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Renewable Electricity Generation in Germany: A Meta-Analysis of Mitigation Scenarios

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Abstract

German energy policy targets envision a share of electricity from renewable energy sources (RES-E) of at least 80% in 2050. How can the transformation of the German electricity sector be achieved and at what costs? This paper addresses these questions by means of a meta-analysis of ten recent model-based mitigation scenarios for Germany. It turns out that the scenarios exploit the three basic strategic options of increasing the share of RES-E—domestic RES-E generation, electricity demand reductions, and RES-E imports—to substantially different extents. Domestic RES-E generation increases in all scenarios, particularly from onshore and offshore wind. Scenarios that rely heavily on reducing electricity demand require a relatively low expansion of domestic RES-E generation. Despite detailed technical analyses, insights on the costs of the transformation remain limited. A discussion of underlying scenario assumptions reveals that it is unclear whether (i) RES-E and system integration technology development will be as cost-competitive as postulated, (ii) implicitly assumed institutional requirements will be realized, and (iii) relevant actors in the transformation process will be incentivized accordingly. Therefore, future research should pursue a thorough assessment of strategic options for transforming the German electricity system that consistently integrates technologies, institutions, and actors.

Keywords: energy strategy, energy system model, transformation costs

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1 Introduction

During the recent years German energy policy has undergone substantial changes, particularly so regarding the electricity sector. In June 2011, after the events in Fukushima, the German Government reconfirmed the accelerated phase-out of nuclear electricity generation until 2022, thus withdrawing the prolongation of the phase-out of on average 12 years that was passed only the year before. At the same time, it amended the target formulation of the Renewable Energy Sources Act, which now specifies an explicit pathway for the development of the share of electricity from renewable energy sources (RES-E) that reaches at least 80% by 2050, with interim steps of 35%, 50%, and 75% by 2020, 2030 and 2040, respectively. The so-called "Energiewende" (energy transition) is by now globally renowned as the first attempt of an industrialized country to decarbonize its energy system solely by means of renewables and energy efficiency improvements (Schiermeier, 2013), embracing to reduce CO_2 emissions by 80-95% in 2050 relative to 1990 (Federal Government, 2010).

But how can Germany attain the long-term target of at least 80% electricity provision from renewable energy sources by 2050, and what are the costs? Finding answers to these questions is clearly of major interest to the German policymaker, and also to the rest of the world observing this experiment from afar. Fundamentally, there are three strategic options to alter the share of RES-E: Increasing domestic RES-E generation, decreasing electricity demand and increasing RES-E imports (Figure 1). In recent years, particularly the option to increase domestic RES-E generation has been exploited. Since the introduction of the Renewable Energy Sources Act in 2000, domestic RES-E generation has continuously increased from 37 TWh to 136 TWh in 2012 (BMWi, 2013), resulting in a share of RES-E share of 22% in 2012 (BMWi, 2013). Hence, there is still a long way to go to attain the 80% target.

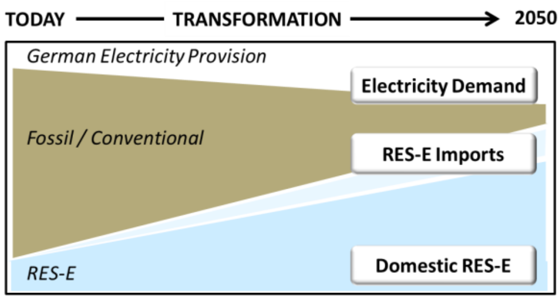

Figure 1. Conceptual overview of strategic options for the long-term transformation of the German electricity sector to attain a share of at least 80% renewable electricity in German electricity provision by 2050.

Political actors have increasingly demanded scientific expertise on how to pursue the "Energiewende", which has led to a variety of studies outlining long-term, model-based mitigation scenarios. These studies illustrate technology pathways for the German energy system that are consistent with the Government targets. Since the starting point of the scenarios constitutes the target formulations for the year 2050, they are normative scenarios in the sense that they specify which developments *ought* to occur for attaining the targets. The scenarios are based on numerical energy-system models with different scopes and scale, each relying on a variety of assumptions.

In order to synthesize the answers that existing mitigation scenario studies provide for the questions above, this paper pursues a comparative meta-analysis of selected mitigation scenarios that are consistent with the targets of the "Energiewende", see Table 1. WWF (2009) was commissioned by the non-governmental organization World Wildlife Fund (WWF) Germany and prepared by the Prognos AG. EWI/GWS/Prognos (2010) outlines a set of mitigation scenarios that analyze different prolongation periods for the nuclear phase-out and was commissioned by the Federal Ministry for Economics and Technology to inform the Government's long-term energy strategy known as the "Energy Concept" (Federal Government, 2010). The "Lead Study" scenarios in DLR/IWES/IFNE (2010; 2012) were commissioned by the Federal Ministry for the Environment and Nuclear Safety and served as a basis for the German National Renewable Action Plan (NREAP) required by the European directive 2009/28/EC. SRU (2010) was commissioned by the German Advisory Council on the Environment (SRU) and prepared by the German Aerospace Center (DLR) in collaboration with the SRU. Aside from SRU (2010), which focuses on the electricity sector alone, all the studies consider the German energy system as a whole. All four studies were relevant to the political debate (Fink and Burck, 2009). In addition, we compare these studies to our own model-based analysis (Schmid and Knopf, 2012), which was prepared over the course of the EU research project 'Engaging Civil Society in Low Carbon Scenarios'.

The specific questions this paper addresses are: Which combinations of strategic options for reaching a share of at least 80% renewables in the German electricity sector by 2050 do the scenario projections suggest? And what are the costs of the transformation? As model-based scenarios require numerous explicit and implicit assumptions, we identify and discuss several underlying assumptions that seem to be crucial, indicated not least by the controversial public and academic debates they have received. The investigation reveals several unanswered research questions that future research needs to tackle for providing sound scientific advice to the process of developing robust energy strategies for Germany.

Table 1. Overview of mitigation scenarios considered in this meta-analysis. * indicates relative to 1990.

Study	Scope	Target Formulation	Selected Scenarios
WWF (2009)	Germany	95% greenhouse gas emission reduction in 2050*	Innovation scenario **[Inn]** and variant **[Inn_CCS]** allowing for carbon capture and sequestration (CCS)
EWI/GWS/Prognos (2010)	Germany and Europe	40 / 85% CO_2 emission reduction in 2020* / 2050*, ≥50% renewables in primary energy demand of 2050	**[A1]**, the scenario with the lowest extension of the nuclear-phase out of 4 years (until 2026)
DLR/IWES/IFNE (2010)	Germany and Europe+ North Africa	80% CO_2 emission reduction in 2050*, RES-E share ≥ 50% / 65% / 80% in 2030 / 2040 / 2050, RES-E share ≥ 100% in 2050 for [B-100%-S/H2]	Scenarios **[A]** and **[B-100%-S/H2]**, which assume a share of 33% [A] and 66% [B] of electro-mobility in 2050's motorized individual transport mileage
DLR/IWES/IFNE (2012)			Updated version of scenario **[A]**, assumes 50% share of electro mobility
Schmid and Knopf (2012)	Germany	Maximize intertemporal welfare under a CO_2 emission budget of 16 Gt over the period 2005-2050	Paradigm shift scenario **[PS]** and its variant **[PS+]**, which additionally allows for CCS and large-scale biofuel production
SRU (2011)	Germany and Europe+ North Africa	100% RES-E share in 2050 (analysis of the electricity sector only)	Scenarios **[2.1.a]** and **[2.1.b]**, which differ in assumptions on electricity demand in 2050 (500 vs. 700 TWh); both impose a zero net-import balance

This paper is structured as follows: Section 2 gives an account of the modeling methods applied in generating the selected scenarios. Section 3 analyzes the scenario projections on the strategic options for the long-term transformation of the German electricity sector to achieve high shares of RES-E and investigates the corresponding costs. Section 4 discusses underlying scenario assumptions that are critical for realizing the scenario projections and briefly indicates the policy leeway for the German Government. Section 5 summarizes and concludes.

2 Applied Modeling Methods

What are the applied methods in the studies for generating the scenario projections in view of the three strategic options for increasing the RES-E share in the German electricity sector? Whilst all the studies base their scenarios on numerical energy system models, they differ significantly with respect to how domestic RES-E generation, electricity demand and RES-E inputs are determined. The methods range from simply imposing exogenous assumptions on their development to having them determined as an endogenous model result. The latter method is the preferable in terms of scientific rigor. The ideal model for developing consistent mitigation scenarios for Germany would represent all relevant systemic processes and their interplay and would generate coherent scenario projections that then could be justified by resorting to the causality structure of the model. However, due to numerical constraints resulting from computer power, solution algorithms as well as methodological challenges (e.g. unobservable data, lack of theoretical understanding of underlying processes) no such model is available to date. Each study pursues different means of coping with these challenges and combines the practices of exogenously assuming developments with endogenous modeling. A common variant is sequentially applying partial models that each focus on different aspects of the energy system and using output of one model as an input to another one. This practice, referred to as soft-coupling, is advantageous when focusing on technological details, but comes at the cost of impeding certain systemic feedback. The following describes the modeling methods applied in the studies for determining domestic RES-E generation, electricity demand and RES-E inputs (Table 2) – to the extent that they are reported in the publications – and highlights key implications of selected explicit or implicit assumptions.

Table 2. Overview of how electricity demand, RES-E capacities and RES-E imports are determined in the studies. Grey shading indicates exogenous assumptions.

<table>
<tr><th>Study</th><th>RES-E capacities</th><th colspan="2">Electricity Demand</th><th>RES-E Imports</th></tr>
<tr><td>WWF (2009)</td><td>Exogenous model input (to dispatch model), taken from DLR (2008)</td><td>Model result (from bottom-up simulation)</td><td>Model input (to dispatch model)</td><td>Residual value</td></tr>
<tr><td>EWI/GWS/Prognos (2010)</td><td>Exogenous model input (to dispatch model), determined by model of renewable energies</td><td>Model result (from bottom-up simulation)</td><td>Model input (to dispatch model)</td><td>Model result (from dispatch model)</td></tr>
<tr><td>DLR/IWES/IFNE (2010; 2012)</td><td>Exogenous model input (to “quantity framework”), based on extrapolation</td><td colspan="2">Model result (from “quantity framework”)</td><td>Model result for selected years (from EU electricity sector model)</td></tr>
<tr><td>Schmid and Knopf (2012)</td><td colspan="3">Model result (from integrated welfare maximization)</td><td>Not considered in model, thus assumed to equal zero</td></tr>
<tr><td>SRU (2011)</td><td>Model result for 2050 (from EU electricity sector model), Interpolation before</td><td colspan="2">Exogenous model input (to EU electricity sector model)</td><td>Assumed to equal zero in selected scenarios</td></tr>
</table>

In order to determine the domestic RES-E generation along with the annual changes in the installed RES-E capacities, the studies rely either on detailed dispatch modeling, optimization methods, or simply spreadsheet calculation. Both WWF (2009) and EWI/GWS/Prognos (2010) apply a dispatch model to determine the cost-minimal dispatch of power plants for covering residual load, i.e. the demand time series minus priority feed-in of fluctuating RES-E technologies. Hence, by construction both RES-E capacity deployment and the associated feed-in must be determined exogenously before running a dispatch model. RES-E capacities are also exogenous to the “quantity framework” applied in DLR/IWES/IFNE (2010; 2012), which is in fact a spreadsheet simulation tool. None of these publications provide in-depth information on the rationale behind the selected RES-E capacity deployment and RES-E feed-in projections. For instance, WWF (2009) relies on the RES-E projections of DLR (2008), which is an earlier version of DLR/IWES/IFNE (2010; 2012). EWI/GWS/Prognos (2010) state: “The scenario construction of the electricity generation sector is further based on a model of renewable energies in Europe that represents several RES-E technologies in a regionally differentiated manner” (p. 28). It remains unclear how particular technologies and their deployment levels were chosen. DLR/IWES/IFNE (2010) state: “The capacity deployment path of RES-E technologies results from an extrapolation of the historical dynamics, under the assumption of priority feed-in for RES-E technologies until 2050.” (p. 46). Here, the technical viability of the chosen technology mix is validated for selected years with the simulation tool SimEE. In Schmid and Knopf (2012) and SRU (2011), the installed RES-E capacities and feed-in are both determined endogenously through optimization methods. Schmid and Knopf (2012) apply the hybrid energy-economy model REMIND-D (Schmid et al., 2012). This model adopts a social-planner perspective with perfect foresight and determines the welfare-optimal domestic RES-E deployment pathway and average annual capacity factor for Germany in five-year time steps. For the year 2050, SRU (2011) applies the European and North African electricity sector model REMix (Scholz, 2010) to determine the cost-optimal dispatch of RES-E technologies imposing a target share of RES-E of 100%. The deployment path between 2010 and 2050 was derived through interpolation. Therefore, nothing can be said about the optimality of the transitional RES-E capacity deployment in SRU (2011).

The approaches for determining future electricity demand range from detailed bottom-up representations over an economic top-down production function to treating demand exogenously by relying on projections of other publications. The first extreme is pursued in both WWF (2009) and EWI/GWS/Prognos (2010), which apply the same detailed bottom-up simulation model of the Prognos AG. It consists of a variety of sectorial sub-modules that generate differentiated projections of industrial, residential and commercial energy demands. One of the model outputs is the annual electricity demand along with its temporal load profile. The “quantity framework” applied in DLR/IWES/IFNE (2010; 2012) is a spreadsheet simulation tool that is similarly bottom-up oriented, but not as detailed as the Prognos demand model. The model REMIND-D used in Schmid and Knopf (2012) determines energy demand endogenously in a top-down approach by means of a calibrated and parameterized production function. Here, electricity demand can respond to changes in the energy system, however, the results depend on the chosen elasticities of substitution. Finally, SRU (2011) consider electricity demand as entirely exogenous input for the REMix model and choose trajectories based on the upper and lower boundary of the range projected in German scenario literature.

Finally, the determination of RES-E imports primarily depends on the regional scope of the applied model(s). In WWF (2009) imports are a residual after considering demand, exogenous domestic RES-E generation and cost-minimal thermal electricity generation. In EWI/GWS/Prognos (2010) the dispatch model has 12 regions and calculates cost-optimal imports and exports. In DLR/IWES/IFNE (2010; 2012), it is not entirely clear how imports are determined. Nevertheless, they are validated with the European electricity sector model REMix that establishes cost-minimal generation and the associated import and export flows for each country. Schmid and Knopf (2012) abstract from imports since REMIND-D is a closed-economy model that consists only of the region Germany. In the selected scenarios of SRU (2011), electricity exchange with neighboring countries is allowed for over the course of the year; however, net electricity imports are imposed to equal zero.

This section has shown that even though all scenarios in this meta-analysis are based on numerical modeling, their projections are partly exogenous assumptions and partly endogenous model results. An important implication of the observation that the expansion of domestic RES-E capacities is assumed exogenously in the majority of the studies is that cost considerations are not necessarily their driving factor (cp. Edenhofer et al., under revision).

3 Comparative analysis of Scenario Projections

Despite that the scenario projections are based on very different modeling approaches, this section provides a comparative analysis thereof. On theoretical grounds this implies a strict "model democracy" in the sense of valuing model-based scenario projections equally regardless of the quality of input assumption and analytical merits (cp. Knutti, 2010), which Section 4 will focus on.

3.1 Strategic Options for Transforming the Electricity Sector

Which combinations of strategic options do the scenarios propose for reaching a share of at least 80% renewables in the German electricity sector by 2050? Before analyzing the scenario projections for each strategic option individually, Figure 2 illustrates the share of domestic RES-E generation in total German electricity consumption/production (depending on the data reported) over time. The crosses indicate the Government Targets as formulated in §1 of the Renewable Electricity Act, which additionally allow for RES-E imports. Those scenarios that are below the cross in 2050 are still consistent with the target as they consider imports in this year, as shown below. An interesting finding is that the scenarios of Schmid and Knopf (2012) and SRU (2010) that do not consider any imports display a significantly faster acceleration in the share of RES-E over the next two decades and reach the Government's 80% minimal target share as early as 2025 to 2035. Four scenarios achieve a RES-E share of 100% in 2050. The scenarios of WWF (2009), EWI/GWS/Prognos (2010) and DLR/IWES/IFNE (2010; 2012) follow almost the same linear trajectory just above the Government's targets until 2040 that corresponds to a linear increase extrapolating the recently observed growth rate: 15 percentage points per decade.

Figure 3 displays the scenario projections on domestic RES-E generation together with historical data. The scenario projections fan out significantly over the long-term: Whilst the spread in RES-E generation amounts to 200-350 TWh in 2020 already, it increases up to as much as 250-700 TWh in 2050. Again, the scenarios that do not consider imports display an accelerated increase in the growth of domestic RES-E generation compared to those ones that do consider imports. The implications of the different expansion strategies would be severe: Whether RES-E generation ought to increase by factor two or five over the coming four decades would make a considerable difference for the design and volume of required RES-E support schemes and, correspondingly, on the future size of the domestic RES-E market. Pursuing a high RES-E expansion strategy would require a doubling of the domestic RES-E market already in the coming decade and thus called for timely action. A low RES-E expansion strategy allowed three additional decades time for the same development.

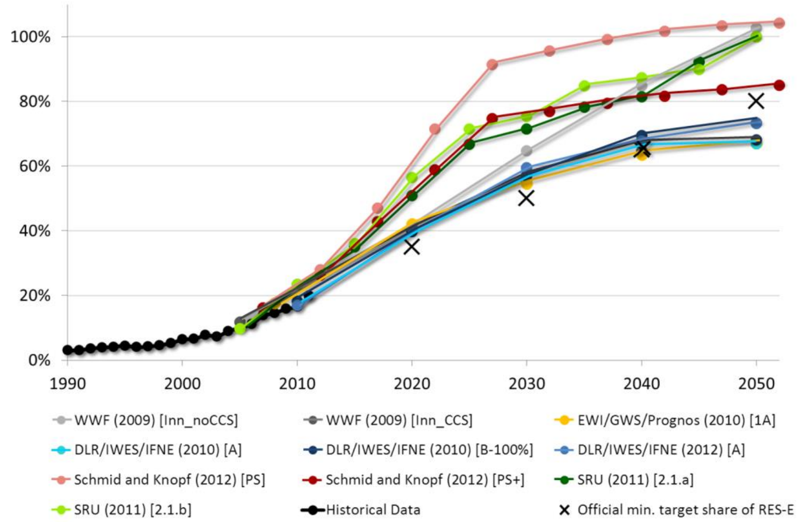

Figure 2. Share of domestic RES-E generation in total German electricity consumption/production (depending on the data provided). Includes historical data (BMU, 2012; BMWi, 2012) and projections from a selection of model-based, long-term mitigation scenarios, see Table 1. Crosses indicate the official minimum targets shares of RES-E in electricity provision of §1(2) of the Renewable Energy Sources Act (that additionally allow for RES-E imports)

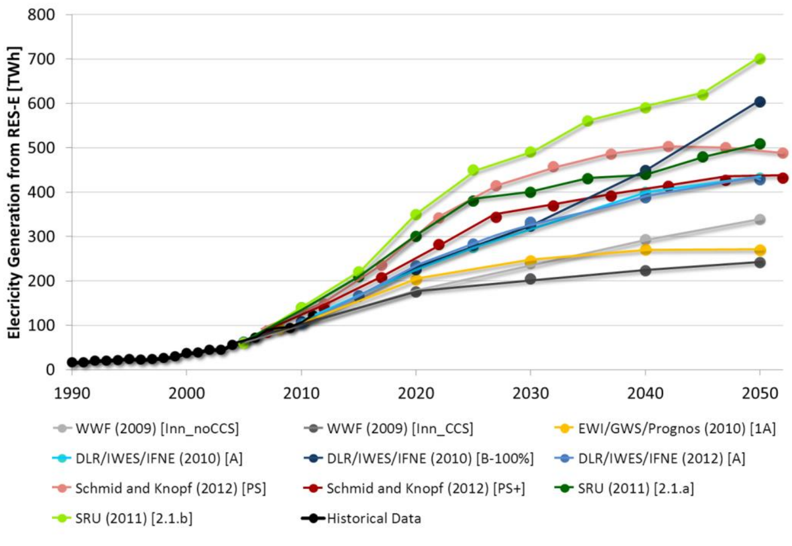

Figure 3. Electricity generation from domestic RES-E. Includes historical data (BMU, 2012) and projections from a selection of model-based, long-term mitigation scenarios, see Table 1.

Which technologies are employed for domestic RES-E generation in the different scenarios? Figure 4 presents the cumulative RES-E generation by technology over the period 2010-2050, excluding hydropower because the limited domestic potential is already exploited. Figure 4 reveals that electricity generation from wind is the most important pillar of the future technology mix in all the scenarios. Together, onshore and offshore wind contribute 2740-11550 TWh (55-70%) of cumulative domestic RES-E generation between 2010 and 2050. With the exception of the SRU (2011) scenarios, in which offshore wind is dominant, the two technologies contribute in roughly equal parts. Electricity generation from biomass provides 1490-2360 TWh (10-30%) across the scenarios. Biomass is a dispatchable RES-E technology that is important for balancing fluctuations from the variable technologies wind and solar photovoltaic (PV). However, the potential of biomass is limited mainly due to ecological concerns (Nitsch et al., 2004). Solar PV, the relatively most expensive technology in terms of levelized cost of electricity today (Fischedick et al., 2011), ostensibly does not play a major role in either of the scenarios with 720-2870 TWh (3-16%) of cumulative domestic RES-E generation. Finally, geothermal electricity generation only plays a role in those scenarios that refrain from RES-E imports contributing 0-2430 TWh (0-13%). The assumed reason is that it is a high cost technology that is only employed when cheap imports are not available. Hence, in relative terms the scenarios suggest that wind offshore and onshore are the most important technologies for domestic RES-E generation, closely followed by biomass, and to a lesser extent solar PV as well as geothermal.

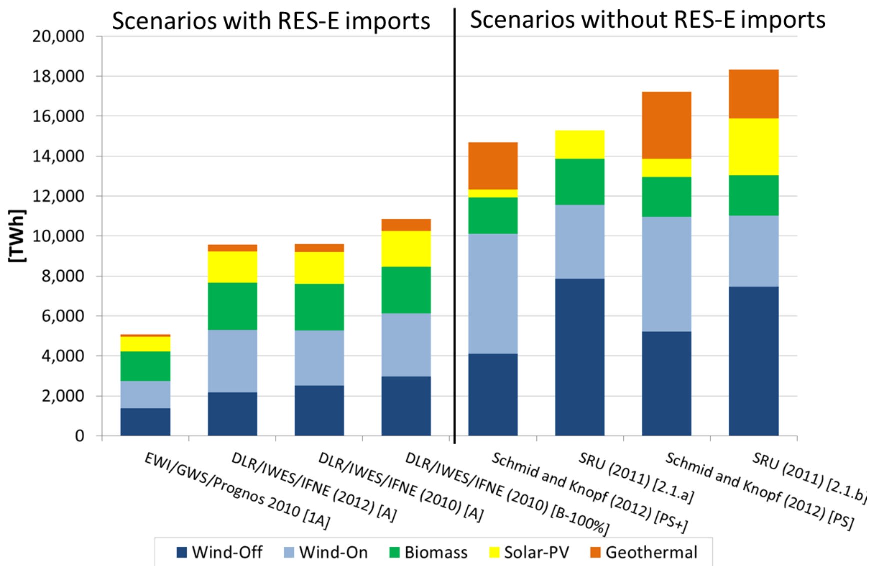

Figure 4. Cumulative domestic RES-E generation over the period 2010 to 2050. Includes projections from a selection of model-based, long-term mitigation scenarios, see Table 1.

Since the share of domestic RES-E generation increases steadily in all the scenarios, those which project a relatively low expansion of domestic RES-E generation are likely to project a relatively lower trajectory for electricity demand. Figure 5, which plots normalized electricity demand with the base year 2010, confirms this intuition. The WWF (2009) and EWI/GWS/Prognos (2010) scenarios project reductions in electricity demand of 25%-35% in 2050 compared to 2010. According to the scenarios, an energy strategy that relies on a comparatively low expansion of domestic RES-E generation must simultaneously induce a decisive turnaround in energy efficiency trends: German electricity demand has increased by 20% over the past two decades, although it has stagnated in recent years. However, this development is attributed to the global financial crisis rather than to dedicated efficiency policies (BMWi, 2010). Such a deliberate energy-saving strategy is also favored by the German Government, which aims to achieve a 10% reduction in electricity demand in 2025 and 25% in 2050 relative to 2008 in its long-term "Energy Concept" (Federal Government, 2010). It is necessary to acknowledge that substantial improvements in energy efficiency improvements in the residential and industrial sectors are not only assumed for scenarios that display a decreasing electricity demand in Figure 3, but also to a certain extent for those that remain stable over time. This is due to two developments: On the one hand, in the transport sector electricity demand is assumed to increase, and on the other hand GDP is projected to grow continuously in all scenarios. Thus, a stable or slightly decreasing electricity demand is tantamount to a decoupling process of electricity consumption from economic growth or, in other words, increasing energy efficiency. The strong upward trend in electricity demand in the scenario DLR/IWES/IFNE (2010) [B100%] between 2040 and 2050 is due to the assumption that by 2050, 41% of the domestically generated and imported electricity is converted to hydrogen in power to gas facilities. The hydrogen is either used in the transport sector as fuel or serves as chemical long-term storage (DLR/IWES/IFNE, 2010, p. 80).

The strategic option of RES-E imports is exploited by all the scenarios that have the option to do so (Figure 6). This would imply that Germany turned from a net exporter of electricity towards a net importing country with 50-200 TWh in 2050. The scenarios assume that this imported electricity is produced from RES-E in European countries; DLR/IWES/IFNE (2010; 2012) additionally allow for imports from North Africa. EWI/GWS/Prognos (2010) in principle also consider nuclear electricity imports but the amounts are not explicitly mentioned. The share of German electricity demand that would be satisfied by imports in 2050 ranges from 11% in the scenario DLR/IWES/IFNE (2012) [A] to considerable 25% in the scenario DLR/IWES/IFNE (2010) [B-100%].

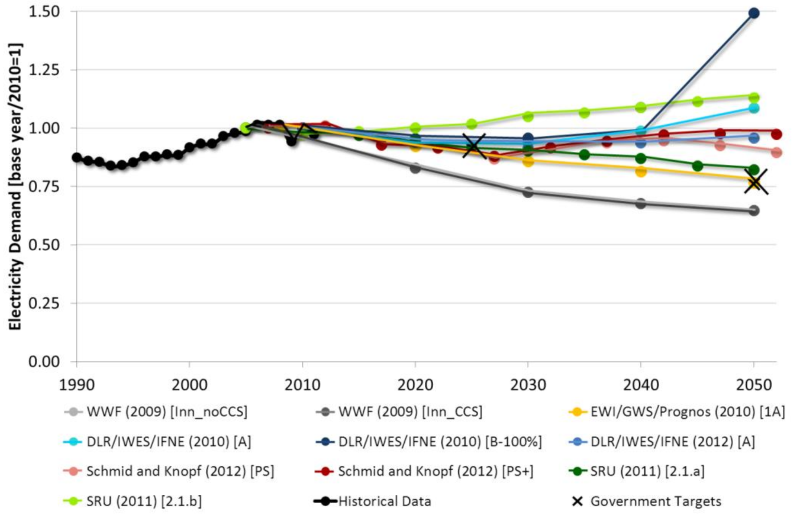

Figure 5. Normalized electricity demand. Includes historical data (BMWi, 2012) with [2010=1] and projections from a selection of model-based, long-term mitigation scenarios with [base year = 1] , see Table 1.

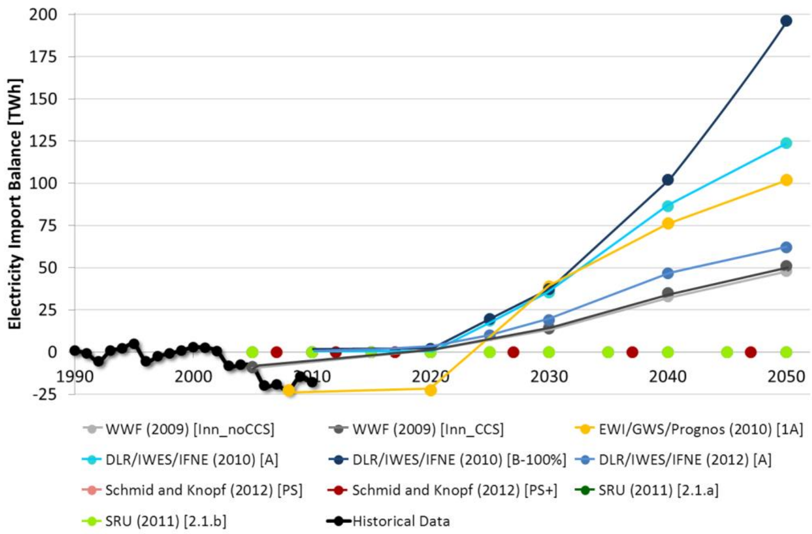

Figure 6. Electricity import balance. Includes historical data (BMWi, 2012) and projections from a selection of model-based, long-term mitigation scenarios, see Table 1. Imports are assumed to be produced with RES-E technologies.

To synthesize the findings of this subsection, the investigation has revealed that the scenarios exploit the strategic options of (i) increasing domestic RES-E generation, (ii) decreasing electricity demand and (iii) increasing RES-E imports to substantially different extents, albeit with some inherent pattern. In order to visualize this pattern, Table 3 provides a stylized comparative account of the extent to which the scenarios emphasize each strategic option by rating them based on three categories. The relative rating is obtained by dividing the spread of the scenario projections for each option in 2050 by three and then attributing +, ++ or +++ to the scenarios, indicating for a scenario that it falls into the bottom, middle or upper third. Note that for electricity demand, the outlier scenario DLR/IWES/IFNE (2012) [100%-SH2] scenario was omitted for calculating the spread in 2050, as it is the only that assumes large-scale hydrogen production from RES-E.

The scenarios cluster in three groups based on the combinations of strategic options employed. The first group heavily relies on exploiting energy efficiency potentials to reduce electricity demand, which is satisfied by relatively low domestic RES-E generation and moderate RES-E imports. The second group refrains from imports and balances moderate to high domestic RES-E generation against high to moderate reductions in electricity demand. A similar focus on domestic RES-E generation is found in the third group, in which relatively higher electricity demand from the electrification of the transport sector and hydrogen generation from RES-E is balanced with RES-E imports. Overall, the scenarios suggest that the long-term target of reaching a share of at least 80% RES-E in the German electricity sector can be achieved with distinct combinations of the three strategic options.

Table 3. Stylized comparative account of the extent to which the scenarios exploit each of the three strategic options for transforming the German electricity sector towards high shares of RES-E.

Scenario	Domestic RES-E	Demand Reduction	RES-E Imports
WWF (2009) [Inn_CCS]	+	+++	+
EWI/GWS/Prognos (2010) [A1]	+	+++	++
WWF (2009) [Inn_noCCS]	+	+++	+
DLR/IWES/IFNE (2012) [A]	++	++	+
SRU (2011) [2.1.a]	++	+++	
Schmid and Knopf (2012) [PS]	++	++	
Schmid and Knopf (2012) [PS+]	++	++	
SRU (2011) [2.1.b]	+++	+	
DLR/IWES/IFNE (2010) [A]	++	+	++
DLR/IWES/IFNE (2010) [B-100%]	+++	+	+++

3.2 Costs of the Transformation

What are costs for transforming the German electricity system towards high shares of RES-E as suggested by the mitigation scenarios? Conceptually, it is important to consider the following cost factors for assessing total transformation costs: (i) Investment costs and operation and maintenance costs for domestic RES-E capacities, (ii) system integration costs to accommodate the temporal and spatial variability of fluctuating RES-E feed-in and (iii) costs for implementing energy efficiency measures (Pahle et al., 2012). It is not possible to perform a structured comparative analysis of the projected costs of the transformation for at least three reasons. First, the studies use different approaches to quantify costs due to the different modeling approaches (cp. Pahle et al., 2012). Second, the studies do not consider all individual cost factors, and, third, costs are reported only selectively. Regarding the approaches to quantify costs, it is common practice to either pursue a top-down analysis of macroeconomic costs induced by the transformation or a bottom-up analysis of costs accrued in the energy system (cp. Capros et al., 2010).

Four studies report the macroeconomic costs of the transformation scenarios compared to a reference scenario; however, both the metrics and the characteristics of the reference scenarios differ significantly. WWF (2009) finds that the [Inn] scenario incurs net additional costs of 0.3% of GDP over the time horizon 2010-2050, relative to a reference scenario that by 2050 achieves a RES-E share of 56% and CO_2 emission reductions of 50% relative to 1990. The scenarios [PS] and [PS+] of Schmid and Knopf (2010) indicate higher cumulative discounted GDP losses of 1.4% and 0.8% over the period 2005-2050, respectively. This is despite the fact that the respective reference scenarios only reduces CO_2 emission by 40% relative to 1990, albeit reaching RES-E shares of 65% and 63%. In contrast, EWI/GWS/Prognos (2010) find that the scenario [A] leads to a GDP that is 0.6% higher in 2050 compared to the reference scenario characterized by 62% CO_2 emission reduction and a 54% RES-E share in 2050. The major reason is the drastic increase in energy efficiency that leads to a comparatively lower primary energy demand and correspondingly to savings in primary energy imports. DLR/IWES/IFNE (2010; 2012) also report cost advantages of the mitigation scenarios [A] accruing to €665 billion and €570 billion in 2050 – in terms of "system-analytic difference costs", i.e. when compared to a fictitious electricity supply based on fossil and nuclear energy that refrains from the use of renewables. The description of the reported metrics makes it clear that it is not possible to compare them in a sensible way. Since all four studies analyze the transformation of the German energy system as a whole, these cost figures cannot explicitly be related to the transformation of the electricity sectors. After all, a comprehensive answer to the question of the macroeconomic costs of the transformation of the German electricity sector is currently missing.

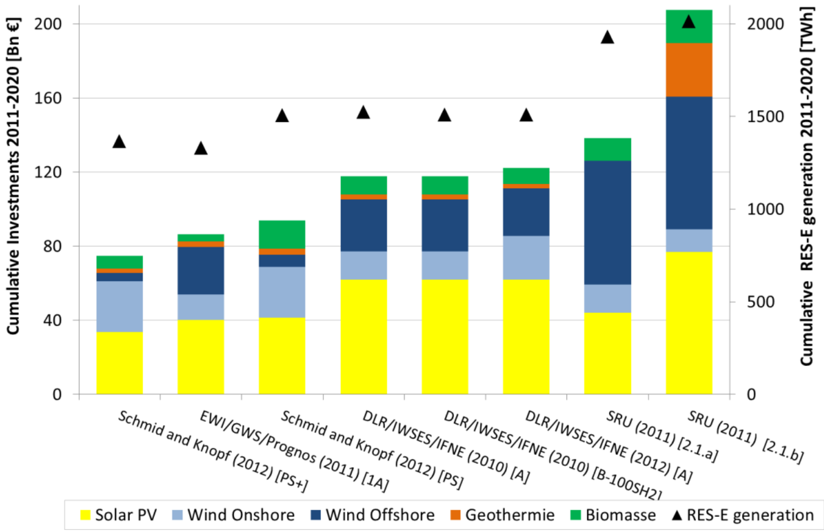

Figure 7. Cumulative RES-E capacity investments and total RES-E electricity generation over the period 2011-2020. The numbers are not discounted, as they were made available to the authors in this manner.

The bottom-up perspective on transformation costs offers itself somewhat more accessible to analysis. Figure 7 illustrates undiscounted cumulative RES-E investments between 2011 and 2020 (the data was made available to the authors in aggregated manner only). The scenarios suggest that the total cumulative investment costs for RES-E capacities over the next decade range between €75-210 billion. In all scenarios approximately half of the investments are directed into solar PV, the other half in wind capacities and a minor share to biomass and geothermal. Considering that across scenarios solar PV delivers only 3-16% of cumulative electricity generation between 2011 and 2050 (cp. Figure 4), the projected investments into solar PV over the next decade appear disproportionate. This is also the case for the de facto investments of 2010 and 2011 in which solar PV had a share of 77% (BMU, 2011; BMU, 2012). The disproportionate share of solar PV in historical investments is due to the fact that the specific investment costs of solar panels have continuously decreased by more than 60% since 2006 (BSW Solar, 2012), but feed-in tariffs have been reduced only sporadically. This resulted in double-digit profit margins and solar-PV attracted as much as 35 Bn € of capital investments in 2010 and 2011 alone. The increasing cost burden induced by the guaranteed feed-in tariff for solar PV led to the adoption of an upper limit of 52 GW of solar PV capacity in the 2012 amendment of the Renewable Energy Sources Act.

Most of the scenarios did not project such a fast growth in solar PV capacity deployment, as becomes evident by the discrepancy between scenario projections and historical deployment data in

Figure 8. It reveals that nearly all scenarios underestimate the strong increase of solar PV deployment in the recent years, while for wind offshore it is the opposite, i.e. all models show increasing deployment while in reality only a few capacities are in place. The upper limit of 52 GW for solar PV support is indicated by the dashed line and coincides with the value in the DLR/IWES/IFNE (2010) scenario, which formed the basis for the German Government's National Renewable Action Plan (NREAP) submitted to the European Union in 2010 (DLR/IWES/IFNE, 2012). On the other hand, regarding wind offshore capacities the feed-in tariff so far led to only 200 MW connected to the grid in June 2012 (Deutsche Wind Guard, 2012). A further 600 MW of offshore projects are under construction, 4852 MW are approved and 1267 MW are under approval (bdew, 2012), adding up to 7.5 GW in projects. This is far below the tentative Government target of 25 GW by 2030 (Federal Government, 2010), which again coincides with the DLR/IWES/IFNE (2010;2012) scenarios. Thus, the scenarios suggest that investments into RES-E capacities should diversify from solar PV to other RES-E technologies, particularly wind offshore. Possible reasons for the discrepancies between model projections and de facto developments will be discussed in Section 4.1.

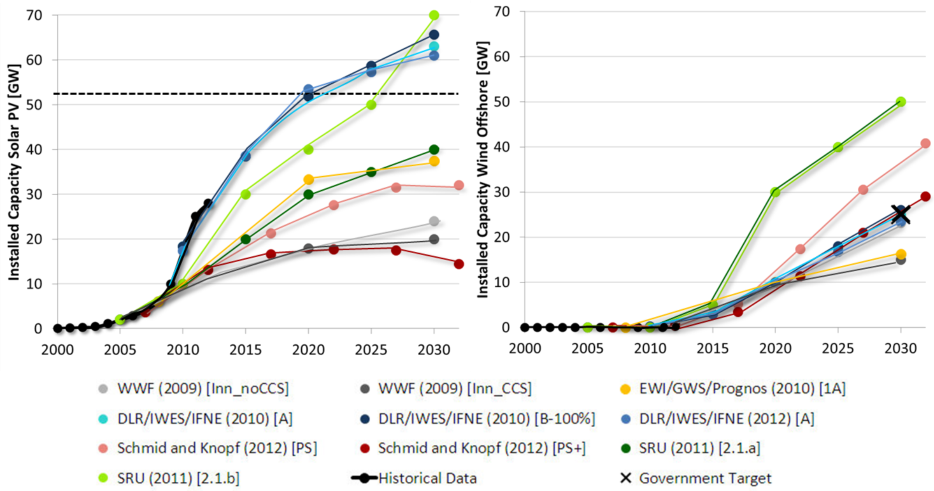

Figure 8. Installed capacities for solar PV (left) and wind offshore (right) until 2030. Includes historical data (BMU, 2013) and projections from a selection of model-based, long-term mitigation scenarios, see Table 1. The dashed line at 52 GW for solar PV is the upper limit fixed in the law of the renewable supporting scheme in Germany, see text.

The reported cost figures for operation and maintenance costs for RES-E capacities, system integration costs and costs for implementing energy efficiency measures are so limited that a comparison is not worthwhile. In fact, the majority of the scenarios take neither system integration costs nor energy-efficiency related expenses into account explicitly. This leads to the observation that the classical triangle of energy policy goals – environmental protection, security of supply and cost-efficiency – is skewed by construction in the mitigation scenarios under analysis: While the environmental protection targets are prescribed in the scenario formulations and energy security is ensured by means of balance equations in the model, system cost minimization plays a subordinate role, particularly in those scenarios that treat RES-E capacity deployment as exogenous assumption.

4 Discussion of Underlying Scenario Assumptions

As regards a German energy strategy for the electricity sector that is consistent with the Government's targets, the previous Section identified the key policy levers: increasing domestic RES-E generation, energy efficiency and RES-E imports. This Section turns towards critically reviewing the scenarios' underlying assumptions concerning these three strategic options. We limit the discussion to those scenario assumptions that seem to be crucial, indicated not least by the controversial public and academic debates they have received. Further, we briefly indicate the leeway for policy intervention of the German Government.

4.1 Increasing Domestic RES-E Generation

The public debate on RES-E capacity expansion in Germany mainly revolves around the question of increasing cost burdens and cost-efficiency as well as potential security of supply issues related to the fluctuating feed-in of electricity generation from wind and solar (Schiermeier, 2013). Regarding these classical energy policy goals, the decisive assumptions in the scenarios are postulated investment cost reductions of RES-E technologies as well as a more or less implicitly assumed built-up of system integration measures to accommodate uncertain, fluctuating and spatially dispersed feed-in. The latter both serves to minimize system costs in the face of high share of RES-E feed-in as well as to ensure security of supply. The following subsequently presents and discusses the model assumptions regarding future reductions of investment costs and the deployment of system integration measures.

A core assumption in all of the studies with regard to system costs is that technological learning processes will occur when capacity deployment is incentivized either by support schemes or the market, leading to substantial reductions in investment costs. This notion of technological learning is referred to as learning-by-doing (cp. Junginger et al., 2010). It has been identified empirically as a statistical relationship between investment costs and cumulative installed capacity, quantified by a parameter known as the learning rate. It expresses the rate at which specific investment costs decrease when cumulative capacity is doubled. For modeling purposes, regression estimates of learning rates are interpolated and either serve as an orientation to estimate cost reductions exogenously or as a direct input for the model, if learning is represented as an endogenous process, thereby influencing the future technology mix. Table 4 presents the learning rates that are reported in the scenario studies. As costs are an important factor, it is problematic that the learning rates are either reported only selectively or not at all in the scenarios that determine RES-E capacity expansion exogenously. Moreover, the choice of learning rates is usually not motivated explicitly.

Table 4. Learning rate assumptions of the different RES-E technologies as reported in the publications.

Publication	Solar PV	Wind Onshore	Wind Offshore	Geo-thermal	Biomass
WWF (2009)	n.a.	n.a.	n.a.	n.a.	n.a.
EWI/GWS/Prognos (2010)	n.a.	n.a.	n.a.	n.a.	n.a.
DLR/IWES/IFNE (2010)	20%	n.a.	10%	n.a.	n.a.
DLR/IWES/IFNE (2012)	20%	n.a.	10%	n.a.	n.a.
Schmid and Knopf (2012)	20%	6%	12%	0%	0%
SRU (2011)	25.9%	11.5%	18.6%	n.a.	2.2%

The application of the learning rate concept in the scenarios postulates a direct and fixed relationship between capacity deployment and cost reductions. Literature provides ample evidence that using learning rates for projecting RES-E investment costs is a method that suffers from serious shortcomings. The estimation of learning rates is highly sensitive to the timing of the underlying data both in terms of when the forecast was made and the duration of the data set (Nemet, 2009). Furthermore, while the explanatory power is generally high in learning rate estimations for the modular technologies such as solar PV (Junginger et al., 2008), it is very low in estimates for offshore wind, where little data exists (Neij, 2008; van der Zwaan et al., 2011). For offshore wind, specific investment costs have actually increased in recent years and future cost-reductions are assessed as uncertain (e.g. Heptonstall et al., 2012; Panzer, 2012). Hence, a learning rate of 10% - 19% for offshore wind as assumed in the scenarios may be challenging to realize. Besides assumptions on specific investment costs, a parameter that indirectly affects the costs of RES-E electricity generation in the scenarios is the assumption about full load hours that RES-E capacities can achieve. Average annual full load hours in energy system models are generally based on meteorological wind speed and solar irradiation data in combination with an average wind turbine and solar panel configuration to derive feed-in. However, realized full load hours are often significantly lower, particularly for wind power. Boccard (2009) (2012) estimates that due to suboptimal siting induced by human and political economy factors, empirical full load hours are 20% lower in Germany than could be expected from meteorological wind speed data. In the future, improved configuration of wind turbines could alleviate this difference (Agora Energiewende, 2013a).

Whether the postulated cost reductions for RES-E deployment actualize in Germany depends on a variety of factors. These include future learning-by-doing effects both on a global and domestic scale, and how market values of RES-E feed-in and perceived technology-specific investment risks develop. Under current legislation any solar PV capacity additions above 52 GW will need to be profitable at market prices. However, the competitiveness of variable renewables decreases with RES-E penetration. They supply electricity at zero marginal costs, leading to low electricity prices during periods with ample wind and/or solar irradiation. This "self-cannibalizing" effect may render the competitiveness of large-scale wind and solar PV capacity deployment more difficult than is acknowledged to date (Edenhofer et al., under revision). Investment risks are not accounted for in the energy system models as they are deterministic models that do not take into account uncertainties besides those covered by different scenario definitions. It is implicitly assumed that sufficient financing can be acquired for RES-E capacity deployment.

The case of wind offshore shows that many real-world constraints are not taken into account in the models, particularly related to investment risks. While the technical potential of wind offshore is abundant in Germany, (IWES, 2012), wind offshore constitutes a centralized, high-risk and high-maintenance technology that is only worthwhile installing on a large scale, as opposed to the modular and low-risk technology solar PV. Solar PV is accessible to small investors, not least indicated by the fact that private persons and farmers pursued 51% of solar PV investments in 2011 (trend:research, 2011), an over proportional share as compared to the overall financing structure for RES-E capacities in Germany. A decisive growth in offshore wind deployment on the contrary requires tapping the capital resources of industry and institutional investors, or pooling private investments. However, returns on investment of wind offshore projects in the German waters are currently small and uncertain (Richter, 2009). In the North Sea, only far-shore projects are allowed due to the Wadden Sea National Park. Since increasing water depths and distance to the shore are the main factors influencing investment costs for offshore wind (Prässler and Schaechtele, 2012), projects in less challenging sites outside of the German seas are more interesting for profit-seeking investors. In fact, German far-shore sites are expected to deliver an acceptable return on investment only upon deployment of high yield wind turbines with 5 MW capacity (Zeelenberg and van der Kloet, 2007). To date, only 37 of these turbines have been installed worldwide, of which 29 are in

Germany (IWES, 2012). The fact that 5 MW turbines are still an immature technology discourages project developers, banks, insurances and financial investors (Richter, 2009). In the RES-E markets, proven reliability of a technology is found to be a necessary condition for investment (Masini and Menichetti, 2012). Many of these aspects are not considered in the models but are implicit assumptions for the realization of the strategic option of increasing RES-E deployment.

But high RES shares not only create a burden on costs – they also have an impact on security of supply. Increasingly high shares of wind and solar PV with their uncertain, fluctuating and spatially dispersed feed-in structure create challenges for system stability, which requires electricity supply to match demand at any time and place. Technical solutions for integrating wind and solar PV into the electricity system include an extension of (i) power grid infrastructure for transporting electricity to demand centers and large-area pooling of fluctuations, (ii) dispatchable generation capacities to provide short-term balancing as well as back-up capacities in low RES-E feed-in periods, (iii) demand side management (DSM) to adapt load to feed-in, reduce peak load, or provide ancillary services, and (iv) storage capacities to cope with fluctuations on both short and long time-scales, thereby avoiding the need for curtailment in high RES-E periods (Sims et al., 2011). Given that all the scenarios report high shares of wind and solar PV (cp. Section 3.2) the question arises of what they assume regarding system integration.

All studies assume at least some system integration options are deployed in the future; however, in most cases the costs are not accounted for (cp. Edenhofer et al., under revision). WWF (2009) assumes that storage capacities and demand-side management will be installed, which translates into higher average full-load hours of conventional, dispatchable power plants in the dispatch model (p. 18). The study remains vague on which storage technologies and DSM options are to be deployed and at what costs. Rather, they provide a qualitative discussion on these issues and frame it as an unresolved research question (p. 476). In EWI/GWS/Prognos (2010, p.187) it is assumed that DSM reduces peak load according to the potentials determined in dena (2010), yet the costs appear not to be included in the model. Whilst storage possibilities are limited to limited domestic pumped hydro storage potentials, the European dispatch model considers power grid expansions between individual countries. DLR/IWES/IFNE (2010; 2012) put a deliberate focus on validating that the exogenously determined RES-E capacity deployment is technically feasible by applying the simulation model SimEE. This model has an hourly resolution and assumes that all system integration options listed above are in place, including adiabatic compressed-air storage and the electrolysis of RES-E power to hydrogen (DLR/IWES/IFNE, 2010, p.95). However, the integration costs are not reported systematically and such an ex-post validation with a simulation tool can by definition not reveal whether the particular configuration of the electricity system is cost-optimal. In Schmid and Knopf (2012) only the integration option of flexible back-up capacities represented explicitly in the model REMIND-D. System effects of uncertain and variable RES-E feed-in are modeled endogenously by a parameterized residual load duration curve approach (Ueckerdt et al., 2011). Finally, the REMix model applied in SRU (2010) endogenously determines European power grid expansion between countries, flexible back-up capacities and the deployment of the storage technologies pumped hydro, adiabatic compressed-air storage and power to hydrogen. While the degree to which system integration measures are considered in the scenarios differs substantially the common denominator is that they are assumed to be in place, be it implicitly or explicitly.

However, none of the options are currently deployed at a level sufficient to integrate rising shares of RES-E as projected by the mitigation scenarios into the German power grid (dena, 2010). In fact the stability of the German power grid was already critical in the winter of 2011/2012 (Federal Network Agency, 2012). In order to guarantee stability and security of electricity supply in the face of substantially rising RES-E shares the deployment of an optimal portfolio of system integration measures needs to be incentivized, which constitutes a considerable challenge and requires decisive institutional reforms as well as fundamental technological progress. Publicly discussed measures include e.g. the speeding up approval procedures for power grid extensions (dena, 2010), reforming the market design of control power markets (Federal Network Agency, 2012) and re-designing the pricing system for end customers in a more flexible fashion to enable DSM (Sims et al., 2011). The only short- and long-term storage technology that constitutes a profitable investment today is pumped hydro storage but Germany’s pumped hydro potential is too small to do the job alone (ETG Task Force Energiespeicher, 2008). All other available technologies are immature and still require considerable effort in research and development to enable their large-scale deployment (ETG Task Force Energiespeicher, 2008). Thus, the deployment of system integration measures needs to accelerate in the mid-term future in order to both ensure security of supply and keep system costs low.

Overall, the policy leeway for the German Government for increasing domestic RES-E generation is rather large, even though numerous challenges need to be tackled on the route. Ultimately the question is at which costs the expansion can be realized and, how these costs are distributed among electricity consumers and whether sufficient investments into RES-E capacity expansion can be stimulated. Among the key recommendations of the International Energy Agency (IEA) are that additional policy measures are needed in order to ensure cost efficiency, effectiveness and a fair distribution of the costs of the Energiewende (IEA, 2013). A possible way of reducing costs could be to put less emphasis on offshore wind and more on onshore wind, which is comparably more cost-efficient (Agora Energiewende, 2013b). Other strategies to keep transformation costs as low as possible could be to avoid the need of excessive domestic RES-E capacity expansion by reducing overall electricity demand through exploiting energy efficiency potentials and importing electricity generated by RES-E capacities in more cost-efficient sites outside of Germany. These options will be reviewed in the following.

4.2 Energy Efficiency

The strategic option of decreasing electricity demand through leveraging energy efficiency potentials is particularly important in the scenarios of WWF (2009) and EWI/GWS/Prognos (2010), which apply a bottom-up model for determining electricity demand. Bottom-up models adopt an engineering perspective by incorporating detailed descriptions of technologies while assuming market adoption of the most efficient technologies (Hourcade and Robinson, 1996). These models postulate that market forces do not operate perfectly and frequently identify an efficiency gap between current technology penetration and the best available techniques. Suggested policy implications of bottom-up models thus are mainly to remove barriers to adoption of the best available technique. In the global energy system models literature, bottom-up models are found to be highly optimistic in terms of technical mitigation potential, due to picking "low-hanging fruits" that may even come at negative price that are in fact not picked today (Grubb et al., 1993; Hourcade and Robinson, 1996). In those scenarios that do not apply a bottom-up model, the rationale behind energy efficiency improvements is not specified further. Instead, electricity demand is simply assumed to follow the postulated trajectory.

Although energy efficiency improvements are a crucial element of all scenarios to a different extent, it constitutes a controversial policy domain in which it is highly unclear whether ambitious targets can be realized. A long-standing debate in literature has observed numerous policy puzzles, the most prominent being the rebound effect. It postulates that an increase in the energy efficiency of a specific energy service may lead to a direct increase in the demand for that service or indirectly increase the demand for other energy-intensive services and, ultimately, increase net energy consumption (Sorrell et al., 2009). Attempts to measure rebound effects are subject to numerous methodological and data measurement problems, however, a recent literature survey suggests that the direct rebound effect may reduce the energy efficiency projections of bottom-up models by as much as 30% (Sorrell, 2007). In any case, rebound effects should be taken into account when designing energy efficiency policies. They may be mitigated through carbon taxes or mitigation caps, i.e. through higher prices on carbon-intensive energy (Sorrell, 2007). A further policy puzzle is that many proposed energy efficiency policies are in fact energy-saving policies that aim to force the incumbent, regulated utilities to implement energy efficiency programs that will after all reduce the demand for their product (Brennan, 2011). Alternative business models seem necessary to exploit energy efficiency opportunities, such as energy contracting. In Germany, one company began offering energy contracting for consumers, but could not establish themselves on the market and withdrew their activities in the end-customer segment in order to focus solely on organizational and institutional customers (Kofler Energies Power AG, 2011).

Behavioral changes are implicitly assumed in the models as it is not possible to model these processes explicitly in technology-focused models that do not consider individual agents. However, literature provides evidence of a collection of market and behavioral failures that intend to explain the difficulties in promoting energy efficiency observed in the past (e.g. Sorrell et al., 2004; Gillingham et al., 2009; Thollander et al., 2010). Many of the identified market failures (e.g. environmental externalities, average-cost electricity pricing, liquidity constraints, R&D and learning-by-doing spillovers) are not unique to energy efficiency, thus they call for a broader policy response including carbon pricing, innovation policies and electricity market reforms. Information and behavioral failures, such as lack and asymmetry of information, principal-agent problems, split incentives, hidden costs or bounded rationality on the other hand call for more specific energy efficiency policies (Gillingham et al., 2009).

Current policies that are targeted at improving the efficient use of energy in Germany have been mainly spurred by European legislation. The “Second National Energy Efficiency Action Plan” (NEEAP) (BMWi, 2011) outlines the mix of policy instruments by means of which the German Government intends to meet the requirements of the European energy efficiency directive (European Parliament and the European Council, 2009). As regards electricity, the major instruments are financial support programs, minimum efficiency requirements and energy labels for appliances, an eco-tax on electricity, self-voluntary programs of industry and information campaigns. However, despite these instruments being in place for the last decade, absolute German electricity demand did not decrease significantly (cp. Figure 5). Having assessed energy efficiency policies and measures in Germany, Schlomann and Eichhammer (2012) conclude that in order to meet the ambitious energy efficiency targets of the German government additional efforts as compared to the second NEEAP are necessary. As the toolbox of policy instruments is not yet exploited there is still substantial leeway for incentivizing the relevant actors and institutions towards a more efficient use of electricity.

4.3 RES-E Imports

Importing RES-E electricity from other European or even North African countries where RES-E generation is more cost-efficient due to more favorable wind speed or solar irradiation sites is a silver bullet in cost-optimizing energy system models. A prominent example are the DLR/IWES/IFNE (2010; 2012) scenarios for which REMix model finds it optimal to significantly increase European grid capacities and import up to 25% of German electricity demand in 2050. In the SRU (2010) scenarios net imports are zero in 2050, however, the large hydro reservoir capacities of Norway are employed to balance fluctuations arising from fluctuating RES-E feed-in in Germany and central Europe. Such model results crucially hinge on the obvious assumptions that (i) RES-E production in non-German countries is actually more cost-efficient, (ii) sufficient power grid capacities to transport the electricity is available and (iii) RES-E capacity deployment starts to increase in these countries as postulated by the models. Moreover, implicit assumptions are that European and/or North African actors cooperate to institutionalize a truly integrated electricity system with shared responsibility for energy security issues and similarly high target shares for RES-E generation.

While the vision of a truly integrated pan-European electricity system promises resource- and cost-efficiency, there are numerous obstacles that yet need to be tackled for paving the road. The decisive assumption that RES-E generation in sites with optimal natural resources in non-German countries is actually more cost-efficient is challenged, e.g. by Dinica (2011), who argues that production costs of RES-E technologies are not only influenced by technology-specific factors, but also technology-complementary, institutional and resource-related factors that are likely to increase with increasing domestic capacity deployment. Such cost factors, e.g. licensing fees, are usually not explicitly taken into account in energy system models, and if so, they are expected to decrease rather than increase in the course of future technology learning. While the expansion of the European power grid is coordinated by the European Network of Transmission System Operators for Electricity (ENTSO-E), the capacity expansion might not be as fast as postulated by the mitigation scenarios. In the past years, transmission projects of pan-European significance have been challenged, significantly delayed or even jeopardized because of a lack of social acceptance, lengthy permitting procedures, difficulties in acquiring financing and inherent uncertainties of predicting the future location of generation capacities, particularly RES-E capacities (ENTSO-E, 2010).

Klessmann et al. (2011) evaluate the current status of renewables deployment, policies and barriers in the European Member States and conclude that the de facto built-up of RES-E capacities in the different Member States is on aggregate beyond the self-imposed quantities as specified in the National Renewable Action Plans (EEA, 2012) and call for increased policy effectiveness in countries that lag behind to close the gap to the top runner countries. The recent "Renewable energy progress report" (European Commission, 2013b) comes to the same conclusion that further efforts will still be needed from the Member States in order to reach the European 2020 targets (20% greenhouse gas emission reduction relative to 1990, 20% share of renewables in final energy demand and 20% energy efficiency improvement). This emphasizes that a truly integrated European electricity system requires fostering and triggering technical, institutional and political developments in a coordinated manner. German policymakers can clearly not determine this alone but can positively influence the negotiations in the direction of a more integrated European electricity system. The current negotiations on a 2030 framework (European Commission, 2013a) are an opportunity that should not be missed, see e.g. Geden and Knopf (2013).

5 Summary and Conclusion

This paper performed a meta-analysis of ten model-based mitigation scenarios for Germany, taken from six recent studies to address the following questions: Which combinations of strategic options for reaching a share of at least 80% renewables in the German electricity sector by 2050 do the scenario projections suggest? And what are the costs of the transformation? The main findings regarding the first question are: (i) In order to attain the long-term target of at least 80% renewables in the German electricity sector, the scenarios exploit the strategic options of domestic RES-E generation, electricity demand reductions and RES-E imports to substantially different extents, (ii) domestic RES-E generation increases in all scenarios with onshore and offshore wind representing the most important technologies, (iii) the scenarios that decisively exploit the strategic option of reducing electricity demand require a relatively low expansion of domestic RES-E generation, and (iv) some models rely heavily on electricity imports from other European Member States. The magnitude and sign of the costs of the transformation remain vague and a structured comparative analysis across scenarios is impeded by the varying methodical approaches to quantify costs, failure to consider all individual cost factors and selective reporting of costs. Furthermore, the reference scenarios used to determine the incremental costs range from a moderate transformation scenario to one with a strong deployment of nuclear and fossil fuels without any renewables. Generally, the analysis of costs appears to play a subordinate role in the scenarios.

The discussion about crucial underlying assumptions of the scenario projections revealed the following recurring themes: It is unclear whether (i) RES-E and system integration technology development will be as cost-competitive as postulated, (ii) the implicitly assumed institutional requirements will be realized, and (iii) the relevant actors in the transformation process will be incentivized accordingly. With respect to the strategic option of increasing domestic RES-E generation, it is unclear whether sufficient financing can be acquired, which is closely linked to how investment risks develop, and whether the necessary system-integration measures will be in place. For the strategic option of decreasing electricity demand, the most daunting question is how to overcome the numerous market failures and policy puzzles in order to incentivize the users of electricity-based energy services to leverage energy-efficiency potentials. Finally, the viability of the strategic option to import RES-E import is uncertain and largely depends on whether policy targets in European Member States will be aligned in order to cooperatively aim for higher shares of RES-E.

It deems that for implementing the strategic options suggested by the mitigation scenarios, technology development, institutional settings and the governance of relevant actors need to be aligned. This finding is perfectly in line with the theoretical insights of literature that intends to characterize the nature of the energy system, arguing that energy systems are best perceived as socio-technical systems in which the elements of technology, institutions and actors play distinct but deeply intertwined roles (e.g. Kroes, 2006; Unruh, 2006; Reichel 2012). A strategy that intends to transform a socio-technical system successfully thus needs to address all elements of the system in a coherent way; else the strategy is likely to encounter barriers to implementation and possibly induces system-wide effects that might even contradict its intended aim. At large, the development of such robust energy strategies is an urgent task while at the same time a formidable challenge for the German policymaker. The process of developing such strategies could benefit from sound scientific advice in several ways that can be deduced from the discussion above and that could feed into a "social learning process" (cp. Edenhofer et al., under revision).

A better understanding of energy technology-diffusion processes from a socio-technical systems perspective could provide a more accurate picture of the actors involved and the institutions required. This applies to technologies on all levels of the electricity system, from supply-side technologies used to generate, distribute and store electricity to demand-side technologies that convert the final energy electricity into energy services. Once a clearer picture of the dependencies in the system emerges, it will be possible to give a more comprehensive account of the prerequisites and consequences of the multiple strategic options for transforming the energy system as well as the nature and magnitude of the corresponding costs – and opportunity costs. Such an assessment could provide a sound scientific basis for informing the German quest to succeed in its self-imposed experiment known as the "Energiewende".

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