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Balancing responsibilities: Effects of growth of variable renewable energy, storage, and undue grid interaction

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ABSTRACT

Electrical energy storage is often proposed as a solution for the mismatch between supply patterns of variable renewable electricity sources and electricity demand patterns. However, effectiveness and usefulness of storage may vary under different circumstances. This study provides an abstract perspective on the merits of electrical energy storage integrated with decentralized supply systems consisting of solar PV and wind power in a meso-level, residential sector context. We used a balancing model to couple demand and supply patterns based on Dutch weather data and assess the resultant loads given various scenarios. Our model results highlight differences in storage effectiveness for solar PV and wind power, and strong diminishing-returns effects. Small storage capacities can be functional in reducing surpluses in overdimensioned supply systems and shortages in under-dimensioned supply systems. However, full elimination of imbalance requires substantial storage capacities. The overall potential of storage to mitigate imbalance of variable renewable energy is limited. Integration of storage in local supply systems may have self-sufficiency and cost-effectiveness benefits for prosumers but may have additional peak load disadvantages for grid operators. Adequate policy measures beyond current curtailment strategies are required to ensure proper distribution of benefits and responsibilities associated with variable renewable energy and storage.

1. Introduction

The share of power from renewable sources in Europe's energy mix is growing. As a result of commitments to climate change mitigation and energy transition policy, this growth is expected to continue (EEA, 2017; REN21, 2017). Between 2017 and 2030, the share of renewable energy in the energy mix of the European Union may double from 17.5% to 34% (EC, 2019; IRENA, 2018). The renewable energy discussed in most future energy scenarios includes electricity generated using a combination of sources that are typically deployed on a decentralized, comparatively small spatial scale, such as solar-photovoltaic cells (solar PV) or wind turbines.

Estimates about the combined shares of solar PV and wind power in electricity generation in the European Union range between 21% and 35% by 2030 (IRENA, 2018; IEA, 2018). In the Netherlands, installed capacity of solar PV is expected to increase from around 4 GW in 2018 to over 14 GW in 2030, and onshore wind from 4 GW to 6.5 GW (Schoots et al., 2017).

Solar PV and wind turbines are scalable technologies, as a result of which deployment occurs at a variety of system scales. In addition to high-capacity installations operated by large utilities, trends observed in the Netherlands and other countries in Northwest Europe indicate that collective or private ownership of medium and small-scale installations is becoming increasingly popular (Hieropgewekt, 2019; Krozer, 2018; Van der Schoor and Scholtens, 2015; Yildiz et al., 2015). Between 2017 and 2019, collective ownership of solar PV in the Netherlands increased fourfold from 37 MW to 142.7 MW. Cooperatively operated wind energy is expected to grow to 308,7 MW by 2020, up from 158.7 MW in 2018 (Hieropgewekt, 2019). Aims of many operators of privately or collectively owned small-scale renewable energy installations (henceforth, prosumers) include increased energy self-reliance, energy-neutrality or even full autarchy (Bauwens, 2016; Van der Schoor and Scholtens, 2015).

With the growing role of solar PV and wind energy in the energy supply mix comes the requirement to re-evaluate the capabilities of the current power infrastructure to cope with such changes. Power from solar PV and wind turbines is often associated with supply variability and/or unpredictability. In general, such decentralized variable

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renewable energy sources (vRES) relate to difficulties to match energy supply and demand (Akhmatov and Knudsen, 2007; Eltawil and Zhao, 2010; Lund, 2005). Due to that inherent mismatch between supply and demand, integration of larger capacities of solar PV and wind increases the risks of structural imbalance in electricity grids (Wolfe, 2008). With growing shares of decentralized vRES, adaptations to the grid itself or the way its users interact with it may be necessary to ensure that operational electricity grid parameters remain within specific bandwidths. Current policy therein is mainly limited to curtailment of electricity generation to prevent surpluses, and deployment of dispatchable (non-renewable) reserves to prevent shortages (Bird et al., 2016; Joos and Staffell, 2018; Schermeyer et al., 2018). While this has been adequate to facilitate energy transition thus far, a policy portfolio limited to those options is unlikely to remain sufficient under circumstances of high vRES penetration rates.

Electrical energy storage (EES) is often considered an essential element of future power systems as it may offer the buffering potential required to expand the integration of vRES (Dell and Rand, 2001; Hall and Bain, 2008; Müller et al., 2017). However, the potential of EES to resolve all imbalance between electricity demand and supply from vRES is subject to practical deployment limitations. Under current circumstances, EES is therefore unlikely to serve as a universal solution for all demand-supply imbalance issues. A fundamental understanding of the extent to which EES may or may not be useful in the integration of EES is essential to the development of adequate energy transition policy.

With this paper we aim to add a more abstract, meso-level perspective to the existing body of research on EES for vRES, and draw attention to the uneven distribution of responsibilities with regard to EES as a result of current policy. Using a balancing model we evaluate the integration potential of electricity derived from solar PV and wind in a context of various scales of community-scale residential sector demand patterns and various storage capacities. The model incorporates hourly demand and supply patterns based on real weather data and residential sector characteristics of the Netherlands. The weather patterns and residential sector demand patterns of the Netherlands can be characterized as highly variable and as such suitable for a representative case study. The challenges associated with balancing demand and supply under such conditions are indicative of a typical situation in which storage may be considered a means to mitigate grid instability. Rather than focusing on case-specific details, we provide a more general overview of the relation between integration of variable renewables and storage. We thereby juxtapose both top-down, utility-level perspectives and bottom-up, prosumer-level perspectives to highlight differences in objectives, requirements and desired functionality between the two.

This paper is structured as follows: the next section elaborates on background and contextual elements on the basis of related literature. In section 3 we describe the methodology followed in this research. Section 4 provides the results of our model simulations. In section 5 we discuss the outcomes of this study and contextualize our findings. Section 6 draws conclusions and derives policy implications from our results.

2. Background and literature review

2.1. vRES integration

Different sources of renewable energy have different typical generation patterns due to variability and/or unpredictability, and thus each has its own characteristic issues with regard to energy system integration and demand-supply balancing. For solar PV, power generation is dependent on the amount of solar irradiation at the location of the installation. Solar irradiation follows a highly predictable day-night sinoid pattern coupled with a seasonal sinoid pattern. Variation and uncertainty with regard to actual irradiation relative to theoretical irradiation may be caused by weather irregularities such as cloud cover and/or precipitation. For power from solar PV, the balancing issue lies not in its predictability, but in scheduling. In Northwestern Europe, solar PV power production peaks around mid-day when irradiation levels are the highest, and drops to negligible levels between sunset and sunrise. Power demand in the residential sector generally peaks after sunset, when solar PV is unable to accommodate that demand. The power supply from wind turbines is, in general, more evenly spread between day and night. The variability of the supply pattern of wind power depends foremost on wind speed and is thus less prone to day-night or seasonal rhythms. Nevertheless, wind power may vary on very short time bases. As a result, power supply from wind turbines suffers from reduced predictability and is therefore also inherently difficult to match with demand.

The consequences of vRES development have thus far been met with a variety of responses, such as advanced demand and supply forecasting tools, market adjustment, feed-in regulations and grid adjustments (Papaefthymiou et al., 2018; DENA, 2017). However, most of these measures are reactionary responses implemented on higher system levels, mostly provisioning for transmission and distribution system operators (TSOs and DSOs). These measures have been adequate for relatively small shares of vRES under gradual supply infrastructure change conditions. The level of policy adjustment, system integration and cooperation between TSOs, DSOs and prosumers required to provide structural solutions for high penetration of decentralized vRES largely remains a topic for debate (Gerard et al., 2018; Hadush and Meeus, 2018). In the meantime, the effects of insufficient policy coordination occasionally become evident through reports of impending threats to system functionality such as grid congestion and capacity constraints at both high and low system levels (Schermeyer et al., 2018; Trommelen, 2016; Turner, 2017; Van den Berg, 2019). Since most vRES deployment still takes place on macro-level scales, policymaking for meso- and micro-level issues often remains neglected. This does not, however, imply that vRES balancing issues don't arise at such lower levels. The need for policy guiding the development of structural solutions to grid balancing is equally high at macro-level systems as it is on meso- and micro-level systems.

2.2. Electricity grid imbalance mitigation

Electrical energy storage (EES) has often been heralded as a structural solution to the increasing grid balancing challenges resulting from larger shares of vRES. Imbalance mitigation involving EES can be operationalized at both the supply side of the energy system and the demand side, and at both low and high system levels (Dell and Rand, 2001; Hall and Bain, 2008; Müller et al., 2017; Nair and Garimella, 2010). Small and medium-scale EES are essential elements in smart grids and associated demand response strategies: novel energy system concepts revolving around peak load management algorithms. While such digital transformation technologies hold a key to managing the pattern volatility of high-vRES energy systems, their effectiveness depends on EES (Zame et al., 2018). Demand response (DR) methods include load shedding (load reduction) and load shifting (moving load over time). Load shedding does not require EES, but its effectiveness is limited. Load shifting, on the other hand, may be a more effective measure to reduce grid imbalance, but only if combined with dedicated EES infrastructure (Dave et al., 2013; Feuerriegel and Neumann, 2016). For load shifting, the flexible component of the demand pattern would be isolated and shifted time. The load shifting potential is determined by the appliance load duration and the maximum time over which the load can be shifted. Without EES, the latter is typically considered limited to a maximum of 24h, but for most appliances the practical load shift time is between 2 and 12 h (Müller and Möst, 2018; Gils, 2014). Moreover, Müller and Möst (2018) indicate that DR without dedicated EES infrastructure becomes much less effective with higher shares of vRES in the supply system. Additional EES would allow more variable load to be shifted over a longer period of time.

Technology propositions for EES span a wide range of possibilities with regard to capacity and purpose. Of the many options under consideration, most seem suboptimal solutions with regard to practical deployability, for instance because of economic drawbacks, state of development or technological constraints (Dunn et al., 2011; Suberu et al., 2014). For instance, widespread attention is paid to the possibility of using batteries present in electric vehicles as a form of electricity buffering in household-scale electricity grids. However, this is subject to several practical considerations such as timing and charge availability (Hoogvliet et al., 2017; Jargstorf and Wickert, 2013; Tan et al., 2016). Moreover, supportive policy with regard to vehicle-to-grid technology is still under development (Kester et al., 2018). Only a small portfolio of EES technologies is currently being implemented or under consideration, including both large grid-scale options such as pumped hydro storage and small household-scale options such as batteries (Van Meerwijk et al., 2016; IRENA, 2017).

2.3. *Stakeholder perspectives and responsibilities*

Large utility companies and grid operators represent one end of the spectrum of perspectives (top-down), while prosumers represent the other end of the spectrum of perspectives (bottom-up). With regard to energy storage and grid management, representatives of both ends of the spectrum pursue different and perhaps opposing or conflicting goals with regard to surpluses and shortages.

Typically, the responsibility to maintain a balance between supply and demand on large-scale electricity grids is born by utility companies and/or grid operators. Small-scale prosumers are not required to bear the same responsibilities. Some limitations and regulations with regard to energy netting notwithstanding, prosumers are typically free to monetize on surplus energy by feeding it into the power grid – often with priority access for renewable energy. Most of the burden of managing surplus renewables fed into the grid and maintaining grid balance remains with the utilities. As such, integration of EES infrastructure at the grid operator and utility level is a logical consequence of the current organizational structure and allocation of responsibilities.

However, small-scale, prosumer-level EES in local energy infrastructure may also offer a number of benefits for both prosumers and utility companies and grid operators alike. For prosumers, integration of EES in a private or community power system increases self-consumption rates, which in turn may offer financial benefits to the prosumer in several ways. By increasing the self-consumption rate, the cost effectiveness of the installation improves (Müller et al., 2017). In addition, a higher self-consumption rate implies a reduction of grid interaction and associated tariffs. Especially in situations where flexible electricity price schemes are applied, having the capacity to reduce grid interaction for peak load handling may lead to a reduction in energy costs (Adika and Wang, 2014; Crespo Del Granado et al., 2016; Feuerriegel and Neumann, 2016; Shirazi and Jadid, 2015). Nevertheless, Eid et al., 2019 indicate that under current circumstances, decentralized grid balancing often comes at higher costs than the currently employed centralized balancing methods.

For grid operators, widespread penetration of household-scale EES would mean increasing local absorption of generation peaks and thus a reduction of surpluses fed to the grid and associated grid management issues. Whether the effects of small-scale EES remain beneficial depends on the level of self-reliance pursued by prosumers. If prosumers become more self-reliant through expansion of locally integrated EES, it means the shortages are reduced and grid operators no longer play a role in supplying electricity in times of limited generation. With surpluses typically having a higher occurrence than shortages, the interaction prosumers will have with the grid will converge towards only feeding in any surplus generation. As a consequence, grid operators may become primarily concerned with the transportation of surplus electricity away from prosumers rather than delivering electricity to satisfy demand. This implies a change of direction of electricity transportation and management adaptation.

The perspectives of both prosumers and grid operators on the development of EES to improve the integration of energy from renewable sources are widely discussed in current scientific literature. The utility-level perspective if often reflected in macro-level studies with a national or regional scope (e.g. Connolly et al., 2011; Elliston et al., 2012; Krajačić et al., 2011a,b; Mason et al., 2010). The prosumer-perspective is typically associated with micro-level studies focusing on microgrid and smart grid development. Such research generally applies a micro-scale approach to derive situation-specific energy balance optimization solutions (ie. Driesen and Belmans, 2006; Driesen and Katiraei, 2008; Mohd et al., 2008; Müller et al., 2017).

3. Methodology

3.1. *Model description*

To assess self-consumption characteristics of decentralized, variable renewable energy under various situational circumstances, we deploy a dynamic energy balance model. The model, constructed in Matlab Simulink, simulates a local energy system in which power demand is fulfilled through allocation of power available from various energy sources. These energy sources include decentralized, variable renewable energy sources (solar PV and wind turbines), storage facilities and the power grid. Fig. 1 provides a schematic representation of our model. Central to our approach is the intentional reduction of technical detail to maintain the abstract and universal character of this study. The scope of our analysis does not encompass non-technical and non-policy related aspects such as economics or the development thereof. The focus of our analysis is on the energy dynamics of the system.

Key indicators used in this research are self-consumption ratios and grid stability indicators. We define self-consumption as the amount of energy generated by a renewable energy source that is directly utilizable in the simulated energy infrastructure. This includes energy that is directly consumed by connected households as per their demand patterns, and the energy that is redirected to storage. For grid stability indicators we differentiate between surpluses, shortages, and neutral periods after maximization of self-consumption. The grid stability indicators are expressed in energy units (MJ) and/or hours per year. Model simulations represent one full year, calculated on an hourly basis.

3.2. *Data, patterns and indicators*

The model input consists of typical supply and demand patterns spanning 8760 h. The input patterns are a mix of actual, historical measurement data and generated or synthesized data. Central to both the supply and demand patterns is actual climate data. Hourly weather data gathered at weather station Eelde, the Netherlands, between 2001 and 2010 (KNMI, 2013), was used as a basis to synthesize a typical climate year that includes normal patterns as well as occasional deviations and anomalies (ECN, 2012a). Weather data includes ambient temperature, solar irradiation and wind speed. The hourly demand and supply patterns used in this study were generated from the typical climate year data (ECN, 2012b; ECN and Benders, 2012). The power demand pattern is a combination of four different patterns, each typical for a different type of residence: newly built, renovated houses, apartments and existing, older houses. Fig. 2 shows the key characteristics of the energy supply patterns of solar PV and wind, respectively, and the combined residential demand pattern.

The original patterns represent a single household or installation. For larger numbers of households or installations, the model applies a normal distribution spread to the patterns to smoothen the multiplication effect of peaks and troughs that would otherwise occur. A number of other assumptions and abstractions apply to the functioning of the model. The model is demand-driven, but the demand is not required to be fulfilled. This means that the model aims to satisfy demand at all times using power directly available from the locally installed renewable power generation infrastructure, or available through the discharging of

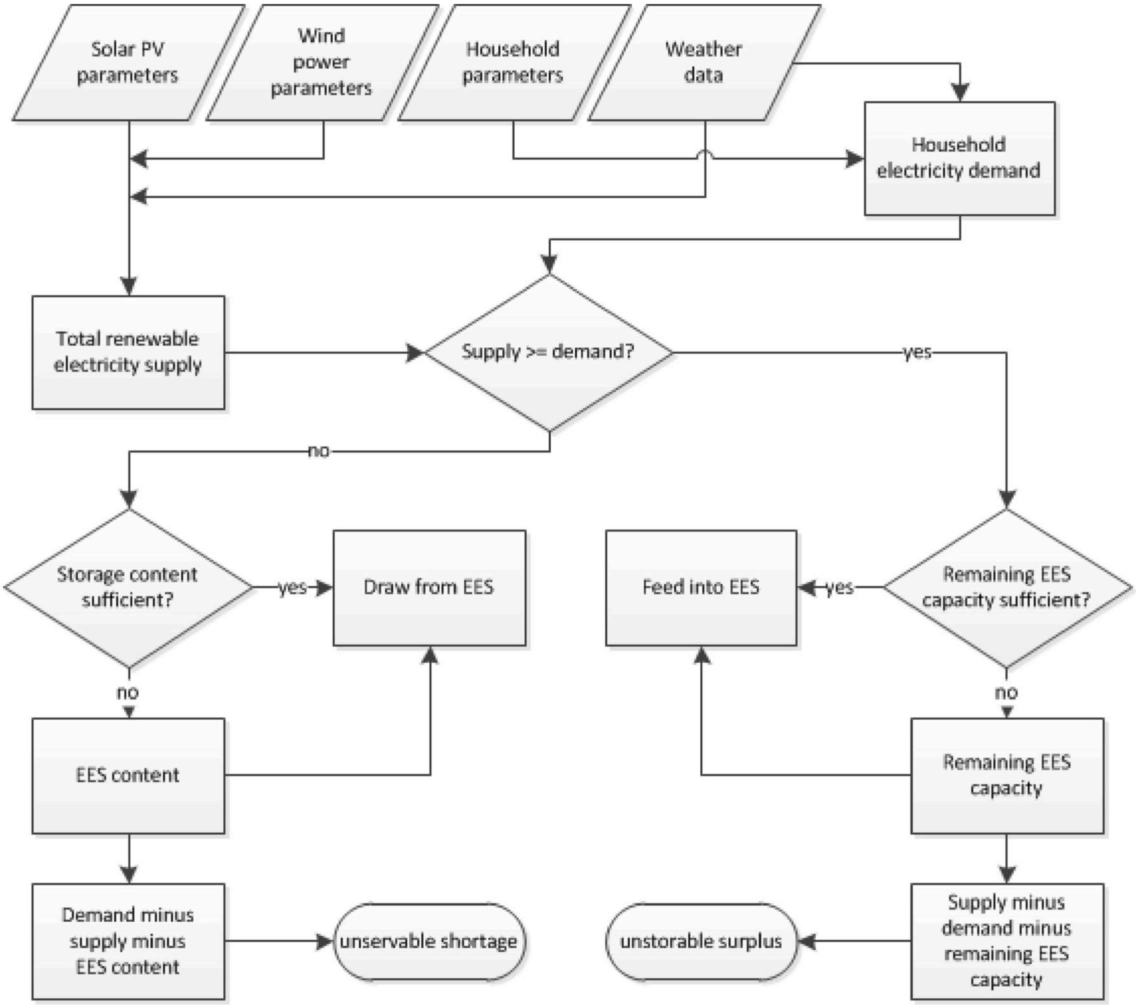

Fig. 1. Schematic representation of the model used in this research.

electric energy storage (EES). Remaining imbalances between power demand and supply are only registered rather than further mitigated. Remaining imbalances can therefore be considered a proxy for required additional interaction with other peripheral energy infrastructure, such as distribution grids. Furthermore, transmission losses and delays are not considered, and the local power infrastructure is modeled following a ‘copper plate’ approach, assuming no capacity limitations with regard to grid lines and interconnections between different parts of the system.

To assess the effects of additional storage infrastructure on the self-consumption characteristics of local energy systems, model simulations involve straightforward surplus-shortage handling using electrical energy storage (EES). The EES infrastructure considered in this research acts as a sink in times of surplus power supply and acts as an additional source in times of undersupply of power. The only operational storage parameter considered is gross storage capacity. EES capacity limits are defined as a percentage of the total annual electricity consumption.

Considering the abstract nature of this study, we disregarded other common technical and non-technical parameters often considered in power storage studies, such as charge and discharge capacities, life time, operational cycles, efficiency and self-discharge. Moreover, we made no a priori assumptions on the type of storage technology, distribution of installations in the system, or specific storage utilization strategies. The latter also extends to demand response strategies (DR) and electric vehicles (EV’s), since we consider both implicit forms of certain storage utilization strategies. The net system-dynamic effects of DR is similar to that of short-term EES, and in terms of capacity limited to the shiftable load of appliances in a small time frame (Gils, 2014; Müller and Möst, 2018; Tronchin et al., 2018). Similarly, effective utilization of the storage capacity of EV’s would require coordination of plug-in grid connections and as such would reflect specific storage timing strategies (Hoogvliet et al., 2017; Jargstorf and Wickert, 2013; Tan et al., 2016).

3.3. Scenario definition

The set of scenarios we simulated consists of combinations of three different key parameters. First, we distinguished between solar PV and wind turbines as two types of variable renewable energy technology. The second distinctive parameter was the capacity of the EES facility. Third, simulations involved a number of different demand sizes. For all the scenarios, the capacity of the renewable energy installation simulated was kept constant, defined as delivering a total annual power supply equivalent to the total annual demand of 250 households – approximately the average size of local energy initiatives in the Netherlands (Hieropgewekt, 2019). The resultant installed capacities of both vRES options differ as a result of different capacity factors. The installations resemble a single medium-sized wind turbine, or a community-sized solar PV installation.

For the baseline scenario, the supply and demand sizes are set at the equivalent of 250 households, without considering EES, to assess the native self-consumption characteristics of power from solar PV and wind turbines. In the baseline scenario, energy supply is nominal and gross annual demand precisely equals gross annual supply. Further model simulations are performed with varying storage capacities, and/or varying sizes of consumer bases, but maintaining the original generation

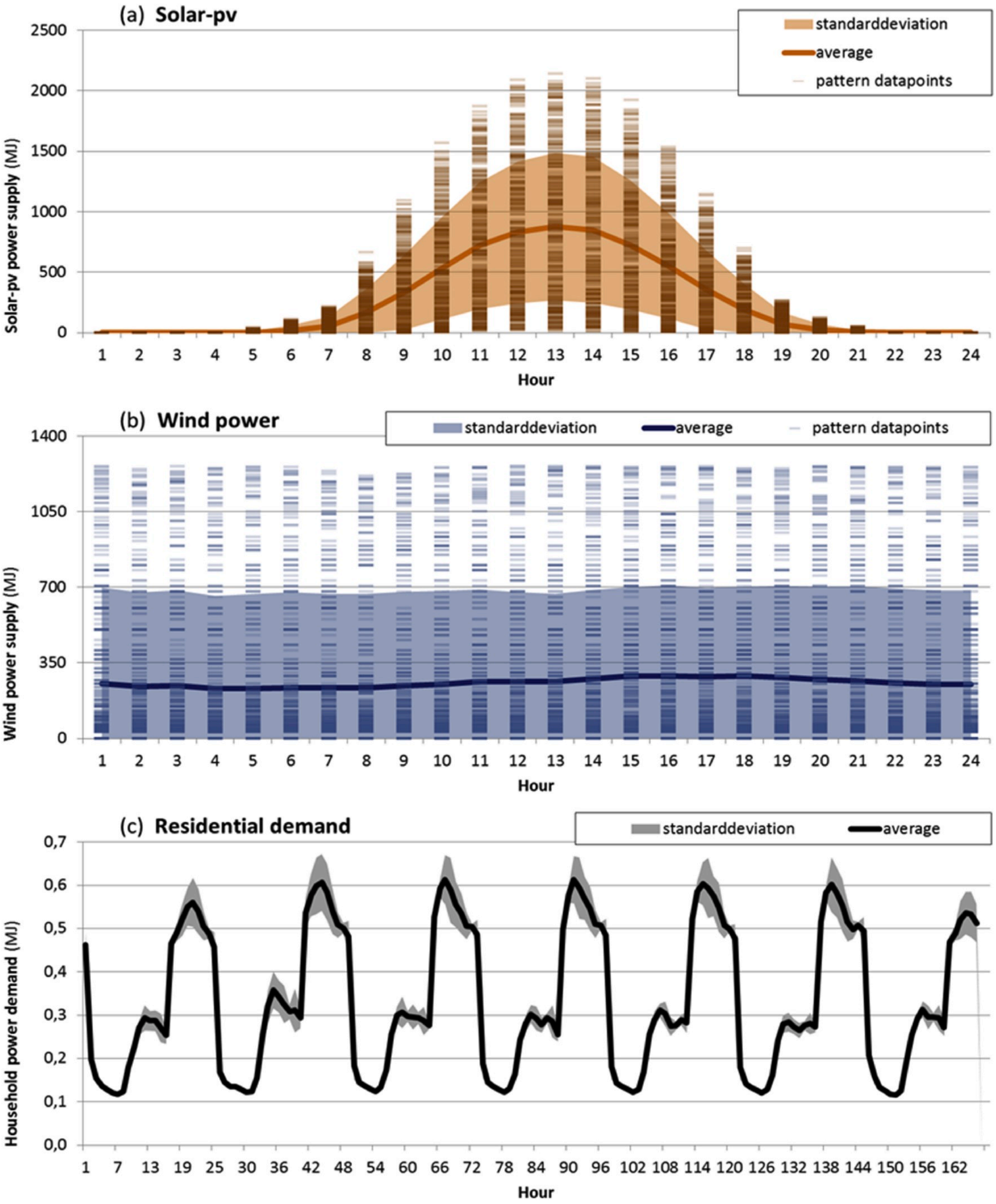

Fig. 2. Supply patterns of solar PV power (a) and wind power (b) and residential sector demand pattern (c) used in this study's model simulations. The solid curves illustrate the average day or week; the shaded areas illustrate the variance in the dataset with a single standard deviation; the individual dashes the actual data points.

capacity. By increasing and decreasing the number of consumers we vary energy demand and thus the native capacity of the consumer pool to absorb the energy generated by the variable source. Since the demand pattern is smoothed for larger numbers of consumers, the potential mismatches between demand and supply decline.

Scenarios with numbers of households smaller than the baseline scenario (<250 households) represent overdimensioned supply systems. In overdimensioned scenarios, the gross annual energy supply exceeds total annual demand. By contrast, in scenarios in which the number of households is larger than the baseline scenario (>250 households) the supply system is underdimensioned. In underdimensioned scenarios, gross annual energy supply is smaller than total annual energy demand. For each of the simulations, we registered the total amount of surplus renewable energy generated over the course of the simulation, and derived the self-consumption rate as the share of the generated electricity that could be accommodated directly, either to fulfill demand or as addition to available storage.

4. Results

The renewable energy technologies used in this paper, solar PV and wind energy, have substantially different typical supply patterns. As a result, they also differ with regard to how those supply patterns align with household demand patterns at various levels of scale, and with various EES-capacities. The behaviour of vRES-EES systems is different between tailored installations with nominal supply (250 households), overdimensioned installations (<250 households), and underdimensioned installations (>250 households). A summarized overview of the differences in behaviour of the different systems is provided in Table 1.

4.1. Systems without EES

The baseline scenario involved a system with a nominal scale supply system, excluding storage, such that total annual supply is equal to total annual demand. The system is thereby net energy neutral. Nevertheless, the model results of the default scenario not including storage indicate that, in order to maintain balance between demand and supply, grid interaction is required during all hourly simulation cycles, the entire year. The number of hours for which demand and supply are balanced or nearly balanced are minimal, if not nonexistent. This applies to supply systems consisting of 100% wind as well as systems with 100% solar PV. The load duration curves (LDC's) in Fig. 3 show the net load for each hour, ordered by magnitude. The LDC's indicate that for approximately one-third of the year, the hourly results are net positive, indicative of a surplus. For two-thirds of the year, the results are net negative, representing a shortage. The total annual surplus is equal to the total annual shortage, reflecting the annual net energy neutrality of nominal supply system design scales. Nevertheless, the number of shortage-hours twice as large as the number of surplus hours, indicating that the average load with which the system feeds surpluses into the local grid is twice as large as the average load in the direction from the grid towards the consumers.

In systems excluding EES, the different variability characteristics of power from solar PV and from wind turbines result in different integration difficulties. Since the supply pattern of wind power is statistically more evenly spread over time, it leads to less surpluses and less shortages than power derived from solar PV (Fig. 3). Moreover, the surplus peaks are smaller for wind power than for solar PV power. Since compensation of larger imbalance and larger peaks requires increased effort, integration of wind energy is less complicated than native integration of solar PV power.

4.2. Systems including EES

Addition of storage with a capacity of 0.1% of annual demand already makes a noticeable difference – albeit more so for solar PV than for wind. Both surplus and shortages of wind are reduced by 16%, while for solar PV the reduction amounts to 38%. For wind, 0.1% storage leads to 2294 h not requiring grid interaction. For solar PV, 0.1% storage results in 3109 h without grid interaction.

The initial gains are best for solar PV, where the addition of a little storage capacity can have a noticeably stronger effect than for wind (Fig. 4). This can be explained from the origins of the mismatch between demand and supply of solar PV: the day-night cycle. The mismatch that occurs between daytime supply and nighttime demand can be mitigated with storage capacity the size of what is consumed over the nighttime period, which is substantially smaller than the capacity required to cover seasonal irradiation fluctuation. Indeed, the solar PV curves in Fig. 4 show that while the initial effect is strong, thereafter any additional gains require larger storage capacities. Wind, on the contrary, is much less prone to day-night cycles or seasonal cycles. As a result, the storage capacities required to further reduce grid interaction in case of wind change more gradually.

As storage capacity increases, both surpluses and shortages diminish and grid interactions decrease. Grid interactions can be avoided for most of the time with a storage capacity of 5%, which for this research corresponds to approximately 163 kWh net storage capacity per household. This order of magnitude storage capacity largely exceeds typical current household-scale EES options or EES capacities of electric vehicles (IRENA, 2017; Hoogvliet et al., 2017; Jargstorf and Wickert, 2013). Moreover, the magnitudes of the surplus and shortage peaks appear to be minimally affected by increasing storage capacity. Fig. 4 shows that at least 12% EES-capacity associated with wind or 23% EES-capacity associated with solar PV is required to eliminate peak surpluses and shortages entirely over the full simulation period.

The self-consumption curves charted in Fig. 5 reflect the notion that initial gains are biggest for solar PV, but for storage capacities beyond 1%, the gains become bigger for wind than for solar PV. From observing various combinations of wind and solar, it shows that for a supply mix consisting of equal shares of solar PV wind, both the high initial gains of solar PV and the long-term gains of wind are present. This also implies that for every solar PV to wind ratio a range of more effective and less effective storage capacities exists.

Fig. 6 illustrates self-consumption and the share in the total energy supply of power from solar PV and wind relative to varying demand scales – i.e. overdimensioned and underdimensioned supply systems. Although the modeled supply systems are scaled such that the total annual supply matches the total annual demand of about 250 households, self-consumption in a nominal system scale situation is fairly minimal. Of the annually generated wind power, approximately 45% can be utilized directly; for solar PV this value is just over 30%. This leaves the vast majority of the generated power requiring alternative destinations. The low self-consumption rate is illustrative for the inherent mismatch between the supply patterns of these variable

Table 1
Summary of results from model simulations of various demand size scales and various storage capacities.

Supply System	Overdimensioned **(<250 households)**	Nominal **(250 households)**	Underdimensioned **(>250 households)**
Excluding EES	• No native balance • Decreasing self-consumption: increasing surpluses • Increasing share of demand: decreasing shortages • Share of demand increase stronger for wind than for solar	• No native balance • Solar imbalance larger than wind imbalance • Surplus peaks larger than shortage peaks	• No native balance • Increasing self-consumption: less surpluses • High self-consumption coupled with strong increase of shortages • Decreasing share of demand: increasing shortages
Including EES	• Addition of small storage coincides with strong increase in balance • Impact of small storage highest for solar PV • Larger storage prone to diminishing returns with regard to balance • Diminishing returns more prominent for solar PV than for wind • Impact of larger storage highest for wind • Elimination of shortages possible with larger storage capacities • Surpluses can be reduced but not eliminated	• Impact of small storage higher for solar than for wind • Impact of larger storage higher for wind than for solar • Imbalance reduction of wind requires less storage than solar • Reduction of wind surplus requires less storage than reduction of wind shortage • Reduction of solar shortage requires less storage than reduction of solar surplus	• Substantial impact only for small storage capacities • Larger storage capacities have little effect on reduction of shortages and surpluses • Surpluses largely absorbed by variation in demand patterns – little or no effect of storage

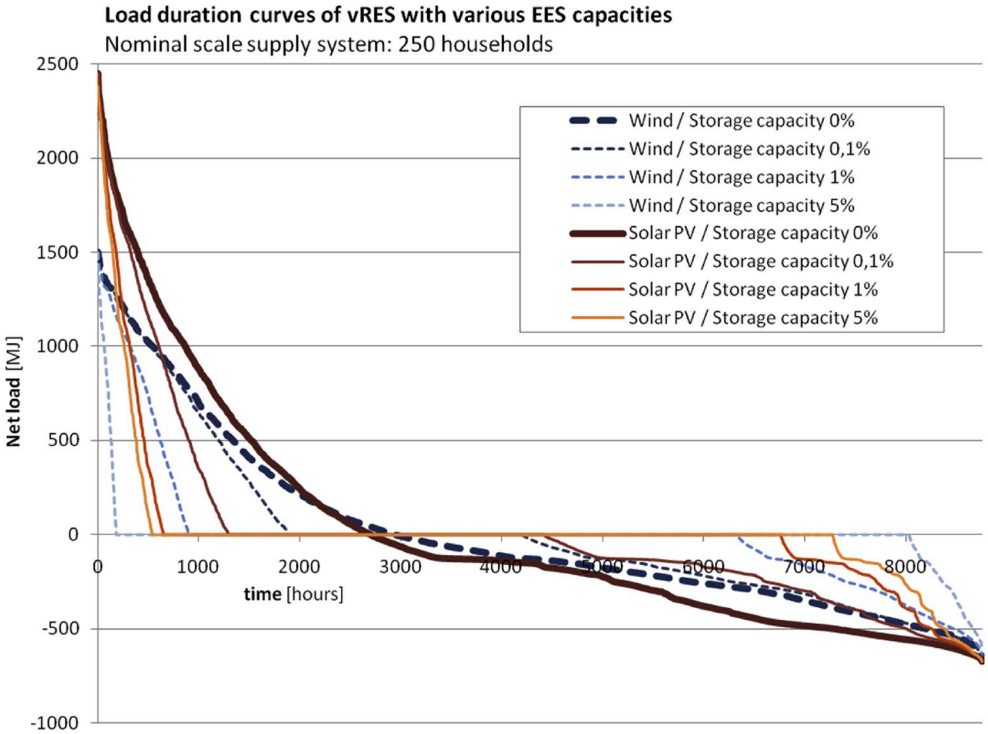

Fig. 3. Load duration curves (LDC's) for wind and solar PV in combination with various storage capacities. The plotted curves represent the net load: the load remaining after accommodating as much of the available supply as possible. Positive values represent surpluses; negative values represent shortages.

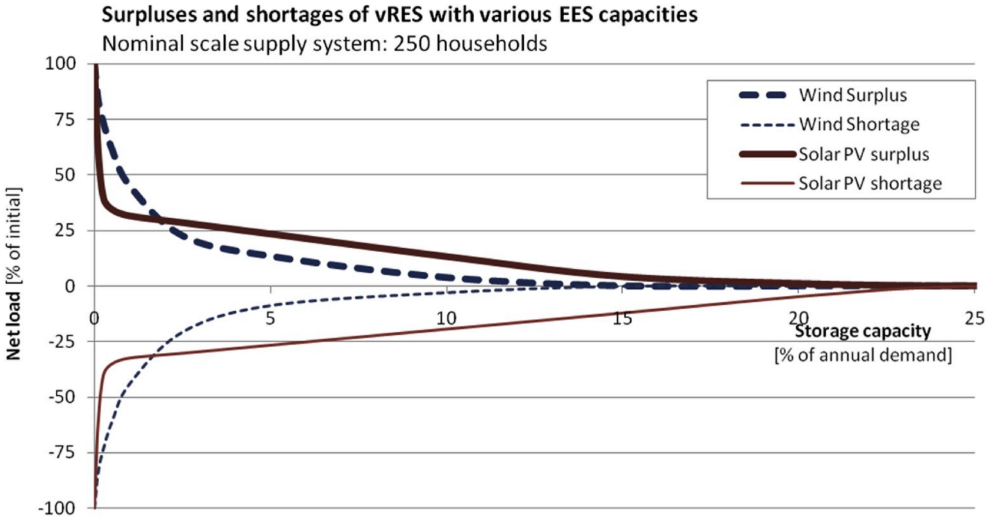

Fig. 4. Net load (surpluses and shortages) relative to various storage capacities. The curves are normalized, with 100% reflecting the total annual surplus/shortage without integration of EES.

renewable energy technologies and typical northwest-European residential sector demand patterns.

For overdimensioned supply systems excluding EES, the shares of electricity from wind or solar PV in the total supply remain relatively stable for all systems overdimensioned by at least a factor five. The share of wind in such overdimensioned systems is approximately 75%, and of solar PV approximately 40% (Fig. 6). For smaller orders of magnitude overdimensioned supply systems, the supply shares of both solar PV and wind power start to decline. Maximizing the supply share requires substantially overdimensioned supply systems for both technologies.

Integration of even relatively small capacity EES greatly reduces the number of hours per year during which shortages, surpluses and grid interaction can be avoided (Figs. 7 and 8). This effect appears most pronounced in a nominal or overdimensioned supply system scale. For underdimensioned supply systems, the number of shortage hours increases whereas the surplus hours rapidly drop to zero, both almost regardless of the storage capacity deployed. Larger EES capacities result in even greater numbers of hours in a year during without supply shortages, but a diminishing returns effects is notably present.

Our model results yielded no indication of native balance in neither nominal, underdimensioned nor overdimensioned supply systems (Figs. 7c and 8c). Moreover, neither shortages nor surpluses were found to be eliminated in any of the investigated overdimensioned systems that do not involve EES. Underdimensioned systems create less surpluses, but complete elimination of surpluses only occurs with supply systems that are significantly underdimensioned. The larger consumer

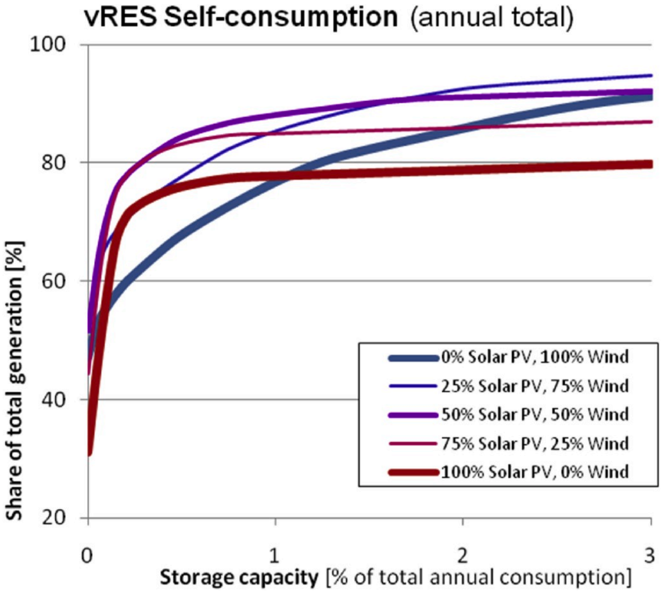

Fig. 5. Self-consumption rates in a nominal supply scale system relative to increasing storage capacities for various proportions of wind and solar PV in the supply mix.

bases are eventually able to absorb all of the production peaks. However, underdimensioned systems are more prone to supply shortages (Fig. 7ab and 8 ab).

5. Discussion

The model simulation approach used in this study offers an unconventional abstract perspective on the potential and limits of electrical energy storage (EES) to manage the integration of variable renewables in a meso-level, residential sector context. By eliminating details related to storage technology and network operation strategies, focus is turned on the more fundamental characteristics of system behaviour under different scenarios. Moreover, this approach allows for a juxtaposition of top-down and bottom-up perspectives on effectiveness of EES with regard to the integration of variable renewable energy sources (vRES) in overdimensioned and underdimensioned supply systems.

The patterns used as input for the model simulations performed in this study are generated on the basis of real historic weather data. This data is region-specific and typical for Northwest Europe, so the insights from this study should be seen accordingly. Nevertheless, the patterns used in this study can be considered to represent worst-case situations. The extent of mismatches between especially solar PV supply peaks and typical residential sector power demand peaks is substantial. The peaks are very pronounced, and with a temporal offset of almost half a natural day those peaks can be considered antiphasic.

By not making explicit assumptions with regard to technical details of EES options, opportunities and limitations that may occur in practice are not part of this study. With changing demand scales and associated changes in EES scales, preferences may shift between different technologies each with different characteristics. Considering the large variety of operational characteristics of different storage technologies (Dunn et al., 2011), the effect of explicit technology choices and associated storage strategies may be considerable (Widén, 2014). This study only considered unconditional utilization of available storage capacity if demand and supply imbalances arise. Moreover, we did not include any current developments in electricity usage in the model, such as increasing use of electric vehicles or electric space heating. We refrained from a priori explicitly defining and implementing any other operational strategies in our model simulations to exclude normative effects and derive consequential storage strategies and policy implications from the model results.

Because our approach explicitly excluded operational details of EES and the systems they are integrated in, as well as any policy directing the roles thereof, the model results inevitably show uncoordinated and seemingly undesired system behaviour. In real-world situations involving supply systems entirely based around vRES, coordination of balance between demand and supply would be integral elements in the development of such a system. Our research therefore does not reflect realistic full-vRES system behaviour – instead the absence of operational details highlights the potential consequences of absence of regulatory policy.

The model results span a range of scenarios of which some might also be considered an unlikely representation of real-world implementations of these systems – at least under current conditions. A clear example of that is the set of model results involving a system setup including 100% storage capacity. Nominal scale supply systems including a storage capacity sufficient to store a full year's demand potentially resolves all issues with regard to surpluses, shortages of any form of grid interaction.

6. Conclusions and policy implications

This study takes a high level perspective of residential sector electricity systems to assess the potential and limits of electrical energy storage (EES) to mitigate imbalances between supply of power from

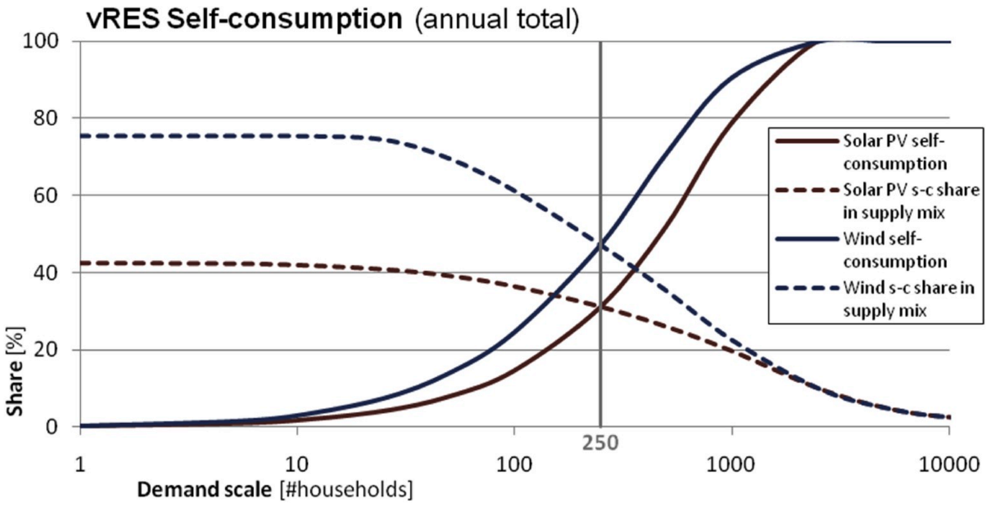

Fig. 6. Self-consumption (s–c) and supply share of wind power and solar PV relative to increasing demand scales. Note the logarithmic scale on the horizontal axis.

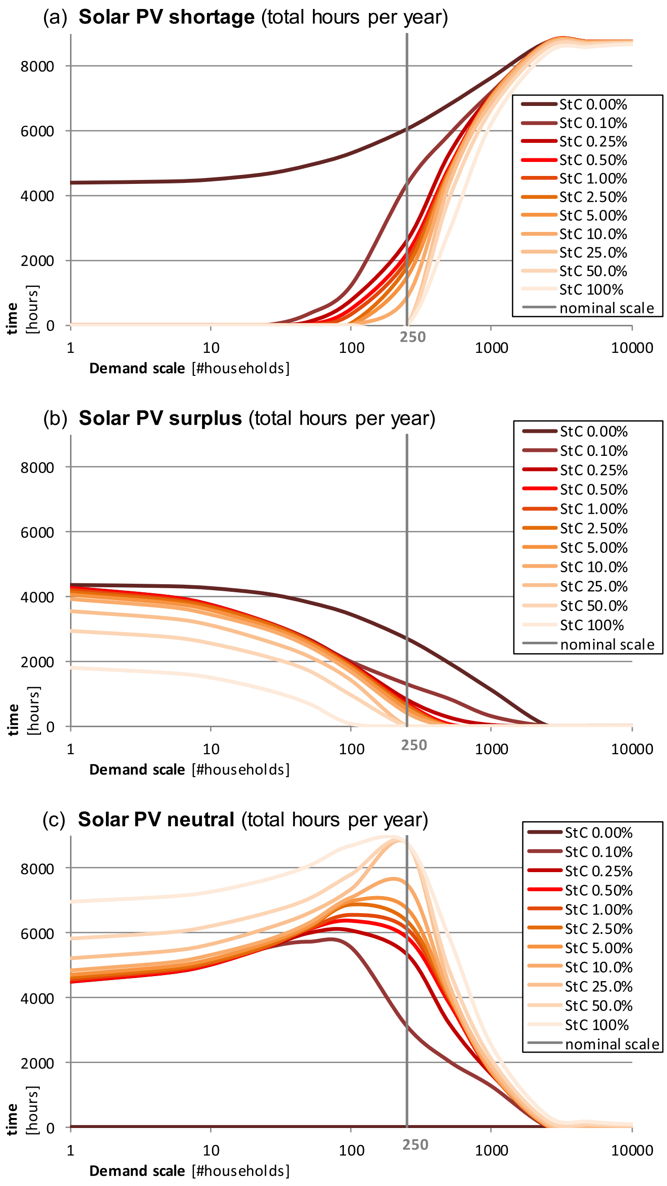

Fig. 7. Overview of effects on the utilization of power from solar PV with different storage scales for different demand scales, represented as the cumulative numbers of hours per year during which shortages (a), surpluses (b), or net neutrality (c) occurs. The combined total of each of the scenario's curves in (a), (b) and (c) equals 8760 simulation hours. StC represents storage capacity in % of total annual demand. Note the logarithmic scale on the horizontal axis.

variable renewable energy sources (vRES) and typical residential sector demand patterns in absence of explicit policy to define associated responsibilities. Methodologically this involved the simulation of several storage scenarios for increasing demand scales in an energy balance model, incorporating real weather data based demand and supply patterns. Essential to the approach followed in this study is strong abstraction and system simplification to highlight the more fundamental behavioural characteristics of power systems including vRES and EES. Through this approach, we highlight the opportunities and limitations associated with EES in overdimensioned and underdimensioned systems for micro-level (prosumers) and meso-level (utilities) energy sector actors. Our model results imply consequential strategies for the deployment of EES that vary between system scales and actors, depending on ambitions and policy-directed responsibilities.

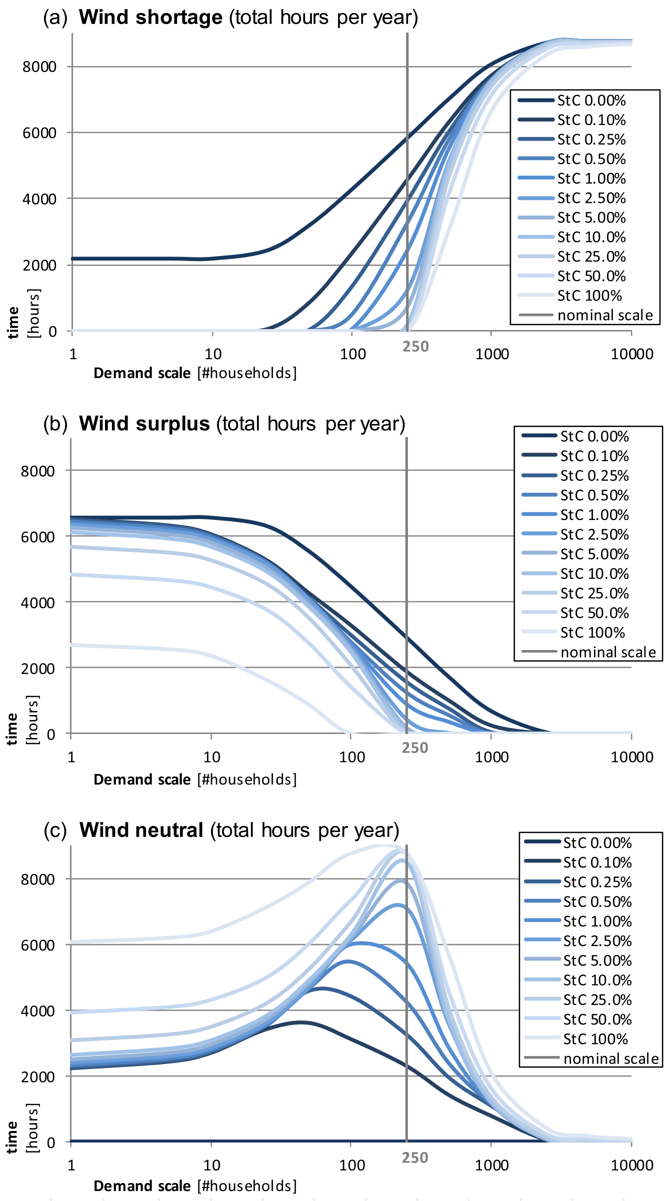

Fig. 8. Overview of effects on the utilization of power from a wind turbine of different storage scales for different demand scales, represented as the cumulative numbers of hours per year during which shortages (a), surpluses (b), or net neutrality (c) occurs. The combined total of each of the scenario's curves in (a), (b) and (c) equals 8760 simulation hours. StC represents storage capacity in % of total annual demand. Note the logarithmic scale on the horizontal axis.

6.1. Consequences of EES on electricity grid dynamics

In nominally dimensioned vRES supply systems, of which the total annual electricity generation precisely matches total annual electricity demand, only a very limited share of the generated power can be consumed directly. The remainder requires additional infrastructure in order to be matched with demand at different points in time. This infrastructure may be a third-party peripheral power grid, decentralized EES integrated in the local system, or a combination of both.

Overdimensioned systems require interaction with a peripheral grid to feed surpluses to, while underdimensioned systems must rely on an external supply system to compensate for shortages. Surpluses and shortages are inevitable in overdimensioned and underdimensioned vRES systems, respectively, regardless of absolute scale or deployment of EES. In nominal systems, full elimination of both surpluses and shortages could be possible in theory, but is likely to be found impossible in practice as a result of low predictability and small deviation margins.

In all relative and absolute vRES system scales, EES may reduce the impact of misaligned supply and demand patterns. This improves the self-consumption rate while potentially reducing the magnitude of surplus peak loads that would need to be fed into the grid without EES. While it would arguably be the prosumers that would benefit most from improved self-consumption, grid operators would benefit from a less volatile feed-in pattern. For both solar-PV and wind power, improvements occur already at minimal EES-capacities, but the effectiveness of additional EES capacity diminishes rapidly thereafter.

In overdimensioned vRES systems, sufficient EES deployment could result in full supply self-reliance of the system owner/operator, eliminating the need to import electricity from a peripheral grid. However, our research found that the EES capacity required for self-sufficiency from vRES-supply is in a range where effectiveness is comparatively low. As a result, prosumers with a supply self-reliance ambition are unlikely to implement any additional storage beyond what is required to eliminate dependency on external supply sources. Under current Dutch policy, prosumers are not required to bear the responsibilities for management of peaks and surpluses. Moreover, prosumers may even monetize on surpluses by feeding them into the grid and letting the grid operators handle the surplus management.

Some surpluses will always remain in overdimensioned supply systems, even if prosumers install EES capacity beyond self-reliance requirements. With larger installed EES capacities the remaining surplus peaks are likely to become sharper and less manageable. As a result, the grid operator may have to deploy additional EES (or alternative infrastructure) the prosumer is not willing and/or not required to deploy. Current Dutch energy policy does not adequately facilitate a redistribution of responsibilities to mitigate this effect.

In underdimensioned vRES supply systems, full prosumer self-reliance is inherently impossible regardless of EES deployment. Instead, deployment of EES in underdimensioned systems may enable prosumers to eliminate the need to feed surpluses to the grid and utilize all local generation locally without interaction with third party energy infrastructure. The EES capacity required for full local consumption depends on the scale on which the system is underdimensioned. The more underdimensioned the supply system is relative to the consumer base, the less EES capacity is required. The consequences for grid operators are diverse. A reduction in vRES surpluses being fed into the grid may imply a reduction of surplus peaks and volatility to manage for grid operators. However, less vRES fed into the grid also implies less availability of distributed renewable power in external grids. Moreover, prosumers covering their own demand imply loss of business for external energy suppliers.

6.2. Consequences of EES for stakeholders

Arguably, there are substantial limits to the benefits for prosumers as well as grid operators of larger-scale local EES deployment. This study acknowledges the claims omnipresent in scientific literature that EES is essential to further the integration of vRES in power systems. Nevertheless, this study also highlights a potential conflict of interest between prosumers and utilities with regard to the function and necessity of EES. While the ambitions of prosumers gravitate towards deployment of EES in their pursuit of maximization of self-reliance or even autarchy, widespread prosumer self-reliance would be akin to competition from a utilities' point of view. Micro- and meso-level deployment and operation of EES by may become a worthwhile business case for utility companies for two reasons. First, it would allow for management of power infrastructure with a high share of variable renewables directly at the source. Secondly, it would enable utility companies to maintain a foothold with prosumers and within community grids with autarchy ambitions. However, aspirations of utility companies may not be compatible with prosumer perceptions of autarchy and conflict with ambitions of prosumers with regard to EES.

The results of this study indicate, however, that the potential of storage to completely fulfill autarchy ambitions of prosumers is limited. Deployment of small-scale EES results in comparatively big leaps in terms of self-reliance for prosumers but larger storage scales appear to be susceptible to diminishing returns and are unlikely to be deployed by prosumers. Larger-scale storage options may more realistically lie within the scope of operational possibilities of utilities. Moreover, larger storage scales show continuous improvements with regard to surplus and shortage management – up to complete elimination of surpluses and shortages if storage capacities and demand scales are sufficiently large.

While these findings acknowledge the essential role of EES in furthering vRES development, our model results also show that the effectiveness of EES to overcome issues of variability and resulting local supply shortages or surpluses is limited. These limitations suggest that EES is unlikely to fulfill a role as a universal solution for imbalance issues, and interactions between prosumers and external grids appear inevitable. However, the roles played by stakeholders in vRES systems may change depending on development of appropriate policy. External grid operators and utilities may change from the current standard of supplying all or most of the required power towards delivering a balancing service and managing occasional shortages or surpluses. Meanwhile, prosumers may be required to become more involved with micro-scale demand and supply balancing.

6.3. Policy implications

The policy implications from our findings revolve around the distribution of responsibilities for balancing demand and supply from vRES over various stakeholders at various levels of scale. Current policy with regard to managing imbalances between demand and supply may differ between countries, but is typically limited to symptom management. Surplus supply is prevented using curtailment, and supply shortages are met with flexible thermal power generation infrastructure. However, this policy extends mainly to large, utility-level electricity generation. On a smaller scale, demand response (DR) may be able to even out part of the imbalances between demand and supply without requiring grid interaction. However, the potential of DR to resolve balancing issues is limited to only the shiftable component of electricity demand. Moreover, most of that shiftable demand can only be postponed on sub-daily time scales. Therefore the potential of DR to resolve imbalances on weekly or seasonal time scales is very small (Tronchin et al., 2018). Moreover, the effectiveness of DR declines rapidly with increasing shares of vRES. Another micro-scale option often considered as part of adaptation to high-vRES penetration is the utilization of electric vehicles (EV's) to act as a flexible buffer to mitigate load peaks. However, the storage capacity offered by current EV battery technology is small in comparison to the requirements shown in this research. In addition, EV's would constitute a buffer of which the presence in the local distribution grid at any time cannot be guaranteed and therefore should not be considered a critical part of reliable electricity infrastructure. Most of the disadvantages associated with either DSM or EV's can be controlled by means of policy regulation, but effective policy to enforce such measures is yet to be developed.

The protective character of current policy with regard to prosumer-level vRES generation creates perverse incentives for EES development and limits optimization of grid interaction and utilization. Sub-optimal grid interactions may be met with grid adaptation to accommodate simultaneous load peaks. Such adaptations could include increasing the load capacity of grids, or the incorporation of buffers and storage options. Grid adaptation may decrease the need for curtailment strategies, and in Northwestern Europe typically falls within the range of responsibilities of grid operators. Under current policy regimes, grid adaptation therefore does not incentivize a redistribution of responsibilities between stakeholders.

Curtailment strategies may include prosumer-level stakeholders, and come in both physical and financial forms. In a physical form, owners of small and large-scale vRES alike may be required to remain within specific parameters with regard to load, duration, location etc., or be prohibited to feeding power into the peripheral grid under specific circumstances altogether. Financial versions of curtailment may involve measures such as a re-arrangement of netting allowance and compensation, or putting a premium on grid interaction under specific circumstances. Such policy could redirect the consequences of variability and simultaneous surplus peak loads to their origins in the form of a financial penalty. Despite the apparent re-distributive power of responsibilities that such policy might have, the effect of such policy would be similar to that of current curtailment strategies: longer payback periods for investments in vRES, which in turn may induce a more general relapse in interest in vRES development.

The current policy framework prominently features grid adaptation and technical curtailment. That framework appears inadequate for current developments in decentralized vRES and EES, leading to suboptimal grid configurations and imbalanced division of responsibilities among stakeholders. Our research indicates that inclusion of prosumer-inclusive policy measures could effectuate more balanced vRES system development. Therefore a revision of current policy frameworks or the development of new, adequate policy frameworks is required to manage the strategic development of curtailment procedures, adaptation of netting arrangements, and/or network redesign. Such policy would facilitate the transitioning of roles of vRES system stakeholders and ensure a proper redistribution of responsibilities with regard to EES deployment strategies and management of demand and supply mismatches.

Declaration of competing interest

We, G.A.H. Laugs, R.M.J. Benders and H.C. Moll, the authors of the manuscript entitled “Balancing responsibilities: effects of growth of variable renewable energy, storage, and undue grid interaction”, have no conflicts of interests to declare.

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