in the model, while mitigation costs remain unaffected.

1. Introduction

Research in the field of climate change mitigation (e.g. [1,2]) has shown that on the road toward a low-carbon power system, several technology options play a role: RES, carbon capture and storage (CCS), biomass and nuclear energy. Among the options considered, RES prove to be especially important for the electricity sector where they take a major role in the decarbonization process. Increasingly large shares of fluctuating renewable energy sources (RES) for electricity generation in countries like Germany (see [3]) and RES targets for larger regions like Europe raise several general questions: How can a large share of fluctuating energy sources be handled by the power system? How does the uneven distribution of renewable potentials affect regional integration possibilities and, more specific, how do these problems influence power system and climate change mitigation costs?

Generally, two very different types of quantitative models are used to assess this kind of questions: Integrated Assessment Models (IAMs), with long time frames, allow for the analysis of different scenarios considering technology investments and climate targets. Dispatch models are applied for the assessment of power system operation given a certain technology mix and considering short time horizons.

Most IAMs can not give satisfactory answers to questions of RES integration due to a reduced temporal resolution or lack of technological details necessary to allow for the computation of long-term scenarios. Dispatch models fall short in the area of scenarios for power system adaption due to the limitation to short time frames. LIMES (Long-term Investment Model for the Electricity Sector) fills a gap by integrating long-term time scales of climate change mitigation and power system investments with the issue of short-term fluctuations of RES integrated in one model.

This study answers the following specific research questions: What are the integration costs when the amount of fluctuating RES within the power system is increased to attain decarbonization targets? Which time scales are relevant when analyzing how short-term fluctuations affect long-term investment paths and mitigation costs and which consequences arise for necessary model resolution?

The remainder of this article is structured as follows: Section 2 presents a literature review on the questions raised in this introduction, Section 3 outlines the methodology, Section 4 presents results and Section 5 concludes.

2. Literature review

In the existing literature, the majority of modeling approaches that include RES as a climate change mitigation option in the power system adopt one of two extremes. Either they investigate long-term scenarios and treat fluctuations of RES in a very stylized manner or they perform short-term simulations that are not capable of considering structural capacity changes over time. Connolly et al. [4] provide a good overview on energy models that are used for the investigation of renewable energy integration, both on long-term and short-term time frames. Long-term IAMs like

* Corresponding author. Tel.: +49 331 288 2427; fax: +49 331 288 2640.
E-mail address: sylvie.ludig@pik-potsdam.de (S. Ludig).

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Table 1
Comparison of modeling approaches for the evaluation of RES fluctuations and the relation to climate policy.

Model	Method and Objective	Model Features		Research Issue	Policy Scenarios	
		Investment Time Horizon	Temporal Resolution		Climate Target	RES Target
BALMOREL [18]	Partial-equilibrium tool for the electricity sector	1–20 years	1h–2 weeks	Bottom up investment and operation optimization	Emission tax	No
ReEDS [21]	Minimization of power system costs over 2-year-periods	2006–2050	16 time slices	Cost assessments of RES targets (Energy policy assessment)	No	Yes
Investment planning model [22]	Least cost investment planning optimization	2005–2020	20 load segments for 52 weeks	Investment scenarios considering intermittent RES sources and transmission requirements	CO_2 price	Yes
LIMES	Intertemporal ESM cost minimization	2005–2100	Variable number of time slices	Long-term assessment of integration of fluctuating RES into power sector under climate constraints	Yes	Yes

ReMIND [5], PERSEUS-CERT [6], MESSAGE-MACRO [7], DEMETER [8] or WITCH [9] represent the reduced availability of RES using highly aggregated parameterizations. Implementations include using load factors or secured capacities – see [10] for an example of fluctuation modeling. These generally use long time steps of five to ten years that do not allow for a more thorough investigation of fluctuation issues. On the other extreme, models with a focus on short-term power plant dispatch either neglect capacity extensions or only consider investments annuities. Lund [11] analyzes wind energy integration into the Danish power system using the EnergyPLAN model to perform technical and economical assessments under different regulatory assumptions. Benitez et al. [12] use a cost minimization model where hourly demand has to be met by existing generators. Maddaloni et al. [13] use a similar approach but include network constraints. DeCarolis and Keith [14] combine an hourly simulation of wind energy output with a minimization of remaining system costs over the time period of the simulation, which is five years only. Other models, such as GTMax [15] or MICOES [16] do not consider periods longer than one year.

To bridge the gap between short-term and long-term analyses, there is the need for models combining both time frames. Furthermore, it is necessary to include a sufficient amount of technological detail to allow for the assessment of measures needed to balance RES fluctuations such as backup and storage technologies.

To date, there are very few models that aim at positioning themselves somewhere in the range spanned between the two approaches mentioned above by bringing both the long-term and short-term aspects together. Some models from the MARKAL/TIMES family [17] introduce a certain number of time slices to represent changes in yearly energy production. BALMOREL [18] allows for a flexible number of years and yearly subdivisions, depending on the study purpose. AEOLIUS is an extension to the PERSEUS model [19] using a 1-year simulation of the German power market including wind power time series derived from the ISI wind model [20]. Both models are solved iteratively. Due to the high computational costs (every single hour of a year is simulated) only a time frame until 2020 is considered. The ReEDS model [21] uses a different approach by introducing several time slices to emulate variations of demand and RE supply during a year. It is solved sequentially by optimizing 2-year intervals for the time frame 2006–2050. Neuhoff et al. [22] use an investment planning model with regional demand and wind output profiles for 20 load segments for 52 weeks but only consider a limited time horizon of 2005–2020. Table 1 shows a comparison of the relevant features of three of the aforementioned models. The modeling focus of most approaches lies on the representation of short to mid-term policy measures. However, technical power plant lifetimes of 40–50 years call for a long-term examination. This also holds for analyses of climate change mitigation options and their respective degree of utilization. LIMES fills this gap by combining long-term and short-term time scales and enables an analysis of the influence of temporal resolution on the technology mix in the electricity sector as well as on power system and climate change mitigation costs. Furthermore, the intertemporal optimization assures the refinancing of investments into generation technologies as the model optimizes capacity expansion under the constraint of short-term variability, leading to varying degrees of power plant utilization.

3. Methodology

LIMES constitutes a power system model minimizing total discounted power system costs for the time period 2005–2100 while meeting exogenously given demand paths. Investments into power generation capacities and their operation subject to the given variability of electricity demand and supply are decision variables to the model. Hence, the built-up of fluctuating RES implies that also investments into capacities balancing these fluctuations are necessary to ensure stable operation of the electricity system. Such capacities include conventional backup technologies or storage technologies. Long distance electricity transmission is not considered as an option to counterbalance RES variability in this study due to the small size of the model region. An overview of relevant model equations is given in Appendix B. The model introduces time slices to allow for the consideration of short time frames alongside long-term investment horizons. These are assessed in detail in Section 3.1. A broad range of electricity generation technologies are included as well as storage technologies (see Sections 4.2 and Appendix A). The model considers climate policy constraints in cost-effectiveness mode, operationalized by either emission trajectories, budgets or CO_2 prices[1](Section 3.3).

LIMES is calibrated to the area of Germany that is covered by the company 50 Hz Transmission GmbH (formerly Vattenfall Transmission, mainly eastern Germany and Hamburg, see Fig. 1). A comparison of model results and region data is conducted in Section 3.4.

The following sections detail the main methodology aspects of LIMES.

3.1. Modeling temporal variability

To represent variability of demand and RES supply within the model, we use a combination of two different approaches: subdivision of a year into different periods oriented at load differences

[1] Furthermore, it is possible to set goals for electricity generation from RES.

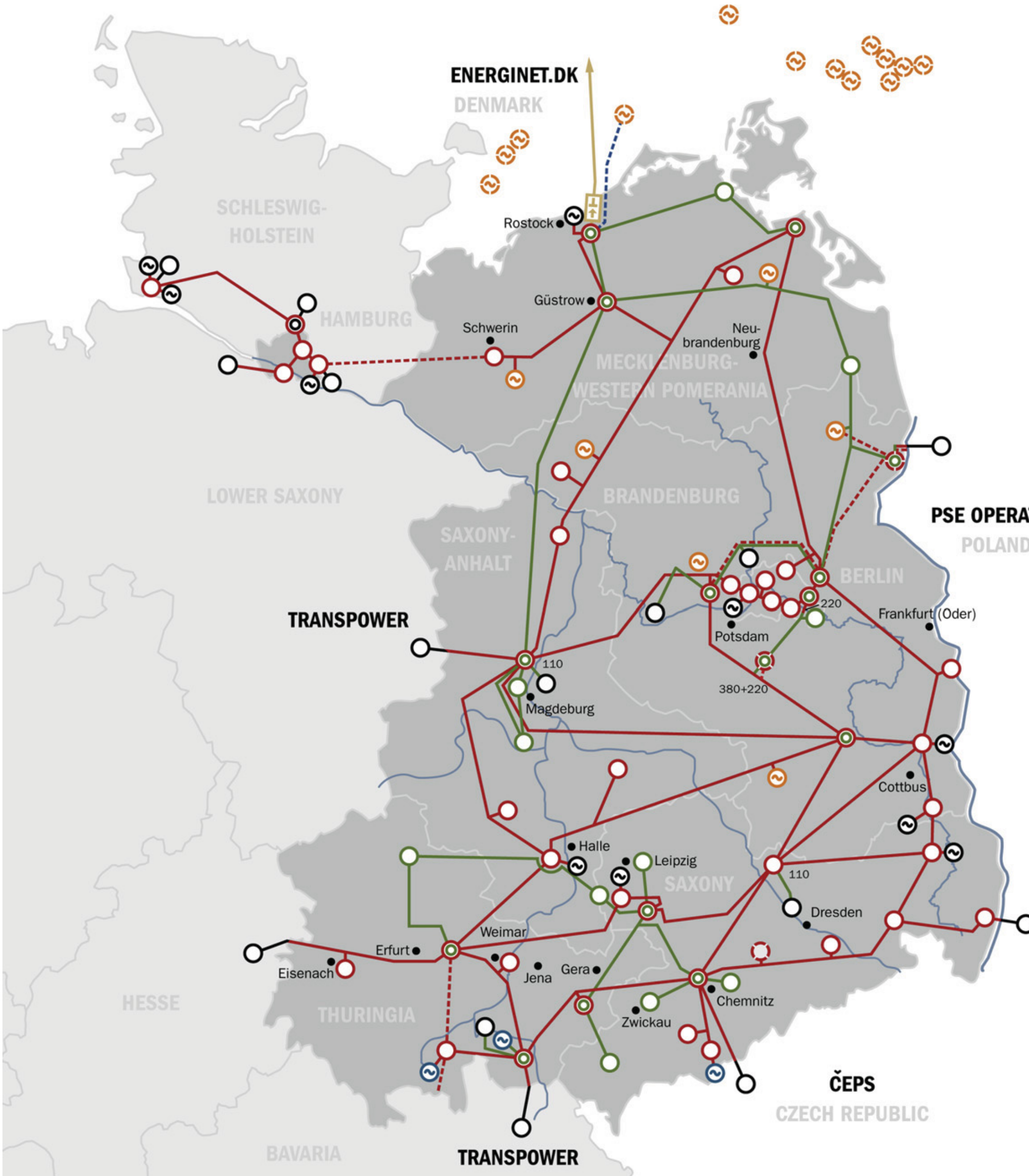

Fig. 1. Map of the Area covered by 50 Hz Transmission GmbH (Figure source: [23]).

and an assessment of fluctuations left uncovered by this parametrization.

Fluctuations are represented within LIMES by dividing a year into various characteristic periods, called time slices hereafter. The time slices differentiate variations between seasons, days of the week and phases of the day. Fig. 2 shows the electricity demand for 16 time slices of the year 2007. Neighboring bars represent 6 h intervals for the spring, summer, autumn and winter season. Other time slice configurations evaluated in this analysis distinguish more or less phases of the day, leading to the settings illustrated in Table 2. The time slices are generated using quarter-hourly data sets for demand, wind feed-in and solar energy feed-in for Eastern Germany, as well as the installed capacities for RES [24–26]. Following a subdivision into four seasons and different times of the day, the data is grouped into the respective time slices. The input values for electricity demand as well as wind and solar capacity

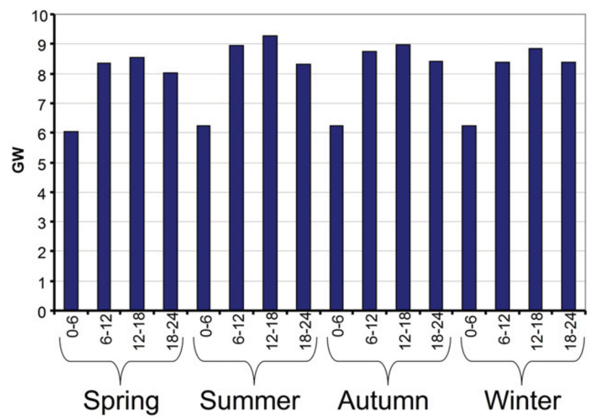

Fig. 2. Mean electricity demand in time slices for the 6 h setup.

Table 2
Different time slice setups evaluated in this analysis.

Time Slice Setup	Number of Time Slices	Time Slice Length
24 h	4	24 h
12 h	8	Day/night (12 h each)
6 h	16	6 h
2 h	48	2 h
1 h	96	1 h

factors are determined by calculating the mean values of the data points belonging to each time slice.

As mentioned above, the underlying data for the representation temporal variation in the model originates from actual time series for RES feed-in and electricity demand. Since time slices are derived through sorting and averaging of this data, no additional stochasticity is introduced. Although uncertainty about fluctuations, especially of wind energy, is an important driver for investments into backup capacities and other balancing options, wind forecasts have shown major improvements over the last years [27]. Their increasing accuracy for short time frames of two to 4 h allow power system operators to take necessary actions for fluctuation balancing in due time. Since the time sales used in LIMES are similar to those relevant for system operation, the deterministic representation of fluctuations deems sufficient. Assessment of necessary backup and balancing capacities is conducted at the end of this section.

To assess which share of total variability contained in the initial data set is covered by the respective time slice setup, we calculate variances for the complete data set and those in the time slices (Eq. (1)).

$$\text{vari\_cover} = 1 - \frac{\sum\limits_{ts}\sum\limits_{j=1:n_{ts}}\left(x_j - \bar{x}_{ts}\right)^2}{\sum\limits_{i=1:n}\left(x_i - \bar{x}_{\text{all}}\right)^2} \quad (1)$$

The variability covered in the respective time slice setup vari_cover is calculated by dividing time slice variability by data set variability: the sum of the n squared differences of all data points x_i in the complete data set to the mean value $\bar{x}_{\text{all}}$ is divided by the sum of the squared differences of all n_{ts} data points x_j belonging to one time slice ts to the mean value of this time slice $\bar{x}_{ts}$, summed overall time slices. Fig. 3 shows the results of this calculation for different time slice setups: with increasing temporal resolution, more and more of the variability of demand and solar energy can be covered. Both display fairly regular daily and seasonal patterns that are caught well by time slices[2]. Wind, however, shows insufficient coverage of variability through time slices. Apart from seasonal variations, which follow regular patterns, wind fluctuations have strong stochastic properties that are difficult to represent using average values for different periods of the year. As mentioned above, high quality wind forecasts ensure stable power system operation despite fluctuations. However, since the time slice method chosen for this model does not cover every aspect of wind energy fluctuations, additional parameterizations have been introduced to represent backup and balancing capacities necessary for system operation.

To approach this shortcoming, we consider variations happening on shorter time scales by analyzing the change of wind electricity generation between different time intervals. Fig. 4 shows the changes of wind power production sorted by magnitude for different time intervals, e.g. the largest drop of wind power production within 2 h was 2645 MW and the largest increase was 2691 MW. From the analysis of these variations, we derive requirements for fast-ramping backup capacities needed within the system (the system has to provide sufficient backup capacities to encounter the largest drop) and supplementary electricity generation needed for fluctuation balancing. Backup and balancing capacity requirements are linked to the installed amount of variable RES to account for the increasing impact on power system operation when reaching higher shares of RES integration.

To account for periods with low electricity generation from wind and high demand, which typically occur during the winter time in the region considered, an additional time slice is introduced. This time slice combines the highest occurring electricity demand in the data set with the lowest observed wind output into a superpeak-slice. A length of 48 h is assumed for the superpeak period. Hence reserve capacities need to be available and system reliability is ensured according to this constraint.

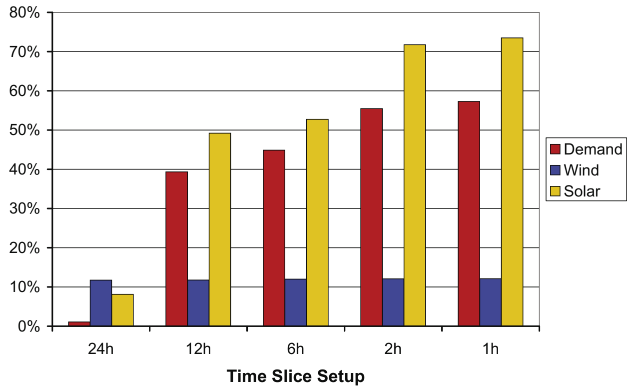

Fig. 3. Share of variability covered by time slices of different lengths.

3.2. Introducing technological detail

The model includes a total of 14 different technologies for producing electricity and one storage technology. This choice is based on the power plant fleet currently installed in the area

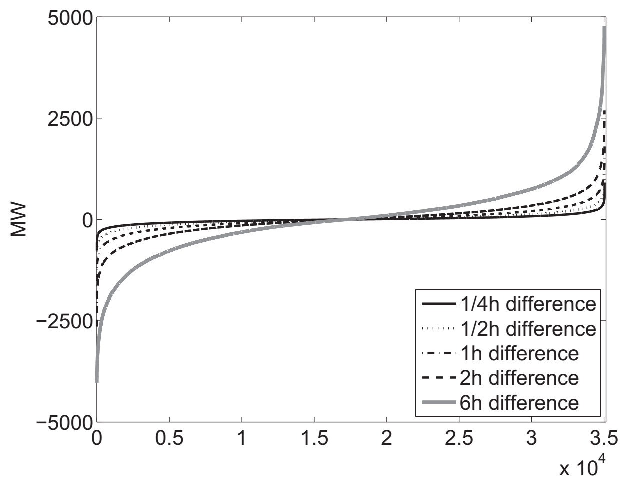

Fig. 4. Load change curve of wind power (The x-axis displays the number of observations in the data set).

[2] Small fluctuations beyond these patterns, e.g. cloud coverage for solar PV or electricity demand spikes can not be represented by time slices due to the averaging process used for their derivation. However, the above analysis shows good coverage of general daily and seasonal patterns for solar energy feed-in and electricity demand.

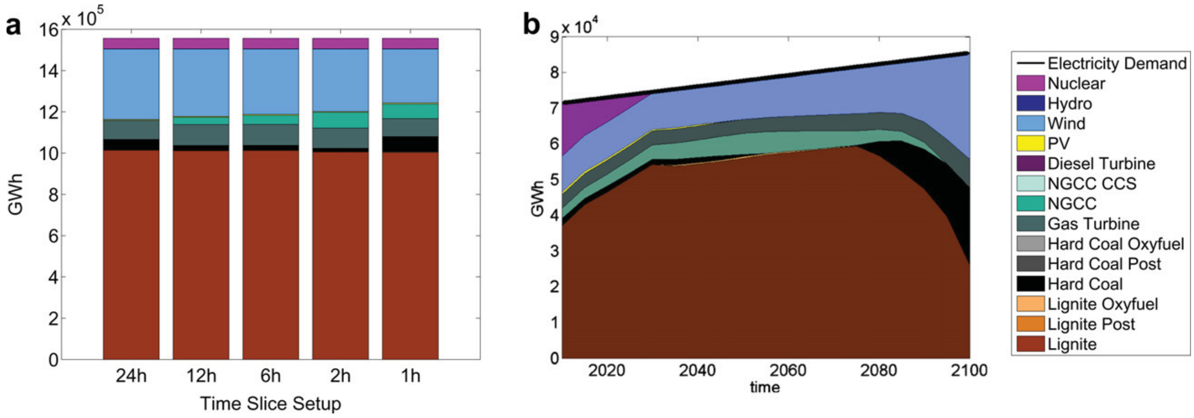

Fig. 5. Reference scenario, BAU case, electricity generation.

considered plus additional options such as carbon capture and storage (CCS). Electricity generation from nuclear power plants is phased out until 2030 and no investments into new nuclear capacities are possible for the model to represent German nuclear policy. Table A.3 in Appendix A displays the techno-economic parameters and the initially installed capacities for all electricity generation technologies considered. The maximum output of a power plant is constrained by the availability factor ν (cf. Eq. B.2 in Appendix B) to represent scheduled outages for maintenance.

Electricity storage is modeled through the introduction of a generic storage technology, which allows for the subsequent assessment of different technologies by introducing the relevant sets of parameters. It consists of two distinct parts: Storage quantity and generation capacities. Both can be extended by investments. There is a constraint on maximum storage duration, allowing for storage only within one representative day. However, to allow for a thorough analysis of different options, storage is not available in the reference cases presented in Section 4.1. Section 4.2 shows an assessment of different storage options in LIMES.

3.3. Climate policy assessment

Climate policy constraints can be introduced using emission trajectories, emission budgets or CO_2 prices, mirroring different policy setups. The long model time horizon allows for an analysis of the impact of international climate agreements on the model region by prescribing emission budgets or CO_2 prices, while emission trajectories can be used to represent local climate policy laws. Because of the small model area, exogenously set CO_2 price paths are used for the assessment of policy impacts in Section 4.

3.4. Calibration and scenario definition

To assess the quality of the model calibration, results for the year 2010 are compared to electricity generation in the region according to the main power producer Vattenfall. According to [28], in 2009, 50 TWh electricity were generated from lignite while only 2.4 TWh were generated in nuclear power plants, due to long outages of the nuclear power plants Brunsbüttel and Krümmel. They both have been offline since mid-2007 after the occurrence of different incidents and have not returned to generating electricity until the end of 2010. LIMES model results for 2010 yield 40 TWh electricity from lignite and 13 TWh from nuclear energy. This is considered a reasonable result, since it can be expected that less electricity would have been generated from lignite, had the nuclear facilities not been offline.

A series of experiments are analyzed subsequently to assess the incremental effects of different setups for temporal resolution within the model on the technology mix in the electricity sector and on power system and climate change mitigation costs. Basically, the reference case distinguishes between a business-as-usual (BAU) scenario and a scenario with policy constraints (POL) where we impose a price path for CO_2 emissions. Based on [1], a price of 15€/tCO_2 is set for 2005 and we assume an exponential increase of 5% per year in accordance with the model interest rate. The reference model version for these assessments is presented in Section 4.1. The storage availability on the electricity mix is discussed in Section 4.2. In Section 4.3, we investigate the impact of feed-in priority for electricity from RES on the power sector composition.

The insights gained from these experiments are combined in Section 4.4 to answer questions about the significance of variability for power system costs as well as climate change mitigation costs.

4. Results

4.1. Reference setup

Fig. 5a displays cumulated electricity generation[3] for the BAU scenario in all five different time slice setups. Common to all is a considerable share of generation from lignite power plants together with a fairly substantial amount of wind energy. The difference between the various time slice setups lies in the amount of variability (of load and renewable energy supply) that can be represented. One would assume that more information about variability leads to less usage of RES as these show different load factors in each time slice. Together with ramping constraints on inflexible fossil fuel technologies, this entails that less wind energy would be used in the system. For the BAU scenario, this trend can clearly be seen in Fig. 5a. The share of wind energy in electricity generation decreases from 22% to 17% as temporal resolution becomes finer. While the usage of natural gas turbines remains fairly constant at about 6%, the share of NGCC rises as mentioned above – wind energy is replaced by natural gas.

For the 1 h setup, Fig. 5b shows evolution of the electricity generation mix over time. As noted in Section 3, the total amount of extractable lignite is constrained, which explains the decrease of lignite use at the end of the century. Also, hard coal plants replace NGCC as natural gas prices increase throughout the century. The

[3] Please note that the reference setup does not contain storage technologies.

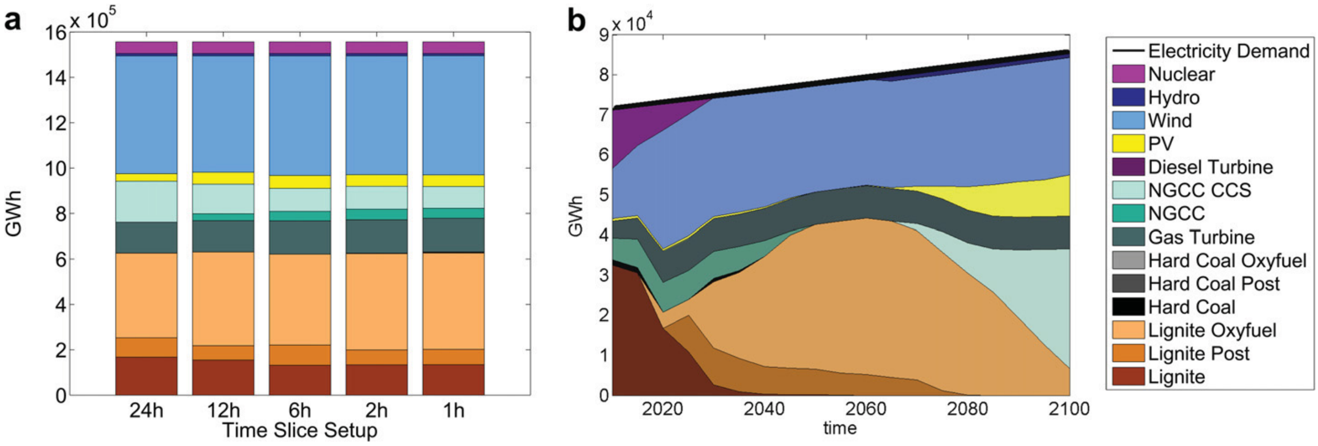

Fig. 6. Reference scenario, POL case, electricity generation.

amount of generation from gas turbines rises with the share of wind energy due to backup constraints.

As a next step, we investigate the impact of a CO_2 price path starting at 15€/tCO_2 (about the current level in the EU ETS) in 2005 on the technology mix in the electricity sector using the same time slice setups as for the BAU scenario. The constraint on emissions leads to shifts in technology usage as can be seen from Fig. 6b for the 1 h setup. While conventional lignite power plants are still used at the beginning of the century, no new capacities are installed and the existing plants are mothballed. Instead, a switch to facilities using CCS is performed. Lignite Oxyfuel and post-combustion plants are introduced and also NGCC generators in use at the beginning of the century are substituted by their counterparts with CCS.

Fig. 6a shows that the evaluation of different time slice choices draws a partly different picture than in the BAU scenario. The technology mix displays an overall share of about 33–34% wind energy in electricity generation for all time slice setups, which is more than 10 percentage points higher than for the BAU scenario. The amount of flexible natural gas turbines and NGCC increases with increasing resolution to balance fluctuations of demand and RES. Usage of NGCC with CCS, less flexible than its counterpart without capture, is reduced. The total amount of electricity production from lignite stays about constant while oxyfuel plants replace conventional capacities to make up for the lower deployment of NGCC with CCS as costs from CO_2 emissions underly the cost minimizing optimization.

4.2. Assessment of storage technologies

To assess the impact of different storage technologies on the usage of natural gas and lignite technologies, we subsequently introduced the following storage technologies into the model: Pumped Hydro Storage, Compressed Air Storage, Lead Acid batteries, Hydrogen Fuel Cells (in combination with electrolysis), Vanadium Redox Flow Batteries and Lithium Ion Batteries. Table A.4 in Appendix A shows the parameterizations chosen for the different storage technologies. The analysis showed that even under optimistic assumptions for investment costs and efficiency of the different technologies, pumped hydro storage was the only

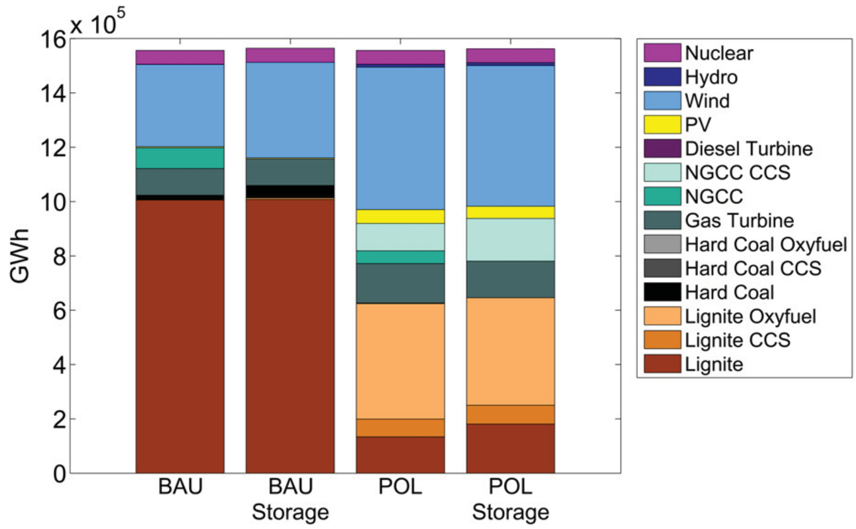

Fig. 7. Electricity generation for scenarios with and without storage (*2h* setup).

technology used before the end of the century. We will thus focus on the results obtained with pumped hydro storage in the following.

The introduction of pumped hydro storage into the model shows interesting impacts on cumulated yearly electricity generation. For the BAU as well as POL model settings (2 h time slice setup), the presence of storage reduces the necessity for flexible NGCC plants to almost zero (Fig. 7). The BAU scenario shows an increased amount of hard coal usage as the lower flexibility of this technology can be balanced by the use of storage. Similarly, the change for the policy setting consists in a higher usage of NGCC plants with carbon capture and lignite, mainly with oxyfuel capture. There is only little change between different time slice setups for experiments with storage availability. Increasing the number of time slices leads to more information about system variability and thus knowledge about the need for flexible generation technologies; storage, however, provides additional power generation flexibility and allows for high usage of slow-ramping power plants. Technology choice is thus influenced only slightly by increasing temporal resolution when storage is available. The same is true for emissions: though the trajectories differ between the cases with and without storage, the same residual emissions threshold of about 50MtCO_2 is observed for POL scenarios with storage.

There is, however, another impact that can be seen when analyzing curtailment of wind power plants as displayed in Fig. 8: in the presence of storage, the installed capacity of wind shows a strongly increased utilization level and curtailments are reduced to less than 5% over the time horizon considered. For the scenario without storage, this picture is largely different as up to 17% of wind power plants switched off due to system constraints.

Fig. 9 displays electricity generation for all 48 time slices (2 h setup). It becomes apparent that wind production during lower demand periods at night is stored to be used for peak electricity demand during the day. This leads to a higher utilization of wind power over the year, thus reducing the need for curtailments. A constraint on maximum storage duration only allows for daily storage but storage accounting shows that even in model runs without this constraint, the technology is mostly used for daily balancing.

4.3. *Feed-in priority for RES*

In several countries, e.g. Germany, electricity from RES is given a priority when it comes to grid feed-in. Curtailments are only

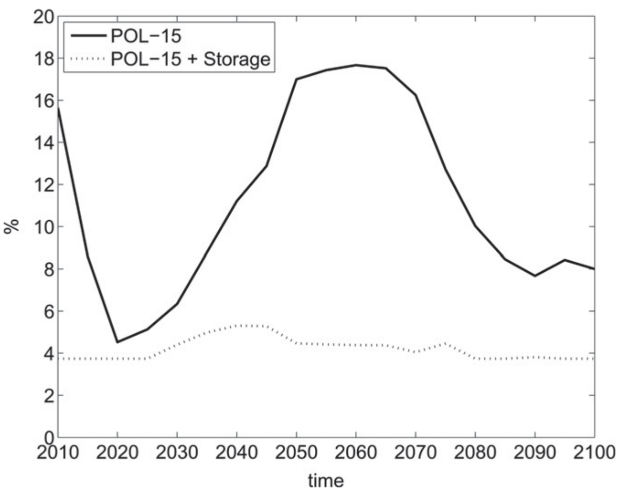

Fig. 8. Wind Curtailment with and without storage (POL, *2h* setup).

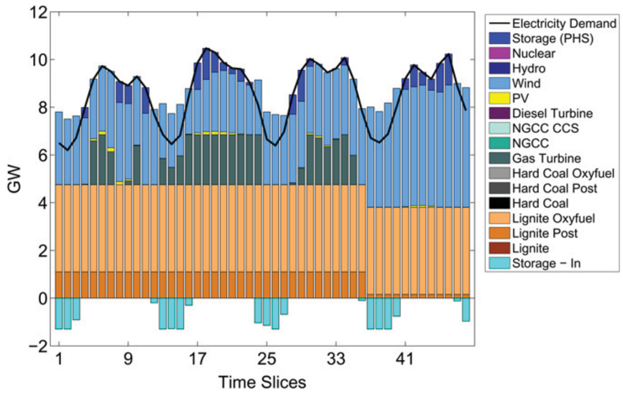

Fig. 9. Electricity generation in 2040 with 24h storage over time slices (POL, *2h* setup).

possible for strictly technical reasons in case of imminent danger for power grid operation [29]. While this preference is a reasonable measure to support RES development and force necessary grid extensions, an assessment of impacts on the operation of conventional power plants and electricity network operation seems reasonable. However, most studies (see e.g. [30,31]) concerning the (mostly financial) repercussions of RES development in Germany treat the feed-in priority as given and do not analyze scenarios where curtailment is possible. One of the few sources analyzing welfare losses induced by priority feed-in are Andor et al. [32] who suggest a revision of RES policies to allow for curtailments to increase social welfare.[4]

For the following analysis, it has to be kept in mind that the present model takes the perspective of a central social planner, optimizing the system as a whole instead of considering the decentral decisions of different players in the market. Furthermore, no technical aspects of electricity grid bottlenecks or power plant wear from frequent ramping of output are taken into account.[5]

Fig. 10 displays cumulated electricity generation for the BAU and POL scenarios, with the first and third bars showing the standard situation where output from all power plants can be reduced (with the curtailment velocity being only limited by ramping abilities of different technologies) and the second and fourth bar presenting model runs where of wind and solar energy must not be curtailed. For the BAU scenarios, the model chooses to reduce investment in wind energy capacities (the share of wind in total energy production drops from 22.5% to 17.1%) and, more substantially, in lignite capacities (64.7%–54.7% of electricity generation) to build up flexible natural gas CC plants instead.

The reduction in wind power production, however, is not observed in the POL scenarios. On the contrary, electricity generation from wind energy increases from 33.7% to 43.3% of total power generated. Inflexible lignite power plants are replaced by mainly gas fueled generation: NGCC, gas turbines and NGCC + CCS to reduce costs from CO_2 emissions. The overall electricity price is lowered through the forced feed-in of mostly wind, reducing refinancing possibilities of inflexible lignite base load plants. The

[4] Social welfare is to be understood as overall benefits to the system from minimized energy system costs. This means in the present situation that plant operators who forego their market opportunity to sell their electricity to customers could be in principle compensated by those plant operators who sell their output to customers at a positive price. In the present example the compensation might be organized via an implementation across time slices. Research about the market design of efficient curtailment is – however – yet in its infancy.

[5] While we consider constraints on ramping abilities of power plants, we do not include reductions of efficiency in part-load situations so far.

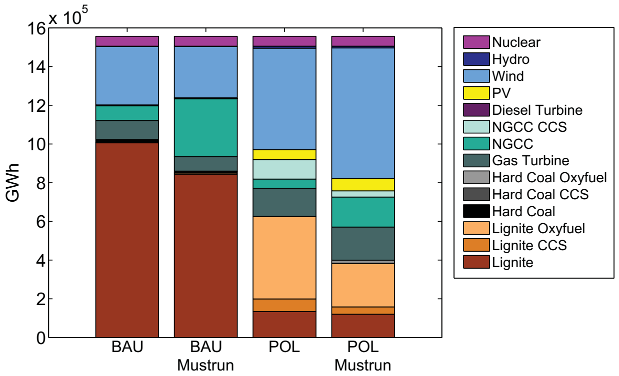

Fig. 10. Cumulated electricity generation for scenarios with and without RES priority feed-in (*2h* setup).

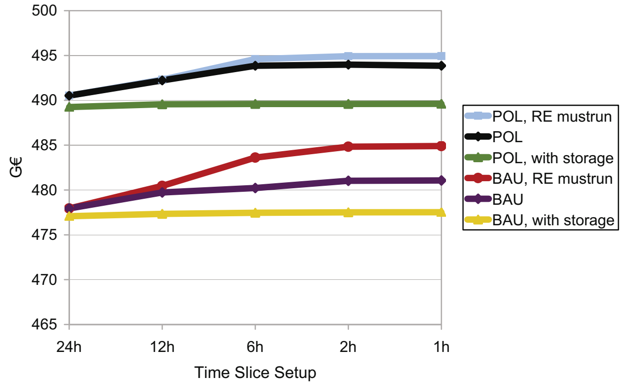

Fig. 11. Comparison of total discounted power system cost for all time slice setups and scenarios.

missing flexibility of RES thus leads to a decrease of lignite oxyfuel usage. Since curtailments are not possible in this case to balance demand fluctuations, additional investments into natural gas technologies are undertaken, thus limiting the amount of lignite oxyfuel plants in the technology mix. An assessment of power system costs for cases with and without feed-in constraints is conducted in Section 4.4.

These results show that the possibility of curtailments of renewable energy technologies is of importance for system operation as this can provide some of the flexibility necessary for balancing of demand variations. This analysis, however, keeps a strict social planner perspective and does not comprise assessments of political support systems that have grid parity of RES as their aim. As the reduction of investment costs for wind and solar energy is an exogenous assumption in this model, it is not possible to assess the impact of learning curve progression through capacity extensions.

4.4. *Cost assessment*

In this section, we assess power system and mitigation costs for the different scenarios presented in the previous sections to assess the effect of different temporal resolutions on cost estimations for the electricity sector.

Fig. 11: shows the total discounted power system costs[6] for BAU and POL scenarios for all time slice setups including model runs with storage availability and RE feed-in priority for different scenarios and time slice setups. Costs increase if more variability is considered in the model, mostly due to the increased use of natural gas technologies where fuel costs rise significantly throughout the century. This trend holds for power system costs of both BAU and policy scenarios, thus leading to the conclusion that models that use an aggregated representation for variability underestimate power system costs.

Fig. 11 also shows that the increase in power system costs level out with increasing temporal resolution. Experiments with a temporal resolution of 1 h for time slices shows only minor cost increases compared to the 2 h setup, pointing to an information threshold after which additional information about variability does not lead to substantial changes in results.

A comparison of different scenarios shows that the most important factor for the level of power system costs is natural gas consumption. Experiments in which storage is available display lower costs while scenarios with RES feed-in constraints, where additional balancing is required, show higher costs.

The difference between total discounted power system costs in BAU and POL scenarios, i.e. mitigation costs, changes only slightly between 2% and 3% for the different setups as can be seen from Fig. 11 by comparing the respective BAU and POL cost trajectories. As the need for flexible technologies in the presence of fluctuation causes higher power system costs already in the BAU scenarios, the difference between BAU and POL costs diminishes leading to similar results for all different time slice setups. While disregarding variability within models can lead to underestimation of power system costs, it does not have a clear effect on mitigation costs.

5. Conclusions and outlook

This analysis investigates impacts on the technology mix for electricity generation and on power system costs using different setups for temporal resolution and varying emission constraints. Increased temporal resolution, representing more of the fluctuations in RES and load, leads to a decrease of the share of inflexible technologies while more flexible power plants are employed to cover electricity demand. The dominant technologies remain wind power and lignite power plants (with or without CCS). As flexible natural gas technologies display higher fuel costs than base load lignite plants, this leads to higher power system costs regardless of whether CO_2 prices are considered or not. However, the increase shows a stabilization, leading to the conclusion that further increases in temporal resolution might not lead to more accurate results. While power system costs increase under parameterizations of time with increasing resolution, climate change mitigation costs display little change.

The availability of storage strongly reduces the need for curtailments of wind energy and displaces NGCC plants almost completely. As the potential for pumped hydro storage is limited in most regions, further research will include several types of storage with differing properties and costs. The interdiction of renewables curtailment in a system without storage leads to significant increases in natural gas usage and, for the BAU scenario, a reduction in wind energy deployment. Our analysis takes a social planner perspective and suggests that decentral explorations including multiple players and policy assessments should take a deeper look into the impacts of RES feed-in priority.

Further research will take a closer look at the temporal resolution based on time slices. The model results gained so far point to the importance of higher temporal resolution. Since time slices

[6] ower system costs consist of investment costs, O&M costs, fuel costs and costs for CO_2 emissions.

designed around electricity demand show limitations for wind variability representation as discussed in Section 3.1, other methods should be investigated for time slice generation. Different clustering methods should help to find time slices that constitute an adequate representation of variability of RES and electricity demand while not overly increasing model complexity and thus numerical cost.

A planned European multi-region version of LIMES as presented conceptually in [33] will allow for investigation of the importance of electricity transmission for the integration of substantial amounts of RES into the electricity mix. Considering a larger geographical area also enables the analysis of pooling effects of regional resources of RES. As a further option for RES integration, demand side management measures will be investigated. This includes price elastic demand and load-shifting measures. Combined heat and power plants with electricity-controlled operation and CCS plants with flexibility for post-combustion measures will complete the technology options.

The combination of these options within one model will allow us to determine the optimal combination of measures to balance variability of RES sources in the electricity sector while providing a cost-optimal solution. Emission targets will add climate protection measures to the picture to provide the necessary long-term scenarios for the energy sector with a sufficiently high temporal resolution to account the effect of fluctuations of RES.

Appendix A. Model data

Appendix A.1. Technologies

The model includes a total of 14 different technologies for producing electricity and one storage technology. This choice is based on the power plant fleet currently installed in the area considered plus additional options such as carbon capture and storage (CCS). Table A.3 Appendix A displays the techno-economic parameters and the initially installed capacities for all electricity generation technologies considered.

Fixed 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 variable O&M Costs do not include fuel costs. Fuel costs are treated below the table in Section Appendix A.2.

Table A.3
Techno-economic parameters (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]	Initial Capacity [GW]	Technical Lifetime [a]
PC [34,35,36]	1100	2	2.11	0.5	50
PC + Post [34,35,36,37]	1800	2	3.52	–	50
PC + Oxy [34,35,36]	1900	2	4.23	–	50
Lignite [34,35,37]	1300	2	2.82	9.3	50
Lignite + Post [34,35]	2100	1	4.58	–	50
Lignite + Oxy [34,35]	2200	2	5.28	–	50
DOT [37,38]	322	3	0.28	–	35
NGT [37,39]	300	3	0.57	1	30
NGCC [39]	500	6	0.16	–	40
NGCC + CCS [38]	850	4	0.58	–	40
Wind (onshore) [38]	1000	3	0	9.5	40
PV [38]	4000	1	0	0.3	30
Hydro [38]	5000	2	0	0.009	80
TNR [40]	–	3	0.87	2.1	60
PHS	1200	0.38	0.76	2.9	–

[a] Abbreviations: PC – Pulverized Coal Power Plant (Hard Coal), Post – Post-combustion capture, Oxy – Oxyfuel Capture, Lignite – Lignite Power Plant, DOT – Diesel Oil Turbine, NGT – Open Cycle Gas Turbine, NGCC – Natural Gas Combined Cycle, Wind – Wind Turbine, PV – Solar Photovoltaics, Hydro – Hydroelectric Power Plant, TNR – Thermonuclear Reactor, PHS – Pumped Storage.
[b] All investment costs are overnight costs. All €-values in this paper are 2005 values.

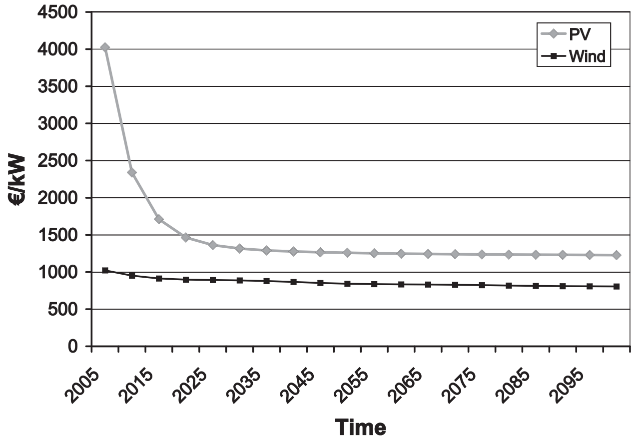

Fig. A.12. Wind and PV investment costs.

Wind and solar photovoltaics are technologies characterized by decreasing investment costs over time due to learning effects. As these are overwhelmingly determined by global capacity increases we do not include learning curves for our model, but introduce an exogenous cost degression deduced from the model ReMIND-D [38]. Fig. A.12 shows the investment cost curves implemented within LIMES.

The technical potential for onshore wind energy in Germany is estimated to be 71^{TWh}/a by Kaltschmitt and Streicher [41]. Using the European Wind Atlas [42], the assumption is made that one third of this potential is situated in the region considered. For photovoltaic energy, we combine data from [43] and [44] to obtain a technical potential of 37^{TWh}/a. Average yearly capacity factors are at about 21% for wind and 8% for PV. To emulate current RES deployment, it is not possible to reduce capacities for wind energy below once installed numbers. Biomass fueled technologies are not considered in the current model setup due to major political insecurity about their projected role and, furthermore, to allow for a better determination of main model trends by limiting the number of technologies considered.

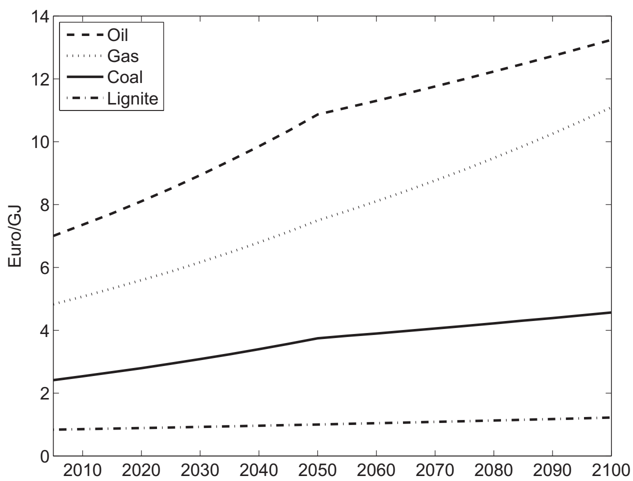

Fig. A.13. Fuel price and cost paths (source: [50,51]).

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Table A.4
Parametrization of storage technologies.

	Inv. costs generator [€/kW]	Inv. costs storage vol. [€/kWh]	Efficiency [%]	O&M fix [%inco/year]	O&M var [€/kW]	Technical lifetime [a]
PHS[a] [45,46]	1500.00	16.10	80	0.5	21.43	80
CAES[b] [45–47]	482.94	40.25	60	1.0	15.23	30
Lead Acid [48,47]	300.00	375.00	70	1.0	56.41	8
H2 FC[c] [45]	800.00	12.07	45	1.0	0.00	15
VRB[d] [45,48]	2500.00	300.00	70	1.0	0.00	10
LiIon[e] [46,48,49]	1.00	500.00	95	1.0	0.00	10

[a] Pumped Hydro Storage.
[b] Compressed Air Energy Storage.
[c] Electrolysis and Hydrogen Fuel Cell.
[d] Electrolysis and Hydrogen Fuel Cell.
[e] Lithium Ion Battery.

Table A.4 shows the parametrization used in Section 4.2.

Appendix A.2. Fossil resources and CCS potential

The 50 Hz Transmission region is assumed to act as a price taker for several fossil fuel types, fuel prices are thus unaffected by demand for fossil energy. Prices for internationally traded hard coal, oil and natural gas are derived from [50] [7] for the period of 2005–2050, and a constant increase of 2% over 5 years is assumed for the second half of the century. For the price of domestic lignite, we assume a growth rate of 5% p.a. starting from [51]. Fuel price evolution over time is presented in Figure A.13. Furthermore, to represent the lignite open cast mine situation in the 50 Hz Transmission region, we introduce a cap on cumulative lignite extraction following [52] for economically extractable resources in approved mines (2.5/Gt). Hence intertemporal optimization implies a scarcity rent that is added to the cost of fuel for lignite.

In line with [53], a total potential of about 10 Gt CO_2 for carbon sequestration is presumed for Germany. We assume that one third of this potential is available for our model region. Power plants equipped with Post-Combustion CCS (PC + CCS, Lignite + CCS, NGCC + CCS) have a capture rate of 90% while Oxyfuel plants are assumed to capture 95% of emissions.

Electricity demand is given exogenously. Starting with 2007 values obtained from [26], an increase of 0.2% p.a. is assumed as this region is expected to experience a moderate development of energy demand. The interest rate is set to 5% p.a.

Appendix B. Model equations

This Section provides an overview on the equations used in the model. A nomenclature containing all variables can be found in Table B.5. The model objective (Eq. B.1) consists of a minimization of total discounted power system costs over the model time frame from 2005 to 2100. Power system costs are the sum of investment costs C_I in technologies i in each time step t and operation and maintenance costs $C_{O\&M}$ and fuel costs C_{Fuel} for each technology in each time slice τ and time step t. Furthermore, costs from the applied CO_2 price C_{Emi} are added to power system costs.

$$\min \sum_t \left(\sum_i C_I(t,i) + \sum_{\tau,i} C_{O\&M}(t,\tau,i) + \sum_{\tau,i} C_{\text{Fuel}}(t,\tau,i) + \sum_\tau C_{Emi}(t,\tau) \right) e^{-\rho t} \quad \text{(B.1)}$$

[7] We use fuel cost path B with a moderate increase.

Table B.5
Nomenclature.

i	Technology
t	Time step
τ	Time slice
ρ	Interest rate
η_i	Transformation efficiency
ℓ_τ	Length of time slice
$C_I\ (t, i)$	Investment costs
$C_{O\&M}\ (t, \tau, i)$	O&M Costs
$C_{\text{Fuel}}\ (t, \tau, i)$	Fuel Costs
$C_{Emi}\ (t, \tau)$	Costs from CO_2 prices
P_i	Electricity generation by technology i
K_i	Capacity of technology i
ν_i	Availability rate
D	Electricity demand
P^j_{in}	Storage input
P^j_{out}	Storage output

Electricity generation P_i is constrained by capacities K_i for each technology i and their availability rate ν_i (Eq. B.2). For renewable energy sources, ν_i depends on grades that distinguish differences in resource potential.

$$P_i(t,\tau) \le \nu_i K_i(t) \quad \forall t,\tau \quad \text{(B.2)}$$

Demand for electricity D and production by the different technologies P_i and storage input P^j_{in} and output P^j_{out} have to be balanced within each time slice τ and each time step t (Eq. B.3).

$$\sum_i P_i(t,\tau) + \sum_j P^j_{\text{out}}(t,\tau) = \sum_j P^j_{\text{in}}(t,\tau) + D(t,\tau) \quad \forall t,\tau \quad \text{(B.3)}$$

From analyses of power drops in the system (as shown in Fig. 4), we derive the maximum backup capacity that needs to be present within the system (relative to the amount of wind and solar power installed). This is introduced into the model as a constraint on necessary backup capacity as shown in Eq. B.4. TE_{BACK} describes the group of technologies providing backup (Gas and Oil Turbines, NGCC, Hydropower and storage) and TE_{REN} contains wind power and photovoltaics.

$$\sum_{i \in \text{TE}_{\text{BACK}}} K_i(t) n \ge \text{maxdropfrac} \cdot K_k(t) \quad \forall t, k \in \text{TE}_{\text{REN}} \quad \text{(B.4)}$$

The same analyses also show how much electricity generation from backup technologies was necessary because of drops in output from renewables. The variable backupprodfrac designates this production relative to the installed capacity of wind power and photovoltaics in Eq. B.5, which shows the constraint on output $P_i(t,\tau)$ of backup facilities.

$$\sum_\tau \sum_{i \in TE_{\text{BACK}}} P_i(t,\tau) \ge \text{backupprodfrac} \cdot K_k(t) \quad \forall t, k \in \text{TE}_{\text{REN}} \quad \text{(B.5)}$$

The storage implemented into the model consists of two parts: the turbine/pump facility, determining how much power can be produced/stored within each time slices and the storage volume limiting the amount of energy storage in the reservoir. Eq. B.6 shows the connection between storage in- and output and storage volume (with η_j being the transformation efficiency of the storage technology and ℓ_τ the length of a time slice) while Eq. B.7 describe the additional capacity constraints for storage.

$$P^k_{\text{stor}}(t,\tau) = P^k_{\text{stor}}(t,\tau-1) + \left(\eta_j \times P^j_{\text{in}}(t,\tau) - P^j_{\text{out}}(t,\tau)\right) \times \ell_\tau \quad \forall t,\tau \quad \text{(B.6)}$$

$$P^j_{in}(t,\tau) \quad \leq \nu^j(\tau)K^j(t) \quad \forall\tau \quad \text{Storage input} \tag{B.7}$$

$$P^j_{out}(t,\tau) \quad \leq \nu^j(\tau)K^j(t) \quad \forall\tau \quad \text{Storage output} \tag{B.8}$$

$$P^k\text{stor}(t,\tau) \quad \leq \nu^k(\tau)K^k(t) \quad \forall\tau \quad \text{Storage quantity} \tag{B.9}$$

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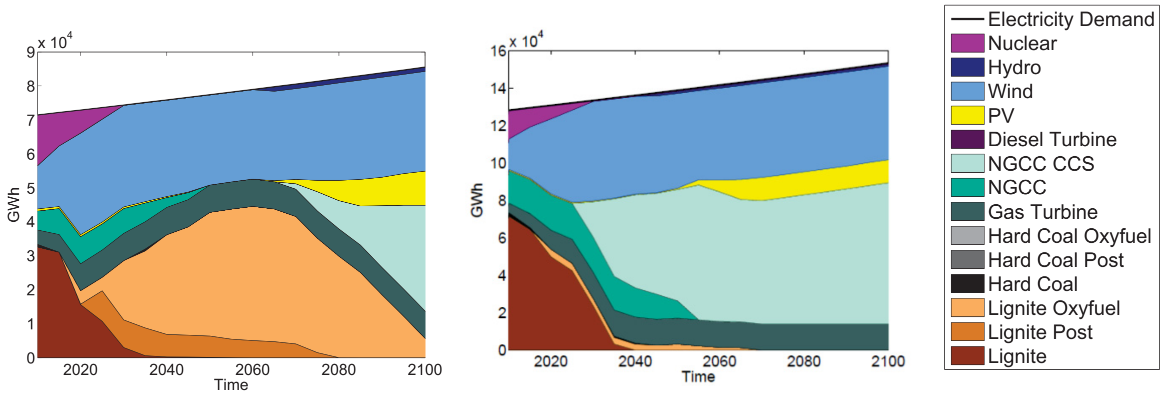
3.9 Additional Information

When the original runs for this paper were performed, data from the website of the German TSO 50Hertz Transmission GmbH (50Hertz Transmission GmbH 2010d) was used to parameterize electricity demand. The values in 50Hertz Transmission GmbH (2010d) represent the amount of power which is transferred form the high voltage transmission grid to the different distribution networks. This value does not take into account that a certain amount of electricity is generated at the level of the distribution grid, e.g. from rooftop solar power or small communal power plants. Comparison with data from LAK (2012) shows that using the values from 50Hertz Transmission GmbH (2010d) underestimates the real amount of electricity generated in the area of the TSO *50Hertz Transmission GmbH* which is considered in this paper. The authors were not aware of this at the time of the publication of the paper. To assess the impact of higher power demand on model results, an additional analysis was conducted and is presented in the following.

The main focus of the initial analysis was the integration of RET into the power system of the TSO *50Hertz Transmission GmbH*. Impacts of storage technologies, RET curtailment possibilities and flexible balancing technologies were analyzed. Results showed substantial amounts of wind energy in combination with lignite power plants equipped with CCS. The increase of temporal resolution in the model showed a preference for flexible generation technologies with an increase of natural gas usage and less lignite.

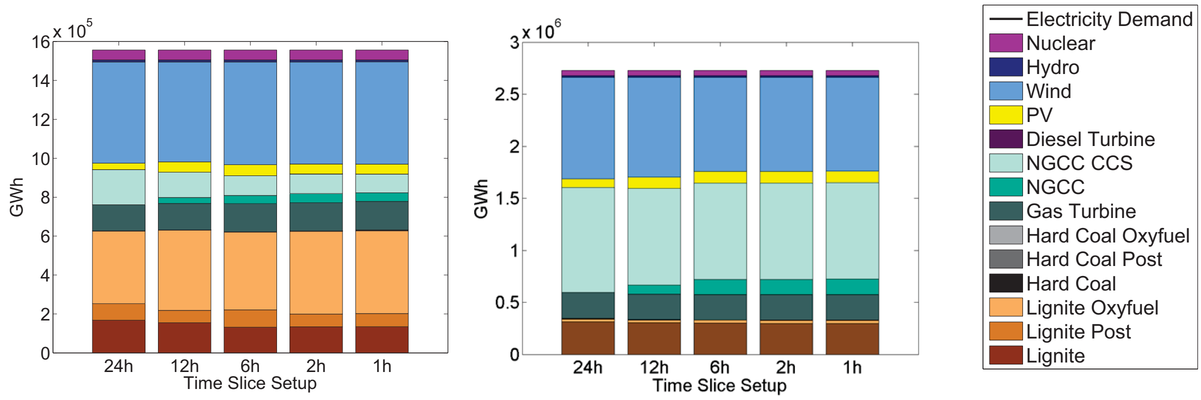
Electricity generation over time is compared in Figure 3.1. Due to the higher power demand, lignite reserves are depleted earlier and natural gas technologies play an earlier and more significant role. The respective shares of wind energy and CCS technologies in the power generation mix stay comparable, but NGCC plants with CCS take the place of Lignite Oxyfuel in the study with higher power demand. As can be seen from Figure 3.2, the switch to technologies with greater flexibility as temporal resolution is increased in the model can still be witnessed for the case with higher power demand. Figure 3.3 shows total discounted power system costs for the low and the high demand case. While the respective numbers are different, the general trend is similar to the one observed in the article.

The overall conclusion from this short analysis is that higher power demand has an impact on the technology mix through faster lignite reserve depletion, on total installed capacities and the total amount of power generation. However, the trends described for the low demand parametrization are also true for higher demand: flexible technologies such as gas turbines displace the less flexible lignite power plants when temporal resolution is increased in the model. Moreover, in both analyses, power system costs increase with resolution but level out with increasing resolution, indicating that a more fine-grained analysis might not bring new insights but only higher numerical cost.



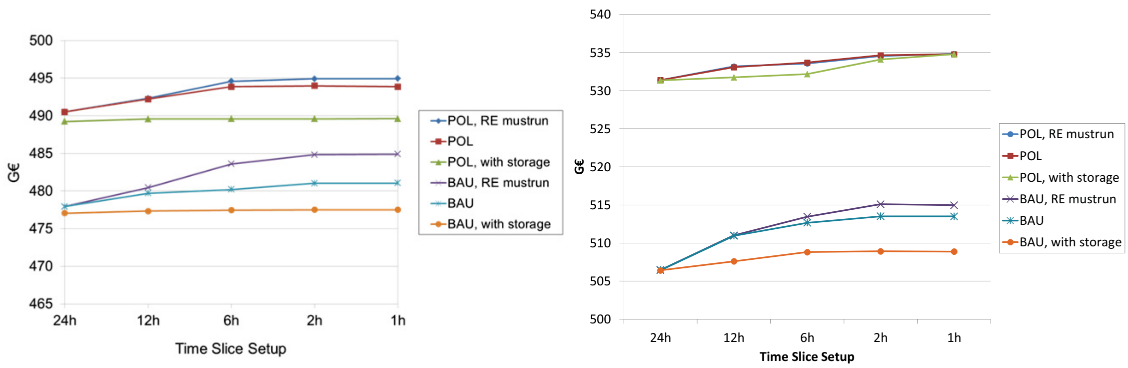
(a) Low demand (Paper Version) **(b)** High demand

Figure 3.1: Comparison of electricity generation over time (POL Case) for model runs with low and high power demand (2h setup) [Please note differences in y-axis scale!]



(a) Low demand (Paper Version) **(b)** High demand

Figure 3.2: Comparison of electricity generation for different time slice setups (POL Case) for model runs with low and high power demand [Please note differences in y-axis scale!]



(a) Low demand (Paper Version) **(b)** High demand

Figure 3.3: Comparison of power system costs for model runs with low and high power demand [Please note differences in y-axis scale!]

Chapter 4

The case of flexible CCS and fluctuating renewable energy*

Sylvie Ludig
Markus Haller
Nico Bauer

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Tackling long-term climate change together: the case of flexible CCS and fluctuating renewable energy

Sylvie Ludig[a*], Markus Haller[a], Nico Bauer[a]

[a]*Potsdam Institue for Climate Impact Research,, Germany*

Abstract

The present study aims at shedding light into the interaction of fluctuating renewables and the operational flexibility of post-combustion capture plants in the framework of a long-term model. We developed a model of the electricity sector taking into account both long-term investment time scales to represent plant fleet development under economic and climate constraints as well as short time scales to consider fluctuations of demand and renewable energy sources. The LIMES model allows us to determine the respective roles of renewables and CCS in climate change mitigation efforts within the electricity sector. Furthermore, we assess the influence of natural gas prices on fuel choice and investigate the shares of competing CCS approaches in the technology mix. We find that the optimal technology mix includes large shares of renewables and simultaneously different competing CCS technologies, depending on emission constraints and fuel prices.

Keywords: Climate Change Mitigation; Variability; Renewables; flexible operation; CO_2 capture

1. Introduction

Assessments of long-term, global mitigation technology strategies[1] highlight the important role of carbon capture and sequestration (CCS) and renewable energy technologies (RET) for the decarbonization of the electricity sector. The Integrated Assessment Models (IAMs) used in such studies consider long time frames to determine optimal investment streams in different low carbon technologies while short term variability of renewable energy sources and demand are represented only on a very simplified level (e.g., see [12]). Consequently, the need to balance variability is not fully represented in the model structure and, thus, the optimal investment choices are subject to critique. The model assumptions may generally overestimate the potential to decarbonize the electricity sector, because balancing of fluctuations might require - at least to some extent - the use of fossil fuels. Hence, the role of RETs may be smaller than suggested by IAMs , especially if stringent emission targets are to be met.

*Corresponding author. Tel.: +49-331-288 2427; fax: +49-331-288 2640.
E-mail address: sylvie.ludig@pik-potsdam.de

[1] The model intercomparison projects presented in [5] and [13] give an example of such assessments.

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Several technology options are available to enable integration of RETs into the electricity system: backup provided by conventional power plants, storage technologies, long-distance electricity transmission and demand side management. Flexible natural gas powered turbines are often considered one of the main options for balancing of fluctuations of renewable energy electricity generation. However, another option might be available: several studies show that coal power stations with post-combustion capture are sufficiently flexible to balance short-run fluctuations ([2, 3, 4, 16]). Steam that is used in the carbon capture unit can be quickly re-allocated to power a turbine while venting the CO_2 in the flue gas. Thus, electricity output as well as CO_2 emissions are temporarily increased to fulfill requirements set by the power system. This operational flexibility of the post-combustion concept is not represented in standard energy system models and consequently not appreciated in the optimal solution of technology choice. An assessment of competing CCS approaches such as oxyfuel and post-combustion technologies is thus necessary to determine their respective roles in carbon-free electricity generation. Additionally, the availability of both flexibly operated CCS coal power plants and natural gas powered turbines for fluctuation balancing raises the question of the influence of fuel prices on the chosen technology mix.

The present study analyses the interaction of fluctuating renewables and the operational flexibility of post-combustion capture plants in the framework of a long-term model. We developed LIMES (Long-term Investment Model for the Electricity Sector), a model of the electricity sector[2] taking into account both long-term investment time scales to investigate plant fleet development under economic and climate constraints as well as short time scales to represent fluctuations of demand and renewable energy sources. The model presented in this paper allows us to answer the following questions: How large are the respective roles of RETs and CCS in the climate change mitigation efforts within the electricity sector? Are competing CCS approaches part of the technology mix simultaneously? Finally, how do natural gas prices affect technology choices?

The remainder of this article is structured as follows: Section 2 highlights important features of the extended LIMES model, Section 3 presents results of the analysis and Section 4 concludes.

2. The extended LIMES model

For the purpose of this investigation, a single-region model of the electricity sector is implemented and calibrated to data[3] of the area of Germany that is covered by the transmission system operator 50Hz Transmission GmbH (formerly Vattenfall Europe Transmission, covering mainly East Germany and Hamburg). A complete model description can be found in [9], this section will illustrate the most important model features as well as extensions made for this study. The model is developed as an intertemporal optimization with the possibility to set emission constraints It takes a social planner perspective with perfect foresight. Fluctuations that arise due to varying demand and fluctuating output of wind energy and solar PV capacities are represented by dividing a year into various characteristic periods ('time slices'). The time slices differentiate variations between seasons, days of the week and phases of the day. From the original data, mean electricity demand is determined for each time slice as well as capacity factors for wind and solar energy. To illustrate the concept of time slices, Figure 1 shows demand for 16 time slices of the year 2007. Neighboring bars represent 6h intervals for the spring, summer, autumn, and winter season. The model allows for usage of different temporal resolutions i.e. different number of time slices. [9] investigates the influence of the chosen temporal resolution on model results. For the analysis in this paper we choose 48 time slices, representing one characteristic day for each season, each of these days subdivided into 2h steps. Along with mean output from wind within each time slice, we consider variations happening on shorter time-scales by analyzing the change of wind electricity generation between different time intervals. From the analysis of these variations, we derive requirements for backup capacities needed within the system and supplementary electricity generation for system balancing.

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[2] The model version presented in this paper consists of a one region setup calibrated to data for the area of East Germany and Hamburg.

[3] We use time series for 2007 with a 15 minute resolution for electricity demand and wind and solar power feed-in which are publicly available on http://www.50hertz-transmission.net/

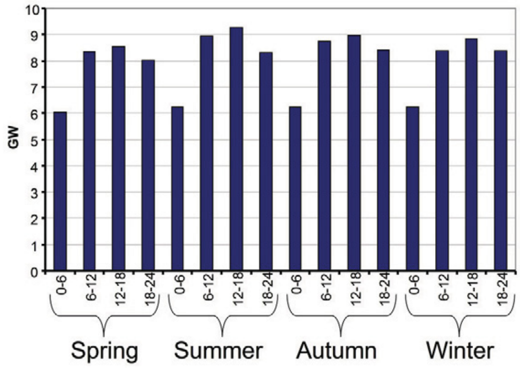

Figure 1: Mean demand in time slices

The model includes 15 different technologies for producing electricity and one storage technology. This choice is based on the technologies currently installed in the region considered and additional options such as different carbon capture and sequestration technologies. As an addition to the standard model version, we include the possibility to turn off post-combustion capture for lignite power plants. The implementation considers a fleet of capture-equipped power plants and allows for the model to choose the share of facilities using capture within each time slice. When capture is turned off, the energy yield is increased but specific emissions increase. As the model uses a budget for emissions allowed over the time-frame considered, emissions will have to be saved elsewhere.

There are several reasons for limiting the flexibility option to post-combustion capture for lignite plants: First, hard coal only plays a minor role in electricity generation in the region considered in this model. Second, while according to [3], turning off CO_2 capture in oxyfuel equipped plants might be technically feasible, the higher complexity of the process does not allow for an easy bypass of the capture-induced energy penalty. Coal power stations with carbon capture following the pre-combustion concept are not considered to exhibit this flexibility.

East Germany is assumed to act as a price taker for several fossil fuel types. Prices for internationally traded hard coal, oil and natural gas are derived from [11] for the period of 2005 to 2050, and a constant increase of 2% over 5 years is assumed for the second half of the century. For the price of domestic lignite, we assume a growth rate of 5% p.a. starting from the numbers given in [6]. Furthermore, to represent the lignite open cast mine situation in the region, we restrict available resources to mines already approved (2.5 GtC). In line with [14] a total potential of 6.34 GtC for carbon sequestration is presumed for Germany. We assume that one third of this potential (2.11 GtC) is available for the region considered in our model. Power plants equipped with Post-Combustion CCS (PC+CCS, Lignite+CCS, NGCC+CCS) display a capture rate of 90% while Oxyfuel plants are assumed to capture 95% of emissions. Electricity demand in LIMES is given exogenously. We start from numbers for the year 2007 obtained from the internet database of 50Hertz Transmission GmbH[4]. An increase of 0.2% per 5 years is assumed as this region is expected to experience a moderate development of energy demand. We use an interest rate of 5% p.a. in the model.

[4] http://www.50hertz-transmission.net/cps/rde/xchg/trm_de/hs.xsl/149.htm

Table 1: Techno-economic parameters (Based on [1, 10, 8])

Technology[5]	Investment costs[6]	Fixed O&M costs	Variable O&M costs	Thermal efficiency	Initial capacity
	$/kW	% Inv. Cost	$/GJ	%	GW
PC	1740	3	1.07	44	0.5
PC + CCS[7]	3000	3	2.67	36	-
PC + Oxy	2680	3	2.14	37	-
Lignite	1875	3	1.07	43	9.3
Lignite + CCS	3000	3	2.67(CCS on) /1.35 (CCS off)	34 (CCS on)/ 43 (CCS off)	-
Lignite + Oxy	2680	3	2.14	35	-
DOT	500	3	0.79	30	-
NGT	440	3	1.59	32	1
NGCC	810	2	0.53	56	-
NGCC + CCS	1370	2	0.94	48	-
Wind (onshore)	1500	3	0	-	9.5
PV	6100	1.5	0	-	0.3
Hydro	3740	2	0	-	0.009
TNR	-[8]	3	1.21	33	2.1
PHS	1250	0.38	0.94	85	2.9

3. Results

To assess the influence of capture flexibility and the respective roles of CCS technologies and RETs, we perform a series of model experiments using different setups concerning fuel prices and technology availability. The scenarios are analyzed regarding the deployment of RET and CCS plants as well as other technologies that address balancing requirements. In particular, we look at the technology choice of alternative CCS plants. Furthermore, we assess the costs of emission mitigation and how they are affected by the availability of flexible CCS technologies.

3.1. Reference Cases

The first reference (REF_{off}) case for this analysis consists of a policy experiment with a cumulative budget for emissions over the model time-span. We adapted the emission budget proposed by [15] for Germany by using a target of 0.9 GtC until 2150 for the region examined here.[9] The REF_{off} case has all technologies available except for storage but does not allow for flexible switching of carbon capture. The electricity mix, which can be seen in Figure 2, displays large shares of lignite technologies and wind energy. Natural gas technologies play a role, mainly for balancing purposes, and lignite plants with oxyfuel capture enter the mix starting in 2050 to allow reaching the climate protection target.

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[5] Abbreviations: PC - Pulverized Coal Power Plant (Hard Coal), CCS - Carbon Capture and Sequestration (Post-Combustion), Oxy - Oxyfuel Capture, Lignite - Lignite Power Plant, DOT - Diesel Oil Turbine, NGT - Open Cycle Gas Turbine, NGCC - Natural Gas Combined Cycle, Wind - Wind Turbine, PV - Solar Photovoltaics, Hydro - Hydroelectric Power Plant, TNR - Thermonuclear Reactor, PHS - Pumped Storage

[6] All US$ Values refer to 2005 values.

[7] CCS denotes post-combustion capture in this model setting.

[8] Electricity generation from nuclear power plants is phased out until 2030 and no investments into new nuclear capacities are possible for the model to represent current German policy on nuclear energy.

[9] [15] propose a cap of 3GtC for all energy production in Germany, which we reduced to 0.9 GtC, since we only consider one part of Germany and only electricity generation.

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When allowing for flexible operation of post-combustion lignite power plants (REF_{on} case, see Figure 3), the picture changes: the amount of natural gas is reduced from 3.8% to 2.3% of cumulated electricity generation and lignite CCS plants enter the electricity mix. These capacities partly replace the older, inflexible lignite plants, which leads to their early introduction in about 2025. While used solely without capture until 2055, post-combustion plants start operating with flexible usage of capture in 2060. After 2075, the technology is almost exclusively used with capture turned on to allow for complying with the imposed emission budget. Figure 4 shows time slices for the year 2065 as an example for the usage of flexible capture within the model. Capture is switched off during the days, when electricity demand is high, while nighttime production is performed with carbon capture.

Lignite oxyfuel plants, being the slightly less expensive option, are the preferred lignite based technologies while aiming for climate protection targets. However, due to the flexibility exhibited by its post-combustion counterpart, both alternatives are deployed concurrently[10]. The emission budget used in this setup plays an important role in the choice of technologies for electricity generation: A sensitivity analysis concerning the chosen emission budget revealed that for cumulative caps below 0.8 GtC, flexible post-combustion power plants are no longer used and oxyfuel capture is the technology of choice. The higher capture rate of oxyfuel facilities is an important asset which outweighs the increased balancing abilities and additional energy output from flexibly operated post-combustion CCS plants.

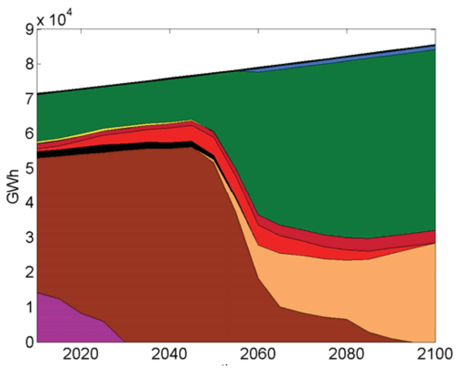

Figure 2: Cumulative yearly electricity production without capture flexibility (REFoff case)

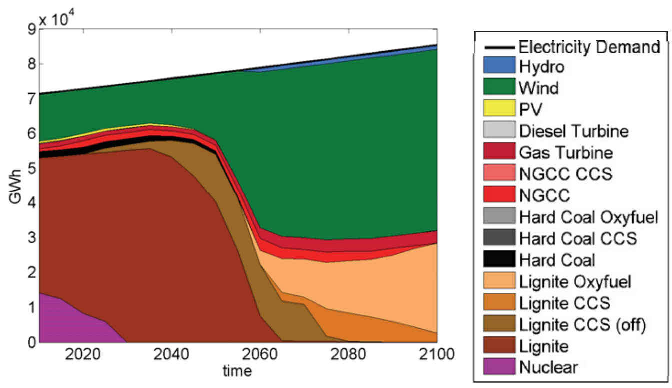

Figure 3: Cumulative yearly electricity production with capture flexibility (REFon case)

3.2. Cost Assessment

An assessment of total discounted energy system costs for the REF_{off} and REF_{on} cases shows that the availability of flexible capture leads to an (albeit small) reduction of costs from 54.57 billion US$ to 54.41 billion US$. The reduction is mostly due to the reduced amount of natural gas that is used in the REF_{on} scenario. Lower energy system costs also induce a reduction of climate change mitigation costs[11] from 1.8% to 1.5% of energy system costs. There are two effects that cause mitigation costs to be relatively low: the emission budget is relatively weak and high wind shares are already present in the case without any climate policy. Since the installed capacities for wind energy in East Germany are already at about 9GW (in 2007), the emissions in the no policy case mostly originate from burning large amounts of lignite. While wind energy and lignite power plants with CCS constitute the least

[10] Due to uncertainty concerning the effective difference in investment costs for post-combustion and oxyfuel technologies, we performed experiments with varying ratios for investment costs. Higher costs for oxyfuel lead to less usage of the latter and more post-combustion plants while the range of years where these are operated with flexible switching of capture remains unchanged.

[11] Mitigation costs are calculated by comparing costs from the policy runs to a business-as-usual (BAU) case without any climate policy measures and no forced extension of renewable energy technologies.

expensive mitigation options and thus take up large shares of the electricity mix, natural gas capacities deployed for balancing strongly influence energy system costs. Flexibly operated post-combustion CCS reduces this role, but its impact is relatively small. To assess the interaction of natural gas capacities and post-combustion CCS under different scenarios, we perform a sensitivity analysis on natural gas prices in Section 3.3.

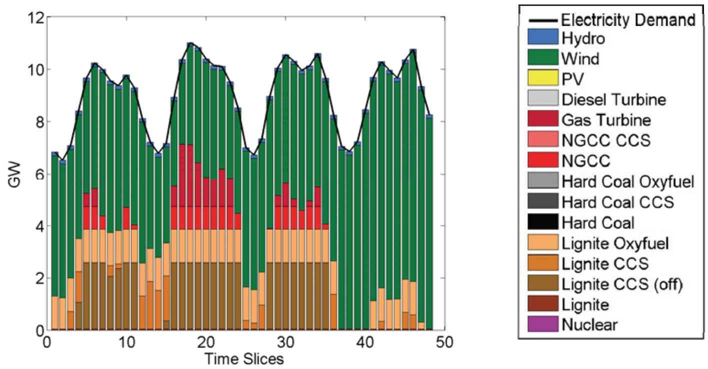

Figure 4: Electricity generation in the year 2065 for the REF_{on} case

3.3. Sensitivity to natural gas prices

As mentioned in Section 3.1, introduction of flexible lignite post-combustion displaces electricity generation from gas combined cycle plants and reduces the overall share of natural gas in the energy mix. The reference case REF_{on} uses a gas price starting at 6$/GJ in 2005, increasing to about 20$/GJ in 2100. To assess the influence of the gas price on technology choice, we conduct a sensitivity analysis using different price paths for natural gas by adding a constant markup of -3$/GJ to +2$/GJ to the initial curve. Figure 5 displays the cumulative electricity generations for the time period of 2005 to 2100 that result from this variation. While balancing constraints require a certain amount of electricity generation from gas turbines, the amount of natural gas used in combined cycle plants decreases for model runs with higher gas prices. For an initial gas price below 4.5$/GJ, natural gas is preferred over lignite with oxyfuel capture. The additional emission from natural gas (which are half those of lignite without capture) are offset partly by reductions after 2100, partly by a reduced usage of lignite. While flexible usage of post-combustion lignite plays a role in all scenarios, its relative share rises for initial prices between 3.5 and 6$/GJ and remains more or less constant beyond 6.5$/GJ. This points to a threshold for this technology, where additional flexible output increase is offset by the lower costs and lower emissions of oxyfuel capture facilities.

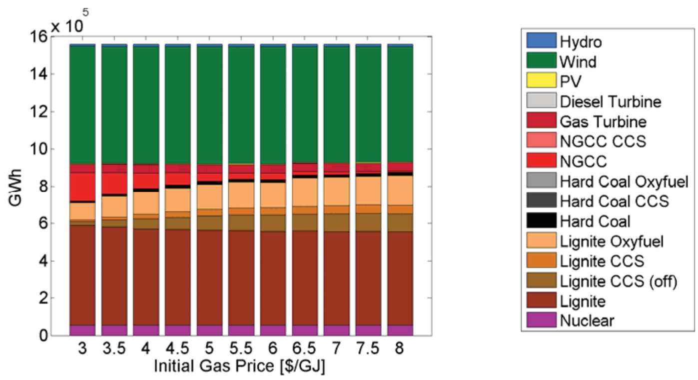

Figure 5: Cumulated electricity generation for 2005-2100 for different gas price scenarios

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3.4. Technology availability and constraints

In addition to the analyses presented above, we conduct two technological assessments: We examine the influence of storage availability on model results and introduced a must-run constraint on wind power plants to represent current policies on renewable power feed-in.

The availability of pumped hydro storage introduces an additional technology to balance variations in electricity demand and renewables availability over the different time slices. While energy losses from storage require additional electricity generation, the latter is mostly produced from wind, thus reducing curtailments and saving fuel costs and emissions. These advantages lead to a clear preference for storage as flexibility option over post-combustion lignite and also partly over natural gas. Lignite CCS is still used but oxyfuel equipped facilities are preferred. Figure 6 presents the resulting cumulated electricity generation, which includes large shares of wind and lignite, some natural gas and lignite oxyfuel. Storage usage reduces energy system costs by 9.8% (compared to the REF_{on} scenario), mostly through natural gas cost savings and by limiting investments to one CCS technology.

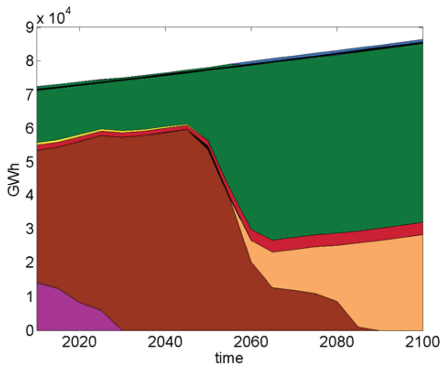

Figure 6: Cumulated electricity generation with storage

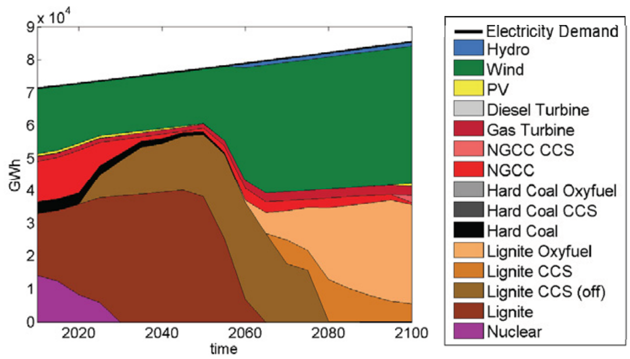

Figure 7: Cumulated electricity generation with must-run constraint for wind

To represent feed-in priority policies for renewables, which exist in several countries, e.g. Germany, we introduced a must-run constraint for wind energy. In contrast to the reference cases, curtailments of wind energy are not possible in this case. Figure 7 displays electricity generation for this scenario. A comparison with Figure 3 shows increased shares in natural gas combined cycle and lignite CCS electricity generation. These flexible technologies allow for balancing of the wind variations throughout the year, contrary to the more inflexible older lignite plants or oxyfuel plants. A large increase of new lignite capacities after 2020 can be attributed to the increased need for flexible operation, as it is assumed that older lignite plants are unable to fulfill balancing requirements. The reduced share of wind energy together with more natural gas and new lignite capacities leads to 13.1% higher energy system costs than in the REF_{on} scenario. Despite its higher costs, the importance of flexible post-combustion for balancing purposes is strongly increased in this scenario.

4. Conclusion and outlook

We present the LIMES model to evaluate the importance of flexible operation of post-combustion CCS plants and to gain insight on optimal technology scenarios for climate change mitigation. Results show a mix of technologies: large amounts of wind energy balanced by natural gas, flexible post-combustion lignite plants or storage technologies. Furthermore, oxyfuel capture plays an important role in base-load electricity generation with low emissions. Introducing flexible capture switching for post-combustion as an additional balancing option leads to a reduction of the natural gas share in the power mix and thus to a reduction of overall costs. The significance of this option is strongly sensitive to the imposed emission budget and prices for natural gas as well as the availability of other technologies. Constraints on curtailments for wind energy lead to additional balancing necessities and increase the share of natural gas and post-combustion power plants. Flexible operation of post-combustion capture for power plants should thus be considered as a technological option in the context of climate change mitigation. However, availability of oxyfuel capture, renewable energy technologies and storage reduces the need for post-combustion CCS and it remains debatable whether the role of this technology will be sufficiently large to justify investments into research and development for both this technology and oxyfuel capture.

The current model setup consists of a single region which is treated as being autarkic. While interconnections to the rest of Germany from this region are limited, this restriction neglects balancing of variability through long-distance electricity transmission. A future model version will include more regions interconnected by power lines, as described in [7]. Despite additional constraints to account for wind power variability, the present model setup does not capture all aspects of temporal fluctuations. Improved time slice setups will address this problem in the future.

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Chapter 5

Decarbonization scenarios for the EU power system*

Markus Haller
Sylvie Ludig
Nico Bauer

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Decarbonization scenarios for the EU and MENA power system: Considering spatial distribution and short term dynamics of renewable generation

Markus Haller *, Sylvie Ludig, Nico Bauer

Potsdam Institute for Climate Impact Research (PIK), Postfach 601203, 14412 Potsdam, Germany

HIGHLIGHTS

- ▸ We present an EU+MENA power system model that considers long term investments and integration of renewables.
- ▸ For low emission targets, renewable integration issues lead to escalating electricity prices.
- ▸ The feasibility frontier can be pushed by adequate transmission and storage investments.
- ▸ The transformation from wind/fossil to wind/solar regime changes integration requirements.
- ▸ Low emission targets can be reached without significant interconnections between EU and MENA regions.

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ABSTRACT

We use the multi-scale power system model LIMES-EU$^+$ to explore coordinated long term expansion pathways for Renewable Energy (RE) generation, long distance transmission and storage capacities for the power sector of the Europe and Middle East/North Africa (MENA) regions that lead to a low emission power system. We show that ambitious emission reduction targets can be achieved at moderate costs by a nearly complete switch to RE sources until 2050, if transmission and storage capacities are expanded adequately. Limiting transmission capacities to current levels leads to higher storage requirements, higher curtailments, and to an increase in temporal and spatial electricity price variations. Results show an escalation of electricity prices if emission reductions exceed a critical value. Adequate expansion of transmission and storage capacities shift this threshold from 70% to 90% emission reductions in 2050 relative to 2010.

1. Introduction

The necessity to reduce greenhouse gas (GHG) emissions to limit anthropogenic climate change has been widely confirmed (IPCC, 2007; UNEP, 2010). The European Union has defined ambitious emission reduction targets for the near and long term future: to reduce domestic GHG emissions by 20% until 2020, and by 80–90% until 2050 (relative to 1990 emissions). The "Roadmap for moving to a competitive low carbon economy in 2050" (EC, 2011) states that domestic emission reductions of 80% would imply overproportional emission reductions of 93–99% in the power sector, owing to the large number of low emission power generation technologies available: fuel switch from coal to gas, power-heat cogeneration (CHP), nuclear power, carbon capture and sequestration (CCS), and a large portfolio of renewable energy (RE) options. But fuel switching and expansion of CHP capacities will not be sufficient to reach ambitious mitigation targets, nuclear power suffers from low public acceptance (especially after the Fukushima accident), and it is uncertain when CCS technology will be ready for large scale deployment. Renewable generation capacities, on the other hand, increased dramatically over the last years. A number of recent studies explore the possibilities for decarbonization of the European power sector, and RE generation dominates many of these scenarios (EWEA, 2011; WWF, 2011; EREC, 2010; ECF, 2010; PWC, 2010).

1.1. A challenge to power system design

The large scale integration of RE technologies into power systems, however, is a demanding task. In its "Special Report on Renewable and Energy Sources and Climate Change Mitigation" IPCC (2011) states that – although RE expansion will not be limited by global technical potentials or fundamental technological barriers – the costs and challenges related to system integration of RE generation may be significant. Due to the uneven spatial distribution and the seasonal, daily, and short

* Corresponding author. Tel.: +49 331 288 2639; fax: +49 331 288 2642.
E-mail address: markus.haller@gmail.com (M. Haller).

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term variability of RE resources, balancing demand and supply requires a combination of dispatchable backup capacities, storage capacities, and the expansion of long distance transmission infrastructure. In Europe and MENA regions, wind onshore and especially offshore potentials are largest in northern and north-western areas, while solar resources are high in the countries surrounding the Mediterranean Sea. Power demand is highest in Central European countries—although demand is projected to increase significantly in the MENA region (Trieb, 2005). The European Commission pushes the establishment of an integrated Trans-European power grid (EC, 2010), however, as power grids have been developed from a purely national perspective, cross-border interconnections are still limited. ENTSO-E (2010) identifies 42 100 km of power lines to be built or refurbished between 2010 and 2020, and claims that integration of RE generation in the Northern and Southern parts of Europe is one of the main drivers. Still, grid expansion is progressing at a limited pace, mostly due to regulatory constraints and long lead times (MVV Consulting, 2007).

But the massive expansion of long distance transmission infrastructure is not be the only possible scenario. If generation capacities are clustered in few regions with high resource endowments, the dependency on electricity imports increases for regions with lower resource availability. This raises energy security concerns in the case that exporting countries are not able – or willing – to deliver the required power. Lilliestam and Ellenbeck (2011) discuss the concerns about European import dependency in the context of the DESERTEC project (Club of Rome, 2008) which promotes large scale power imports of solar generated power from MENA countries. This issue is also important on a national scale: for example, a study commissioned by the German government (SRU, 2010) analyzes the feasibility of a completely renewable based German power system that does not require power imports.

1.2. A challenge to power system modeling

Investment decisions regarding RE generation, transmission and storage capacities are tightly interconnected. It can be expected that coordinated long term planning for these assets, while taking seasonal, daily and short term dynamics of supply and demand into account, would significantly ease the large scale integration of RE generation. Most model-based studies, however, do not take up such a systemic view. The various model approaches that are used to analyze long term scenarios for power systems can be categorized as follows:

Integrated assessment models. These models usually cover multiple sectors, have long time horizons, coarse spatial resolution, and represent variability and spatial distribution of RE sources by using highly aggregated parameterizations. Examples are REMIND (Leimbach et al., 2010), WITCH (Bosetti et al., 2006), MESSAGE-MACRO (Messner and Schrattenholzer, 2000) and POLES (Russ and Criqui, 2007) on a global scale, and PRIMES (Capros et al., 2010) on the European level.

System operation models. These models represent technical characteristics of the power system in great detail. Although they do not consider long term changes of capacities endogenously, they can be used for analyzing the technical feasibility and cost effective operation of power system scenarios. Examples on a European scale are ELMOD (Leuthold et al., 2008), representing the European transmission infrastructure with great detail, and ReMIX (SRU, 2010), which calculates hourly dispatch and transmission flows for a complete year.

Hybrid approaches. These approaches aim at representing long term investment and short term operation decisions in a single framework. The ReEDS (Short et al., 2009) and the US-REGEN (Blanford and Niemeyer, 2011) models follow this approach. Both represent the United States' power system. Hybrid approaches for the Europe and MENA region are scarce: Möst and Fichtner (2010) calculate long term scenarios with the investment model PERSEUS-RET and validate them with the dispatch model AEOLIUS, but there is no hard link between the two models. TIMES-PET (Kypreos et al., 2008) is an European power system model that takes transmission requirements and system operation into account, but it does not include the MENA region and has only 12 time slices to represent short term dynamics. Pina et al. (2011) present another TIMES application with a better representation of short term fluctuations, but the model is calibrated to an isolated island system and does not consider transmission requirements.

So far, there is a lack of multi-scale models that could deliver coordinated long term scenarios for the EU and MENA power systems by considering spatial distribution and short term dynamics of supply and demand endogenously. The LIMES-EU$^+$ model, which is presented in this paper, fills this gap. We use it to analyze how the power sector of the European and MENA regions can be decarbonized by relying on RE resources. The following research questions are explored:

- What reduction levels of power system emission reductions are technically and economically feasible by expanding RE generation—without relying on CCS or building new nuclear power plants?
- What role does an interconnected European and Mediterranean transmission grid play, and how does its availability effect feasible RE penetration levels?
- What are cost effective investment pathways that, in the long term, lead to a decarbonized power system?

The paper is structured as follows: Section 2 introduces the structure of the LIMES-EU$^+$ model and gives an overview of the parameterization. In Section 3.1 we analyze the transition process that leads to a low carbon power system. Section 3.2 takes a closer look at the system in 2050—we investigate the structure of an adequate overlay grid and show how the cost effective choice of RE technologies depends on the availability of grid expansion beyond current levels. In Section 3.3, we perform a sensitivity analysis and show how CO_2 and electricity prices depend on the emission reduction target. Section 4 summarizes the paper and draws some final conclusions.

A detailed documentation of the model formulation and model parameters is provided in the supplementary material.

2. Methodology

2.1. Model structure

LIMES is a partial, multi-regional electricity sector modeling framework. It minimizes total discounted power system costs (investments, fuel, fixed and variable operation and maintenance) over a long time horizon. The model regions differ with respect to their power demand profiles and renewable potential endowments. Regions are interconnected by long distance transmission lines. Build-up and technical depreciation of generation and storage capacities in each region, as well as of transmission capacities between the regions, are modeled explicitly. Short term fluctuation of power demand and RE supply is represented by characteristic time slices. In each time step and region, supply and demand (which is price inelastic) need to be balanced for each time slice, given the available generation, transmission and storage capacities. By determining investment decisions and dispatch of capacities

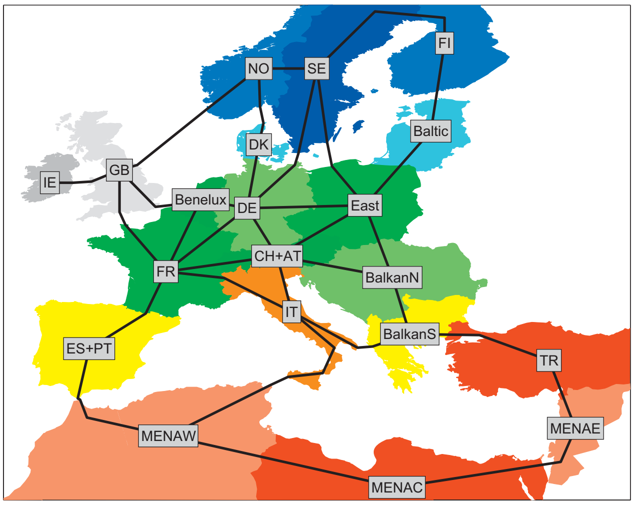

Fig. 1. Regional layout of the LIMES-EU$^+$ model.

Table 1
Aggregation of model regions to region groups (for data visualization only).

Region group	Model regions
EUNorth	NO, SE, FI, Baltic
EUCentral	DE, FR, Benelux, East, BalkanN, CH+AT
GB+IE	GB, IE
EUSouth	ES+PT, IT, BalkanS
MENA	MENAE, MENAC, MENAW, TR

endogenously, it is ensured that all investments are refinanced by the rents that are generated over time. The model takes on a social planner perspective, implying perfect foresight and perfect information. LIMES is formulated as a linear programming (LP) problem. It is implemented in GAMS (2010) and solved with the CPLEX solver.

The LIMES-EU$^+$ model represents the power system of the EU-27 member countries, Norway, Switzerland, and the Middle Eastern and North African countries surrounding the Mediterranean Sea (MENA region). It has 20 geographical regions that are connected by 32 transmission corridors (Fig. 1). To simplify the visualization of results in this paper, these regions are aggregated to region groups (see Table 1).

Long term investment decisions are modeled in 5 year time steps from 2010 to 2050. Short term fluctuation patterns are represented by 49 time slices. There are four seasons, each with three characteristic days that cover low, medium and high RE supply regimes. Each day is represented by four time slices, each one with a length of 6 h. An additional super peak time slice represents high demand and low RE supply. A selection algorithm ensures that the 12 characteristic days adequately represent temporal and spatial fluctuation patterns.[1]

2.2. Parameterization

Nine generation technologies are available: coal, gas and nuclear power plants, biomass IGCC, large hydropower, wind onshore/offshore, photovoltaic (PV) and concentrating solar power (CSP). Carbon capture and storage (CCS) is not taken into account, and it is assumed that no nuclear power plants will be built, although existing plants remain in operation until the end of their technical lifetime.[2] We assume decreasing specific investment costs for solar and wind generation technologies.[3] High voltage AC lines are used as transmission technology. Investment costs for overland lines and sea cables are differentiated. Transmission losses are assumed to be linearly correlated with transmission distance. Two generic storage technologies allow for day/night storage and intra-seasonal storage. CSP is modeled with integrated day/night storage. Tables 2–4 give an overview of the technoeconomical parameters of generation, storage and transmission technologies.

Wind onshore/offshore, PV and CSP resources and fluctuation patterns have been derived from gridded meteorological data (Kalnay et al., 1996). Model input consists of installable generation capacities per region as well as maximum capacity factors per region and time slice. The method for calculating these parameters is based on EEA (2009) and Hoogwijk (2004).[4] Each region features

Table 2
Parameters of generation technologies. For technologies with decreasing investment costs the costs in 2010 and 2050 are given. The availability factor of hydropower is subject to seasonal variations. Availability of fluctuating RE (⁎) depends on region, resource grade and time slice. Monetary units are given in 2008 present values.

Technology	Investment costs (€/kW)	Fixed O&M (%/a)	Variable O&M (ct/kW)	Availability factor (%/a)	Life time (a)	Build time (a)
Nuclear PP	3200	3	0.28	80	60	3.1
Coal PP	1100	2	0.68	80	50	2.2
Gas CC PP	500	6	0.05	80	40	1.3
Hydropower	3000	2	0.00	33–41	80	1.8
Biomass IGCC	1500	4	0.29	80	40	1.3
Wind onshore	970→750	3	0.00	⁎	30	0.8
Wind offshore	2170→1680	5	0.00	⁎	30	0.8
Solar PV	2820→865	1	0.00	⁎	30	0.5
CSP	6480→3640	3	0.00	⁎	35	1.0

Table 3
Parameters of storage technologies.

Technology	Investment costs (€/kW)	Fixed O&M (%/a)	Variable O&M (ct/kW)	Round trip efficiency (%)	Life time (a)	Build time (a)
Day/night storage	1500	0.5	0.24	80	80	1.8
Day to day storage	2500	1	0.00	70	10	0.8

Table 4
Parameters of transmission technologies.

Technology	Investment costs (€/kW km)	Fixed O&M (%/a)	Variable O&M (ct/kW km)	Losses (%/1000 km)	Life time (a)	Build time (a)
Overland line	0.38	0	0	7	50	5
Sea cable	3.8	0	0	7	50	5

[1] Details are provided in the supplementary material.

[2] For the sake of simplicity, reactors already under construction (e.g. France, Finland) are neglected, as well as national plans for phasing out existing reactors (Germany).

[3] The supplementary material provides details on cost curves.

[4] Details are provided in the supplementary material.

three resource grades with decreasing maximum capacity factors to represent generation sites of different qualities.

For each region and grade, maximum full load hours per year can be calculated by aggregating maximum capacity factors across all time slices. If sorted by resource quality, these can be used to construct regional renewable supply curves. Fig. 2 shows these supply curves for aggregated model regions.

Biomass based power generation is assumed to be fully dispatchable. Region constraints on biomass consumption are taken from EEA (2007).

Initial generation capacities are based on the Chalmers Energy Infrastructure database Kjärstad and Johnsson (2007) and IEA (2010a,b). Initial transmission capacities are based on net transfer capacities (NTCs) published by ENTSO-E. Demand profiles are based on ENTSO-E load data. Demand projections until 2050 are taken from Capros et al. (2010) and IEA (2010a,b). We assume a maximum transmission expansion rate of 1 GW/a per cross border interconnection. Price developments for coal natural gas and uranium are based on BMU (2008). For biomass we assume a constant price of 2.5 €/GJ.

Climate policy targets are represented by applying annual emission caps. In this paper we refer to emission reduction targets in 2050 relative to emissions in 2010. Emission caps decrease linearly from 2010 to 2050. There are no regionally differentiated emission targets; the cost effective allocation of reductions across regions is determined endogenously.

2.3. Limitations and scope

The strength of the LIMES-EU^{+} model lies in its integrated, multi-scale perspective. It is important, however, to keep in mind the limitations of this approach. In terms of short term dynamics, the selection of characteristical days and the low temporal resolution of 6 h per time slice leads to a loss of information regarding extreme events and fluctuations on very short time scales (as shown in Haydt et al., 2011). Fluctuations on very large time scales ("good" and "bad" wind years) and forecast uncertainty are not taken into account.[5] In terms of grid representation, the model does not consider power flow distribution effects.[6] All these simplifications may lead to an underestimation of system integration challenges.

On the other hand, there are model characteristics and assumptions that may lead to an overestimation of these challenges: as power demand is assumed to be price inelastic, system integration cannot be facilitated by adapting demand profiles to match fluctuating supply. Considering the scenario design, the efforts of reaching ambitious mitigation targets may be overestimated by excluding other mitigation options besides RE generation. A mixture of nuclear power, CCS and RE generation may well be cost effective from a system point of view. In this study, nuclear power and CCS are excluded ex ante in order to evaluate the feasibility of high RE scenarios. An economic comparison of these alternatives is beyond the scope of this paper.

Lastly, it should be noted that, while social acceptance hampers the current deployment of nuclear power and CCS, it may also become an important issue in high RE share scenarios (e.g. public opposition regarding wind turbine installations and transmission lines). These aspects are not considered in this study.

[5] It should be noted that the super peak time slice, which is characterized by high demand and low renewable supply in all model regions, ensures that sufficient backup capacities are built to guarantee system adequacy in extreme events.

[6] Haller et al. (2012) show in a conceptual framework considering power flow constraints, while significantly increasing numerical costs, have little effect on long term system development.

3. Results and discussion

Table 5 shows the four scenarios that are presented.

To explore the role of an interconnected trans-European and Mediterranean grid, we compare scenarios where power transfers between regions are allowed, but transmission capacities are limited to current levels, with scenarios allowing for grid expansion. Both grid scenarios are shown for a 90% emission reduction target and for a Business as Usual (BAU) scenario without climate policy constraints.

Section 3.1 discusses — in aggregated the long term transformation process that is required to reach the desired target system in 2050. Section 3.2 takes a closer look at the power system in 2050 — we show regional generation mixes, grid structures and generation dispatch across the year. In Section 3.3 a sensitivity analysis with respect to emission caps is performed, and the effect of large RE shares on CO_2 prices and electricity prices is analyzed.

3.1. Long term system development

Fig. 3 shows the generation mix over time (aggregated across all regions) for the `PolGrid` scenario. Existing nuclear power plants are phased out according to their remaining technical lifetime. Coal based generation also decreases to meet emission caps. There are no investments in new coal power plants; however, there is a partial switch from gas to coal in 2015 by changing the dispatch of existing overcapacities. This does not conflict with the imposed emission targets due to the aggressive expansion of onshore wind turbines. An expansion of offshore wind does not take place before 2030. Solar based generation enters the system in 2035, with PV being the dominant technology. The share of dispatchable technologies (gas, hydropower and biomass) remains at about 25% to provide balancing services. The share of gas generation increases after 2030 (which coincides with the expansion of wind offshore and solar based generation), but is limited by the emission constraint.

Fig. 4 summarizes the development of several power system characteristics over time. The generation share of fluctuating RE increases to 75% for both policy scenarios, and it increases to about 40% in the absence of emission caps. This shows that a substantial expansion of RE generation is economically competitive without applying climate policy constraints, but that policy is required to reach ambitious targets. In the absence of emission caps, gas power plants are almost completely replaced by coal power plants. This leads to a coal/RE mix scenario, where emissions in 2050 are 20–40% higher than in 2010, despite the increased RE shares.[7] Foregoing the option of transmission expansion leads only to a small reduction of RE shares in the BAU case—this shows that the incentive to expand transmission capacities is significantly smaller if no climate policy is applied. For the policy scenarios the import share of consumption[8] increases from 4% in 2010 to 20% in 2050. In the BAU scenario, transmission plays a minor role, and the import share levels out at about 8% in 2050. Storage plays only a minor role until 2030, but in the `PolGrid` and `PolNoGrid` scenarios it is expanded significantly afterwards—this coincides with the expansion of solar based generation. The storage charge to total generation ratio increases to 10% if transmission is allowed. Foregoing the option to expand transmission capacities leads to an increase of this parameter to 15%. Despite these increased investments in storage capacities curtailments increase to 14% if transmission is not available.

[7] See Section 3.3 for a sensitivity analysis regarding different emission caps, and the resulting CO_2 prices in 2050.

[8] The import share of consumption is defined as demand which is not met by domestic resources, divided by total demand. It is determined individually for each model region and aggregated afterwards.

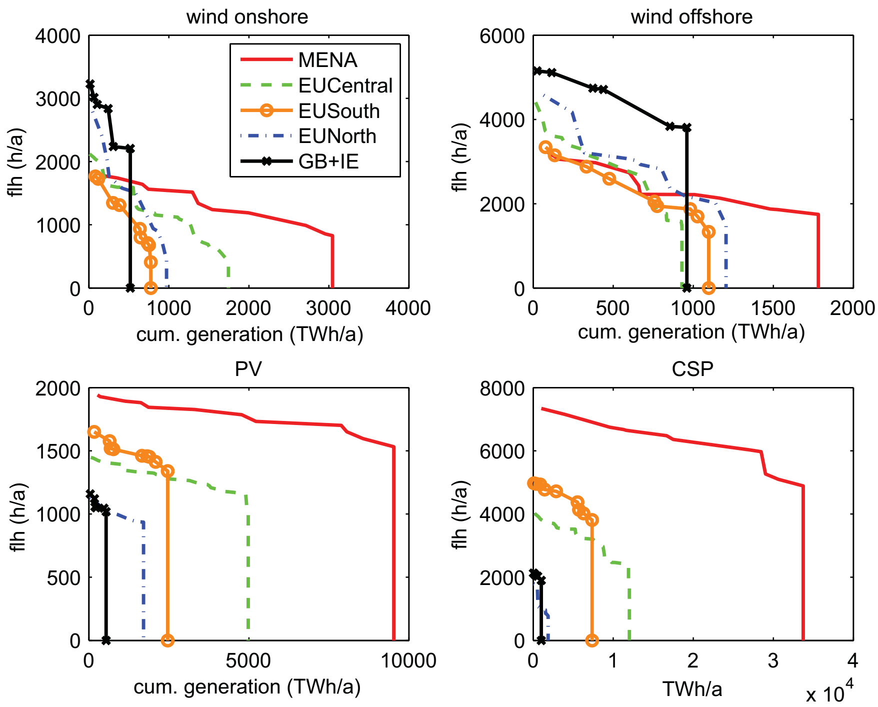

Fig. 2. RE potentials (marginal annual full load hours over total generated power) for aggregated region groups.

Table 5
List of scenarios.

Scenario	Emission reduction until 2050 (rel. to 2010)	Transmission expansion beyond 2010 levels
PolGrid	90%	Yes
PolNoGrid	90%	No
BAUGrid	None	Yes
BAUNoGrid	None	No

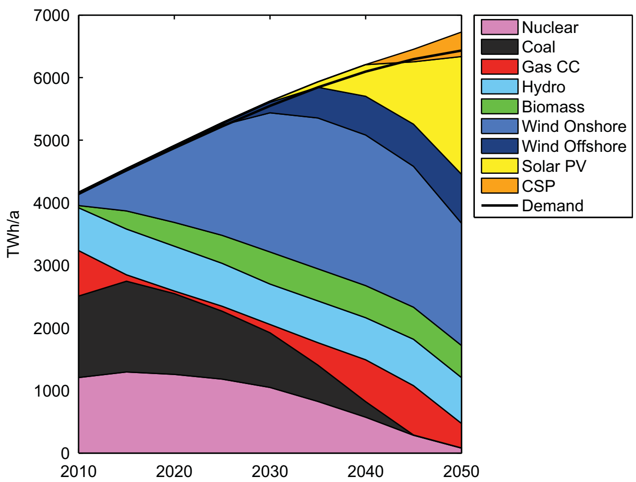

Fig. 3. Generation mix over time for the PolGrid scenario, aggregated across all regions.

3.2. The power system in 2050

This section takes a closer look at the power system in 2050 for the two policy scenarios.

Fig. 5 shows regional generation mixes in 2050 for the PolGrid and PolNoGrid scenarios. If transmission expansion is allowed, it plays an important role—although all regions exploit their domestic RE resources to a certain extent. Central European regions are net importers (mainly Germany, Eastern Europe and the Benelux countries), with import shares of 30–60% of total consumption. The main exporters are the Scandinavian countries (hydro and wind), Great Britain and Ireland (wind), and southern European and north African regions (PV and CSP). CSP, while making only a small contribution to overall generation, reaches large shares in the eastern and western MENA regions. In the PolNoGrid scenario, the lack of imports in Central European countries is mainly compensated by an expansion of domestic PV capacities, which displace wind onshore and offshore generation capacities in Norway and GB.

Fig. 6 shows installed transmission capacities and net flows in 2050 for the PolGrid scenario. The major transmission corridors are from Scandinavia, Great Britain and Spain to central European countries. Connections between MENA regions and Europe do exist, but they play a minor role. Turkey imports power from central and eastern MENA regions.

Fig. 7 shows net transmission over time across the major transmission corridors that have been identified above (see Table 1 for a definition of region groups). Net flows increase rapidly from 2010 onwards. Flow patterns show a shift between two regimes: until 2030, Northern European countries and the British Islands export electricity not only to central Europe, but also to the southern regions. After 2030, coinciding with the expansion of solar based generation, exports to the southern regions decrease, and MENA and southern European countries become net exporters in 2035 and 2040, respectively.

Fig. 8 shows generation across time slices in 2050 for Germany, which is the largest net importer in the PolGrid scenario. In this scenario, wind onshore and offshore dominate the generation mix, and supply and demand fluctuations are almost completely balanced by imports. Additional generation by gas power plants

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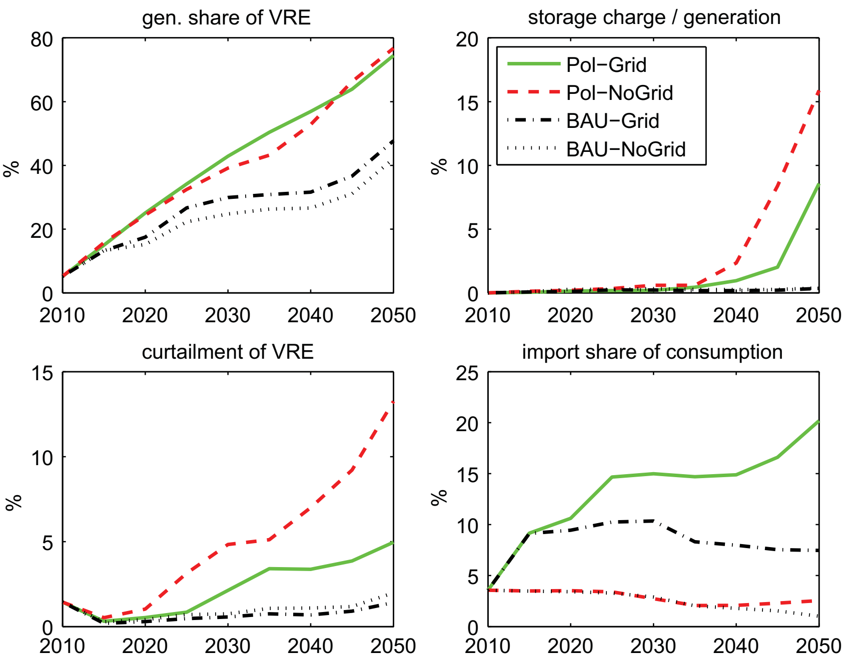

Fig. 4. Long term system development for all scenarios. The panels show generation share of fluctuating RE, storage charge to total generation ratio, import to total consumption ratio, and curtailments of fluctuating RE.

mainly occurs on winter days with low wind supply. Storage capacities are very small. In the `PolNoGrid` scenario, PV capacities are expanded significantly, which leads to large generation surplus during daytime. This is compensated by large day/night storage capacities to shift this surplus to the night time slices.

3.3. CO_2 and electricity prices

Fig. 9 shows endogenously calculated CO_2 prices and electricity prices in 2050 that result from applying different emission caps. It shows results for the `Grid` and `NoGrid` configurations analyzed above, and additionally for a configuration where neither transmission nor storage expansion is allowed. CO_2 prices are larger than zero for 2050 emission levels of 120–140% rel. to 2010. Thus, emissions would increase by 20–40% (depending on the availability to expand transmission capacities) if no emission caps were applied. This is caused by an expansion of coal generation which replaces gas (due to lower fuel prices) and nuclear (because we assume that no new nuclear power plants will be built), an effect that overcompensates the increase of RE generation shares to 40% (see Fig. 4). Prices increase moderately up to emission reductions of 60%. For more ambitious targets, the results show a nonlinear increase. This indicates that there is a feasibility frontier where the increasing share of RE generation leads to serious integration issues.

The increase of average electricity prices is less pronounced than the increase of CO_2 prices. Marginal costs for every additional ton of CO_2 are high, but due to the low level of residual emissions, this leads to a decreasing cost mark-up for the average electricity price.[9]

Allowing for the expansion of transmission and storage capacities has two effects: firstly, it leads to a general reduction of CO_2 prices and electricity prices. For moderate emission caps (less than 60% reductions), these price differences amount to 70−120 €/tCO_2 and 0.8–1.2 ct/kW h, respectively. Secondly, it shifts the frontier where prices increase above tolerable levels to more ambitious emission targets. The threshold after which electricity price increases escalate lies between 70% and 90%, depending on the availability of transmission and storage.

The increasing share of fluctuating RE has an additional effect: it leads to an increase in temporal and spatial price variations. Fig. 10 shows cumulative distribution functions of electricity prices in 2050 for all regions and time slices.[10] In the absence of emission caps (`BAUGrid` and `BAUNoGrid` scenarios) price variations are very moderate, and the availability of transmission expansion has only a small effect. In the `PolGrid` and `PolNoGrid` scenarios, however, price variations are much more pronounced, and foregoing the option to expand transmission capacities leads to a significant increase of price variations. About 24% and 35% of all prices are zero (for `PolGrid` and `PolNoGrid` scenarios, respectively), indicating that supply exceeds demand in the respective time slices and regions—a situation that would pose severe problems for a market that relies on marginal pricing methods, as it is currently the case in the EU.

4. Conclusions

We explore long term decarbonization strategies for the power sector of the European and MENA regions. Analyses have been performed using the LIMES-EU$^+$ model, a multi-scale power system model that integrates long term investment decisions in generation, transmission and storage capacities as well as the effects of short term fluctuation of renewable supply. We show that – if transmission and storage capacities are expanded well

[9] Both CO_2 price and electricity price are marginals (of emission and energy balance constraint, respectively) determined endogenously during the optimization process. Thus, the CO_2 price is included in the electricity price.

[10] Prices for the super peak time slice are not shown, as they increase well above 100 ct/kW h.

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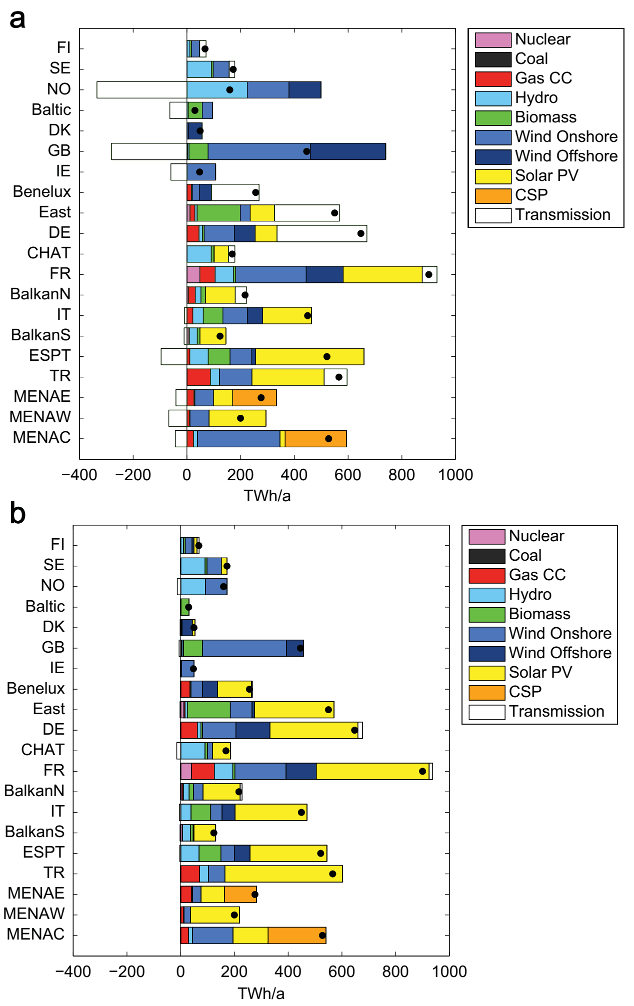

Fig. 5. Regional generation mix in 2050 for the `PolGrid` and `PolNoGrid` scenarios. The dots mark domestic demand. (a) `PolGrid` scenario and (b) `PolNoGrid` scenario.

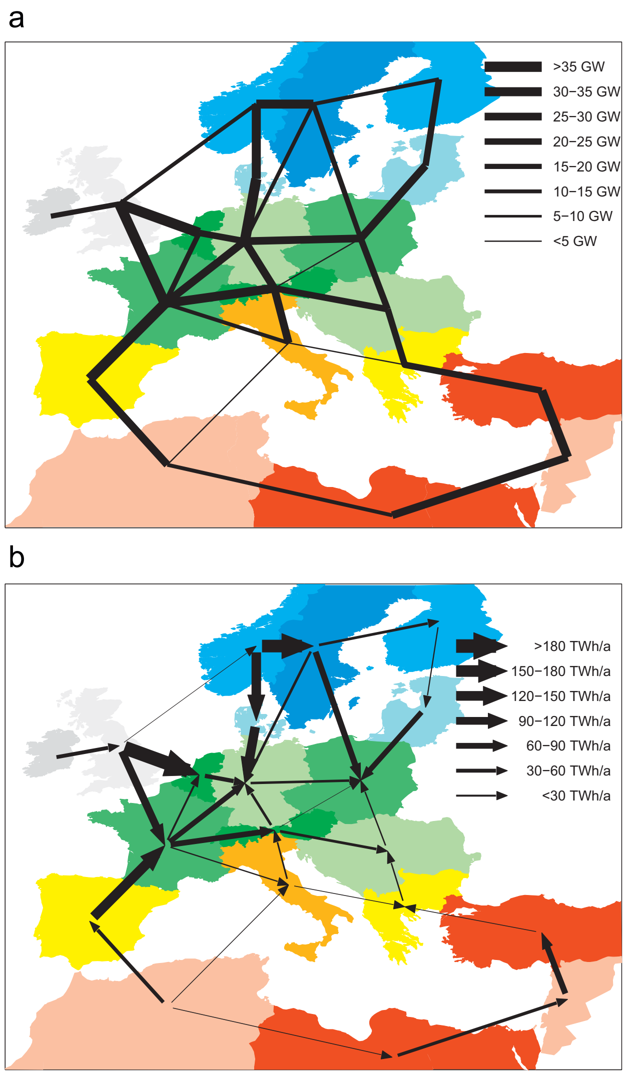

Fig. 6. Transmission capacities and net transmission flows in 2050 (`PolGrid` scenario). (a) Transmission capacities and (b) net transmission flows.

above their current levels – a near complete decarbonization of the power sector can be achieved at moderate costs. Although every region exploits its domestic RE resources to some extent, long distance transmission plays an important role. Up to 2030 transmission capacities are expanded to transfer power generated by wind onshore and offshore from Scandinavia and the British Islands to central and southern European regions. After 2030 PV and CSP capacities are expanded, and southern European countries become net exporters as well. In 2050, central European countries import 30–60% of their domestic demand. These results show that creating an interconnected power system for the EU and MENA regions does not only require significant transmission capacity expansions; it also strongly increases import dependency of central European regions. This may raise concerns regarding energy security—although in this study, the major share of power exchanges occurs within the EU region. Power exports from MENA to European countries increase after 2040, but they play a minor role.

The study also shows that emission reductions of up to 90% are still feasible without expanding transmission capacities. This leads to a fragmented system without major long distance power transfers, where each region is able to meet its domestic demand

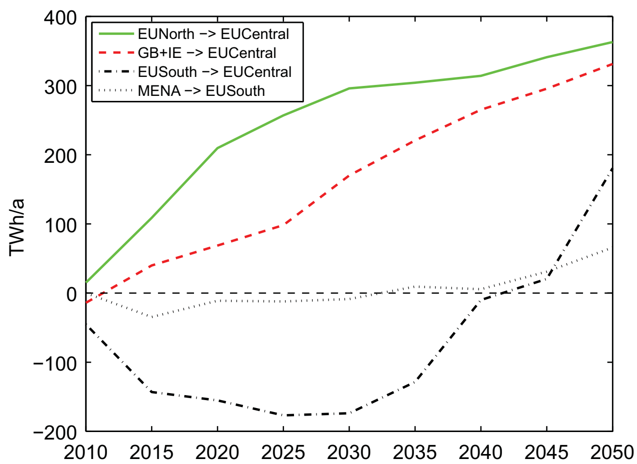

Fig. 7. Net transmission flows over time across the four major transmission corridors (`PolGrid` scenario).

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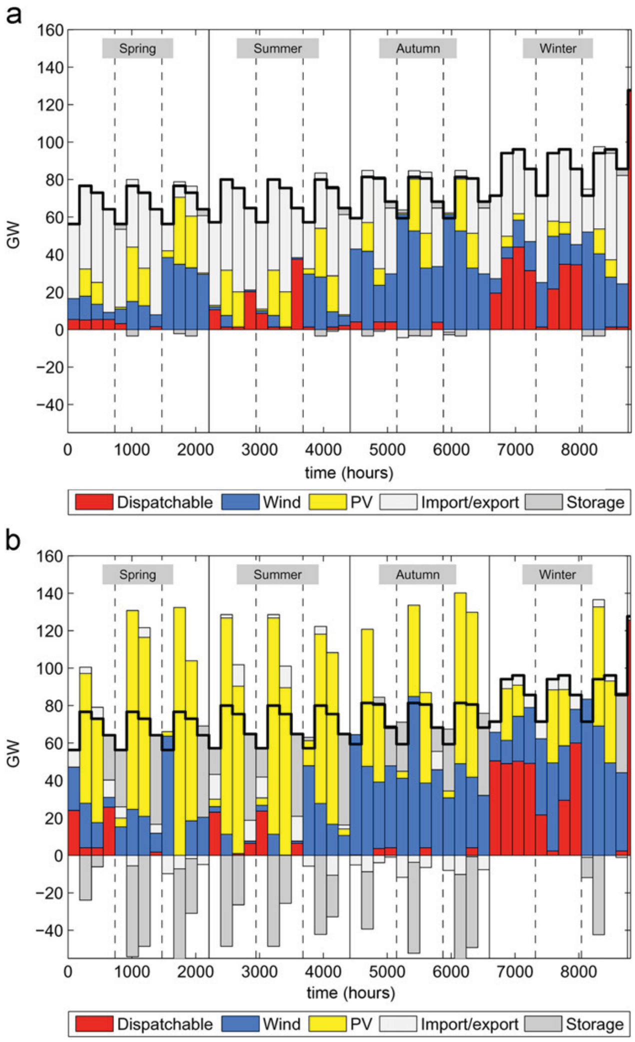

Fig. 8. Generation mix across time slices in 2050, for Germany (`PolGrid` and `PolNoGrid` scenarios). The black line represents domestic demand. To improve readability, technologies have been aggregated to groups (dispatchable: coal, gas, hydropower, biomass, nuclear; wind: wind onshore/offshore; storage: day/night and intra-day storage). (a) `PolGrid` scenario and (b) `PolNoGrid` scenario.

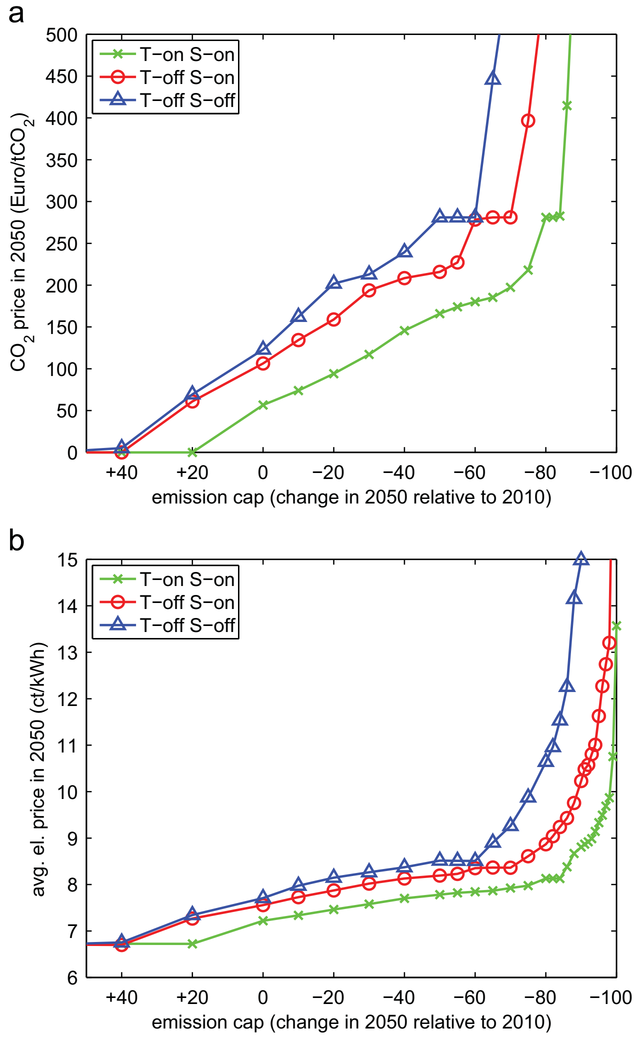

Fig. 9. CO_2 prices and electricity prices in 2050 depend on the emission cap and the availability of transmission and storage expansion. (a) CO_2 prices in 2050 and (b) electricity prices in 2050.

without relying on imports. In this case, solar PV is used to a much greater extent in central European regions, which requires large storage capacities to account for diurnal supply fluctuations.

We identify a threshold for emission reductions where CO_2 prices and electricity prices escalate. By expanding transmission and storage capacities beyond their current levels, this threshold can be shifted from 70% to 90% reductions up to 2050.

High shares of fluctuating RE lead to a significant increase in temporal and spatial price variations. Marginal pricing methods, as they are currently used on the European power markets, are likely to fail under these conditions. This indicates that the development of adequate market designs (e.g. capacity markets) is an important requirement for managing the transition to a renewable based power system.

The LIMES-EU$^+$ approach fills a gap in the current literature by delivering long term power system scenarios that take RE integration issues explicitly into account. It does not intend to replace bottom-up models with higher technological, temporal and spatial resolution—these are very well suited to analyze the technical and economical feasibility of a desired target system. Its strength lies

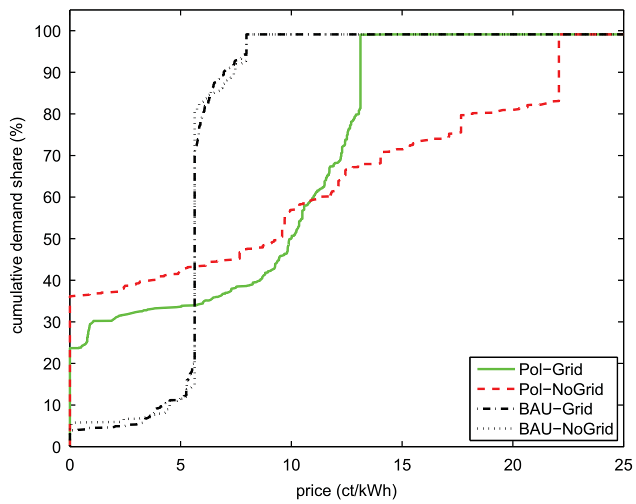

Fig. 10. Cumulative distribution function of electricity prices in 2050 (prices for all regions and time slices).

in the ability to analyze pathways which can be taken to reach a long term target.

There are many opportunities for future work. An important issue is to validate the presented scenarios with a detailed bottom-up model. Inside the LIMES-EU$^+$ model, there is still some room (in terms of numerical cost) to increase short term temporal resolution—this may be especially important to represent fluctuations of wind supply. Acquiring higher resolution meteorological is very demanding and was out of the scope of this paper. An interesting issue is to explore different regional or national climate policies—the model would be well suited to examine which harmonized or fragmented climate policy measures are required to incentivize RE expansion and to reach emission targets. Another important topic is the feasibility of scenarios with combined expansion of RE and other low carbon generation options (nuclear and CCS).

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2012.04.069.

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Chapter 6

Expansion strategies for power generation and transmission in Germany*

Sylvie Ludig
Eva Schmid
Markus Haller
Nico Bauer

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A sensitivity analysis of expansion strategies for German transmission corridors under uncertainty of demand development and technology availability

Sylvie Ludig[1,*], Eva Schmid[1], Markus Haller[1], Nico Bauer[1]

Potsdam Institute for Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany

Abstract

The long-term energy strategy by the German government in 2010 and 2011 contains plans for a substantial CO_2 emission reduction and high shares of renewable energy in electricity production along with an accelerated nuclear phase-out. The importance of power grid expansion to achieve these goals is often underlined, yet little investigated in an integrated framework considering a joint optimization of generation technology and transmission line capacity. We apply the energy system model LIMES-D to analyze integrated scenarios for the expansion of power generation and transmission in Germany until 2050. Short-term fluctuations of demand and renewable energy output are accounted for via an improved time slice approach. A sensitivity analysis investigates the impact of uncertainties in power demand and technology availability. Results indicate that a reduction of power demand and the availability of offshore wind energy and carbon capture and storage play a crucial role for scenarios to comply with the government's CO_2 emission limitation and renewable energy targets. A broad technology portfolio could hedge against future power demand increases while still reaching decarbonization and renewable energy targets. Furthermore, timely grid capacity expansion, especially for eastern and north-south connections, will be important for a cost-effective power system transformation.

Keywords: Renewable energy, Variability, Power Sector Decarbonization

*Tel.: +49 331 288 2427; Fax.: +49 331 288 2640
Email address: sylvie.ludig@pik-potsdam.de (Sylvie Ludig)

1. Introduction

In its energy concept from 2010 and the subsequent amendment in 2011 (Federal Government, 2011), the German government set ambitious long-term targets for CO_2 emission reductions, energy generation from renewable energy technologies (RET) and energy efficiency. While the energy transformation will affect all sectors, the power sector might experience the most thorough transformation. Plans for a significant decarbonization, a share of 80% RET in the power sector in 2050 aimed for in the Renewable Energy Sources Act (EEG, Deutscher Bundestag (2009)) and the nuclear phase out until 2022 (Deutscher Bundestag – 17. Wahlperiode, 2011) will all lead to changes within the electricity sector. While Germany is already partly on its way to meet these targets (e.g. 20% RES in electricity generation in 2011 (BMU, 2012)), their full adoption will have a fundamental impact on the power system.

Three problems are detailed in the following that could prevent a successful implementation of these plans: temporal and spatial variability of RET, uncertainty about the availability of certain low-carbon technologies and uncertainty about future electricity demand. Regional potentials for RET and demand centers are unevenly distributed throughout the country, thus an inadequately developed grid can lead to power distribution problems. In fact, the vast majority of decarbonization scenarios for Germany (Schmid et al., 2012b) show high amounts of wind energy (onshore and offshore). Since the potential for these two technologies is largest in the northern regions of the country, the question about the necessary transmission grid capacities for the transport of such large amounts of electricity from the North to southern demand centers arises. However, Germany is represented as a single region within these studies, without a detailed regional assessment of transmission needs within the country. Besides spatial aspects, short-term fluctuations of RET also need to be taken into account since their variability calls for additional measures e.g. backup through conventional technologies or electricity storage. Low carbon technologies, such as fossil plants equipped with CCS and large-scale offshore wind energy, play a crucial role in various scenarios for the German power sector (e.g. Schlesinger et al., 2010; Nitsch et al., 2010). However, it is uncertain whether these technologies will be widely available in due time to support decarbonization strategies owing to technical challenges and public acceptance problems. Finally, since future electricity demand might be reduced, e.g. by energy efficiency measures, but also increased e.g. by electrification of other sectors such as transport, no unambiguous projection is available.

This paper aims at determining technology portfolios and transmission corridor expansions that allow reaching targets for RET shares and CO_2 emission reductions. It presents scenarios for the German power sector in a sensitivity analysis of demand projections and the availability of CCS and offshore wind. These scenarios need to account for long-term intertemporal development of capacities for both generation and transmission of electricity, combined with short-term investigation of fluctuation effects. This allows to determine technology portfolios that meet the target values of climate protection, cost effectiveness and security of supply. Furthermore, to ensure that during the transformation of the power system refinancing of neither investments in generation technologies nor of those into electricity grid expansion are jeopardized due to a mismatch of their developments, it is necessary to coordinate their expansion. One criterion for such robust scenarios is an endogenous determination of capacities for transmission and generation to ensure their coherent development over the complete transition period instead of considering only a target year. Furthermore, high temporal and spatial resolution allow for detailed investigations of RET integration problems. So far, however, 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 most studies treat one or more aspects while disregarding others and fail to provide robust integrated scenarios covering both generation and transmission of electricity. Table 1 presents a review of recent studies and different models used for the investigation of 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: first, studies centered around the current energy transformation plans, second, Integrated Assessment and Energy System models for Germany, third, grid studies for Germany and fourth, recent integrated models investigating both transmission and generation for Germany or Europe.

Several studies investigating the development of the German power sector were published in 2010: Nitsch et al. (2010) for the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Schlesinger et al. (2010) for the Federal Ministry of Economics and Technology and SRU

Table 1: Comparison of RES integration and grid expansion studies for Germany and Europe (- indicates absence of a feature, + its availability).

	Intertemporal endogenous capacity	Transition 2010–2050	Grid		Temporal Resolution
			Within D	To others	
Schlesinger et al. (2010)	conventional only	+	-	+	+
Nitsch et al. (2010)	-	+	-	validation only	validation only
SRU (2010)	-	-	cost assess.	+	+
Klaus et al. (2010)	-	-	-	-	+
Kirchner and Matthes (2009)	conventional only	+	-	-	+
REMIND-D (Schmid et al., 2012a)	+	+	-	-	RLDC approach
TIMES-D (Blesl et al., 2007)	+	+	-	-	-
IKARUS (Markewitz et al., 1996)	+	+	-	-	-
PERSEUS (Enzensberger, 2003; Rosen et al., 2007)	+	+	-	+	with AEOLIUS
German Energy Agency (2010b)	-	-	+	-	-
ELMOD (Leuthold et al., 2009b)	-	-	+	+	-
URBS-D (Heitmann and Hamacher, 2009)	-	-	+	+	+
URBS-EU (Schaber et al., 2012)	-	-	+	+	+
DIMENSION (Fürsch et al., 2012)	unclear[4]	+	-	+	+
LIMES-EU^{+} (Haller et al., 2012b)	+	+	-	+	+
LIMES-D (this study)	+	+	+	-	+

(2010) for the German Advisory Council on the Environment. The models used within these studies mainly cover generation technologies needed for the energy transformation and treat network issues only briefly. This is also valid for the studies presented by Klaus et al. (2010) and Kirchner and Matthes (2009). Several models (Schmid et al. (2012a); Blesl et al. (2007); Markewitz et al. (1996); Enzensberger (2003)) have been used in the past for the investigation of energy scenarios for Germany, however, most of these models focus largely on the energy system as a whole and either omit spatial consideration of power transmission or use rough approximations. German Energy Agency (2010b); Leuthold et al. (2009b); Weigt et al. (2010); Leuthold et al. (2009a); Weigt (2009), on the other hand use more detailed representations of the German power grid but only treat power generation capacity development exogenously. In 2012, German TSOs presented a plan for transmission network development based on previously defined scenarios (50Hertz Transmission GmbH et al.). This report uses scenarios from Schlesinger et al. (2010) and Nitsch et al. (2010) for the development of generation capacities in Germany to investigate necessary power grid extensions via a heuristic, iterative process. 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 (2009) and Schaber et al. (2012) 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. (2012), allows for assessments of power generation and transmission transformations for Europe. Similarily, Haller et al. (2012b) present scenarios for Europe and the MENA region with the multi-scale power system model LIMES-EU$^+$, including a analysis of results for Germany. However, within DIMENSION and LIMES-EU$^+$, Germany is represented as a single region. Since inadequate 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.

For this analysis, LIMES (Ludig et al., 2011; Haller et al., 2012b,a) 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 high-RET scenarios. LIMES-D thus provides the framework to answer questions about the combined requirements for capacity extension and grid enhancements in the light of ambitious targets for RET and climate protection. Additionally, a range of scenarios are investigated in a sensitivity analysis to assess uncertain parameters such as technology availability and power demand to answer the following research questions: What are important expansion strategies for transmission corridors that should be at the core of future network development plans for Germany? Does the level of electricity demand influence the choice of technological options for decarbonization? What is the role of offshore wind energy and CCS in electricity sector transformation scenarios?

The remainder of this article is structured as follows: Section 2.1 presents the model setup of LIMES-D, Section 2.2 discusses scenario assumptions and Section 3 presents results. A comparison of results to those of other studies is presented in Section 4 and Section 5 concludes.

2. Methodology

This section first provides information on the main features of the model LIMES-D used within this analysis (Section 2.1) with an emphasis on the implementation of regional detail and temporal variability. In a second part (Section 2.2), scenario definitions used for the sensitivity analysis are described and assumptions on technology uncertainties and long-term demand projections are described.

2.1. Model Setup

LIMES-D is a partial, multi-regional electricity sector modeling framework that performs an intertemporal minimization of total discounted power system costs for the time frame 2010-2050 (for an in-depth description of the model, see Ludig et al. (2011); Haller et al. (2012a,b)). These consist of investment costs, operation and maintenance (O&M) 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 for technologies implemented in LIMES-D can be found in Appendix A.

2.1.1. Regional Structure

Regional differences for RET potential and power demand within Germany are represented by 5 regions designed along the four regions of the German Transmission System Operators (TSOs) *50Hertz Transmission GmbH*, *TenneT TSO GmbH*, *Amprion GmbH* and *EnBW Transportnetze AG*[1]. 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 long distance HVAC transmission lines. Initial capacities for transmission lines are based on own calculations derived from Net Transfer Capacity (NTC) values by Hohmeyer et al. (2011). Table A.5 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. However, despite only covering an aggregated view of the German grid within LIMES-D for reasons of limiting numerical complexity, 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. Second, offshore wind, when available, will be connected to the northernmost regions[2], 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[3].

Model regions differ by (i) magnitude and temporal pattern of electricity demand, (ii) endowment with RET potential and (iii) 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

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

[2] 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.

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

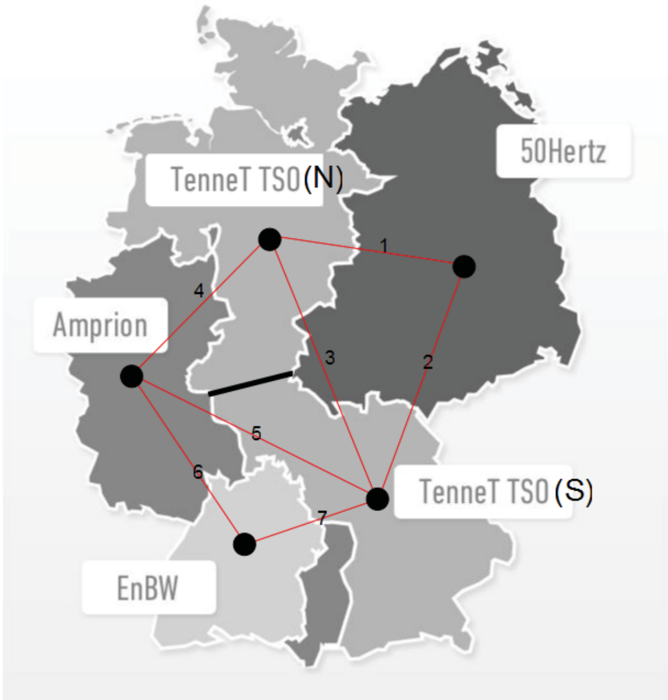


Figure 1: Model regions and long-distance transmission corridors in LIMES-D (Map source: http://netzentwicklungsplan.de/sites/default/files/bilder/karte_0.pdf)

Table 2: Overview of important regional parameters

		50Hertz	*Tennet (N)*	*Tennet (S)*	*Amprion*	*EnBW*
Demand[a,b,c,d,e]	[TWh]	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] Länderarbeitskreis Energiebilanzen (2012) [b] 50Hertz Transmission GmbH (2010c) [c] TenneT TSO GmbH (2010c) [d] Amprion GmbH (2010b) [e] TransnetBW GmbH (2010b) [f] Bofinger et al. (2011) [g] European Environment Agency (2009) [h] Hoogwijk (2004) [i] Súri et al. (2007) [k] DEBRIV (2009) [l] Knopf et al. (2010)

potentials for onshore wind is highest in the northern regions *50Hertz* and *Tennet (N)*. Solar potential, on the other hand, is higher in the south (mainly *EnBW* and *Tennet (S)* where the main demand centers are located.

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 RET targets. Their current formulation in the plans laid out by Federal Government (2011) implies that RET power imports are a possible means to cover domestic RET share targets. In LIMES-D, as consumption equals generation, the RET target is harder to achieve, thus providing a conservative assessment of how to attain it.

2.1.2. Consideration of Short-term Variability

The representation of temporal variability of RET constitutes the second modeling challenge when investigating scenarios with high RET shares. One possible solution used in several studies (Ludig et al., 2011; Nicolosi et al., 2010) 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 of power demand and supply of RET. 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

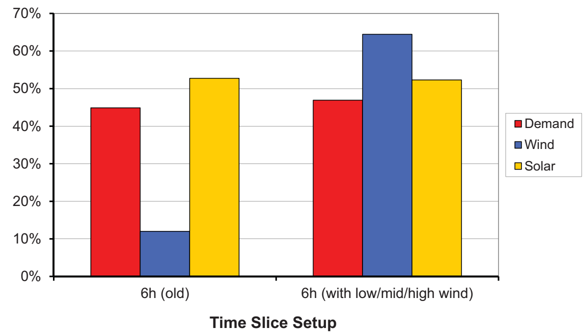


Figure 2: Comparison of time slice setups with and without differentiation of low, medium and high wind feed-in for a setup with time slices representing 6h of each characteristic day.

data[4]. 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. However, as discussed in Ludig et al. (2011), 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 RET can be balanced as well as coverage of longer still wind periods. 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[5].

[4] 50Hertz Transmission GmbH (2010b,a,c); Amprion GmbH (2010c,a,b); TenneT TSO GmbH (2010b,a,c); TransnetBW GmbH (2010c,a,b)

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

2.1.3. Long-term Scenarios and Policy Assumptions

The time horizon within LIMES-D is 2010-2050 to enable the analysis of long-term scenarios for the power sector. Investment decisions into generation and transmission capacities and power plant dispatch are determined endogenously for each 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[6] and set exogenously for each time slice. 2010 values are based on TSO data[7] time series and Länderarbeitskreis Energiebilanzen (2012) 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 or imports from another region. In the reference setup, a near-constant annual increase of 0.2% is assumed. This accounts for the effects of decreasing population on the one hand and increasing GDP as well as demographic change leading to increases in the number of households on the other hand. Furthermore, demand trends from other studies are considered in the scenario setup to investigate the impact of efficiency policies (see Section 2.2). An initial model calibration ensures that demand is met by generation in each region for the first time step.

Targets within Federal Government (2011) are used as a starting point for this investigation, thus German CO_2 emission reduction and RET plans are imposed in all scenarios. Since Federal Government (2011) only contains general CO_2 emission reduction targets, a power sector CO_2 emission reduction of 98% in 2050[8] was set in LIMES-D based on considerations for power sector decarbonization in European Commission (2011). Furthermore, the nuclear phase out until 2022 and a target of 80% RET in the power mix in 2050 are implemented in the model.

2.2. Sensitivity Analysis

In this paper, uncertainties about the evolution of the electricity sector are considered through a sensitivity analysis varying power demand and technology availability. This section provides a definition of the scenarios presented in Section 3.

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

[7] 50Hertz Transmission GmbH (2010c); Amprion GmbH (2010b); TenneT TSO GmbH (2010c); TransnetBW GmbH (2010b)

[8] compared to 0.35 $GtCO_2$ in 1990

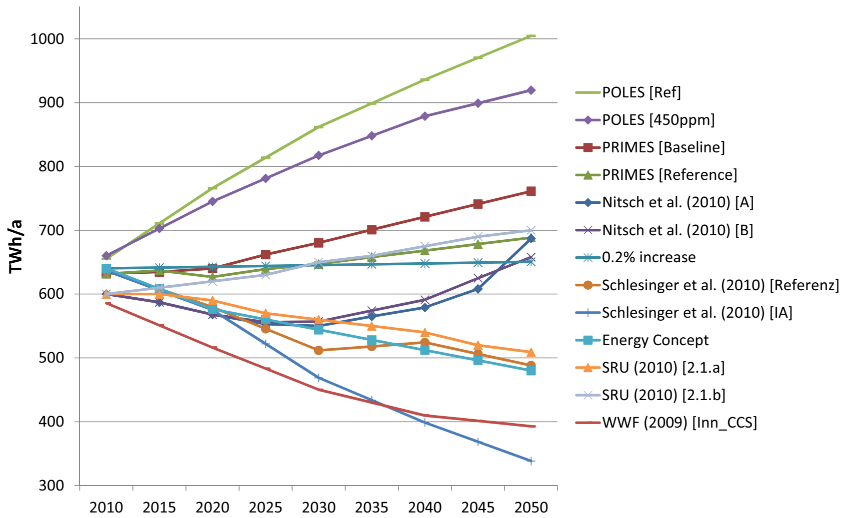


Figure 3: Different scenarios for total annual gross electricity generation in Germany

The level of electricity demand is set exogenously in LIMES-D. However,while it is to be expected that projections for future energy demand differ due to their underlying assumptions, the spread of power demand scenarios for Germany is impressive (see Figure 3). The models PRIMES (Capros et al., 2010) and POLES (Kitous et al., 2010) assume rising demand, Nitsch et al. (2010) expect demand to be decreasing and subsequently increasing while Schlesinger et al. (2010) preview demand to drop until 2050. The plans presented in Federal Government (2011) foresee energy efficiency measures to reduce power demand by 25% (compared to 2008 values) by 2050.

To take this spread into account, the main scenarios presented in Section 3 contain three different projection paths for demand: 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 (2011). 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 RET target and

Table 3: Sensitivity analysis scenario overview

	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 CO_2 emission reduction target is impossible due to residual emissions from balancing constraints (see Section 2.1.2), the PRIMES Baseline scenario was selected. Lower demand scenarios than the one based on Federal Government (2011) 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.

Subsequently, technology constrained scenarios are analyzed to check the influence of the availability of CCS and offshore wind energy on technology and grid expansion choices. 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).

The Discussion of the results will start with a description of the reference scenario in Section 3.1. 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 3.2 then presents the first part of the sensitivity analysis: a comparison of scenarios with different assumptions for electricity demand which allows to determine the impact of the demand level on technology choices and grid capacity extensions. The second part of the sensitivity analysis is conducted in Section 3.3 where the impact of non-availability of CCS or offshore wind energy on the feasibility of government targets within LIMES-D is discussed. Furthermore, technology portfolios and grid expansion corridors are examined for feasible scenarios. Finally, power system costs are compared for all cases to evaluate the economic impacts of the uncertainties investigated in this analysis.

3. Results

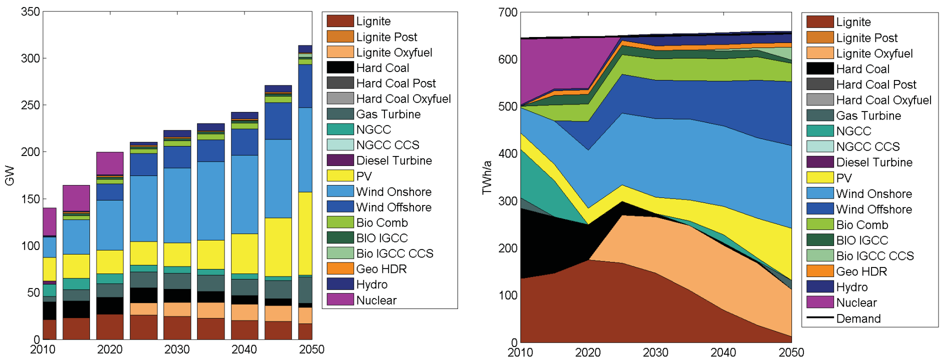
3.1. Reference Case

This section discusses the reference case *All Opt Med* with a moderate power demand and no constraints on technological availability through an investigation of the development of capacities for transmission and generation and of the power generation mix. Model results from LIMES-D show a significant transformation of the power generation technology mix for Germany from 2010 to 2050 (see Figure 4). As expected due to the RET and CO_2 emission reduction targets, capacity developments shown in Figure 4a include high increases in RET capacities, mainly for wind (onshore and later offshore) and solar PV. Contrary to recent trends (BMU, 2012), installations of solar PV are only minor for the coming decades until their capacity sees stronger increases after 2030. Gas turbines are installed mainly due to backup and balancing requirements (see also Section 2.1) and lignite power plants with oxyfuel capture enter the technology mix. Conventional hard coal and lignite capacities, on the other hand, mostly 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[9] will be almost completed, nuclear energy still plays a fairly important role in the power mix. Within the initial phase, electricity generation from natural gas, lignite and hard coal takes up substantial shares. While wind energy and other RET capacities 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 RET dominated mix. However, despite the high share of RET 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 (gas turbines and NGCC) vary throughout time, their capacity stays fairly constant as less efficient but more flexible gas turbines are installed in favor of the less flexible NGCC. For balancing and backup purposes, a certain amount

[9] All German nuclear power plants will go out of operation until 2022 (see Deutscher Bundestag – 17. Wahlperiode, 2011).



(a) Capacity (b) Generation

Figure 4: Technology Mix for Germany 2010-2050, *All Opt Med* case

of natural gas and biomass capacities needs to be installed (relative to the share of RET) to cover for sudden power drops by fluctuating renewables (see Section 2.1.2 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 RET with a decreasing but still important 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 RET 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 German Energy Agency (2005, 2010b) 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 mostly phased out until 2050 and largely replaced by imports while the *TenneT (S)* region in the south switches almost completely to RET generation with a large share of solar PV. Overall, there is a strong increase in RET generation with remaining shares of lignite in the north and large increases of north-south transmission capacities while changes in regions further south consist in a stronger interconnection of regions with a near complete switch to RET.

3.2. Sensitivity Analysis – Part 1: Varying Electricity Demand

The first part of the sensitivity analysis investigates the impact of different power demand scenarios for Germany on the generation mix and on transmission grids. First, a comparison of power generation in 2050 for the three different demand cases is presented in Figure 7. The resulting technology mix shows similar technologies for all cases but some notable differences occur in their respective shares. Large amounts of RET, partly induced by the imposed 80% RET targets, dominate the installed capacities with some additional natural gas and lignite-based generation, the latter

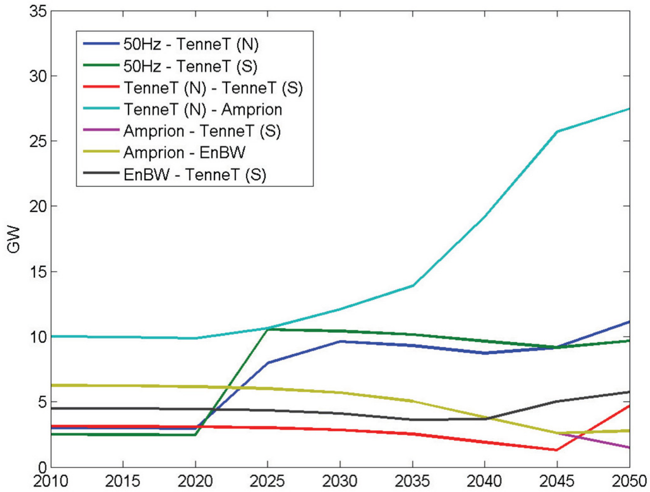
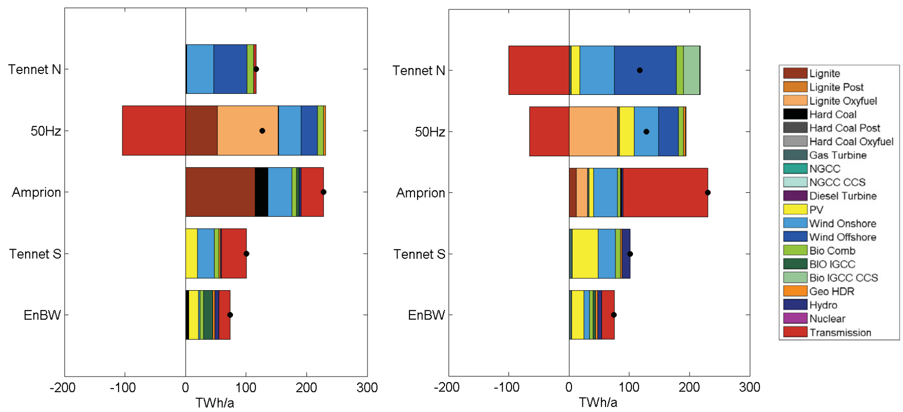


Figure 5: Transmission capacities between regions *All Opt Med* case



(a) 2025 (b) 2050

Figure 6: Regional electricity mixes in 2025 and 2050, *All Opt Med* case. The black marker indicates the demand for each region.

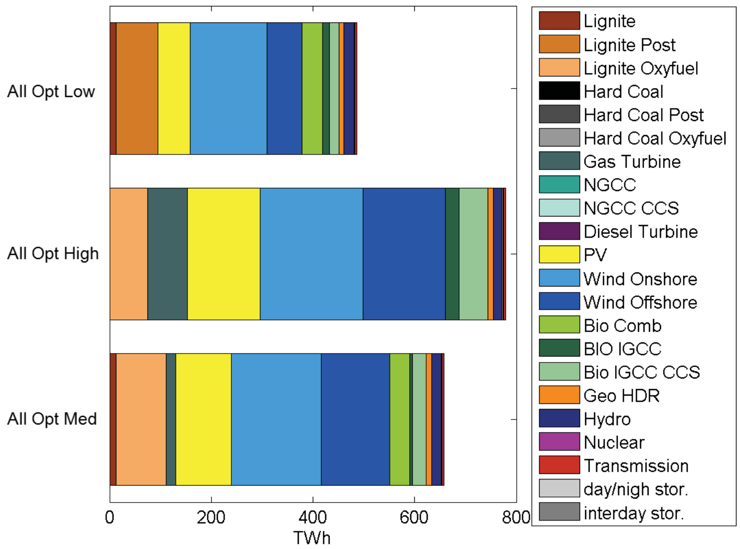
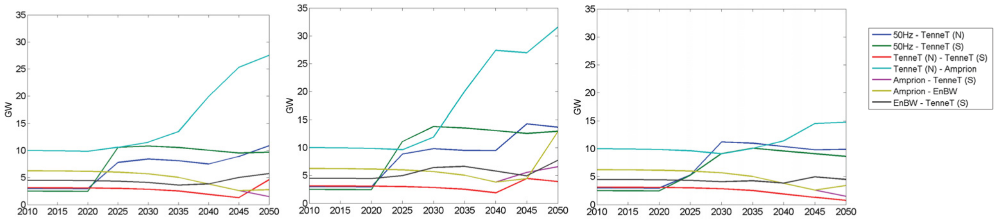


Figure 7: Comparison of the 2050 Generation mix for Germany for the *All Opt* cases

being equipped with CCS. While the higher demand cases employ lignite in combination with oxyfuel capture, the *All Opt Low* case 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.

Since differences in power generation also affect requirements for transmission, transmission capacity expansion pathways for the different *All Opt* cases are analyzed in a second step (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



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

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

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 are similar in their high shares of RET but differ in the chosen CCS technologies due to CO_2 emission constraints.
- 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.
- No feasible solution for reaching all targets can be found for very high demand scenarios (see discussion in Section 2.2).

3.3. Sensitivity Analysis – Part 2: Technology Availability

In the previous section, model results for different demand scenarios are presented with an optimistic stance on technological availability. Since political, public or technical obstacles could limit the deployment of some technologies, an analysis of scenarios with different constraints is presented in the following. The availability of CCS on a commercial scale in the near future is unclear (see e.g. von Hirschhausen et al., 2012) and while offshore wind energy plays an important role in scenarios for future power generation in Germany, technical problems and most of all a lacking connection to the onshore grid might inhibit the large-scale implementation of this technology for a long time.

The main finding for this part of the sensitivity analysis is that no feasible solution can be achieved under the current CO_2 emission and RET 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). Limited potentials for the remaining RET and 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 RET. However, when a reduction of power demand as planned by Federal Government (2011) is achieved, both the absence of CCS or of offshore wind can be compensated. However, if both options are unavailable, there is again no solution to the optimization problem even under reduced electricity demand in this case.

Considering the large spread of power demand projections for Germany as well as current insecurity about widespread availability of CCS and offshore wind, these scenarios indicate that a successful implementation of current government targets is challenging. Even if successful efficiency measures lead to a decrease of power demand, an accelerated electrification of other sectors such as transport can limit power demand reductions. For reaching decarbonization and RET share 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, where 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 technologies which reach the limits of their respective economic potential (see Section 2.1.1 for details on regional potential for RET in LIMES-D). 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 RET generation reduces the overall need for transmission capacity expansions. In the *No CCS Low* case, displayed in Figure 10c, a different

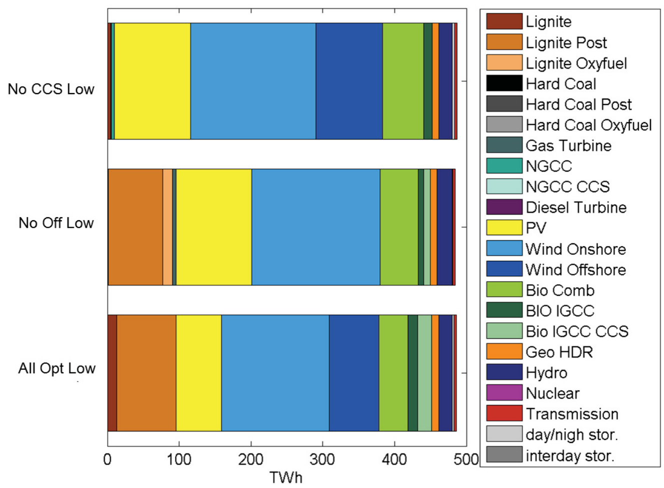


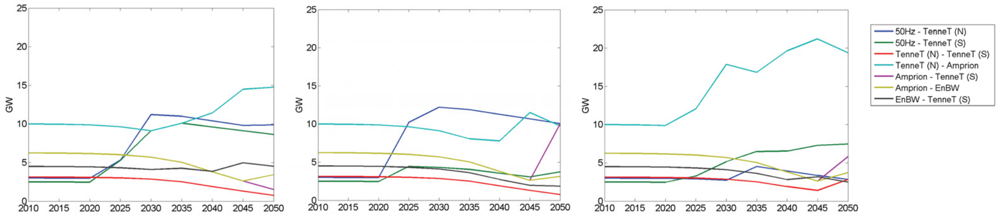
Figure 9: Generation mixes for Germany in 2050 (*Low* demand case)

pattern emerges. Since lignite usage is reduced by the non-availability of CCS, the importance of the connection of the *50Hertz* region (where the most important lignite resources are located) to 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 offshore wind and CCS, determines transmission capacity requirements.

In addition to the scenarios where 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 RET targets.

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

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



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

Figure 10: Transmission capacity expansion for *Low* cases

- 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.

3.4. Power System Cost Comparison

Beyond questions of technical feasibility, it is instructive to compare costs for all scenarios. Figure 11 shows total discounted power system costs differences for the cases discussed above. Percentages indicate the difference between the case with constraints and the respective *All Opt* case for each of the demand scenarios. As detailed in this section, the unavailability of CCS leads to a significantly different generation mix and also strongly influences transmission line expansions while solar PV and onshore wind mostly compensate the absence of offshore wind. This is mirrored in Figure 11 where the *No CCS Low* case entails 2.2% higher power system costs than *All Opt Low* whereas the difference for *No Off Low* is only at 1%.

As an additional sensitivity analysis, a case without any grid extensions was considered. In this scenario (*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

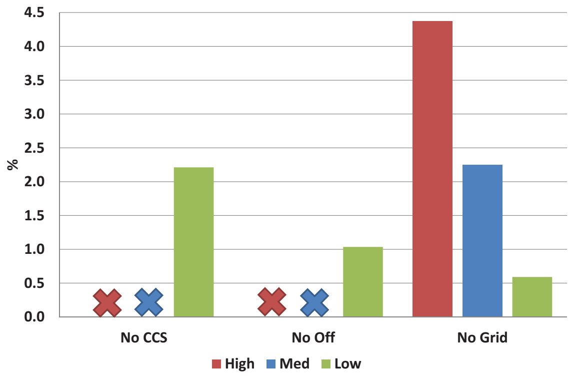


Figure 11: Comparison of total discounted power system costs for different technology availabilities (percentages indicate the difference between the case with constraints and the respective *All Opt* case for each of the demand scenarios, a cross indicates that there was no feasible solution for the respective scenario)

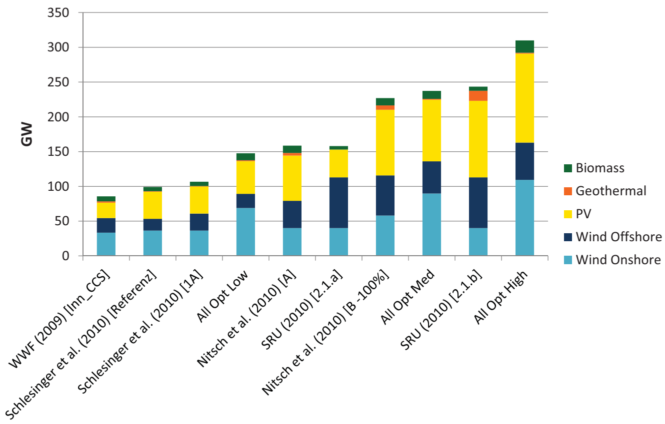


Figure 12: Installed RET Capacities in 2050 for different studies compared to LIMES-D scenarios (bracket indicates scenario name within resp. study)

for *No grid Low* are only 0.6% higher than for *All Opt Low*. This shows that regional RET potentials, in combination with the current power grid, are sufficient to allow for a successful energy transformation but go along with overall cost increases.

4. Comparison to Other Studies

To provide an evaluation of LIMES-D model scenarios, this section presents a comparison of installed RET capacities 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 interesting to compare results for the year 2050.

As shown in Figure 3 in Section 2.2, 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 (Kirchner and Matthes, 2009) to 761 TWh (*PRIMES Baseline* (Capros et al., 2010)). This is reflected in Figure 12 where total installed RET capacity for Kirchner and Matthes (2009) is a low 82.20 GW while capacities for other studies are significantly higher. Power demand in 2050 is similar for Nitsch et al. (2010) *B* and the LIMES-D *All Opt Med* scenario which is reflected in comparable overall installed RET capacities for 2050. These scenarios additionally assume similar target shares for RET which also contributes to the similarity of installed RET capacities. The effect of different underlying political assumptions is reflected in different values for LIMES-D *All Opt Low* and Schlesinger et al. (2010) *[Referenz]* which both have similar power demand in 2050 but fairly different RET capacities.

Relative shares of RET 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 RET potentials. 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. (2011) 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 (2010b) and 50Hertz Transmission GmbH et al. 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.

5. Discussion and Conclusion

This paper presents an analysis of different scenarios for electricity generation in Germany and resulting transmission pathways. For all scenarios, German government plans for a reduction of electricity related CO_2 emissions and the legally binding target of 80% RET in the power mix in 2050 are imposed on the model LIMES-D. Then, to assess the impact of different demand projections and technology availability, different sensitivity analyses are performed.

In a first step, low, moderate and high projections for electricity demand are implemented. 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 since reaching the RET target and the CO_2 emission reduction target is impossible due to residual emissions from balancing constraints. This is important since even when 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 RET, could alleviate this constraint. To investigate this aspect, further analyses with LIMES-D shall include connections to other countries, e.g. via the integration of LIMES-D into LIMES-EU^+ (Haller et al., 2012b).

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. 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 RET require some amount of balancing by gas turbines, 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 decarbonization and RET share targets, more so since recent discussions have stressed that demand reductions as planned by the German government might be unlikely (Cramton and Ockenfels, 2012).

Low 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 RET, 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 storage, 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.

A conclusion from the sensitivity analyses is that all scenarios show substantial needs for transmission grid expansion in Germany. The connection of north-eastern Germany to the other regions as well as general north-south linking of regions are common to all cases but the extent of the necessary grid capacity increases depend on technology availability and underlying power demand. 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. A second conclusion is that 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. A broad technology portfolio could hedge against future power demand increases to enable reaching decarbonization and RET share targets and, more important, transmission line expansions should be planned with a careful consideration of available generation technologies.

Appendix A. 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.

Fixed 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 variable O&M costs do not include fuel costs. Fuel costs are parameterized on the basis of Nitsch (2008) (path *B*)[10] for fossil fuels and Bauer et al. (2010) for uranium and biomass. Figure A.13 shows fuel prices paths for LIMES-D.

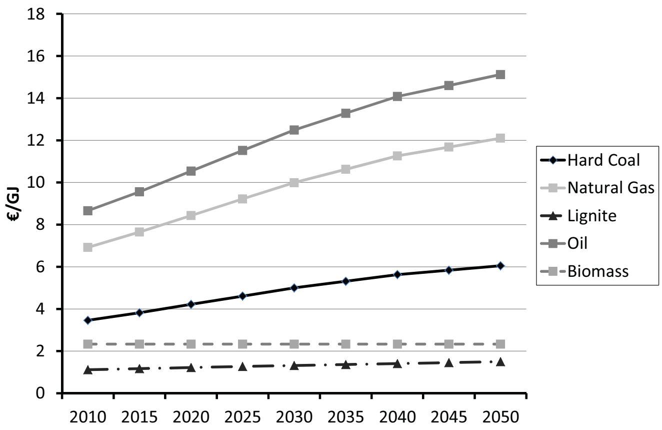


Figure A.13: Fuel prices in LIMES-D

Initial capacities for transmission lines are based on NTC values from Hohmeyer et al. (2011). Table A.5 provides an overview of initial NTC in LIMES-D.

[10]There are two main assessments of fuel prices for Germany, namely Nitsch et al. (2010) and Schlesinger et al. (2010). 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.4: Techno-economic parameters (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
Wind (onshore)[g]	1200	3	0	30
Wind (offshore)[g]	2500	5	0	30
PV[g]	4900	1	0	30
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: PC - Pulverized Coal Power Plant (Hard Coal), Post - Post-combustion Capture, Oxy - Oxyfuel Capture, Lignite - Lignite Power Plant, DOT - Diesel Oil Turbine, NGT - Open Cycle Gas Turbine, NGCC - Natural Gas Combined Cycle, Wind - Wind Turbine, PV - Solar Photovoltaics, Geo HDR - Geothermal Hot Dry Rock, Hydro - Hydroelectric Power Plant, TNR - Thermonuclear Reactor, PHS - Pumped Storage
[b] All investment costs are overnight costs. All €-values are 2005 values.
[c] Hake et al. (2009) [d] Schlesinger et al. (2010)
[e] Massachusetts Institute of Technology (2007) [f] German Energy Agency (2010a) [g] Schmid et al. (2012a) [h] Krey (2006) [i] Bauer et al. (2010)

Table A.5: 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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Chapter 7

Synthesis and Outlook

The aim of this thesis has been to investigate the role of renewable energy technologies and CCS in decarbonization strategies for the electricity sector. The scope of the analysis was twofold: (i) compare integration options for high shares of RET in the LIMES modeling framework and (ii) investigate the interplay of RET and CCS in decarbonization scenarios for the power sector. The analysis of these questions has been undertaken through a series of model-based studies. Results show high shares of RET are crucial in strategies for CO_2 emission mitigation while the availability of CCS reduces the cost of decarbonization. Coordinated scenarios for the expansion of technologies for generation, storage and transmission of electricity are employed to investigate future power systems, taking into account regional specifics and temporal evolution.

The analysis has been carried out in five articles which are included in Chapters 2 to 6. Each chapter covers a specific part of the topic characterized by a specific research question as presented in Section 1.5. These questions are recapitulated below in a synthesis of the main results of this thesis, together with a short overview on the respective chapter (Section 7.1). Section 7.2 discusses model assumptions and suitability and Section 7.3 provides an outlook on further research.

7.1 Synthesis of results

What is the impact of delayed investments into infrastructure for transmission and storage of electricity on the expansion of renewable energy technologies under an emission tax?

In Chapter 2, a three-region conceptual model of the power sector was introduced to investigate the role of investments into long-distance transmission and electricity storage on RET integration. Results show that the expansion of transmission and storage capacities is crucial for ensuring an optimal expansion of RET power generation. Delayed investments into transmission lead to non-optimal siting of RET, entailing lower RET capacity factors and higher shares of fossil fuels and thus also higher GHG emissions. Achievable shares of RET in electricity generation and overall system costs are influenced strongly by delayed transmission expansions or missing storage capacities. While costs of investments into grid expansions or storage are small in comparison to overall power system costs, the indirect effects of delayed investments on power system costs are significant because of the aforementioned effects. Overall costs are lowest if both transmission and storage are available and neither option can be a complete substitute for the other. While this last result might change according to the specifics of the respective power system, it can be concluded that investments into infrastructure for transmission and storage are crucial to the integration of large shares of RET into the power system.

Does increased temporal resolution influence results for investment decisions into RET and other low carbon generation options?

Introducing higher temporal resolution into a power system model leads to a better representation of fluctuations of variable RET and demand. In model results, increasing temporal resolution leads to an increasing share of flexible technologies such as gas turbines and to a decrease of investment into less flexible technologies. For the region of the German TSO *50Hertz Transmission GmbH*, this entails lower shares of lignite in the power mix, both with and without CCS, while the share of wind energy remains more or less constant. It can thus be concluded that an adequate representation of fluctuations is important since technology choice is influenced by knowledge on variability. Furthermore, the expansion of RET with a fluctuating output such as wind energy should be accompanied with increasing capacities of flexible technologies and storage. Widespread use of CCS, which is considered to lower flexibility of power plants could limit RET expansion.

An analysis of total discounted power system cost shows an increase with increasing resolution, mainly due to the higher shares of natural gas in power generation in the high resolution experiments. An interesting finding, however, is that mitigation costs[1] relative to a baseline remain similar throughout all experiments, since the representation of higher temporal resolution leads to similar effects in scenarios with and without climate policy.

Can additional flexibility of Post-Combustion CCS be a RET integration option and does it change the relevance of CCS for electricity generation under climate change mitigation strategies?

Chapter 4 presented an investigation of flexible operation of Post-combustion CCS power plants, introducing the possibility to stop CO_2 capture to temporarily increase electricity generation. An analysis with a one-region LIMES model[2] shows that flexible operation of Post-combustion CCS can play a role in variability balancing under certain conditions. These include high gas prices or the unavailability of storage as well as situations where curtailment of output from wind turbines is not allowed.

[1] In this chapter, climate policy is implemented through an emission budget, limiting the amount of CO_2 that can be emitted.

[2] Chapter 4 is based on the same version of LIMES that is applied in Chapter 3

Flexible operation could be an interesting option for conventional plants retrofitted with carbon capture facilities. However, considering the limited conditions under which flexible operation of Post-combustion CCS power plants is a viable option for fluctuation management, the question should be raised whether research into both Post-combustion CCS and oxyfuel capture is justified. Limiting development efforts to one single capture technology could lead to improved system operation characteristics and possibly also reduced investment costs of this technology.

Which decarbonization scenarios for the European Union with high shares of renewable energy can be realized with and without increases of transmission capacity between countries?

In Chapter 5, scenarios for an extensive decarbonization of the European power sector are analyzed. Results show that very high shares of RET as well as low emission targets can be realized at moderate costs if capacities for power storage and transmission are expanded well above their current levels. Scenarios initially mainly show a domestic use of RE potentials, however, over time a preference for RET siting in areas with high potential emerges. This leads to an increasing specialization in some regions and a progressing interdependency between European countries. Southern regions mainly expand capacities for solar PV and CSP while northern European countries invest in wind energy (both onshore and offshore) and Scandinavia increases hydro capacities. Consequently, central European countries import 30-60% of their power demand in 2050, raising questions of domestic energy security.

An additional analysis limiting transmission capacities at current levels, shows that emission reductions of up to 90% are attainable in Europe even with today's net transfer capacities. However, large amounts of storage are necessary in this case to balance diurnal fluctuations of RET: A significant increase of mainly PV in all countries, especially in central European countries such as Germany leads to strong diurnal output variations. Both in cases with and without transmission grid expansions, a significant increase in temporal and spatial price variations can be witnessed.

Which expansion strategies for power generation technologies and transmission corridors that should be at the core of future network development plans for Germany?

Chapter 6 presents a sensitivity analysis of scenarios for the expansion of capacities for transmission and generation of electricity in Germany under targets for high RET shares and a significant power sector decarbonization. Uncertainties about electricity demand projections and about the availability of CCS and large-scale offshore wind energy present major factors of influence for the development of the power system. Results show that a broad technology portfolio can hedge against future demand increases while still allowing to reach targets for RET shares or GHG emission reductions. In cases with rising or even moderate demand, both offshore wind energy and CCS are necessary to attain a near complete decarbonization of the power sector as well as RET shares of 80% (German government targets). Even in case of decreasing demand, either CCS or offshore wind are needed.

All scenarios show substantial needs for the expansion of transmission corridors, especially those linking eastern and western Germany as well as north-south connections. However, technology availability influences the significance of the different regional interconnections. While the non-availability of CCS increases the importance of north-south connections to transport electricity from onshore and offshore wind parks to southern and western demand centers, the resulting transmission corridors for scenarios without offshore wind are different: the role of north-south interconnections is diminished and only the link between eastern and western Germany is reinforced. Increased use of lignite from eastern mines and more distributed RET-based generation are at the core of this result.

Summary of important results

- Availability of long-distance transmission leads to better siting of RET and thus higher possible RET shares in power generation and higher capacity factors.

- Indirect effects of delayed grid expansions are high relative to investment costs for new transmission lines.

- Better representation of fluctuations in the LIMES modeling framework through higher temporal resolution leads to preference of flexible technologies over baseload technologies.

- Resulting total discounted power system costs are higher through better representation of effects of temporal variability, however there is little influence on results for mitigation costs relative to a respective baseline.

- Flexible CCS could play a role in RET variability management, although only under limited circumstances such as high gas prices and the absence of storage.

- A near-complete decarbonization of the EU power sector is possible with and without transmission expansions, however, costs are significantly lower when transmission and storage available.

- The absence of transmission expansion increases storage requirements due to high shares of solar energy in central European countries and thus increased diurnal variations.

- High shares of RET lead to significant temporal and spatial price variations.

- The level of electricity demand plays an important role for the realization of RET and decarbonization targets in Germany, however, a broad technology portfolio allows to reach targets even when efficiency goals are not reached.

- Scenarios without CCS or offshore wind energy are infeasible in case of constant or rising demand, in scenarios with decreasing demand at least one of the two needs to be available.

- Technology availability influences expansion of transmission in Germany: without offshore wind energy, local RET potentials and lignite resources limit need for long-distance transmission from north to south, absence of CCS increases expansion of offshore wind and thus induces higher transmission requirements.

7.2 Discussion

Results from Chapters 2 to 6 are based on the model LIMES. This section provides a synthesis of important results and analyzes main model features. First, Section 7.2.1 discusses model results for relevant technologies and summarizes findings from different calibrated model versions. Then, Section 7.2.2 inspects relevant model features and investigates possible shortcomings and improvement possibilities.

7.2.1 Technology choices in power sector decarbonization scenarios

This thesis takes a multi-level approach to discuss issues of CO_2 emission reduction and RET integration. The multi-level approach investigating nested regions (Eastern Germany, Germany and Europe) uses different scopes on RET integration under climate change mitigation scenarios. Using a varying regional focus, different power generation technologies are selected for the respective studies, depending on the underlying research question. This section provides a synthesis of the most important results and discusses the sensitivities of technology parameterizations.

Renewable energy technologies play an increasingly important role in all decarbonization scenarios[3] investigated in this thesis. This is in line with results from large scale global studies as described in Section 1.1 in the introduction to this thesis. In Chapter 5, scenarios for the European Union show that very high shares of RET are possible when storage and transmission capacities are extended and a limited amount of flexible gas turbines are available. Model results for Germany (Chapter 6 indicate similar results. Wind and solar energy, which are the most technologically mature among variable RET, take up a large share among renewable technologies in most scenarios.

CCS, another important decarbonization option alongside RET in the studies presented in Section 1.1, could play a role in mitigation scenarios e.g. for Germany, however on a lesser scale than RET. Since large-scale deployment of CCS are still rare and its public acceptance is limited, it is important to investigate emission reduction scenarios without CCS and evaluate the impacts of the non-availability of this technology. For Europe, results from Chapter 5 show that a significant reduction of CO_2 emissions is possible without the use of CCS. Scenarios with CCS were not investigated in this chapter but it can be assumed from other studies (e.g. Chapter 6) that overall power system costs could have been reduced through the usage of CCS. Since, in contrast to RET, fossil power plants equipped with CCS

[3]RET play an important role in all scenarios, both with and without climate policy. However, they prove to be crucial under climate policy constraints.

do not require backup by flexible gas turbines or storage facilities, climate change mitigation targets could be easier to reach, despite residual emissions of CCS power plants. To sum up, LIMES model results on decarbonization scenarios for Germany and Europe suggest that while CCS might not be necessary to achieve far-reaching emission reduction goals, mitigation costs could be reduced when CCS is available.

Another major result from Chapters 2, 5 and 6 is the importance of investments into transmission capacities. While investment costs of transmission infrastructure are low compared to total power system costs, the impact of transmission capacity expansions on RET siting, achievable RET capacity factors and overall cost reductions is significant. Power transmission thus plays an salient role in strategies for large-scale RET deployment and emission reduction. Furthermore, results from Chapter 6 show that available generation technologies have a strong influence on the relative importance of transmission corridors, since different power generation fleets impose different requirements on the underlying transmission grid. For example, decentralized RET generation require distribution grid extensions whereas large-scale offshore wind energy depend on long-distance transmission lines for the transport of electricity to demand centers. These results underline the need for integrated models such as LIMES where capacities for generation and transmission are both determined endogenously and show that further developments of temporal and spatial variability representation, as discussed in the following Section 7.2.2, can improve results for power sector decarbonization RET integration scenarios.

7.2.2 Model Review

Results from the previous chapters have shown that the LIMES model is adequate for investigating different pathways leading to a sustainable energy system. By combining expansion of capacities for generation, storage and transmission of electricity in one model, it is possible to analyze scenarios for the transformation of the power system from its current state to a far-reaching decarbonization and high shares of RET. Moreover, the integration of high resolution for short-term variability and spatial potential differences into long-term scenario analysis allows to represent the specific challenges arising from RET fluctuations. Another important model feature in this context is the intertemporal optimization which ensures refinancing of investments and thus consistency of capacity development pathways in LIMES scenarios. However, the amount of detail for spatial and temporal resolution is still limited in LIMES. This section takes a look at the implementations of temporal and spatial detail and investigates shortcomings and opportunities for improvement.

Temporal resolution

While, as shown in Sections 3.3 and 6.2, different designs of time slices can cover a significant amount of temporal variability, there are some limitations to the concept. The averaging of data required to generate time slices from the respective source smoothes part of the variability in the initial information. Grouping data from different times of the day of four seasons leads to a representation of general fluctuations, providing basic information of patterns to the model. However, daily changes of fluctuation patterns and irregularities that could possibly cause problems can not be represented using time slices. This is especially relevant for the representation of wind energy, where significant stochastic characteristics can be observed. Additional backup capacities need to be in place to guarantee system stability in case of irregularities and generation from these capacities might be underestimated by simple time slices. As an attempt to account for these requirements, the LIMES framework contains a parametrization based on wind energy feed-in data, assessing maximum output changes over the period of a year and determining backup capacity and generation needs. Chapter 3 contains a detailed description of this parametrization.

Another critical aspect of the time slice implementation is the sequential order of events in time, which is especially relevant when considering storage technologies. Since each time slice is an aggregate for a part of a day for a whole season, it is questionable whether time slices for each of these days can be considered subsequent, all the more for the respective days among each other. Within the studies presented in Chapters 2 to 6 in this thesis, time slices within one day are considered subsequent while the sequence of days is not assumed in most cases (with the exception of Chapter 3). The impact of this assumption on the storage implementation in LIMES and especially on results for capacities and operation of storage should be assessed to determine a possible bias of results.

One possibility to avoid the sequence issue within the respective days would be the implementation of characteristic days instead of time slices for temporal resolution (e.g. Fürsch et al. 2012). However, the selection of adequate characteristic days is complex when data bias is to be avoided and this implementation does not solve the problem of the adequate representation of stochastic wind variability as discussed above. One way to provide a better representation of wind fluctuations could be the application of clustering algorithms such as those discussed in Marton et al. (e.g. 2008).

Spatial Resolution

Spatial resolution in LIMES is limited to regions of different sizes which are interconnected by long-distance transmission lines. This representation allows for the determination of important corridors for the transport of electricity; furthermore the impacts of far-reaching interconnection of regional entities or countries (e.g. in EU27) on generation technology choice can be investigated. However, there are substantial limits to this simplification of the underlying transmission grid. Power grid shortcomings on a sub-regional scale can not be accounted for and the representation of actual power flows is not possible. Since, in a worst case scenario, problems on a single power line can lead to far-reaching blackouts[4], an aggregated analysis as conducted in LIMES can not provide complete information about system stability issues. A detailed investigation of n-1 system security[5] is not possible in the LIMES

[4] In 2006, the disconnection of a single power line led to a massive blackout in Europe, see e.g. http://www.zeit.de/online/2006/45/Stromausfall.

[5] A good explanation of the n-1 security in power systems can be found in Kirschen and Strbac 2004.

framework, however, security of supply is ensured by matching power demand and generation and through the introduction of additional constraints such as superpeak time-slices[6] and mandatory RET backup.

7.3 Further research

This section provides suggestions for further research, both using the LIMES model and beyond power system modeling. Section 7.2.2 took a look a the implementations of temporal and spatial resolution in LIMES, and recommended developments for the time slice and transmission grid implementations. Beyond these improvements, the current computational cost of LIMES would allow an increase of temporal and spatial resolution and results from Chapter 3 show that it could be worthwhile to explore the combined limits of the representation of RET variation in time and space. That way it could be possible to derive a model version with adequate temporal and spatial resolution to answer relevant questions about power sector decarbonization and RET integration but limit computational cost to an acceptable level.

Furthermore, a combination of the regional focus of the LIMES-EU$^+$ model with the technical detail contained in LIMES-D would enable a broader focus on power sector decarbonization issues and allow for a more comprehensive investigation of technological options for RET integration and CO_2 emission reduction. The incorporation of CCS into the technology portfolio of LIMES-EU$^+$ could provide a more diversified picture of decarbonization options for the European Union and allow a comparison to other studies such as Fürsch et al. (2011).

One possibility to validate the transmission corridors determined in LIMES could be provided by a soft-coupling with a detailed grid model such as ELMOD (e.g. F. U. Leuthold et al. 2008). Generation capacity results from LIMES could be fed into ELMOD and the resulting grid reinforcement requirements could then be compared to transmission corridors as determined in LIMES.

Furthermore, the implementation of DCLF constraints as discussed in Chapter 2 could improve results for extended versions of the model such as LIMES-EU$^+$ or LIMES-D. While the conceptual model in Chapter 2 does not show large differences for implementations with or without DCLF, results for larger meshed grids in multi-region models could differ when load flow constraints are taken into account. In meshed grids, loop flows and indirect flows can be represented adequately through DCLF constraints, while an implementation based on simple import/export balances can not. However, there are two reasons why multi-region versions of LIMES do not use a DCLF implementation: First, the implementation of load flow constraints requires non-linear programming and thus a different GAMS solver. Numerical complexity and thus computational cost is much higher: the multi-region LIMES-EU$^+$ version takes less time to find a solution than the 3-region conceptual model presented in Chapter 2. Second, since LIMES-D and LIMES-EU$^+$ use aggregated transmission corridors and do not represent actual power lines, usage of DCLF

[6] The superpeak time slice is used to represent periods with high demand and low RET supply. For more information, please refer to Chapters 3 and 5.

constraints can only provide information about flows on these aggregated routes while disregarding possible problems in the remaining network.

Another interesting analysis concerns data for wind feed-in used in the model. There are substantial differences in total wind energy based generation between different years (see e.g. Sensfuss et al. 2003) and the choice of a time series for the deduction of wind energy load factors for LIMES could thus put a bias into the resulting wind capacities and generation. It is therefore interesting to compare model results using different wind base years and determine the bias to e.g. power system costs and technology choices.

High levels of RET in the power system in combination with some natural gas raise the question of power market design adequacy. In the current electricity market, investments into power plants are refinanced by selling generated electricity. In systems with high shares of RET, however, especially gas power plants would be rarely used due to their high fuel and variable costs. Cheaper coal-fired power plants, on the other hand, might not be technically adequate to frequent output ramping as required by RET fluctuations. There should thus be research into an market design which promotes investments into flexible plants and recompenses installed backup capacity to provide adequate response to RET variability. First investigations by Cramton and Ockenfels (2012) and F. Matthes et al. (2012) show that a capacity market, where operators are remunerated to hold capacities available could be a solution, but more research is needed to determine the adequate measures for each power system.

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Nomenclature

BAU	Business-As-Usual
CAES	Compressed Air Energy Storage
CCS	Carbon Capture and Storage
CHP	Power Heat Cogeneration
CSP	Concentrated Solar Power
DCLF	Direct Current Load Flow
DLR	German Aerospace Center (Deutsches Institut für Luft- und Raumfahrt)
EEG	Renewable Energy Sources Act (Erneuerbare Energien Gesetz)
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EU ETS	European Emission Trading Scheme
GHG	Greenhouse Gas
HDR	Geothermal Hot Dry Rock
HVDC	High Voltage Direct Current
IAM	Integrated Assessment Model
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
IWES	Fraunhofer Institute for Wind Energy and Energy System Technology (Fraunhofer-Institut für Windenergie und Energiesystemtechnik)
LIMES	Long-term Investment Model for the Electricity Sector
LP	Linear Programming
MENA	Middle East/North Africa
NGCC	Natural Gas Combined Cycle
NGT	Natural Gas Turbine
NLP	Non-linear Programming
NTC	Net Transfer Capacity
O&M	Operation and Maintenance
PC	Pulverized Coal power plant
PHS	Pumped Hydro Storage
POL	Policy
PV	Photovoltaic Energy
RE	Renewable Energy
REMIND	REfined Model of INvestment and technological Development
RES	Renewable Energy Sources
RET	Renewable Energy Technologies
SRU	German Advisory Council on the Environment (Sachverständigenrat für Umweltfragen)

TNR	Thermonuclear Reactor
TSO	Transmission System Operator
UBA	Federal Environment Agency (Umweltbundesamt)

Statement of Contribution

The five core chapters of this thesis (Chapters 2 to 6) are the result of collaborations in this PhD project between the author of this thesis and her advisors and colleagues. The author of this thesis has made extensive contributions to the contents of all five papers, from conceptual design and technical development to writing.

This section details the contribution of the author to the four papers and acknowledges major contributions of others.

Chapter 2: This chapter uses the LIMES modeling framework which has been designed and implemented jointly by the author and Markus Haller. The development of LIMES was supervised by Nico Bauer, who contributed guidance and helpful input to the implementation. Markus Haller implemented the representation of transmission infrastructure in the model. The author developed and implemented the time-slice framework for the representation of temporal resolution. Markus Haller performed the model experiments and wrote the article, with extensive revisions by the author and Nico Bauer.

Chapter 3: This chapter uses the LIMES modeling framework which has been designed and implemented jointly by the author and Markus Haller. The development of LIMES was supervised by Nico Bauer, who contributed guidance and helpful input to the implementation. The author is solely responsible for implementing the Eastern Germany version of the LIMES model, designing and performing the model experiments and writing the article, with revisions by the other authors. Markus Haller contributed to the implementation of storage and Eva Schmid contributed to the parametrization of the model, especially with regard to techno-economical parameters of generation technologies. Nico Bauer contributed to the framing of the research question.

Chapter 4: This chapter uses the LIMES modeling framework which has been designed and implemented jointly by the author and Markus Haller. The development of LIMES was supervised by Nico Bauer, who contributed guidance and helpful input to the implementation. The author is solely responsible for parameterizing and implementing flexible operation of Lignite power plants with CCS in the LIMES model, performing the model experiments and writing the article, with revisions by Markus Haller and Nico Bauer. Nico Bauer also contributed to the framing of the research question.

Chapter 5: This chapter uses the LIMES modeling framework which has been designed and implemented jointly by the author and Markus Haller. The development of LIMES was supervised by Nico Bauer, who contributed guidance and helpful input to the implementation. Markus Haller was responsible for implementing the EU and MENA version of the LIMES model. The author contributed to the parametrization of power generation and transmission technologies. Furthermore, the author contributed to the improvement of the storage implementation. Markus Haller conducted the model experiments and wrote the article, with revisions by the author and Nico Bauer.

Chapter 6: This chapter uses the LIMES modeling framework which has been designed and implemented jointly by the author and Markus Haller. The development of LIMES was supervised by Nico Bauer, who contributed guidance and helpful input to the implementation. The author is solely responsible for parameterizing and implementing the Germany version of the LIMES model. Markus Haller contributed to the improvement of the time-slice implementation. The author collaborated with Eva Schmid on the framing of research questions and the development of the article structure. The author performed the model experiments and wrote the article, with revisions by the other authors.

Tools and Resources

This dissertation relies heavily on numerical modeling. Naturally, a number of software tools were used to create and run the models, and to process, analyze and visualize the results. This section lists these tools.

Modeling The LIMES modeling framework was implemented in GAMS (GAMS Home Page 2012). The CONOPT3 (ARKI Consulting and Development 2012) and CPLEX (GAMS 2012) solvers were used to solve NLP and LP model formulations,respectively. Multi-run experiments were performed with SimEnv (Flechsig et al. 2012). All code projects were managed using the Subversion version control system[7].

Data Processing The MathWorks' MATLAB[8], version 7.5 (R2007b) was used for all data pre- and postprocessing work. The MATLAB Mapping Toolbox11 was used to process geospatial data.

ComVis (Matkovic et al. 2008) was used for more complex results visualization tasks.

Typesetting This document was prepared using LaTeX 2_ε[9], particularly the pdfpages package (Matthias 2012), to include Chapters 2 to 6 in their given layouts. JabRef (JabRef Development Team 2012) was used for literature management.

[7] `http://subversion.apache.org/`
[8] `http://www.mathworks.de/products/matlab/`
[9] `http://www.latex-project.org/intro.html`

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