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Annual Review of Resource Economics The Economics of Variable Renewable Energy and Electricity Storage

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Abstract

The transformation of the electricity sector is a central element of the transition to a decarbonized economy. Conventional generators powered by fossil fuels have to be replaced by variable renewable energy (VRE) sources in combination with electricity storage and other options for providing temporal flexibility. We discuss the market dynamics of increasing VRE penetration and its integration in the electricity system. We describe the merit-order effect (the decline of wholesale electricity prices as VRE penetration increases) and the cannibalization effect (the decline of VRE value as its penetration increases). We further review the role of electricity storage and other flexibility options for integrating variable renewables and how storage can contribute to mitigating the two mentioned effects. We also use a stylized open-source model to provide some graphical intuition on these issues. While relatively high shares of VRE are achievable with moderate amounts of electricity storage, the role of long-duration storage increases as the VRE share approaches 100%.

1. INTRODUCTION

Externalities: costs or benefits derived from an activity that affects an uninvolved third party

Variable renewable energy (VRE):

energy sources whose availability depends on weather conditions and daily and seasonal cycles

Merit-order effect:

decline of wholesale electricity prices as VRE penetration increases

Supplemental Material >

"Climate change is the mother of all externalities: larger, more complex, and more uncertain than any other environmental problem" (Tol 2009, p. 29). Electricity and heat production account for 25% of global CO_2 emissions (Edenhofer et al. 2014), and all energy-related emissions represent almost three-quarters of the total (Friedlingstein et al. 2019). Fast and substantial emissions reductions related to energy use are essential for mitigating climate change. Compared to other sectors, the electricity sector offers particularly attractive low-cost mitigation options, given the availability of low-carbon energy technologies (IEA 2020a).

The use of renewable energy sources is the primary and most promising strategy for fast and deep decarbonization of the electricity sector in terms of sustainability, affordability, and availability (abundance of economically viable and secure resources). Beyond today's power sectors, renewable electricity can also be used to substitute fossil fuels in other sectors, such as heating and transport, a strategy often referred to as sector coupling. Owing to limited potentials of dispatchable renewable energy sources, such as bioenergy, hydropower, and geothermal energy, most countries focus on the expansion of variable renewable energy (VRE) sources. These include solar photovoltaics (PV) as well as onshore and offshore wind power.

However, integrating high shares of VRE into the electricity sector is not without challenges. Traditional electricity markets were characterized by large, dispatchable electricity generation technologies that adjust production to meet the variable electricity demand at every time. In a deeply decarbonized electricity system with high VRE penetration, however, smaller-scale and distributed VRE generators have to be complemented with options that provide temporal flexibility and geographical balancing. One good option for providing temporal flexibility is electricity storage, which is the focus of this article. Yet several alternative flexibility options on both the demand and supply sides may complement or partly substitute electricity storage. These include demand-side management, dispatchable generation, and sector coupling. Geographical balancing can also help to address temporal flexibility issues (see Section 3.1.3.4).

The International Energy Agency (IEA) estimates that in a sustainable development scenario where the Paris Agreement is met, variable renewables should provide 42% of electricity by 2040, compared to the 7% of the generation mix they represented in 2018 (see **Supplemental Figure 1**). Similarly, whereas the main form of electricity storage is currently pumped hydro, accounting for 95% of the total installed power capacity in 2018, the IEA estimates that battery storage will grow from a capacity of 8 GW in 2018 to 330 GW in 2040, thus representing more than half of the storage power capacity (IEA 2018, 2019b). Considering that both the Intergovernmental Panel on Climate Change (IPCC) (Creutzig et al. 2017) and the IEA (Hoekstra et al. 2017) tend to underestimate VRE developments in general and solar deployment in particular, these estimations are likely a lower bound of the potential VRE contribution to a decarbonized electricity system. Several studies demonstrate the technical and economic viability of a fully renewable electricity supply in Europe (Child et al. 2019) and worldwide (Jacobson et al. 2017).

Given the prominence of VRE and electricity storage technologies in decarbonized electricity systems, we discuss the economics of VRE, storage, and their interactions. Section 2 reviews the economics of VRE compared to conventional dispatchable technologies and highlights their electricity market impacts, in particular the merit-order and cannibalization effects. Section 3 introduces electricity storage and discusses applications and competing sources of flexibility (Section 3.1), reviews the literature on the interaction between VRE and electricity storage (Section 3.2), and provides graphical intuition on the changing role and value of electricity storage under increasing VRE shares (Section 3.3).

2. THE ECONOMICS OF VARIABLE RENEWABLE ENERGY SOURCES

2.1. Why Variable Renewables?

Fossil fuels (oil, gas, and coal) have dominated the energy mix since the Industrial Revolution, currently accounting for 84.3% of the global primary energy supply and 72.8% of global electricity generation (BP 2020). Fossil fuels have a high energy density and are suitable for multiple applications, but they have high external costs related to CO_2 emissions, local pollution, and human toxicity, among others (Ecofys 2014, Karkour et al. 2020).

The Paris Agreement set the goal to reduce CO_2 emissions to limit global warming "well below" 2°C with respect to preindustrial levels. Given that Earth has already warmed by 1°C (Masson-Delmotte et al. 2018), this goal entails rapid decarbonization of all economic sectors, in which the electricity sector plays a major role. This rapid decarbonization goal requires that current fossil fuel use must be replaced by low-carbon technologies in a relatively short time. To have a perspective of the scale of this challenge, the IEA estimates that \$US740 billion will have to be invested annually up to 2030 in clean energy technologies in a sustainable development scenario, compared to the \$480 billion invested in 2018 (IEA 2020b).

Future energy technologies must address three energy policy targets, which are sometimes traded off against each other: sustainability, availability, and affordability. Sustainability entails that new energy technologies must be low carbon and also come with low other external costs, such as biodiversity loss, safety risks, or local pollution. Availability means that energy resources must be abundant, secure, and widely accessible. Opposite to fossil fuels or uranium, renewable energy sources provide an annual flow of energy that is available worldwide and whose energy potential exceeds current and prospective global energy needs (**Supplemental Figure 2**). Finally, affordability requires that the technologies that exploit these resources have a reasonable cost in relation to the value they provide and compared to the alternatives. Wind and solar costs have dropped dramatically in the last decade and are already within the cost range of fossil fuels (IRENA 2020), even without accounting for external costs (**Supplemental Figure 2**). Additionally, the declining VRE cost is expected to continue (Mayer et al. 2015, Agora Energiewende 2017, Vartiainen et al. 2020).

2.2. Dispatchable Versus Variable Technologies

In electricity systems, supply and demand must be equal at every point in time to keep a stable grid frequency. In most markets, electricity demand shows substantial temporal variations, but large parts of the demand do not respond to prices in the short term. Accordingly, electricity supply has to continuously adapt to meet demand, which historically led to the widespread use of dispatchable generation technologies in most markets. This section explores the differences between conventional dispatchable technologies and variable renewable energy sources.

2.2.1. Dispatchable technologies. Conventional technologies have different degrees of dispatchability, ranging from what are often referred to as baseload technologies, such as nuclear, that mostly produce evenly across all hours, to peak load technologies, such as gas turbines, that generally offer higher operational flexibility and only produce during hours of high demand. Generation technologies differ with respect to their ability to ramp up and down in the short term and the related costs (Schill et al. 2017a). Baseload technologies usually have high capital cost and low variable cost, and their output is often relatively inflexible in the short term. In contrast, peaking technologies have lower capital costs and higher variable costs, and they are better able to ramp up or down production in the short term. The composition of the electricity system supply is therefore determined by the operational flexibility and cost structure of the different technologies, which determine their ability to meet demand. This can be summarized in screening

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curves representing the cost structure of each technology and their equivalent load duration curves showing how each technology covers a segment of demand during a year (Stoft 2002).

Curtailment:

reduction in the output of a generator from what it could otherwise produce given available resources **2.2.2.** Variable technologies. The economics of wind (van Kooten 2016) and solar (Baker et al. 2013) power differ from that of dispatchable technologies (Borenstein 2012, Hirth et al. 2016). The main difference is that VRE technologies can only generate when the resource is available. Thus, once a plant is installed, producers have no control over production beyond curtailment. VRE sources further have a specific cost structure with virtually zero variable costs and relatively high fixed costs. Variability occurs at different timescales and differs for wind and solar power. Very short-term variability, caused, for example, by clouds in the case of PV, can be easily smoothed out by aggregating installations over larger areas. Diurnal cycles are caused by the earth's rotation and generally require some form of energy storage. Finally, annual seasonality, caused by the tilt of the earth's axis, is the hardest form of variability, as it requires longer-term flexibility across seasons.

As an exemplary illustration of variable renewable patterns, **Figure 1** shows normalized (0–1 for each region and technology) wind and solar generation in California and Germany during 2016. Short-term variability is smoothed out by the countrywide/statewide spatial aggregation and averaging of the hours of each month (in local time). Solar cycles are homogeneous across regions: Solar always generates only by day and more in summer than in winter. Because solar seasonality is smoother as we approach the equator, differences between summer and winter generation are smaller in California than in Germany. Wind power is more location-specific: Whereas wind produces more energy during the night than at noon in both regions, the seasonal peak is in summer in California and winter in Germany.

2.2.3. The value of dispatchable versus variable generation. Variable renewables differ from dispatchable technologies in terms of both costs and value (Joskow 2011). Lamont (2008) provides an analytical formulation of the difference between the marginal values of VRE and dispatchable technologies. The marginal value (MV_D) of a dispatchable generator is the sum of the difference between the hourly electricity price (λ_b) and the generator's variable cost (VC) (assumed constant) for all the hours when the generator produces at its maximum capacity (b^*):

$$MV_D = \sum_{b^*} (\lambda_b - VC).$$
 1.



The marginal value of a variable generator is the average electricity price $(\overline{\lambda})$ times the average capacity factor (actual production as a fraction of peak capacity, \overline{CF}) plus the covariance between

Figure 1

Solar power has more homogeneous generation patterns across regions, but wind patterns are more location specific. Normalized average hourly (local times) wind and solar generation per month in California (*top*) and Germany (*bottom*) in 2016. California data from CAISO adapted from López Prol et al. (2020), Germany data from the Open Power System Data platform (Wiese et al. 2019).

the hourly price and hourly capacity factor $[cov(\lambda, CF)]$ for all hours of the year (*H*). The first summand represents the average unit revenues of the generator, whereas the second captures its load-matching capability, i.e., the correlation between demand and supply patterns:

$$MV_{VRE} = \left[\overline{\lambda} \cdot \overline{CF} + \operatorname{cov}(\lambda, CF)\right] \cdot H.$$

Although the marginal value of dispatchable technologies depends on a random variable (price) and constant (variable cost), the marginal value of VRE depends on the covariance between price and capacity factors. Because VRE sources have zero variable costs, increasing VRE penetration reduces electricity prices due to the merit-order effect. The covariance between price and capacity factor depends on the share of VRE sources, as the price will generally be lower the higher the VRE penetration, all other factors held constant. The merit-order effect (reduction of prices as VRE penetration increases; see Section 2.3) and the cannibalization effect (reduction of VRE value as penetration increases; see Section 2.5) have been theoretically explained in the literature and empirically estimated in countries with relatively high VRE penetration. The next sections introduce a graphical conceptualization of these phenomena and review the corresponding empirical findings.

2.3. The Merit-Order Effect

Electricity is a perfectly homogeneous good in three dimensions: time, space, and lead time between contract and delivery (Hirth et al. 2016). This entails that the market clears at marginal cost for every time, location, and market run off-peak, but the price may substantially vary across these three dimensions, depending on the market design. Because VRE sources have zero variable costs, higher penetration of VRE depresses wholesale electricity prices. The equilibrium price and quantity of electricity delivered each hour to the market are given by the intersection between demand and supply.

Demand (D) is usually assumed to be perfectly inelastic in the short term, as most consumers so far do not respond to real-time prices. For this reason, it is represented as a vertical straight line in **Figure 2**. This is not the case in forward markets, as consumers can plan ahead for their consumption and bid accordingly. Additionally, demand elasticity is likely to increase in the future



Figure 2

The merit-order effect of variable renewable energy (VRE) sources in wholesale electricity markets. (*a*) Demand perspective and (*b*) supply perspective. Demand curves are represented as perfectly inelastic vertical lines. Each step of the stylized supply curve shows three distinct technologies with increasing variable costs. The arrows represent the change induced in the market by increasing penetration of VRE sources. Gray shows parameters that are unchanged by VRE, orange (*subscript 0*) shows the situation without VRE, and blue (*subscript 1*) shows the situation with VRE. Abbreviations: *D*, demand; *P*, price; *Q*, quantity; *S*, supply.

in most markets, as different measures of demand response are likely to be implemented to provide flexibility to the electricity system. Still, we represent demand as perfectly inelastic in **Figure 2** for simplicity.

The supply (*S*) curve is given by the variable cost (or the opportunity cost of fuel) of all power plants sorted in ascending order from lower to higher. **Figure 2** represents a simplified supply curve with three steps representing three technologies with different variable costs. The technology with lower variable costs on the left side of the supply curve could be referred to as a baseload technology, such as lignite or nuclear. The middle step represents a mid-load technology, such as hard coal or combined-cycle gas turbines, and the last step of the supply curve represents a peaking technology, such as open-cycle gas or oil turbines.

In this basic setting of a wholesale electricity market, increasing VRE generation can be interpreted as a lower residual demand, also referred to as net load (**Figure 2***a*), or as a higher zero variable cost supply (**Figure 2***b*). From a demand perspective, VRE generation is represented as a lower net load. The demand curve shifts to the left ($D_0 \rightarrow D_1$), and therefore the price declines ($P_0 \rightarrow P_1$) as the technology setting the price is now the lower-cost mid-load rather than the peak-load technology (**Figure 2***a*). From a supply perspective, increasing VRE generation shifts the supply curve to the right as new zero variable cost is supplied to the market ($S_0 \rightarrow S_1$). The same price effect comes into play, lowering wholesale electricity prices from P_0 to P_1 .

The dynamics of the merit-order effect are well explained in the electricity market economics literature (Stoft 2002, Green & Léautier 2015, Léautier 2019), and the effect has also been widely studied in the numerical and empirical literature. The numerical literature provides ex-ante estimations of the merit-order effect with different types of electricity market models. The advantage of such market simulations is that they provide insights into potential future scenarios before they actually happen. Early examples of this type of ex-ante modeling exercise to quantify the merit-order effect are by Sáenz de Miera et al. (2008), who estimate the effect using a dispatch model in Spain; Sensfuß et al. (2008), who apply an agent-based model to Germany; and Mills & Wiser (2012), who use a dispatch and investment model in California.

As VRE penetration increases, empirical ex-post studies with actual historical market data estimate the merit-order effect in wholesale electricity markets. Most studies find evidence of the depressing effect of VRE penetration on wholesale prices in countries/states with high penetration, such as Germany (Cludius et al. 2014), Italy (Clò et al. 2015), Spain (Gelabert et al. 2011), Australia (Csereklyei et al. 2019), California (Woo et al. 2016), and Texas (Woo et al. 2011). A cross-country analysis of the main European power markets shows consistent negative results across countries (Welisch et al. 2016). Likewise, a review of the merit-order effect in the United States confirms the depressing effect of VRE on wholesale electricity markets, although this effect is relatively small compared to that of gas prices (Mills et al. 2020), which have decreased significantly since 2008. In general, the merit-order effect of solar is stronger than that of wind, as its generation pattern is more concentrated during daytime hours (see **Figure 1**).

2.4. Price Volatility

Given the inherent variability of VRE, it is generally understood that increasing VRE penetration increases wholesale price volatility. Seel et al. (2018) find that wholesale price variability increases as solar and (to a lesser extent) wind generation increases across the main US electricity markets using a capacity expansion and unit commitment model.

However, the empirical evidence on the effect of VRE penetration on price volatility is mixed. The effects are specific to (*a*) the considered time frame (hourly, daily, or weekly volatility), (*b*) the VRE technology (solar or wind have different generation patterns and therefore differing effects), and (*c*) the conditions of the electricity system itself (market design, availability of flexibility options, demand patterns, etc.). For instance, Rintamäki et al. (2017) find that although weekly volatility increases in both Germany and Denmark due to increasing wind and solar penetration, the daily volatility patterns differ. Wind decreases daily volatility in Denmark, but increases it in Germany, whereas solar decreases daily volatility in Germany.

Similarly, Kyritsis et al. (2017) find that solar energy decreases price volatility in Germany by scaling down the use of peak-load power plants, whereas wind increases the volatility due to increased flexibility needs. Both Rai & Nunn (2020) in Australia and Ballester & Furió (2015) in Spain find that VRE sources increase volatility but reduce the persistence of price spikes. Finally, Ciarreta et al. (2020) show that market design and VRE regulation choices may reduce price

volatility even as VRE penetration increases. Although volatility is usually regarded as a negative feature to be minimized because it creates uncertainty, it may turn out to be an essential part of wholesale electricity prices to provide the right investment incentive signals for an efficient integration of variable renewables (Wolak 2019). Exposing electricity consumers to dynamic prices may help to reduce both price volatility by increasing demand elasticity and integration costs (Andersen et al. 2019).

2.5. The Cannibalization Effect

Although an increase in supply causes a price decline in any market, the cannibalization effect is a specific phenomenon of VRE penetration in current electricity markets. This is due to the specific properties of the good electricity and the characteristics of VRE.

Because electricity is a perfectly homogeneous good with relatively inelastic, time-varying demand and relatively high bulk storage costs, it is governed by peak-load pricing. Peak-load pricing theory entails that off-peak prices reflect short-run marginal operational costs, whereas fixed costs are recovered through peak-load scarcity prices (Boiteux 1949, Wenders 1976). Energy-only markets in theory reflect peak-load pricing, but most real-world electricity markets cap prices, such that fixed costs of peak generators are usually recovered through some kind of explicit or implicit capacity payment rather than through scarcity prices (cf. Cramton & Ockenfels 2012, Cramton 2017).

Variable renewables have virtually zero short-run marginal cost and their generation potential varies over time. Together with the constraint that supply and demand have to be balanced at every time, these conditions entail that prices drop whenever VRE generation enters the market. Depending on the existence and design of renewable support schemes, as well as on flexibility constraints of other generators, prices can even become negative when VRE supply exceeds demand.

The cannibalization effect can be illustrated through stylized price duration curves, representing prices in the wholesale market for all of the 8,760 hours of a year in descending order. **Figure 3***a* represents the merit-order effect observed in the wholesale electricity market. As VRE penetration increases, prices decline (the price duration curve shifts downward), and the average wholesale electricity price declines from $\overline{p_0}$ to $\overline{p_1}$.

Figure 3*b* represents a stylized price duration curve for a VRE technology such as solar PV, i.e., the price received by this VRE generator during every hour of production. Solar is typically correlated with electricity demand and therefore benefits from higher peak-time electricity prices. For this reason, the unit revenue (generation-weighted electricity prices, also called market value) received by solar generators at low penetration is higher than the average wholesale electricity price in this example.

However, as solar penetration increases, the merit-order effect depresses electricity prices. As the merit-order effect happens primarily during the hours of high solar energy availability, Price duration curve: this curve sorts all hourly wholesale prices of a year in descending order



The merit-order [decline of wholesale electricity prices as variable renewable energy (VRE) penetration levels increase] and cannibalization (decline of the market values and value factors of VRE as their penetration levels increase) effects. Price duration curves (prices for each hour of the year sorted in descending order) for the electricity market (*a*) and for a VRE generator (*b*) with low (*orange*, *subscript 0*) and high (*blue*, *subscript 1*) VRE penetration.

the unit revenues received by solar PV generators fall, $\overline{p_0^{VRE}} \rightarrow \overline{p_1^{VRE}}$, stronger than the average wholesale electricity price. The absolute cannibalization effect is the fall of VRE unit revenues. The relative cannibalization effect refers to the fact that VRE unit revenues fall faster than average wholesale electricity prices and is represented by the fraction between both. This can also be expressed using the value factor concept. A value factor of 1 (or 100%) means that the unit revenues received by VRE generators are exactly the same as the average wholesale price. The value factor is smaller than 1 when VRE unit revenues fall below average wholesale prices.

Additionally, higher VRE penetration makes the price duration curves steeper (Green & Vasilakos 2011) because VRE increases the difference between hours with low and high prices. When VRE sources are producing, the merit-order effect depresses prices. However, given the increased flexibility needs of the electricity system, prices may increase at other times due to the required ramp-up of more flexible generators with higher marginal cost (Bushnell & Novan 2018).

As with the merit-order effect, there is rich literature estimating the declining value of variable renewables both ex-ante with numerical models and ex-post with econometric methods. Ex-ante dispatch and investment models are used to estimate the optimal penetration of variable renewables under different scenarios (Hirth 2015) and the declining market value of wind and solar in different conditions (Hirth 2013, Eising et al. 2020, Mills et al. 2020). Additionally, Mills & Wiser (2014) estimate the potential of different strategies to mitigate the cannibalization effect of wind and solar. They find that geographic diversification is the most promising strategy to mitigate the declining value trend of wind power at high penetration and low-cost storage for PV. The mitigating effect of storage and flexibility is discussed in more detail in Section 3.

From an empirical perspective, several studies report the declining value of wind and solar technologies (Welisch et al. 2016, Zipp 2017). Clò & D'Adamo (2015) show that increasing solar penetration reduces its own value but increases the value of gas in the Italian wholesale electricity market. López Prol et al. (2020) define and estimate the absolute and relative cannibalization and cross-cannibalization (between VRE technologies) effects in the California wholesale electricity market. Whereas wind decreases its own value and solar value, in both relative and absolute terms, solar decreases its own market value and value factor but increases the wind value factor. Given

Absolute cannibalization

effect: decline of VRE unit revenues (generation-weighted electricity prices) as VRE penetration increases

Relative cannibalization

effect: decline of VRE value factors (unit revenues divided by wholesale electricity prices) as VRE penetration increases the findings of Bushnell & Novan (2018), this might be because when the sun sets, more flexible generators with higher marginal cost are necessary to cover declining solar production, thus increasing wholesale prices at the time when wind generation increases.

The literature agrees that increasing VRE penetration decreases the resources' market value (absolute cannibalization) at a faster pace than the fall of wholesale prices (relative cannibalization) due to the merit-order effect. Ex-post estimations show that the cannibalization effect increases for higher VRE penetration (López Prol et al. 2020), but ex-ante market models show that market value tends to stabilize as penetration increases (Hirth 2013). This reflects the different time frames of both types of methods: Although econometric models estimate the cannibalization effect in the short term in the existing electricity system, numerical capacity expansion models optimally adapt installed capacities to cope with higher shares of VRE.

2.6. A Value Perspective of Integration Costs

Integrating VRE sources into current electricity systems that have been designed for dispatchable generation technologies entails integration costs derived from the variability (profile costs), uncertainty (balancing costs), and location specificity (grid costs) of VRE resources (Ueckerdt et al. 2013). Hirth et al. (2015) show that integration costs can be estimated from a cost perspective as the additional system costs caused by VRE integration, or from a value perspective as the difference between wholesale prices and VRE market values. Because the value factor is the ratio between a technology's market value (unit revenues) and wholesale electricity prices, the evolution of the value factor (the relative cannibalization effect) can be interpreted as a value estimation of the technology-specific integration cost.

3. THE ECONOMICS OF ELECTRICITY STORAGE FOR VARIABLE RENEWABLE ENERGY INTEGRATION

3.1. Why Electricity Storage?

The use of electricity storage is an important option for addressing the variability challenges of wind and solar power discussed above. Electricity storage may be broadly defined as a technology that takes up electrical energy at a given point in time and releases it again at a later point in time, irrespective of the form in which energy is stored in between. Electricity storage can balance the variable patterns of renewable supply and demand and thus mitigates both the merit-order and cannibalization effects.

3.1.1. Technologies. A wide range of electricity storage technologies is available (Luo et al. 2015, World Energy Counc. 2016, Gür 2018). These differ with respect to various technoeconomic parameters, such as round-trip efficiency, specific investment costs for power and energy capacity, variable costs, and technical lifetime. Driven by these parameter differences, typical energy-to-power (E/P) ratios emerge for each technology, the inverse of which is also referred to as the C-rate. For example, the E/P ratio is only a few hours for stationary Li-ion batteries, may exceed 10 hours for pumped hydro storage plants, and can surpass several weeks for hydrogenbased electricity storage. Further, electricity storage technologies come at very different scales. For example, stationary batteries are highly modular and can be deployed at the scale of individual households with energy capacities of only a few kWh, but also at the grid scale in the multi-MWh range. Pumped hydro plants, in contrast, are usually both lumpier and much larger, with energy capacity in the GWh range. Future hydrogen storage may well reach the TWh range.

In recent years, substantial research and development activities and a scaling up in production have led to substantial cost decreases of electrochemical storage technologies, which are expected Residual load: also known as residual or net demand; the electricity demand of a given period, minus the potential VRE generation in the same period to continue in the future (Schmidt et al. 2017, 2019; Lazard 2019). In the medium run, Li-ion batteries may become the dominant storage technology (Beuse et al. 2020). Various storage technologies are already available and technologically proven today, although they are not necessarily economical in current power markets (Brown et al. 2018a). This is partly because of economic and regulatory barriers in many markets, which prevent storage from being fully compensated for the many services it could deliver to the electricity system (Sioshansi et al. 2012, Castillo & Gayme 2014).

3.1.2. Applications. There are many different applications for electricity storage (Palizban & Kauhaniemi 2016). A well-known and widely used application is bulk electricity storage, i.e., shifting substantial quantities of electricity from one point in time to another point in time. This business model is also referred to as energy arbitrage in wholesale electricity markets, which entails buying and storing electricity in periods of low prices and selling it again in higher-price periods. In doing so, the price difference has to pay for the variable storage costs, including the round-trip losses. From an overall system perspective, bulk electricity storage allows increasing the use of generators with low variable costs and decreasing the use of generators with high variable costs. With increasing shares of VRE, this becomes more relevant, particularly in the case of temporary renewable surplus generation that would otherwise have to be curtailed (Denholm et al. 2013).

Aside from energy arbitrage, many other potential applications for electricity storage are not necessarily organized by markets (Denholm et al. 2010, Castillo & Gayme 2014). These include (*a*) a reduction of residual load gradients, which translates into reduced ramping needs of thermal generators; (*b*) the provision of different types of ancillary services, particularly balancing power; (*c*) the provision of peak or firm generation capacity; (*d*) a supplementation or deferral of investments into transmission or distribution grid infrastructure; and (*e*) multiple end-user applications, including energy supply cost optimization and power quality or stability. These applications can be translated into different types of value created by electricity storage in the energy sector, such as arbitrage, flexibility, reserve, capacity, or grid-related values. Importantly, storage facilities may be able to combine several of these applications at least to some extent (Staffell & Rustomji 2016, Stephan et al. 2016). Many model-based studies nonetheless focus on only one or two sources of storage value, and hardly any cover all of them.

3.1.3. Alternative flexibility options. Aside from electricity storage, there are many other and partially competing options for providing temporal flexibility to the electricity sector (Lund et al. 2015). These belong to either the supply side or demand side and may be grouped into different categories. Depending on electricity flowing into and/or out of the flexibility option, we distinguish the categories Power-to-Power, X-to-Power, or Power-to-X, following Schill et al. (2015) and Schill (2020). Electricity storage by definition belongs to the Power-to-Power category.

3.1.3.1. *Power-to-Power.* Demand-side management measures can have similar electricity sector impacts as electricity storage (Hale et al. 2018). If a part of the electricity demand is shifted from hour n to hour n + 1 (by decreasing the load in hour n and correspondingly increasing it in hour n + 1), this has a similar power sector effect as discharging an electricity storage facility in hour n and charging it again in hour n + 1. Realizing demand-side flexibility may require digitalization (IEA 2017) to automatize demand response to prices and market design changes to allow agents to capture the value they generate to the system by providing flexibility (Joskow 2019, Leslie et al. 2020). For clarity, here we only include shifting of such electricity demand that already exists in traditional power sectors, e.g., in residential applications or industrial processes, and not additional future loads related to increased sector coupling.

3.1.3.2. X-to-Power. This category includes any technologies that generate electricity at the time of demand. These comprise conventional dispatchable generators and also measures to operate flexibility-constrained assets such as combined heat and power generation plants in a more flexible way. VRE overcapacity with curtailment may also be categorized here.

3.1.3.3. Power-to-X. This group of options includes new and potentially flexible electric loads related to the coupling of the power sector and other sectors. Such sector coupling is a primary option to facilitate deeply decarbonized future energy systems (de Coninck et al. 2018). For example, electricity can be used in different segments of the heating sector via heat pumps or direct resistive heating (Bloess et al. 2018, Madeddu et al. 2020), in the mobility sector via battery-electric vehicles (Armaroli & Balzani 2011), or in various transportation or industrial applications, which are harder to electrify, via electrolysis-based hydrogen or synthetic liquid fuels (Schiebahn et al. 2015, Mansilla et al. 2018, Runge et al. 2019, IEA 2019a). Such sector coupling allows making use of other, and potentially cheaper, energy storage options than stationary electricity storage, such as thermal energy storage, electric vehicle batteries, or storage of hydrogen or derived synthetic liquid fuels. Note that we define Power-to-X as any process where electricity permanently flows out of the power sector. In case of later reconversion to electricity, e.g., if electricity is generated from hydrogen or synthetic liquid fuels again, this is treated as a Power-to-Power option (cf. Yan et al. 2019). Battery-electric vehicles that discharge electricity back to the grid (vehicle-to-grid) provide both Power-to-X (the part of electricity used for driving) and Power-to-Power (the part of electricity fed back to the grid) functionalities (cf. Taljegard et al. 2019).

3.1.3.4. *Geographical balancing.* Geographical balancing is another option to provide temporal flexibility for variable renewable integration (Fürsch et al. 2013, Steinke et al. 2013), as illustrated for the United States (MacDonald et al. 2016) and Europe (Schlachtberger et al. 2017). This is because the time patterns of VRE availability and electricity demand are usually not perfectly correlated between different locations (Engeland et al. 2017). Transmission expansion can thus facilitate the balancing of renewable supply and demand over wide areas. In theory, annual and diurnal solar cycles could be balanced using interhemispheric connections to offset seasonal patterns (Grossmann et al. 2014, Aghahosseini et al. 2019), yet the practical feasibility of this option remains unclear.

3.2. Modeling the Interaction Between Storage and Variable Renewables

A broad literature has investigated the role and value of electricity storage in electricity sectors with VRE. Analyses vary in terms of geographical coverage and time horizon as well as the methodological approaches used (Zerrahn & Schill 2017, Blanco & Faaij 2018). Several earlier studies use price-taking arbitrage models, drawing on historic electricity market prices. Another strand of the literature uses models based on time series of variable renewable availability and load, and a third strand uses electricity sector models, often with a capacity expansion approach. The latter may be considered the state-of-the-art approach to quantify the value of electricity storage in future scenarios with very high shares of variable renewables. Bistline et al. (2020) review and discuss the representation of energy storage in respective long-term models.

3.2.1. Price-taker arbitrage models. Several studies have investigated the value of electricity storage using price-taker models and historic wholesale price data. Such studies generally focus on the arbitrage value of storage and, by design, cannot say much about the long-run value of storage in settings with higher renewable penetration. Sioshansi et al. (2009) explore the value of electricity storage using historical price data from the PJM market (a large regional transmission

organization in the United States) and find a generally increasing arbitrage value between 2002 and 2007 but also large regional differences. Bradbury et al. (2014) use historical market prices of seven US markets to optimize the sizing and dispatch of various energy storage technologies. They find very low E/P ratios for most storage technologies and up to eight hours for pumped hydro and compressed air storage. McConnell et al. (2015) analyze the value of electricity storage in the Australian National Electricity Market and find that it hardly increases any more for E/P ratios above six hours.

3.2.2. Time series–based models. Analyses based on time series of renewable availability and load allow a more forward-looking investigation of the role of electricity storage for renewable integration. Heide et al. (2010) investigate the seasonal balancing of wind and solar in a pan-European 100% renewable scenario, under the assumption of substantial transmission infrastructure being in place. Seasonal long-duration storage with a capacity equaling 1.5–1.8 times the average monthly load is needed to balance excess PV generation in summer with excess wind generation in winter. In a comparable setting, Rasmussen et al. (2012) find that a mix of short-term storage and long-term power-to-gas-to-power storage with an energy capacity of less than 1% of the yearly load suffices for achieving a fully renewable energy supply in Europe.

For Germany, Weitemeyer et al. (2015) show that electricity storage may not be required up to a VRE share of 50%. Above that, storage needs increase, which is especially true for long-duration storage in settings beyond 80% renewable penetration. Also using a time series–based approach, Raynaud et al. (2018) analyze the occurrence of energy droughts from variable renewables in Europe, i.e., periods of high residual load. They find that relatively small electricity storage capacity suffices to mitigate such energy draughts.

3.2.3. Capacity expansion models. In another strand of literature, detailed power sector models are used to analyze the role of electricity storage in future VRE scenarios. In general, such models are able to consider both the arbitrage and capacity values of storage. Some models further allow covering additional system values, such as the contribution of storage to the provision of balancing reserves.

The literature agrees that storage power capacity remains moderate even in scenarios with substantial carbon emissions reductions. However, the need for long-duration storage significantly increases as VRE penetration approaches 100% and in the absence of other flexibility options. Schill & Zerrahn (2018) show this for Germany, Safaei & Keith (2015) and de Sisternes et al. (2016) for Texas, Tong et al. (2020) for the contiguous United States, and Ziegler et al. (2019) for four US regions. Dowling et al. (2020) likewise highlight the importance of long-duration electricity storage for fully VRE-based power sectors.

The system value of storage, defined as the reduction of the total system costs caused by its incremental deployment, decreases with increasing storage capacity deployment (Heuberger et al. 2017). Mallapragada et al. (2020) show that the value of electricity storage is largely related to the deferral of generation and transmission capacity in the long run. They also find that variable renewables and storage are complements to some extent, as the penetration of one increases the value of the other, but at the same time also competitors, as storage can be replaced by VRE overcapacity and curtailment. That means that although both VRE and storage values decrease as their penetration increases, ceteris paribus, their combined deployment mitigates the decline in their system value.

3.2.4. Interaction of electricity storage and renewable curtailment. Many analyses, including several of the ones discussed above, address the interaction of renewable curtailment

and electricity storage. In an early article, Denholm & Hand (2011) investigate this for future scenarios of Texas. With medium penetration of VRE, only small storage capacities are needed to keep renewable curtailment low, yet if the VRE share increases to 80%, more substantial electricity storage with a capacity of about one day of average demand is required to keep renewable curtailment below 10%.

Using a simple dispatch model, Schill (2014) derives similar findings for mid- to long-term scenarios for Germany. He shows that electricity storage needs substantially decrease if small levels of VRE curtailment are allowed. If, on the contrary, renewable curtailment is restricted, electricity storage needs vastly increase. This is because the most extreme renewable surplus events come with very high power and energy, which then determine storage dimensioning. Similarly, avoiding must-run of thermal generators also substantially mitigates electricity storage needs.

Sinn (2017) revisits this issue, a priori ruling out the possibility of renewable curtailment. Using a German time series of wind, solar, and load, he illustrates that storage needs in such a setting very substantially increase and argues that this may put the viability of the renewable energy transition into question. In an open-source replication study, Zerrahn et al. (2018) show that storage needs strongly decrease if renewable curtailment is not artificially constrained. With a stylized optimization model, they further show that a mix of VRE curtailment and storage deployment minimizes overall system costs, and that optimal electricity storage capacities may decrease further if flexible Power-to-X options are also considered.

3.3. Graphical Intuition on the Changing Role and Value of Electricity Storage

In the following, we aim to provide some graphical intuition on the changing role of electricity storage under increasing VRE shares. We do so with residual load duration curves (RLDCs), price duration curves, and market values calculated with a stylized open-source capacity expansion model. This model is a much-reduced version of the model DIETER, which was first presented by Zerrahn & Schill (2017) and subsequently expanded and applied in various other publications, as listed in Gaete-Morales et al. (2021). The reduced model version, which has been used for high-level illustrations before (Zerrahn et al. 2018, Schill 2020), determines cost-minimal generation and storage capacities as well as their optimal dispatch for different shares of VRE in final yearly demand, which is enforced by a respective constraint. This can be interpreted as a setting in which renewable generators receive an energy-based premium on top of their wholesale market revenues, such that the desired VRE share is perfectly met. The model only considers five generation technologies (hard coal, open- and closed-cycle gas turbines, solar PV, and wind power), one stylized storage technology (parameterized as pumped hydro storage), and a single region (Germany, one node). Hourly electricity demand is assumed to be fully price inelastic. The model is freely available under a permissive license (Schill & Zerrahn 2020). Given the stylized nature of this model, the focus is not on the numbers, but on qualitative insights and the general mechanisms at play. Additional information is provided in the Supplemental Material.

3.3.1. Residual load and price duration curves. Figure 4*a* illustrates how the RLDC changes with increasing shares of VRE. As VRE penetration increases, the RLDC shifts downward on its right-hand side. The number of hours during which the residual load is negative, i.e., the VRE generation potential exceeds the electric load, increases substantially beyond a renewable share of 20%, and the magnitude of peak negative residual load also grows strongly (cf. Schill 2014). The left-hand side of the RLDC hardly decreases with increasing renewable penetration, which reflects a small contribution of wind power and solar PV to the provision of firm capacity. If the VRE share increases to 90%, renewable surplus energy occurs in nearly every second hour of the

Residual load duration curve (RLDC): this curve sorts all hourly residual load values of a year in descending order

Supplemental Material >





(a) Residual load duration curves and (b) price duration curves for different variable renewable energy (VRE) penetration levels in a stylized German setting. With increasing VRE penetration, both curves decrease, particularly on their right-hand sides. This is because of increasing renewable surplus generation.

year. The shape of the RLDC also changes, which is driven by different cost-minimizing shares of wind and solar power for different VRE penetrations. In the parameterization used here, only PV is deployed in the 20% setting, which regularly leads to low residual load values during summer days and explains the bend on the right-hand side. In settings with higher VRE shares, wind power with smoother generation profiles is increasingly deployed.

Figure 4b shows price duration curves for the same illustrative example, as well as weighted average wholesale prices. The ordinate is capped, leaving out high peak prices in a few hours to improve visibility. Using a cost-minimization approach, we do not explicitly model market prices but interpret the dual variable of the energy constraint as a wholesale price, as often done in modelbased energy economic analyses (Brown & Reichenberg 2021). With increasing VRE penetration, the price duration curve shifts downward on the right-hand side, similar to the RLDC, which corresponds to higher renewable surplus generation. Prices may even become negative. This may be interpreted such that the objective value, i.e., overall system costs, would decrease if more electricity would be consumed in this hour. This is because the binding VRE constraint could be more easily achieved if consumption increased during hours of renewable curtailment. Negative prices can also be interpreted as the price-setting bids of VRE generators that receive a positive, energy-based feed-in remuneration. In an alternative setting, where VRE deployment is not driven by a minimum renewable energy share constraint (i.e., by energy-based support), but by CO_2 pricing, wholesale prices never turn negative (Supplemental Figure 3). When interpreting these results, the reader should also keep in mind that electricity consumers usually also have to carry the costs of renewable support, so electricity bills that also include such support payments never become negative. We further assume a fully price-inelastic demand, and that the total system costs only partially include the external costs of conventional generators.

Supplemental Material >



Figure 5

Residual load and optimal electricity storage use for variable renewable energy (VRE) penetration levels of (*a*) 40%, (*b*) 60%, (*c*) 80%, and (*d*) 90% in a stylized German setting. The areas below the zero lines represent renewable surplus generation, which is partly curtailed and partly taken up by electricity storage. Storage is discharged again to meet demand in hours with positive residual load, together with dispatchable generators.

3.3.2. The changing role of storage. Figure 5 shows the changing use of electricity storage with increasing VRE penetration. In the stylized setting used here, no storage is deployed below a VRE share of 30%. For medium VRE shares, optimal storage investments are moderate, but they increase disproportionately with higher variable renewable penetration. For 40% VRE (**Figure 5***a*), the optimal storage power rating corresponds to 9% of the annual peak load. If the VRE share increases to 60%, 80%, or 90% (**Figure 5***b*–*d*), storage power increases to 27%, 75% and 78% of the peak load. The optimal storage energy capacity increases even more, from 0.01% of the yearly electricity demand in the 40% VRE case to 0.03% (60%), 0.11% (80%), and 0.21% (90%).

Accordingly, storage is increasingly used with higher VRE penetration. Importantly, storage is never deployed to fully take up renewable surplus generation in a least-cost solution, as this would require excessive and underutilized investments into storage power and, even more so, storage energy capacity (cf. Schill 2014, Zerrahn et al. 2018). In a cost-minimizing solution, there will accordingly always be some level of renewable curtailment, absent geographical balancing, flexible Power-to-X, or other low-cost flexibility options (cf. Schill 2020). **Figure 5** also shows that storage is used to smooth the generation of the three dispatchable technologies modeled



Figure 6

Market values (MV) and levelized costs of electricity (LCOE) for solar photovoltaics and wind power for increasing variable renewable energy (VRE) penetration levels in a stylized German setting. With increasing VRE penetration, LCOE increase and MV decrease. This effect is much more pronounced in a setting without any storage technology (*solid lines*) compared to a setting with storage (*dasbed lines*).

here, i.e., to optimize their full-load hours, depending on their fixed and variable cost structures (cf. Section 2.2). The use of hard coal, which is the baseload technology in this setting, decreases with increasing renewable penetration and is completely crowded out in the 90% VRE case.

Electricity storage hardly contributes to peak residual load supply in settings with moderate VRE shares. Instead, storage deployment is driven mainly by taking up renewable surplus energy in the 40% and 60% VRE cases, i.e., by the right-hand side of the RLDC (**Figure 5***a*,*b*). This changes for very high VRE shares, where storage is increasingly used to also supply peak residual load on the right-hand side of the RLDC (**Figure 5***d*). This also requires larger investments in storage energy capacity, as increasing amounts of renewable surplus energy have to be shifted over longer periods of time. In 100% VRE settings, where no other X-to-Power options are left, electricity storage would have to supply the total peak residual load and fully balance seasonal fluctuations.

Levelized cost of energy (LCOE):

average unit net present cost of electricity generation for a technology over its lifetime **3.3.3.** Wind and solar costs and values. Figure 6 illustrates the market values and levelized costs of energy (LCOE) for solar PV and wind power for the same stylized example as above and also in an equivalent setting without storage. The cannibalization effect is clearly visible: With increasing VRE penetration, the market values of wind and solar deteriorate. This is particularly true for solar PV, driven by regular diurnal generation patterns. This finding is in line with the empirical literature discussed in Section 2.5.

At the same time, the levelized costs of wind and solar energy increase, reflecting increasing levels of curtailment. The difference between the market value and the LCOE can be interpreted as the required renewable support per unit, which also equals the dual of the VRE constraint in

the optimization model. Note that up to a VRE share of 40%, the market value of wind and solar is greater than their LCOE, which reflects the fact that the cost-minimizing renewable share (only partially considering the externalities of conventional generators) in this stylized parameterization is somewhat above 40%. It should be noted that the decreasing market value is driven by negative prices caused by the binding VRE constraint in the model. In an alternative model setting, in which increasing VRE shares are not driven by a respective constraint, but by increasing CO_2 pricing, wholesale prices never become negative. Likewise, the market values of wind and solar do not deteriorate in such a setting with increasing VRE shares, but always correspond to the respective levelized costs. This is shown by Brown & Reichenberg (2021) and illustrated in **Supplemental Figure 4**. This is because increasing CO_2 prices internalizes climate change costs and therefore allows VRE to capture that mitigation value, thus compensating the cannibalization effect of their increasing penetration.

The comparison between the market values of wind and solar with and without storage reveals the impact of storage on mitigating the cannibalization effect. **Supplemental Figure 5** illustrates the effects of storage on residual load and price duration curves and VRE market values in more detail. The decline of VRE unit revenues, particularly for solar, would be stronger in the absence of storage. Likewise, their levelized cost would increase faster as penetration increases due to higher curtailment.

3.4. Beyond Stationary Grid-Scale Electricity Storage

Although we have focused on stationary grid-scale electricity storage, decentralized small-scale electricity storage is becoming more relevant in many markets. Decentralized PV-battery systems allow households and commercial electricity consumers to increase their levels of PV self-consumption. This can be beneficial if the self-generated electricity is cheaper than the retail tariff of the grid electricity it substitutes (Schill et al. 2017b), as is already the case in many countries (Lang et al. 2016, López Prol & Steininger 2020). Yet the power sector implications of widespread PV-battery adoption and their interaction with grid-scale electricity storage are only partially understood so far (Say et al. 2020).

Battery-electric vehicles are a particularly interesting case, as they entail new and potentially flexible loads in the power sector that could also feed back electricity to the grid. The latter concept has been discussed for many years under the label vehicle-to-grid (Kempton & Tomić 2005). Accordingly, battery-electric vehicles potentially combine Power-to-X and Power-to-Power properties. Owing to technical, economic, and social barriers, vehicle-to-grid has hardly been used in practice so far. Yet this may change in the near future, considering the current massive rollout of battery-electric vehicles in many countries. Dallinger et al. (2013) illustrate potential benefits of future grid-connected vehicle fleets for VRE integration in California and Germany.

In general, various future sector coupling options could supply additional flexibility to the electricity system. For example, Brown et al. (2018b) find that flexible charging of electric vehicle batteries could balance daily PV fluctuations, and Power-to-Heat applications with thermal energy storage could balance longer-duration wind power variability. Likewise, Schill (2020) illustrates that flexible sector coupling may substantially reduce the need for electricity storage in settings with medium VRE penetration, as it reduces renewable surplus energy (right-hand side of the RLDC; compare **Figure 4***a*). Yet in 100% VRE settings, this storage-mitigating effect of flexible Power-to-X options vanishes, as electricity storage is still required to supply positive residual load (left-hand side of the RLDC). Temporally inflexible sector coupling, in contrast, would increase the flexibility needs of the power sector.

Supplemental Material >

4. CONCLUSIONS

We have discussed the literature on the interactions between increasing VRE penetration, electricity storage, and electricity prices. Increasing penetration of VRE lowers wholesale electricity prices due to the merit-order effect. Because this happens at times of high VRE penetration, VRE market values fall (absolute cannibalization effect), and they fall even faster than electricity prices, causing a decline of technology-specific value factors (unit revenues divided by average wholesale electricity prices). The decreasing value factor (relative cannibalization effect) can be interpreted as the evolution of VRE integration costs from a value perspective.

Although VRE penetration is generally thought to increase price volatility, empirical evidence is mixed. Effects of VRE on price volatility depend on the generation pattern of the VRE technology, the considered time scale, and the characteristics of the electricity system itself, such as availability of flexibility, demand patterns, and market design.

Electricity storage and other flexibility options mitigate the cannibalization effect of VRE and stabilize electricity prices. VRE and electricity storage are complementary in the sense that higher penetration of one increases the value of the other. However, they are to some degree also substitutes, as storage can be replaced by VRE overcapacity and curtailment. Storage also shows diminishing marginal returns because each additional unit of capacity provides lower value to the system.

Although we have focused here on electricity storage, several other forms of power sector flexibility can contribute to integrating high shares of variable renewables. This includes Powerto-Power options such as demand response, Power-to-X options related to sector coupling, and geographical balancing. Both the optimal mix of all of these flexibility options and their market interactions are not yet fully understood.

Future research should thus address in more detail the interactions between grid-scale and decentralized electricity storage, as well as various sector coupling options. This also requires taking the operational characteristics of decentralized batteries into account, which heavily depend on end-user behavior and retail market design. Likewise, the flexibility potentials and constraints of various Power-to-X processes and their repercussions on electricity storage and VRE market dynamics should be studied in more detail.

Further, market design and regulatory frameworks may have to be adjusted to enable all flexibility options to capture the various values they may provide to the system. This is necessary to achieve welfare-optimal deployment of each technology in the real world. Yet the necessary adjustments may differ strongly between markets and jurisdictions and are also subject to further research.

SUMMARY POINTS

- 1. Variable renewable energy (VRE) sources are a central strategy to achieve a decarbonized energy system.
- 2. Increasing VRE penetration depresses wholesale electricity prices (merit-order effect).
- 3. Increasing VRE penetration reduces its own value (cannibalization effect).
- 4. Increasing VRE penetration needs to be complemented by electricity storage and other flexibility options.
- 5. Long-duration storage needs substantially increase as VRE penetration approaches 100%.
- 6. Electricity storage mitigates both the merit-order and cannibalization effects.

FUTURE ISSUES

- 1. Future market design should enable agents to capture the various values that storage and other flexibility options provide.
- 2. Decentralized electricity storage and sector coupling will have an increasing role in decarbonized electricity systems.
- 3. Future research should analyze in more detail how the economics of VRE interact with centralized and decentralized storage and sector coupling options.

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