Renewables Intermittency: Operational Limits and Implications for Long-Term Energy System Models

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Renewables Intermittency: Operational Limits and Implications for Long-Term Energy System Models

Erik Delarue*† and Jennifer Morris‡

Abstract

In several regions of the world, the share of intermittent renewables (such as wind and solar PV) in electricity generation is rapidly increasing. The current share of these renewable energy sources (RES) can still more or less be handled by existing systems and flexibility, benefiting from remaining excess capacity of dispatchable (backup) generation and links to other grids that can balance the intermittency. However, often higher levels of intermittent RES are envisaged for the future, posing significant challenges on system operation and planning. In assessing possible energy futures, long-term energy system models are typically used. The representation of RES in such models needs careful attention, as intermittent RES come with a number of specific characteristics, making them different from conventional dispatchable generation. This paper focuses on technical implications related to systems trying to achieve high shares of renewable electricity. The relevance of demand and RES generation profiles are demonstrated. After some threshold, a sharp decreasing relationship between installed RES capacity and marginal contribution in terms of generation is identified; therefore, even with perfect backup, a technical limit exists on achievable RES shares. The impact of RES on net demand peak reduction is also addressed. In the absence of system flexibility, substantial backup is required to ensure reliable electricity provision. The role of different flexibility instruments is explored and is found to be significant. Reflections are provided on options to include these aspects in long-term energy system models.

Contents

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1. INTRODUCTION

The share of renewable energy sources (RES) has been increasing drastically in recent years in various power systems across the globe. Also towards the future, the amount of RES is projected to grow further. Economic and technical models are often deployed to optimize the overall transition of energy systems, and inform policy makers and other stakeholders. A wide set of models exist, all with specific capabilities and characteristics. In long-term energy system models which consider investment decisions, two general model types can be distinguished: 1) top-down economic models and 2) bottom-up engineering cost models. Top-down models represent microeconomic principles, but often lack technological detail, such as physical engineering constraints. On the other hand, bottom-up models are rich in technological detail, but lack economic details and feedbacks from other sectors. The aim of this paper is to address the implications of the specific generation pattern of intermittent RES, focusing on systems aiming for high shares of RES generation. Lessons are drawn on how these implications can be accounted for in top-down economic models.

This paper starts with a brief description of the main features of top-down and bottom up long-term energy system models. The next section details why RES are different from conventional generation sources. Focus then turns on systems with high shares of RES and corresponding implications. An operational model is developed and used in this regard. Finally, the representation of RES in long-term models is discussed, and integration of key features (as identified from the modeling exercise) in this framework is discussed. The final section concludes.

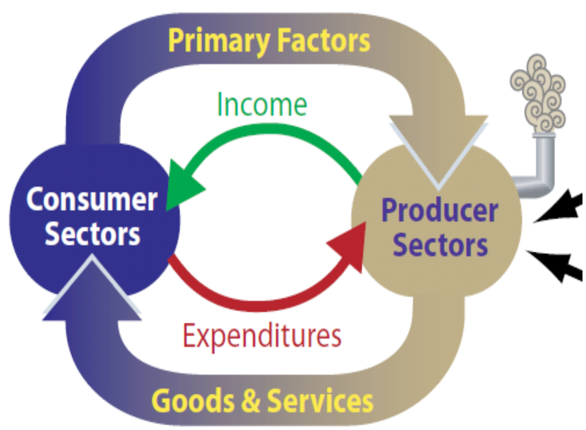

Figure 1. Computable General Equilibrium circular flow (Source: Paltsev *et al.*, 2005).

2. LONG-TERM ENERGY SYSTEM MODELS

2.1 Top-Down Economic Models

Top-down models represent economy-wide relationships, can measure social welfare, and are suitable for simulating a wide variety of policies and their impacts. Computable General Equilibrium (CGE) models are a primary type of top-down economic model. CGE models represent the circular flow of goods and services in the economy (**Figure 1**). Consumers (households) supply capital and labor services to the producing sectors, which in turn supply goods and services to consumers. The models also represent the reverse flow of payments that corresponds to the flow of goods and services: households receive payments from the producing sectors for the labor and capital services they provide, and in turn use that income to pay producers for the goods and services they consume. CGE models track all of these transactions within and across multiple sectors as well as among different regions. Supply, demand, and prices are determined endogenously by all sectors being in equilibrium and all markets clearing.

CGE models focused on energy and environmental policy exist at various levels of economic aggregation. At a high level of aggregation is the Dynamic Integrated model of Climate and the Economy (DICE) (Nordhaus, 1992), and its extensions such as RICE (Nordhaus and Yang, 1996), ENTICE (Popp, 2004), and ENTICE-BR (Popp, 2006). These macroeconomic models are built upon the neoclassical Ramsey optimal growth framework, in which growth is driven by capital accumulation and economic equilibrium is reached when the utility function is optimized inter-temporally. These models are highly aggregated, often representing the economy with a single sector, or very few, and production of a single final good. Details about the productive inputs (e.g., capital, labor, and energy) are also limited.

Other economic models follow a more disaggregated, multi-sector economic framework and are constructed from input-output data for the economy. These models are particularly useful for studying the economy-wide impacts of policies as well as sector-specific decisions. Examples are the MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005), the EPA's Applied Dynamic Analysis of the Global Economy (ADAGE) model (Ross, 2007), Purdue University's Global Trade Analysis Project (GTAP) Model (Hertel, 1997), and Charles River Associates' Multi-region National (MRN) model (Smith, 2007).

Overall, CGE models are very powerful tools for assessing the economy-wide impacts of policies because they capture feedbacks throughout the economy. For this reason, it is a particularly appropriate tool to study the impacts of electricity sector strategies and policies. Changes in the electricity sector affect other sectors throughout the economy, and a CGE model can capture those effects. For example, if a policy causes electricity prices to increase, the prices of goods produced using electricity can also increase, and consumers may have less money to spend in other sectors. Electricity may also become important to the transportation sector through plug-in (hybrid) electric vehicles, or affect the agricultural sector by using biomass for generation and competing for land resources. The key point is that a CGE model captures all of these ripple and feedback effects throughout an economy and can therefore provide an accurate estimate of the full economy-wide cost of a policy or strategy.

While focusing on economic details of market flows, CGE models often make simplifications when it comes to technical detail. Common simplifications are to aggregate sectors, include a subset of representative technologies, and make assumptions about the general impact of details that are not explicitly represented. In the electricity sector, CGE models often lack the full suite of technology options as well as operational constraints such as ramping or transmission congestion. Such details are only implicitly included in the relative costs of the represented technologies.

2.2 Bottom-up Engineering Cost Models

Bottom-up engineering cost models use engineering data and principles to represent detailed technical characteristics. With such a high level of technical detail, keeping these models tractable requires a direct cost accounting framework or a partial-equilibrium perspective. A partial-equilibrium model represents one or several sectors in great detail, but does not capture interactions between these sectors and the rest of the economy. As a result, supply, demand, and prices are all exogenous inputs to these types of models. The structure and solution approach of these models varies considerably. Most use a linear-programming or mixed-integer programming optimization framework. Some of the most well-known optimization models for electricity and environmental policy analysis are the MARKAL/TIMES model (Loulou *et al.*, 2004), the National Renewable Energy Laboratory's ReEDS (Regional Energy Deployment System) model (Short *et al.*, 2011), the International Institute for Applied Systems Analysis (IIASA) MESSAGE model (Messner, 1997), and the EPA's Integrated Planning Model (IPM) (US EPA, 2010). These models are specifically designed to study the energy and/or electricity sector. They capture multiple regions, time periods, and technologies (typically 20 or more electricity generation technology types).

Bottom-up models typically seek to identify the least-cost method of operating and/or expanding electricity generation technologies in order to meet demand. Engineering and operational constraints are often included, such as access to and costs of transmission, the availability and quality of renewable resources, ancillary service requirements and their costs, and physical limitations of operating different types of power plants (Short *et al.*, 2011). When only considering system operation (not investment), dedicated highly detailed models exist. These models operate on a power plant basis, with time resolutions of 1 hour or even 15 minutes (so-called 'Unit Commitment' models fall within this class of models). The detail in bottom-up models allows for the explicit and more realistic consideration of how different technologies within the system interact. However, bottom-up models lack an economy-wide framework and therefore cannot provide measures of economy-wide consumption or policy costs.

Both top-down and bottom-up models must be able to represent high levels of RES. The following sections explore the implications of high RES systems that are used to inform modeling approaches, focusing on long-term economic models.

3. WHAT MAKES RES DIFFERENT?

Several forms of renewables have specific characteristics, making them different from conventional generation. For instance wind and solar photovoltaics (PV) are classified as intermittent renewables[1]. This means they have a variable profile (which at best can only be controlled downward) and they are to some extent unpredictable. These and several other characteristics (discussed below) pose important implications on representing these RES in long-term models. First, RES characteristics are discussed; second, the economic and technical implications are addressed; and third, possible flexibility options are presented.

[1] In the remainder of this paper, the notation "Renewables" (or "RES") refers to intermittent RES.

3.1 RES Characteristics

Intermittent RES come with a number of specific characteristics. In this brief discussion, we largely follow the assessment as provided by the IEA (2014).

First, intermittent RES typically have a zero marginal cost. As they do not consume fuel, they generate at zero cost; hence, this has implications for electricity market prices. These prices are lowered during moments when RES are generating (i.e., the so-called merit order effect). This way, the average price is lowered, and also the price profile is adapted, in line with the resulting residual load profile.

Second, intermittent RES face a variable electricity generation profile. They generate according to meteorological conditions. Control of the output is not possible in the upward direction (unless it is knowingly operated below its possible output), and at best only downwards (so-called curtailment, i.e., not making use of possible generation). This variability can be quite substantial, with significant changes over relatively short periods. Relevant time scales to consider are changes from 15 minutes up to days or weeks. In addition to fast changes, consistent periods of either high or low (zero) output have an important impact on power system operation and planning. An example of the variability of wind and solar PV generation is shown in **Figure 2**, for normalized measured Belgian data from a two-week period in 2013.

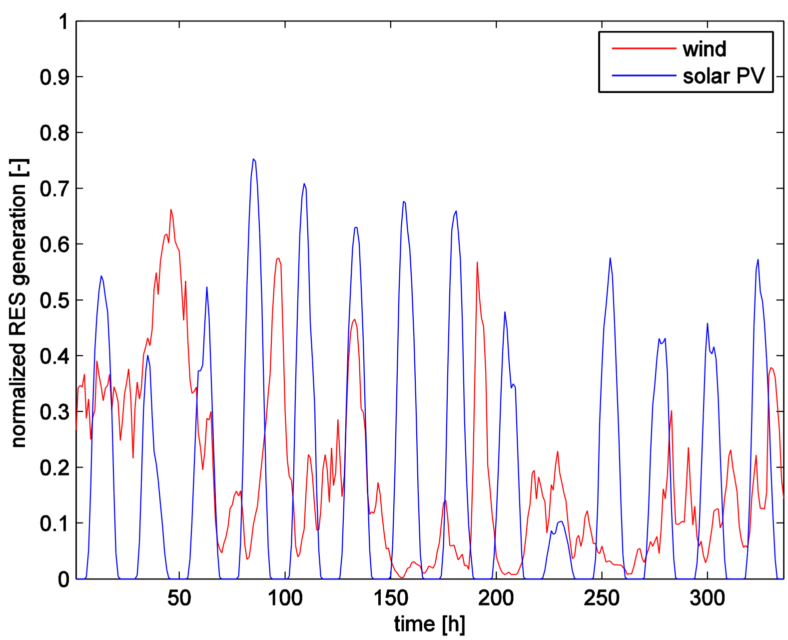

Figure 2. Illustration of wind and solar PV variability. Normalized hourly measured data for a two-week period selection of the year 2013.

Third, intermittent RES face uncertainty on their output. In contrast to dispatchable generation, which can be precisely controlled, the output of RES needs to be forecasted, and significant errors can occur. To ensure a reliable system operation, reserves must be present in the system to deal with forecast errors.

Fourth, RES are constrained by location. The RES resource (e.g., wind and sun) needs to be harvested where it occurs—unlike conventional fuels, it cannot be transported. Optimal locations for RES are typically remote areas, such as desserts for sun, and off-shore locations for wind. In such cases, specific network expansions might be required to connect such locations to existing grid infrastructure.

A fifth characteristic is that RES are modular, meaning their unit size is much smaller compared to conventional plants. Wind turbines come in ranges of 1–7 megawatts (MW), while a single solar PV panel is typically a few kilowatts (kW). This compares to conventional plants of several hundreds of MW. For an equal amount of installed capacity (not yet speaking of electricity generation), a vast amount of RES units is required. These RES might also be connected to the distribution grid (rather than to the transmission grid as is the case for conventional generation plants), and pose new challenges in this regard.

A sixth and final element is that RES can be termed non-synchronous. Conventional power plants are typically coupled to the transmission grid with large synchronous generators. This way, a direct electro-mechanical link is provided in the system: the generators are rotating at a speed equivalent to the electricity system's frequency. As such, kinetic inertia is provided, contributing to system stability. RES on the other hand are typically connected through power electronics to the grid, not having this synchronously rotating generator. These power electronics can simulate such system inertia. However, transmission system operators typically require a minimum share of instantaneous electricity generation originating from conventional (synchronous) power plants, for system stability reasons (possibly complemented by reasons related to voltage stability issues) (Eirgrid, 2013). As an example, in Germany, the minimum share of instantaneous conventional generation is being set at about 20% (IEA, 2014).

3.2 Economic and Technical Implications

Given the characteristics of intermittent RES as discussed above, these RES have an impact on the overall operation of the electricity system. This subsection elaborates briefly on the economic and technical implications. For a full overview, including the regulatory perspective, refer to Perez-Arriaga and Batlle (2012).

3.2.1 Economic Implications

The costs of wind and especially solar PV have come down significantly over the past years. In the recent past, these forms of RES typically could enjoy subsidies in a wide range of countries. For most of these installations, this RES subsidy is to continue for another 10–20 years. For new installations, however, most countries have now moved away from (substantial) subsidies.

Given the intermittency of RES, it is difficult to use the cost notion of "Levelized Cost of Electricity - LCOE", typically used for conventional generation (Joskow, 2011). When RES generate electricity, they lower the price of electricity at those specific moments (given their zero marginal cost generation), and where renewable penetration has been aggressive prices can fall to zero or even can become negative. Thus, in absence of subsidies, or mandated feed-in tariffs that pay a fixed price for intermittent power regardless of the demand, the average value of renewable generation will fall as capacity expands, and at some point the value will fall below the cost of further capacity additions. After this point, additional RES would no longer be competitive, as the electricity price would have come down to a level too low to recover investment costs (Hirth, 2013).

The integration of RES in the electric power system also causes additional system costs. First, as the level of uncertainty is being increased, additional RES require additional reserves in the system, which come at certain cost. Second, on a longer time frame, considering a power system's adequacy (i.e., ensuring sufficient investments/capacity to cover the load), RES cannot account for the same level of firm dispatchable capacity as conventional power plants do. Additional capacity might be required, often referred to as back-up capacity. A third cost aspect relates to network costs, occurring both on a transmission level (e.g., to connect remote locations such as off-shore wind farms), and on a distribution level, where reinforcements might be required to deal with high, bidirectional flows (e.g. those that result from high solar PV penetration).

3.2.2 Technical Implications

From a technical perspective, implications regarding RES can be considered on the generation and the network side (both transmission and distribution). On the generation side, a balance between instantaneous load and generation needs being ensured. The variability and unpredictability of RES pose additional challenges here. Also the possible required minimum level of conventional generation needs being considered. Regarding the networks, grid stability (voltage control, reactive power) needs being safeguarded. As mentioned earlier, the fact that RES face locational restrictions might create a need for transmission grid expansion. As far as modularity is concerned, the distribution grid in particular might need reinforcements.

In the remainder of this paper, focus will be on the *technical implications* of RES deployment for the *electricity generation* system. Elements related to the overall economics, or grid-related aspects are clearly as relevant, and parallels can often be drawn. The scope is restricted this way to allow for a more in-depth analysis.

Regarding the technical challenges of RES for the electricity generation system, a further sub-division can be made.

1. The first challenge is ensuring reliable system operation—balancing load and supply at all times. This relates to dealing with potentially steeper ramps in the residual load profile, and with the higher levels of uncertainty. A vast amount of academic research in the field of power system engineering is being devoted to this area.
2. The second challenge relates to systems aiming at high shares of RES (often 80% or more). To achieve a high share of RES in terms of electricity generation, the level of installed capacity needs being significant, given the limited load (capacity) factors of RES (20%–40% for wind; 10–20% for solar PV). Furthermore, given a certain original load profile, this implies that instantaneous RES generation will exceed

demand at certain moments. When this generation needs to be curtailed (in absence of sufficient system flexibility), this has implications on the relationship between installed RES capacity and the actual achieved share of RES generation (and clearly also on the economics of RES).

3. The third challenge concerns the level of reduction of the residual demand peak. Current systems typically still have an existing conventional power plant fleet large enough to ensure generation can meet peak demand. However, when in the future the electricity generation system can no longer rely on such sufficiently high levels of depreciated capacity, new investments will be required in power plants facing low load factors, necessary to cover net-demand peaks when RES are generating little or nothing. This relates to the so-called back-up issue.

In the remainder of this paper, the focus is on items 2 and 3 as listed above, and on the representation of RES in long-term models. Possible upper limits of RES "absorption" related to achieving certain shares of RES will be focused upon, together with the conventional system requirements for a secure operation. The opportunities of different flexibility options will be discussed in this regard.

3.3 System Options to Deal with RES

A number of flexibility mechanisms exist to deal with RES intermittency issues: dispatchable generation, curtailment, grid extensions, storage, and demand side integration. Clearly, not all of these flexibility options are equivalent or even directly comparable.

Conventional dispatchable generation is required to meet part of the electricity demand (i.e., the part not being covered by RES generation). When this generation is flexible in dynamic terms, it is also well suited to deal with a potentially highly variable net load profile. But even without large fluctuations, generation capacity is required for basic electricity generation.

Curtailment can be seen as sort of a counterpart of flexible dispatchable generation. When instantaneous RES generation exceeds original demand (and no other flexibilities are present or usable at the time), curtailment of RES is required to keep the supply-demand balance. Furthermore, also in terms of balancing, curtailment might be needed to mitigate high fluctuations in the net load profile.

Generation and curtailment each provide flexibility in a single direction: generation can only be used "upward", producing additional electricity; it cannot help when RES generation exceeds demand. Curtailment on the other hand can only provide "downward" control; it cannot help when there is insufficient RES generation to meet the load.

Considering the electric network as flexibility instrument is not straightforward. Networks are required both in horizontal (geographic) dimension, connecting different regions, and in a vertical dimension, connecting large generators and consumers at high voltage (i.e., the transmission grid) with household consumers and possibly local generation at low voltage levels (i.e., the distribution grid). Expanding and reinforcing the grid is therefore beneficial to create geographic aggregation in the horizontal dimension, thereby smoothing out variability and uncertainty to some extent. Additionally, a strong vertical grid that is sufficiently controllable (smart grid) allows capture of the full potential of local flexibility (generation, demand and storage).

In this regard, a sufficiently strong network is essentially a precondition for the other flexibility instruments. A stronger network enhances system reliability and allows for an overall more efficient system operation, by allowing the system to make use of the most efficient generation and flexibility options.

Apart from flexibility reasons, newly deployed RES may also simply require new networks in order to be connected to the system. Locations with good resources for RES might be at rather remote locations, away from current systems and load centers. Examples are off-shore locations for wind, or deserts for large scale solar PV.

The two final flexibility means—storage and demand response—may provide flexibility in two directions: they can absorb excess electricity, or can generate (or consume less in case of demand response). Electricity storage is currently still dominated by pumped hydro storage. This means of storage has ratings comparable to conventional power plants, and can typically (when purely considering the storage part) store an amount of energy at rated capacity of an order of magnitude of several hours. As storage is also quite flexible in terms of changing its output, or moving from charging to discharging mode or vice versa, it is also well suited to deal with steep variations and unpredictability. Future storage options might be provided by compressed air energy storage, batteries, conversion to other energy carriers (e.g. power-to-gas), etc., all having their specific characteristics.

At the demand side, demand can be influenced by real-time prices or other incentives. Demand can be changed in absolute terms (increase or decrease, given certain elasticity), or can be shifted in time. The latter option, demand shift, is to some extent similar to storage. The time span that can be bridged is, however, limited. The use of an application or process can typically be shifted for at most several hours. Examples include for instance the operation of deferrable loads such as washing machines, dryers or freezers; devices related to heating, ventilation and air-conditioning; and in the future the charging of an electric vehicle.

4. IMPLICATIONS OF HIGH RES SHARE FOR ELECTRICITY GENERATION

This section explores high RES system effects, especially the impact of possible curtailment and net-demand peak reduction. First, the general principles are discussed. Second, an assessment of the different flexibility options is provided.

4.1 System Set-up

Considering the variability of RES, a crucial distinction to be made is between electricity generation (energy, aggregated over time) and instantaneous power delivery (bounded by installed capacity). When a certain share of electricity generation from RES is aimed for, a substantial level of installed capacity is required, given the relatively low load factors. When moving to systems with very high shares of RES, interactions with the original demand pattern become more relevant. With increasing levels of installed RES capacity, RES generation will exceed original load levels more frequently, possibly creating the need for curtailment.

For the analysis, Belgian data is used as a case study. The Belgian time series for demand, and wind and solar PV generation are taken for the year 2013, all on an hourly basis. Data originates from the Belgian Transmission System Operator (TSO) Elia (2014). Wind makes up 60% of the considered RES profile, while solar PV takes up the other 40% (in energy terms). In the following analysis, the RES profile will be scaled to attain desired levels of RES.

The presented case study is to a very large extent generalizable. Clearly, specific quantitative results obtained in the analysis are dependent on the input data used (in this case, the 2013 time series for Belgium). However, further analysis has demonstrated that when using time series for RES (wind and solar PV) and load for other European countries, results turn out to be very similar (both qualitatively and quantitatively). This relates both to the similar behavioral patterns determining the electricity load, and similar geographic conditions determining wind and solar PV generation. When considering regions with structurally different load and RES patterns, results might differ to some extent quantitatively, but the order of magnitudes and qualitative effects (as will be described further) remain valid.

At first, the analysis is based on the time series of load and RES with a focus on excess generation and net-demand peak reduction. A flexible generation system is considered, complemented in a later stage of the analysis (Section 4.4) with flexibility instruments (storage, demand response and grids). A linear optimization model is set up and used in this regard.

Figure 3 presents the original average daily demand (in blue), together with the residual demand[2] when the amount of RES is increased to a share of 40% (in green) and 80% (in red), respectively, assuming all energy generated from RES can be captured or absorbed in the system. As can be seen from the figure, however, the average daily demand turns negative at several points in time. When these RES profiles are expressed on an hourly time frame, the 40% RES also faces negative values. As an example, a two week period of hourly data is presented in **Figure 4** (corresponding to the same period as considered in Figure 2). Negative demand means that there is more RES than can be used and thus curtailment, storage, or an upward demand response is necessary. In addition, both Figure 3 and Figure 4 illustrate that there are moments of very little RES generation—when the residual demand is (nearly) equal to the original demand. Those occurrences indicate the need for back-up generation, utilizing storage or downward demand response.

[2] In the remainder of this paper, residual or net demand is used to refer to the original demand minus the (possible) generation from RES.

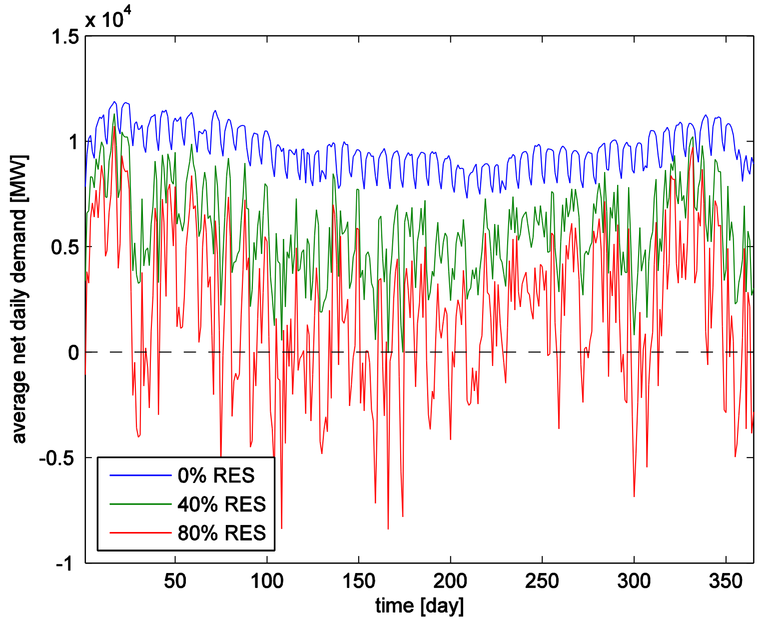

Figure 3. Average net daily demand for different shares of RES.

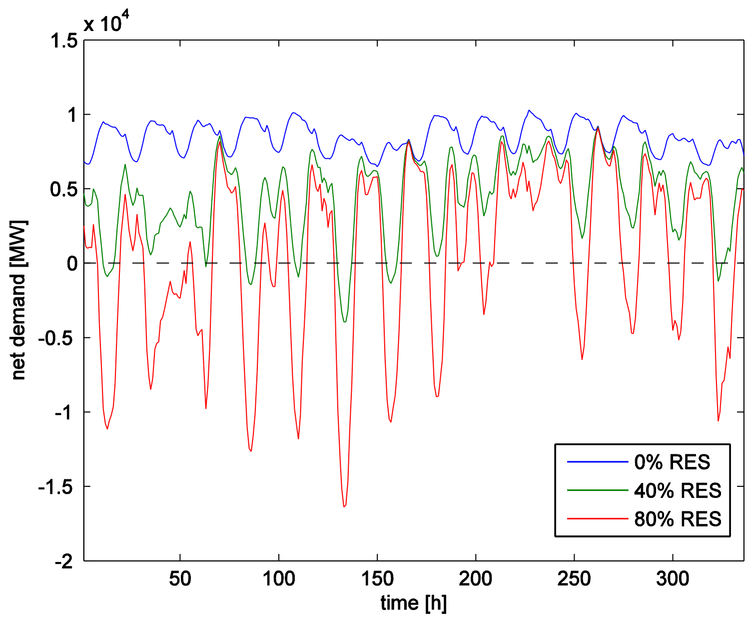

Figure 4. Illustration of detailed hourly net-demand profile for different shares of RES.

4.2 Impact of RES Curtailment on RES Shares

If the considered system would have insufficient flexibility to deal with negative net demand, and all RES generation that exceeds demand would need to be curtailed, the actual achieved RES share would be clearly lower than the targeted level on an annual basis.

Figure 5 presents the relationship between installed RES capacity and actually "absorbed" RES generation, if curtailment is the only way to deal with negative net demand (solid line). This contrasts to the linear relationship between installed capacity and RES generation, if all this RES generation (including the generation exceeding demand) could be absorbed by the system.

From this figure, it is clear that at a certain level of installed RES capacity, the marginal contribution of the RES to generation decreases sharply. Additional installed RES capacity will mostly be generating when there is already sufficient RES to cover demand, and hence will be (at least partly) curtailed. Put differently, for increasing the desired shares of RES generation, from certain point, a more than proportional level of installed RES capacity will be required. On Figure 5, the level of curtailment can be read as the horizontal difference (i.e., for a given level of installed RES capacity) between the full and the dashed line. For the considered data, curtailment starts playing a role at RES shares of about 40%.

In Figure 5, a combination of wind and solar PV was considered and used as RES. **Figure 6** presents the relationship between actual RES share and installed capacity when only considering wind, and **Figure 7** presents the relationship when only considering solar PV. The outcome for only wind (Figure 6) is similar to the mix of wind and solar PV considered in Figure 5. When only considering solar PV (Figure 7), the outcome differs significantly. Because of the sharp, diurnal pattern of solar PV, at a certain point PV generation covers most of the load during daytime. Adding more PV capacity to the system will not lead to much generation when needed, leading to the very sharp rise in the considered curve. In this case, it is difficult to achieve RES shares of about 30–40% solely with solar PV.

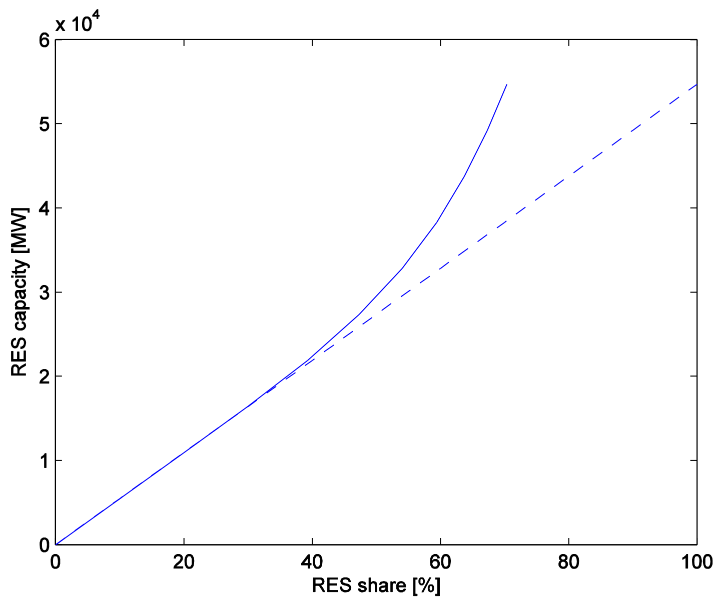

Figure 5. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity. In this setting, flexible generation and curtailment are possible (no other flexibility instruments).

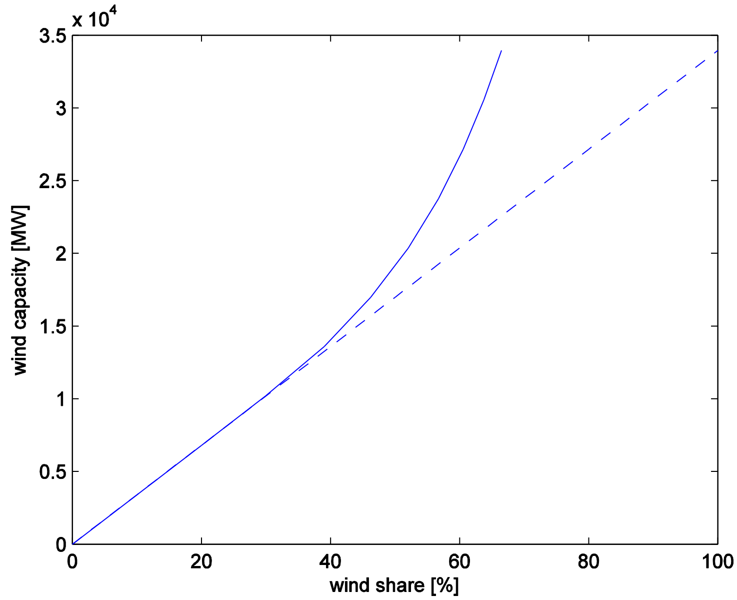

Figure 6. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity. RES in this case only consists of wind. In this setting, flexible generation and curtailment are possible (no other flexibility instruments).

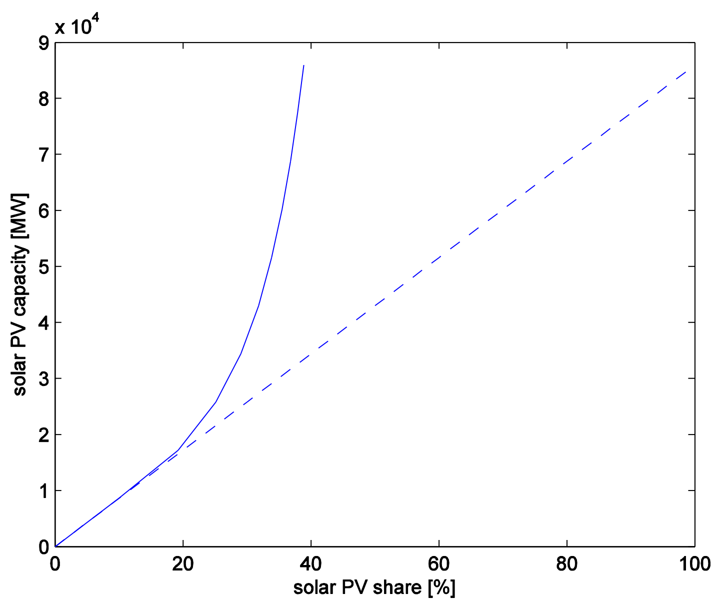

Figure 7. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity. RES in this case only consists of solar PV. In this setting, flexible generation and curtailment are possible (no other flexibility instruments).

The analysis so far has provided results assuming a perfectly flexible generation system in place—a residual demand between zero and the maximum load could be covered with conventional generation without limitations. However, as discussed in Section 3.1, TSOs might impose certain minimum levels of conventional (synchronous) generation, for reasons of system stability (or additionally, for voltage control). Such a minimum level could also reflect a certain share of incompressible base load generation, such as inflexible nuclear or large steam plants (e.g., coal or lignite fired). **Figure 8** presents results for the absorbable share of RES generation in the system for different levels of an imposed minimum generation by conventional sources. Clearly, the higher this minimum level, the more difficult it is to attain high shares of RES. The impact of this constraint is quite significant, as can be seen from the figure. For example, at a minimum required level of conventional generation of 30%, curtailment of RES starts at shares of about 30%, and rises quite sharply; RES shares of about 50% already require substantial curtailment (i.e., almost half of the possible RES generation would be curtailed).

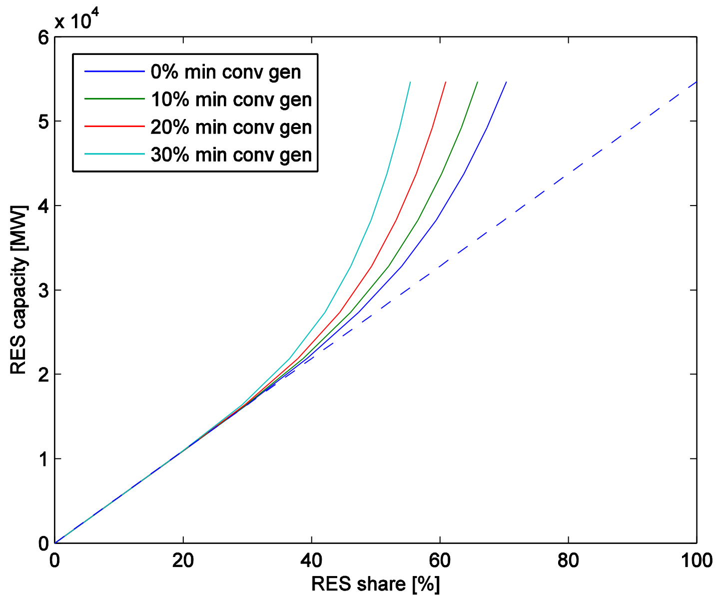

Figure 8. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity, at different levels of a required minimum level of conventional generation. Case with no flexibility instruments in place (except curtailment).

4.3 Reduction of Residual Demand Peak

The evolutions of the net load for different targeted RES shares can also be presented on a well-known load duration curve (on such a graph, all 8760 hourly net-load values are sorted). This is presented in **Figure 9** for different targeted RES shares. As can be seen, at a RES level of 40% minimum hourly net demand starts to go below zero.

This figure relates to the previous discussion as follows. When one considers RES generation only in energy terms, making abstraction of when RES are generating, the linear relationship between installed RES capacity and RES energy share holds (i.e., the dashed line in Figure 5). This corresponds to the indicated targeted RES share in Figure 9. The negative parts of the presented curves in this case would still contribute to generation (e.g., with massive perfect storage). For the 100% RES target line, this means the positive 'surface' on the graph equals the negative part. The negative part in this case would somehow (e.g., through this perfect storage) compensate for the positive part. If, however, the negative part of the curve would be curtailed, the actual share of RES achieved would be lower. The surface of the positive part of the curve then needs to be compared to the reference curve (zero RES).

Figure 9 also provides information on how RES might reduce the net demand peak, as the highest net demand in the various considered cases is depicted as the very first point of the graphs. **Figure 10** provides a more detailed view on this part of Figure 9. In this case, as can be seen, the net peak demand is only reduced in a very limited way by RES. This means there are still moments of high load when there is little or no RES generation. This of course depends on the specifics of the data considered. In Western European countries, highest load typically occurs on a winter evening. Hence, there is no solar PV generation, and it might happen that wind generation at one of these high demand periods is also low or zero.

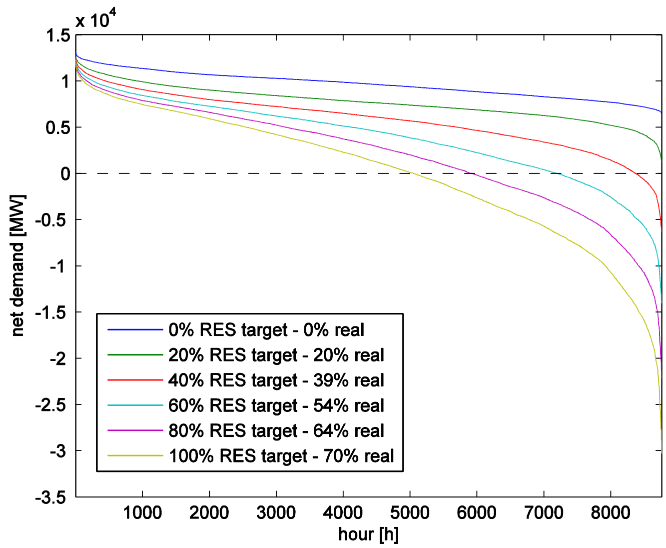

Figure 9. Load duration based curves, for different levels of RES deployment. The indicated targeted RES share is the share when all RES generation contributes to meeting load (even when exceeding demand). The real share is the RES share achieved when RES generation exceeding demand would be curtailed.

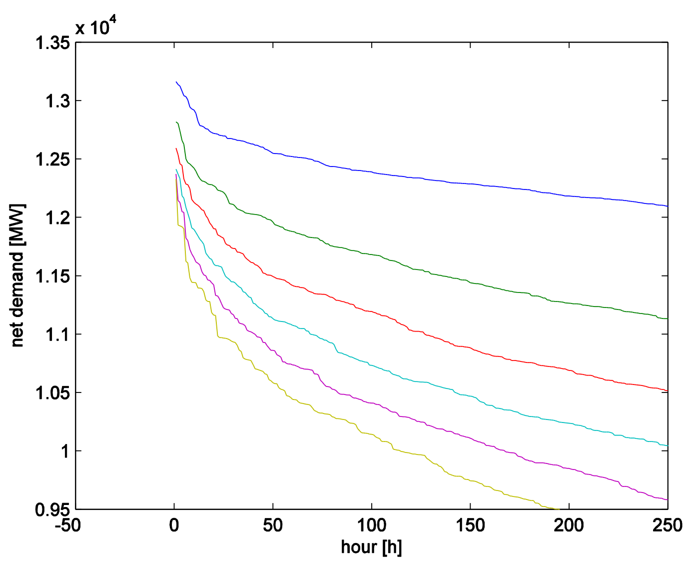

Figure 10. Detail of highest net load levels, of load duration based curves for different levels of RES deployment.

4.4 Impact of Flexibility Options to Enhance RES Integration

In this section, the impact of different flexibility instruments is analyzed. Both the share of RES generation that can be absorbed, as well as the net-demand peak reduction will be assessed. A Linear Programming (LP) optimization model is set-up and used to incorporate the different flexibility options.

4.4.1 Storage

Different levels of storage are considered, i.e., in terms of capacities of the charge and discharge maximum power (assumed to be equal). The maximum storage reservoir in energy terms is assumed to be reached when charging for 5 hours at nominal capacity. The storage efficiency is assumed to be 75%.

To first illustrate the functioning of storage, an example is presented in **Figure 11** of the net load in a consecutive two-week period (same as the one illustrated in Figure 4), before and after the correction by the storage unit. The example is for the 80% targeted RES share and 4 GW of storage (referring to the charge or discharge capacity). As can be seen, the storage is able to mitigate the negative load to some extent. Especially in the second half of the considered period, the need for curtailment is often eliminated. In the first half, however, the net-load after storage correction still reaches significant negative values, implying curtailment.

Figure 12 presents the relationship between the actual achieved share of RES generation and the installed capacity of RES. The case of zero storage corresponds to Figure 5. Clearly, storage being present in the system allows for absorbing more RES generation and requires less curtailment. However, it still remains difficult to achieve very high shares of RES at the considered levels of storage.

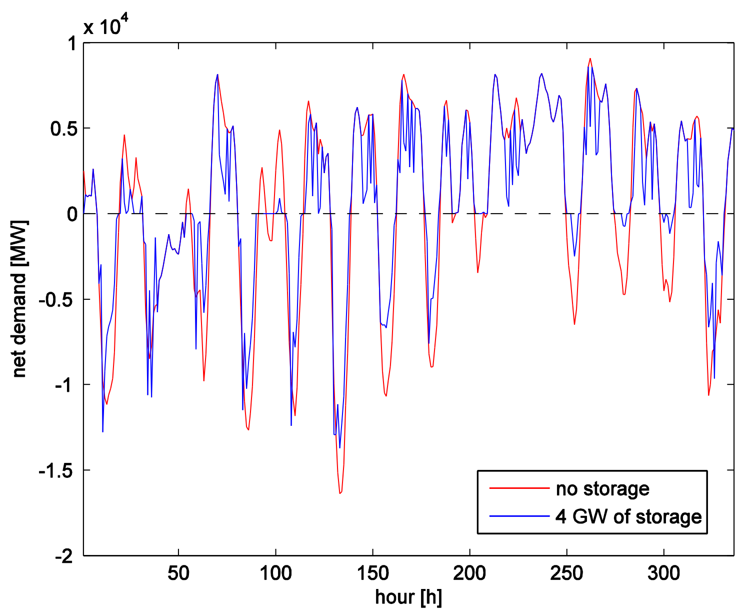

Figure 11. Example of use of storage, for the 80% targeted RES share, for a two week period.

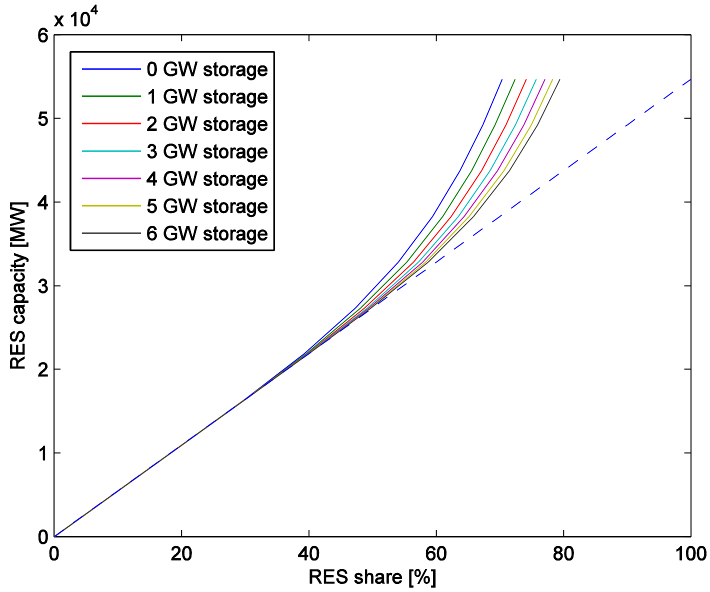

Figure 12. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity, at different levels of storage.

It is interesting to extend the analysis for storage, applying it to the cases where RES consists exclusively of either wind or solar PV. **Figure 13** and **Figure 14** present results for these cases, respectively. The impact of storage for solar PV is significant, and in line with the impact for the combination of RES. When RES consists exclusively of wind, the picture is remarkably different—the impact of storage is more limited here. This relates to the time constants of wind power variability, which can be of an order of magnitude of days or even weeks (e.g., large wind fronts passing by, or consecutive periods of very little wind). The implemented energy storage has a capacity of 5 hours at full capacity, meaning this is too low to have a great impact for wind. Next, the impact of storage on the reduction of the net demand peak is considered. Panel (a) of **Figure 15** presents the net demand peak for different levels of actually achieved RES generation shares (corresponding to Figure 12) and different levels of storage. The net demand peak reduces as the share of RES increases. The reference in absence of storage corresponds to the results discussed earlier (Figure 9 and Figure 10). The deployment of storage clearly reduces the net demand peak. In absence of RES, the peak can be reduced (though the marginal reduction for increasing levels of storage rapidly decreases). With RES, its impact on the reduction of the peak is dependent on the level of storage present in the system. The higher the level of storage, the greater the impact of RES will be. This is also illustrated in panel (b) of the figure. This plot presents the net demand peak reduction as the share of the installed capacity of RES. Hence, it corresponds to some extent to what in the literature is referred to as capacity credit (Wilton *et al.*, 2014). In this case, the case with no RES and no storage is taken as reference (the peak reduction should be seen as a result when RES enter the system in combination with storage). With storage, relatively high values are attained at low levels of RES share. However, as the share of RES increases, this indicator decreases quite sharply. This means additional RES are not able to actually further reduce the net demand peak in a proportional way.

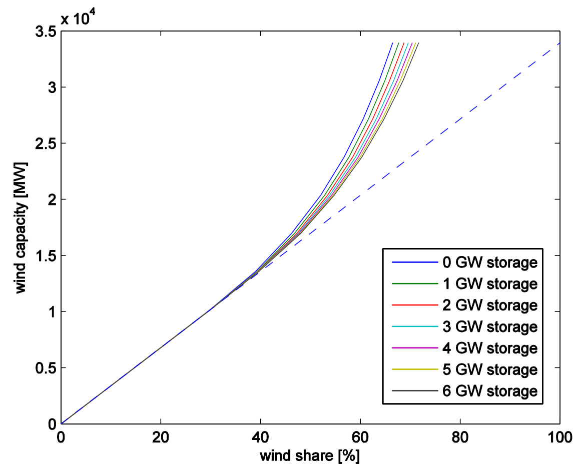

Figure 13. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity, at different levels of storage. RES in this case only consists of wind.

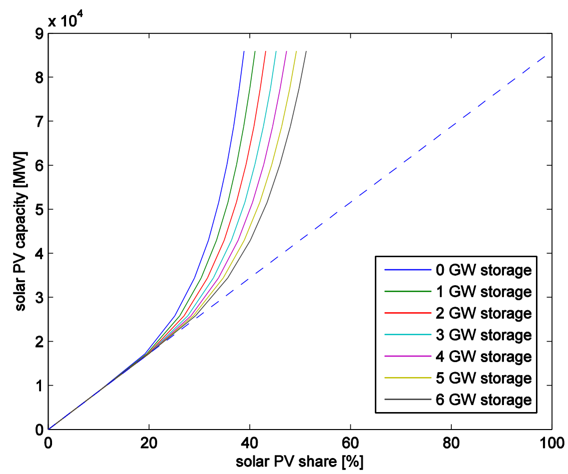

Figure 14. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity, at different levels of storage. RES in this case only consists of solar PV.

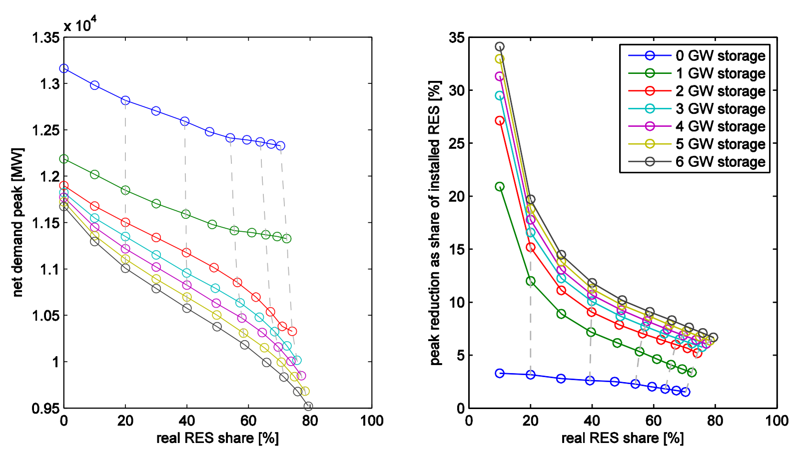

Figure 15. Implications of storage on net demand peak reduction. The LHS Panel (a) presents the absolute reduction of the net demand peak for different levels of actually achieved RES share and storage deployment. The RHS Panel (b) presents the relative net demand peak reduction compared to the installed RES capacity, again for different levels of RES and storage.

4.4.2 Demand Response

Similar to the implementation and discussion of storage, now demand response is considered as a means of flexibility. Focus is on so-called demand shifting. A certain fraction of the demand is allowed to be shifted to adjacent hours. The maximum amount shiftable to other hours is in this case assumed to decrease linearly with the distance from the considered hour. For example, if 15% of the demand is shiftable up to 3 h, this implies that 15% is shiftable to the hour right before or after the considered hour, 10% is shiftable to 2 hours before or after, and 5% is shiftable to 3 hours before or after. The aggregate of the demand shifted to these hours is still limited to 15%. **Table 1** presents an illustration of the limits on demand shifted in this case.

Table 1. Illustration of share of demand being shiftable to certain hours.

h-3	h-2	h-1	h	h+1	h+2	h+3
5%	10%	15%	0	15%	10%	5%

This way of representing demand response aims to represent possibilities at the demand side in a rather general way. Other modeling options would be to explicitly model flexibilities of appliances or processes allowing for time shifting. The aim here is merely to introduce increasing levels of demand flexibility and to identify the impacts on achievable RES shares and net demand peak reduction.

The impact of the considered way of demand response (at different rates) on the absorption of RES generation is presented in **Figure 16**. Similar to storage, demand response facilitates the integration of RES, leading to higher achievable RES shares. However, the level to which this occurs is relatively limited. Even at very flexible demand response (30% shiftable, up to 6 hours), the reduction of required curtailment is rather small.

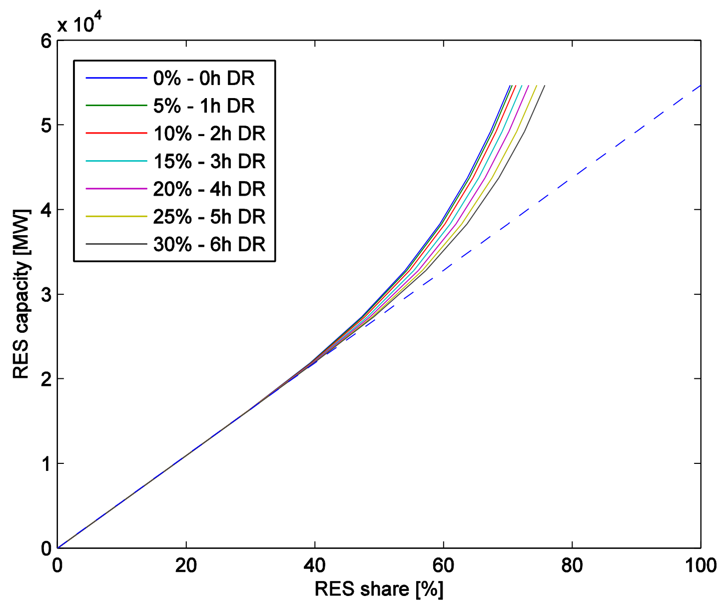

Figure 16. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity, at different levels of demand response (DR).

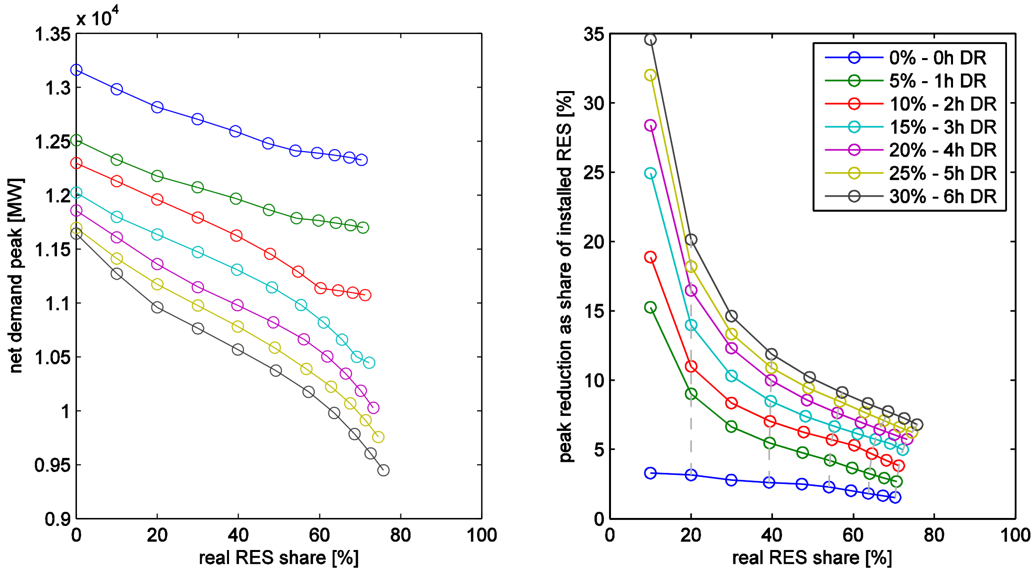

Figure 17. Implications of demand response on net demand peak reduction. The LHS Panel (a) presents the absolute reduction of the net demand peak for different levels of actually achieved RES share and demand response. The RHS Panel (b) presents the relative net demand peak reduction compared to the installed RES capacity, again for different levels of RES and demand response.

The implications of demand response on net demand peak reduction are presented in **Figure 17**. Similar to storage, demand response reduces the net demand peak, also in absence of RES. The impact of RES is again greater when demand response is possible in the system (panel (a)). The peak reduction expressed as share of installed RES capacity is highly dependent on the level of demand response considered being combined to the RES deployment, and sharply decreases with the level of RES installed (panel (b)).

4.4.3 Electric Network

As discussed in Section 3.3, interconnections can facilitate RES integration. There is, however, no clear way to generalize the impact of such interconnections. When for instance considering solar PV, the correlation between a country's generation and that of a neighboring country is likely to be quite high[3] (e.g., correlation between hourly values of Belgium and Germany was 0.9 for the year 2013). The correlation for wind might be lower, but still significantly positive. Furthermore, there still might be moments of very low or even zero wind generation, across areas as large as Europe (Cosseron *et al.*, 2013; IEA, 2014). Variability can be smoothed out to some extent by geographic aggregation. The resulting profile, however, still remains volatile, and in regions such as Europe, cross-border interconnections are at levels far from achieving an actual copper plate representation.

In this analysis, the flexibility of cross-border interconnections is represented as follows. A first limit is set based on the actual instantaneous generation of RES that can be imported or

[3] The correlation between generation patterns of solar PV will always be relatively high and positive, given the diurnal pattern.

exported. It is assumed that the exchange is limited to a fixed share of this instantaneous level. This limit represents the fact that RES generation tends to be (highly) correlated across borders. A second limit (general absolute upper bound) is assigned to the cross-border interconnections. This represents the physical limits of the country's cross-border interconnection capacity. Third, on a yearly basis, the net imported amount of RES electricity is set to be equal to the net exported amount of RES electricity.

Simulations have been carried out where the RES import and export are limited to 25% of the instantaneous RES generation (first limit as discussed above), for various levels of absolute interconnection capacity ranging from 0 up to 6 GW (second limit). Results are presented in **Figure 18**. At low RES shares, connections are first limited by the absolute value, while at higher RES shares, the relative exchange limitation (25%) becomes binding. Also here, under the assumptions of the analysis, networks may allow reaching higher RES shares, but the overall impact tends to be limited.

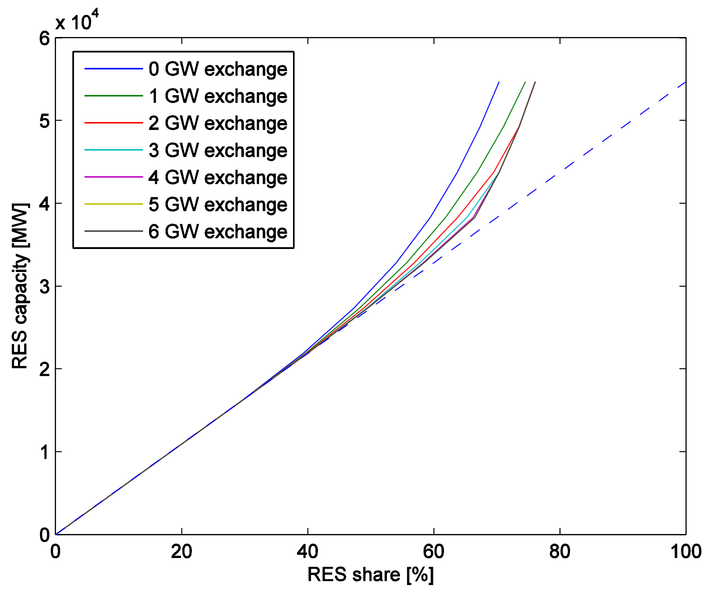

Figure 18. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity, at different levels of cross-border interconnection.

Limiting the tradable amount of RES relative to the instantaneous RES share (in this case 25%), implies that the net demand peak reduction is not really changed compared to the reference case (no flexibilities). After all, the highest net-load occurs during moments of low RES generation. At these moments, the import of RES-based electricity is limited, proportional to this low instantaneous RES generation.

4.4.4 Flexibility Combination

The flexibility options as discussed earlier can be combined. In line with the assumptions for each of the flexibility options as described before, **Figure 19** presents results for the implementation of 3 GW of storage, 15% demand response and 3 GW of cross-border capacity: results are presented for implementing each of these flexibilities individually, and then all three combined. The results for the case of a combination of 6 GW of storage, 30% demand response and 6 GW exchange is also presented. Combinations of such (relatively high) levels of flexibility clearly benefit the level of RES share that can be attained and curtailment levels are significantly reduced. Limitations on the final achievable RES shares (given the considered levels of flexibility) still remain.

Figure 19 has been constructed with no minimum limit on the share on conventional instantaneous generation. When a 20% minimum share is imposed (reference is also shown in Figure 8), the considered flexibility options and combinations improve RES integration as displayed in **Figure 20**. Also here, flexibility combinations reduce curtailment significantly, but clear limits on the achievable RES share remain. Comparing Figure 19 to Figure 20, a minimum level of conventional generation significantly impacts curtailment and achievable RES shares, even in presence of flexibility instruments.

The net demand peak levels for the considered flexibility options and combinations are presented in **Figure 21** (panel (a)). This figure is set up for the case with no requirement on minimum conventional generation levels. The similar figure for the 20% minimum case is, however, pretty similar—the net-demand peak levels are identical, only the shares of actually achieved RES shares are at higher levels (as is clear from Figure 19 and Figure 20). The greater the level of flexibility, the higher the impact RES have on the net demand peak. From panel (b) it can be seen that when RES are being introduced together with significant levels of flexibility, the impact can be quite significant. This relative peak reduction still rapidly decreases as RES shares increase.

As a further illustration, the net load duration curves for the 60% targeted RES share are presented in **Figure 22** for the various flexibilities considered and their combinations (in the case with no minimum conventional generation requirement). The net-load presented is the original load minus the generation from renewables, and after correction by the flexibility instruments. The flexibility options aim to avoid curtailment (i.e., negative net load on the figure) as much as possible. All curves (except for the curve with no flexibility) have several moments of zero net load. The combination of 3 GW of storage, 15% demand response and 3 GW of exchange almost completely abandon the need for curtailment. In the case of the combination of the highest flexibilities, no curtailment is required (no negative net load on the figure). The figure also shows to what extent the highest net load can be reduced by these flexibilities (intersection with y-axis).

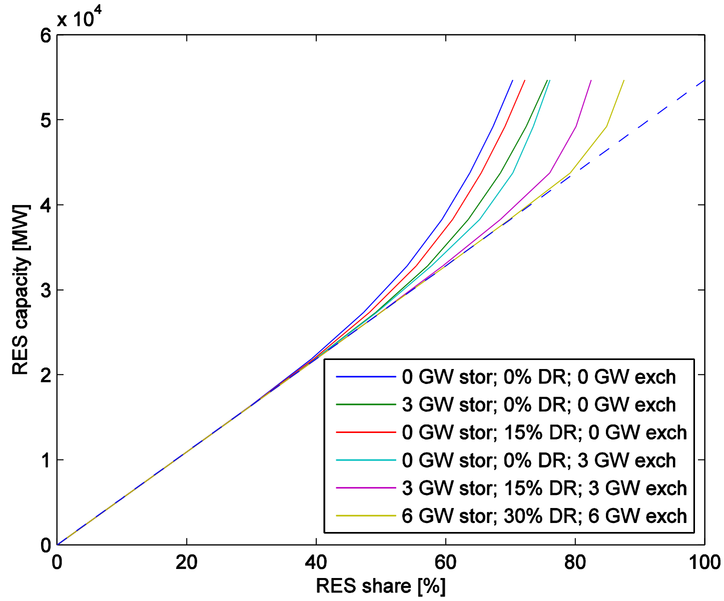

Figure 19. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity, for different flexibility instruments and their combinations.

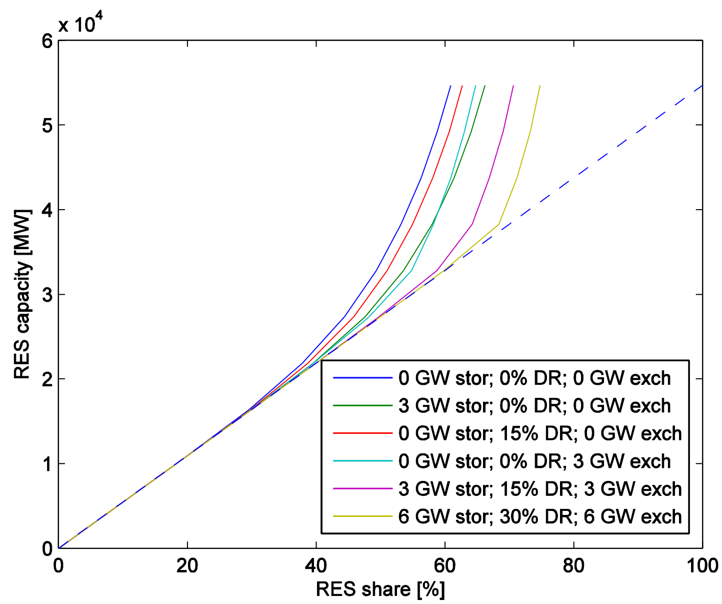

Figure 20. Relationship between actual (achievable) RES share (in energy terms) and installed RES capacity, for different flexibility instruments and their combinations. A minimum required level of conventional generation of 20% is imposed.

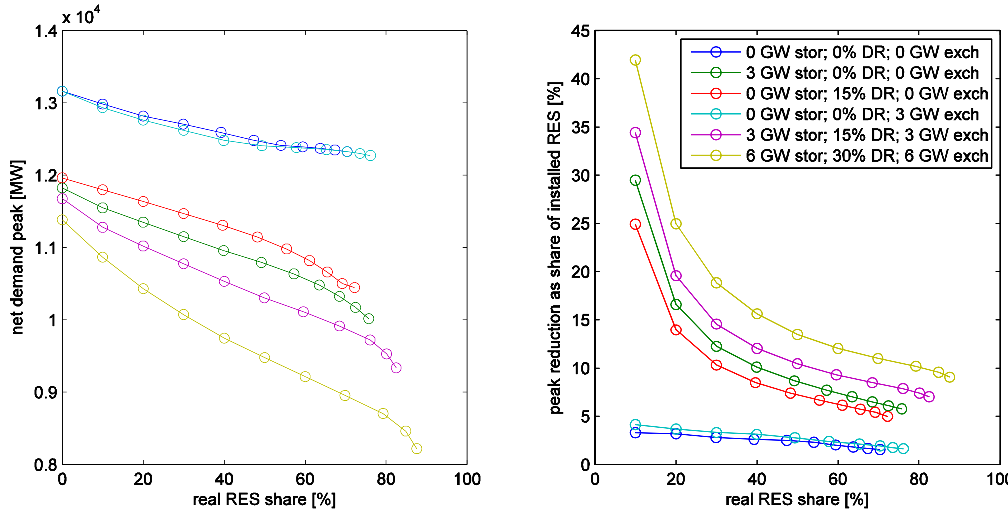

Figure 21. Implications of different flexibility options and their combinations on net demand peak reduction. The LHS Panel (a) presents the absolute reduction of the net demand peak for different levels of actually achieved RES share and flexibility options. The RHS Panel (b) presents the relative net demand peak reduction compared to the installed RES capacity, again for different levels of RES and flexibility options.

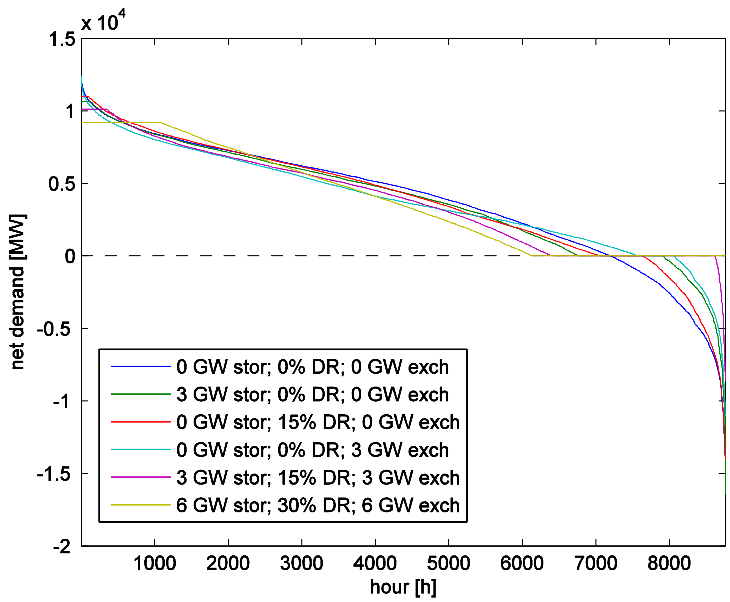

Figure 22. Load duration curves for 60% targeted RES share, for various combinations of flexibility options.

5. INCLUDING RES IN LONG-TERM INVESTMENT MODELING

In this section, the representation of RES in energy system models is discussed, with specific focus on the operational implications of RES as identified in the previous section.

5.1 Current Representation of RES in Long-term Investment Models

Bottom-up models have a higher technical detail compared to top-down models. The adequate inclusion of RES in such bottom-up models however can still face shortcomings. Next to the time steps considered for investment (e.g., every 5 years), these models also consider the operation of the system. In this regard, one year can be represented by a number of time slices. RES can be modeled with a specific load factor or with a specific profile for the given time slices. The number of time slices varies across models and specific settings. It can be as low as 12 (to represent a seasonal and day-night variation), up to 8760 (all hours of the year). To represent RES variability in an appropriate manner, sufficient time slices are required, together with an actual variable RES profile. When profiles are averaged over time, the implications of RES variability are largely lost. Models can further take into account a so-called peaking equation, to ensure sufficient generation capacity. In this equation, the overall installed capacity (taking into account the capacity credit) needs to be higher than the yearly peak demand increased with a certain safety margin.

These models have an operational dimension, and as such make a distinction between installed capacity and RES generation. To capture the RES effects as described in this paper, it is essential to take into account a sufficient number of time slices and preserve the fluctuating (i.e., not averaged out) RES profiles (Poncelet *et al.*, 2014).

In the remainder of this section, the incorporation of RES in top-down models, and specifically CGE models, is discussed. Top-down models have a macro-economic focus, and correspondingly typically lower technical detail. Different technologies can be considered, but no distinction is made between installed capacity and electricity generation. This means a fixed load (capacity) factor for each technology is assumed, and no variable RES profiles are taken into account. Appropriately setting up and using CGE models for analyses with significant shares of RES is a clear challenge (Tapia-Ahumada *et al.*, 2014).

There are several different approaches to representing RES in CGE models. Here we focus on the MIT EPPA model to discuss various approaches. The latest version of the EPPA model (EPPA6) represents 18 regions, 14 sectors, and 10 advanced backstop electricity technologies. The cost of advanced electricity technologies, including renewables, is determined by the cost markup, which is the cost relative to conventional electricity in the base year of the model. The markup is determined by a levelized cost of electricity (LCOE) calculation that uses base year values for capital costs, fixed and variable operation and maintenance costs, plant lifetime, capacity factors, fuel costs, etc. Over time and under policy, the cost of the advanced technologies relative to conventional generation will change endogenously. Advanced technologies will only enter the market when economically competitive, or explicitly forced by policy.

One approach is to model renewables as imperfect substitutes to other generation. In the EPPA model, at lower penetration levels renewables are an imperfect substitute for other electricity generation technologies because of the variability of resources (see Paltsev *et al.*, 2005). It is assumed these are located at sites with access to the best quality resources, at locations most easily integrated into the grid, and at levels where variable resources can be accommodated without significant investment in storage or backup. The elasticity of substitution between renewables and electricity generated by other technologies creates a gradually increasing cost of production as the share of renewables increases in the generation mix. Thus, further expansion as a share of overall generation of electricity comes at greater cost (due to locations far from demand and the grid and the need for transmission as well as storage or backup). This formulation allows gradual penetration only as the prices of other generation technologies continue to rise, and tends to limit the share of electricity that can be generated by wind and solar.

Another approach is to model renewables with fixed backup requirements. In the EPPA model, large-scale renewables are represented with two renewable backstop technologies: large scale wind with biomass backup, and large scale wind with natural gas backup (see Morris *et al.*, 2010). Unlike regular wind or solar, large-scale wind with biomass or gas backup is modeled as a perfect substitute for other electricity because the backup makes up for intermittency. The elasticity of substitution does not create a gradually increasing cost of production as the share of these two technologies increases in the generation mix. The additional costs for large-scale wind (backup or storage[4] and transmission) are incorporated into the costs of the new technologies. For wind with backup, it is assumed that for every kW installed capacity of wind there is one kW installed capacity of backup (either biomass or gas).[5] The backup allows the combined plant to be fully reliable because whenever the wind is not blowing demand can still be met through the backup.

Building on the fixed backup requirement approach, another approach is to model flexibility requirements for renewables. One version of the EPPA model represents renewables as requiring increasing "flexibility" as the share of renewables grows (see Karkatsouli, 2013). This flexibility can only be attained from conventional generation sources. One can think of this as a credit trading system—conventional generation produces "flexibility credits" that can be sold to renewable generators, which require the credits to produce electricity. This approach essentially requires increasing levels of backup capacity as the share of renewable generation increases, as opposed to a fixed backup requirement.

A final approach to include RES in a top-down model is to link it with a bottom-up model, to create a "hybrid" model. There are a few examples of such models that link high level, aggregated macroeconomic models (similar to DICE) to bottom-up engineering models, such as the Model

[4] A storage system is an alternative to backup capacity. However, compressed air, pumped hydro, batteries, and other technologies are generally more expensive at this time, making backup capacity more likely.

[5] Studies have shown that there are times when the wind is still for hours or even days at a time over expansive regions (Cosseron *et al.*, 2013)—see Figure 2. While spreading out wind sites reduces the number of hours with low or zero wind, there is still an effective limit imposed by intermittency. Regardless of how much wind capacity is built, there are still periods when the wind does not blow and backup capacity must be utilized to meet the load. This may create the need for an installed capacity of backup generation of 1 kW for every kW of installed capacity of wind. Even though these backup plants would rarely operate, they would need to be capable of replacing all wind generation if necessary. In the EPPA model it is assumed that the backup is only needed 7% of the time (for the rare occurrences when there is no wind).

for Evaluating the Regional and Global Effects of GHG reduction policies (MERGE) (Manne *et al.*, 1995) and the World Induced Technical Change Hybrid Model (WITCH) (Bosetti *et al.*, 2006). In addition, the U.S. version of the EPPA model, USREP (Caron and Rausch, 2013), which is highly disaggregated with numerous electricity technologies represented, has been linked to the National Renewable Energy Laboratory's ReEDS (Regional Energy Deployment System) model (Short *et al.*, 2011; Rausch and Mowers, 2012). Tapia-Ahumada *et al.* (2014) have linked the USREP model to the bottom-up electricity model EleMod. These hybrid models attempt to take advantage of the details and constraints represented in the engineering models as well as the economic forces represented in the economic models. Linking the two can be quite difficult.

5.2 Key Insights for High RES Modeling

The analysis provided in this paper offers important insights for high RES modeling. CGE models have mostly focused on the problems created by low instantaneous RES generation in systems with high levels of RES. Modeling RES as requiring backup generation is a solution. Given that there are times of almost zero wind over large expanses of Europe (Cosseron *et al.*, 2013; IEA, 2014), requiring 1-for-1 backup may be an appropriate model assumption, in absence of other flexibility options. As has been demonstrated, explicit mechanisms for demand response, storage, and grid exchange could also be added to CGE models to handle low instantaneous demand. Such additions would increase the cost of a system with high RES.

Less focus has been given to high instantaneous RES generation in CGE models. A key insight from this analysis is that the need to curtail wind generation has a significant impact on the generation system. Even perfectly backed-up renewable generation will face the costs of curtailment. This analysis shows that, due to needed curtailment, the required RES capacity increases non-linearly with the desired share of RES generation, and that there are effective technical limits to the share of RES attainable. Even if one was willing to pay to build enormous amounts of capacity, given the shapes of the curves (e.g., Figure 5), it is unlikely that intermittent RES generation could reach much beyond 80% of total generation. This relationship between required capacity and RES generation share could be represented in a CGE model. One approach would be to increase the level of inputs required to produce one unit of renewable output as the share of renewable output increases. In the EPPA model, this could be done by changing the renewable markup cost over time as a function of output. Increased required capacity as RES shares increase essentially decreases the capacity factor. So the capacity factor could be made a function of the share of RES and put into the LCOE calculation to therefore make the markup a function of the share of RES. This relationship could then be implemented in a model like EPPA in order to better represent the dynamics created by high RES systems in cases of high instantaneous RES generation. This analysis also shows how demand response, storage, and grid exchange impact the relationship between renewable capacity and generation. Those mechanisms explicitly represented in a CGE model would add further richness to the dynamics of high RES systems.

6. CONCLUSIONS

Intermittent RES come with a number of specific characteristics, having an impact on the economic and technical operation of power systems. In this paper, focus is on the impact of the variable RES generation profile, and especially on implications towards the actual share of RES generation that can be achieved and on the reduction in the net-demand peak.

At low RES penetration, the relationship between installed capacity and generation is linear, meaning the share of RES generation rises proportionally with the installed capacity. However, when the RES capacity increases further, instantaneous RES generation might start exceeding the original demand at certain moments in time. If the system has no proper flexibility instruments in place, this excess RES generation needs to be curtailed. The amount of RES curtailment rises very sharply from a certain level of installed capacity, effectively imposing an upper bound on 'absorbable' RES generation shares. Additionally, when minimum requirements are set on the share of conventional generation for reasons of system stability, the level of required curtailment increases even further. Flexibility instruments such as storage, demand response and electric networks benefit the amount of RES generation that can be absorbed, but limits (and hence, curtailment requirements) remain.

RES also have an impact on the peak in net demand that occurs in the system. However, even in cases with relatively high amounts of installed RES capacities, the reduction in net-demand peak turns out to be very limited. Specific moments in time with a high original load and low instantaneous RES generation remain present. Flexibility options turn out to have a significant impact in this regard.

The observed effects of intermittent RES have important implications when including RES in energy system models. In bottom-up models, the RES implications as identified in this paper can be addressed by including an operational time dimension with a high enough resolution, and preservation of original (i.e., not averaged-out) load and RES profiles. Regarding top-down models, such as CGE, RES intermittency might need to be addressed more specifically. In essence, variability-related effects are difficult to account for, as these models do not consider an operational time dimension. There typically is a fixed relationship between installed capacity and electricity generated over the year (i.e., a fixed load factor). As such, systems are being optimized using technologies with a fixed LCOE. However, when dealing with intermittent RES, the actual variable RES generation profile triggers specific effects. The analysis of this paper has highlighted the need for curtailment and the limited impact on net-demand peak reduction. In addition, increasing amounts of RES capacity clearly impacts the shape of the load duration curve, and correspondingly impacts the load factor of different technologies and their LCOEs. All these effects are further influenced by the level of available flexibility options such as storage, demand response and electric networks.

When introducing intermittent RES in top-down models, the need for backup requirement and sufficient operational flexibility requirements have to some extent been addressed in the existing literature. To account for excess instantaneous RES generation and required curtailment, future adaptations to top-down models might be required. An important step is making certain parameters dependent on the amount of RES being deployed. Especially addressing the load factor in this regard seems useful (note that it would be also useful to adapt the load factor for conventional technologies, depending on the penetration of RES). By making this load factor dependent on the amount of RES installed, the LCOE and the markup cost are influenced. This way, the decreasing contribution in energy terms at increasing shares of installed RES capacity can be represented to some extent.

The availability and impact of potential flexibility instruments also needs better representation, as it has a significant impact. We finally wish to emphasize that even with perfect one-to-one backup, there are limitations on the share of electricity generation that can be achieved from RES. This curtailment requirement is typically overlooked in current modeling.

7. REFERENCES

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