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Perspective

The role of batteries in meeting the PV terawatt challenge

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SUMMARY

What role have batteries to play in the transition toward terawatt levels of photovoltaics? In this perspective, we attempt to answer this question by looking at technical, economic, and ecological features of PV-battery systems. We argue that the window of opportunity for batteries lies in the capacities of a few kWh/kW$_P$, the exact amount depending on various factors including battery cost, degradation rate, location, load profile, diversification of renewable energy sources, and interconnections. Using a simple PV plus battery model, we illustrate that such storage capacities efficiently reduce fluctuations in electricity generation, enabling higher PV adoption rates at competitive costs, and with a carbon footprint that is at least five times lower than that of the current energy mixes. Using sensible capacities, batteries are a powerful companion for solar energy, yet technical, economic, and policy innovations are needed to expand adoption. We see longer battery lifetimes and low capacity degradation rates are the most impactful technological parameters. Economic efforts should aim to reduce balance of plant costs and create better market opportunities for stationary storage, whereas policies should provide a strong regulatory framework to facilitate multipurpose usage and sector coupling.

Context & scale

In this perspective, we discuss the potential role of stationary batteries as a supporting technology to extend the deployment of photovoltaic power. As the transition to clean electricity progresses, supporting technologies for managing supply and demand gain importance. A variety of such technologies exist, and we will likely adopt a mixture, the consistency of which will depend on, among other things, weather and climate, geological factors, economic conditions, and local policies and regulations. The goal of this work is to explore how batteries can best support photovoltaics looking at performance indicators and economic and ecological factors. We find that the addition of moderate battery capacities provides a good compromise between added flexibility and added costs and environmental impact. Extending battery lifetime, reducing pack but also system costs, efficient recycling, and devising a strong supporting regulatory framework are needed to enable batteries as a strong companion for photovoltaics in the energy transition.

INTRODUCTION: THE TERAWATT CHALLENGE

The term "terawatt challenge" was coined by Richard E. Smalley[1] in 2003 who described it as a program to "adapting our energy infrastructure to simultaneously address diminishing oil resources and rising levels of atmospheric CO_2." Addressing this challenge calls for the installation of multi-terawatt solar PV and wind capacities and will involve major transitions in our energy infrastructure.[2] Decisions lie ahead of us about investments in technologies for energy generation, transmission and distribution, and usage.[3] Although wind and solar capacities are projected to expand and become the largest contributors to global power generation,[4] complementary technologies to ease the transition to renewables are necessary.[5] Central to the terawatt challenge is an increase in electrification and the overall efficiency of power use,[1,3] for example, in the transportation and heating sector. Supporting technologies for renewables include storage in batteries and/or pumped hydro energy storage,[6] power-to-gas (PtG)[7] or power-to-X (PtX) approaches, extended transmission lines,[8,9] power to vehicles,[10] and load-shifting concepts.[11]

The technical and economic interactions among generation, transmission, storage, and end use are complex and, owing to continuous innovation, in flux. Multiple studies discuss scenarios of how very high levels of renewable energy contribution[12–17] can be reached and propose different strategies. Technically, any mechanism to shift energy in space or time can be used to enable 100% renewable contributions locally or globally.

However, the use of a single mechanism will result in conditions that are neither ecologically nor economically favorable or sustainable. Scenarios with high renewable contributions, consequently, work with a portfolio of options. Conversely, this means that no particular technology is essential or without alternative. The contribution of a particular technology, like storage, is not fixed, but rather lies within a window of opportunity defined intrinsically by technical, economic, and ecological performance and extrinsically by factors like regulatory frameworks. In this perspective, we provide our opinion about the opportunities and challenges of grid-scale battery storage to support the extension of photovoltaic (PV) capacity from a technical, economic, and ecological perspective. The constructive use of batteries means that they enable more electricity from renewables at low cost and with a small carbon footprint. In the following section, we motivate how batteries support the extension of renewables by molding the power generation profile. We define the utility of batteries by their ability to provide flexibility to PV power generation and show that this definition can be used to find a reference battery capacity. We then discuss the economic and the environmental implications of combining solar energy and battery storage. Finally, we discuss barriers for the adoption of stationary batteries.

BATTERIES AS AN ENABLER FOR TERAWATT PHOTOVOLTAICS

To understand basic features of PV-battery systems, we explore a simplified scenario. In this scenario, we only look at the ability of batteries to improve the overlap between the solar resource and a constant load. A constant load was chosen because it is the most challenging part to satisfy with PV in any load profile. The battery capacity we are looking for is the one that provides the maximum improvement in this overlap and will be referred to as reference capacity. This approach can be thought of as representing a behind-the-meter system in the sense that it ignores the rest of the power supply infrastructure. It especially ignores synergies through coupling with transmission and end use and will overestimate the flexibility-enabling capacity. However, generally, it does not matter whether batteries and PV system are co-located or not.

The value of such an investigation is to provide insight into the dynamics of how battery capacities are able to support an extension of the installed PV capacity with an easy-to-follow example. We will use this example to show that batteries have the ability to act as an enabler for much higher PV adoption levels than currently realized. We will also discuss some of the pitfalls of such a simplification.

Co-installing PV panels and batteries allows shifting the delivery of electricity from times of high production to times of low or no production. This shift changes the degree of the variability of the PV-battery system power output by smoothing out oscillations. To illustrate this change, we define a uniformity factor U, given by

$$U = \frac{\int \left(P_g(t) + P_s(t) - P_c(t)\right) dt}{P_{max} \cdot \Delta t} \quad \text{(Equation 1)}$$

In this equation, $P_g(t)$ is the power generated by the panel, $P_c(t)$ is the amount of power curtailed by the solar panels per time, Δt is the time interval used (in this study 1 year), and $P_s(t)$ is the power flowing into and out of the battery, mathematically given by

$$P_S(t)dt = \begin{cases} \left(P_{max} - P_g(t)\right)dt \text{ for } 0 < \int dt P_S(t) < cap \\ \int P_S(t)dt \left[2 \cdot \Theta\left(P_{max} - P_g(t)\right) - 1\right] \text{ else} \end{cases} \quad \text{(Equation 2)}$$

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P_{max} is the constant power level below which all non-curtailed energy is generated and *cap* is the ideal battery capacity at 100% round trip efficiency. Actual battery capacities need to be adjusted by inversely scaling the obtained ideal values with the battery-specific round trip efficiency. P_{max} is derived by self-consistently solving the following equation:

$$c\int\left(P_g(t)+P_s(t)\right)dt \overset{!}{=} \int\left[\left(P_g(t)+P_s(t)-P_{max}\right).\Theta\left(P_g(t)+P_s(t)-P_{max}\right)\right]dt$$

(Equation 3)

Θ is the Heaviside step function, which is used to manage charging and discharging close to capacity limits in Equation 2 and results in only generation above P_{max} contributing to the integral on the right side in Equation 3. c is the curtailed fraction of total energy. To minimize the impact of curtailment, we use a very small value of 1% in this work. Allowing a small amount of curtailment is justified, because it is economically beneficial, can provide grid services, and contributes to grid stability.[18] 1% curtailment is sufficient, as it eliminates rare events of very high generation. Although having a small amount of curtailment is beneficial, larger amounts have very little impact on the results. An illustration on how U is calculated is shown in Figure 1A. The generation profile (shown in red color) is altered through the introduction of batteries and curtailment. The overlap between the altered profile and P_{max}, the maximum value of these profiles minus curtailment, is improved as greater battery capacities are introduced.

The defined uniformity factor is similar to the capacity factor.[19] However, there are some important differences. Capacity factors are derived from measured plant performance, whereas the uniformity factor is calculated using idealized assumptions. In addition, the uniformity factor uses a constant reference power (P_{max}), whereas capacity factors use the actual time-dependent load profile for a given installation.

However, U itself is just the means to the end of determining the reference batter capacity. The upper part of Figure 1B shows the uniformity factor as a function of added battery capacity (*cap*) for three exemplar locations: Nuremberg, Denver, and Singapore. The reference capacity is obtained from the first derivative of this function, shown in the lower part of the figure. The reference capacity is the maximum of the derivative, i.e., the battery capacity that comes with the highest increase in uniformity. In Nuremberg, adding 3.0 kWh/kW$_P$ of storage boosts U by a factor of 2.25 from 16% to 36%. In Denver, adding 3.8 kWh/kW$_P$ results in a boost of a factor 2.5 from 23% to 57%. In Singapore, adding storage has the biggest effect of how much PV can be added to the grid, because of the lack of larger seasonal fluctuations. An addition of 3.4 kWh/kW$_P$ of storage boosts U by a factor of 3.2 from 21% to 66%. Note that the exact values of U are very sensitive to the shape of the load profile. However, improvements in U and the reference capacity only show a small sensitivity to it because the main utility of batteries, at least in small quantities, is to cut peak generation, and the exact time to where the cut power is shifted is of little significance to the improvement in U. It should be noted that our definition of battery utility focuses on PV capacity expansion. In practice, batteries will also be used for other purposes such as frequency regulation.

All calculations were performed over 1 year by using solar insolation for the year 2013, for which the most comprehensive data set for all following calculations was available, and a solar panel with 20% conversion efficiency.

The simplified analysis shown in Figure 1 has the advantage of being easily comprehensible and providing a general idea about the dynamics of unlocking the potential for photovoltaics by adding batteries. We already alluded to the fact that the

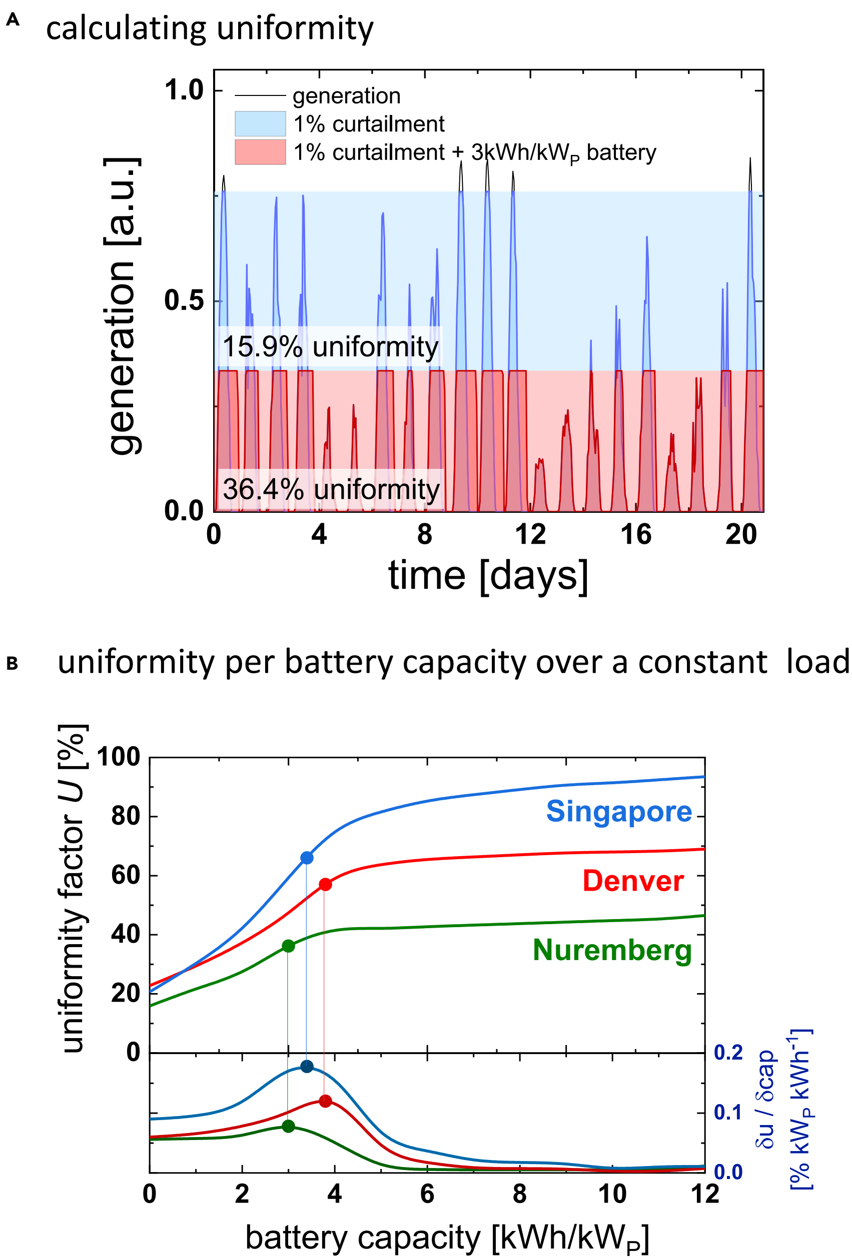


Figure 1. Uniformity factors for PV

(A) Sketch about the calculation of the uniformity factor. The uniformity factor *U* is the ratio of the area under the generation curve and the rectangle defined by maximum generation. Curtailment and storage both flatten generation, resulting in greater uniformity.

(B) *U* as a function of battery capacity for three locations: Singapore (blue), Denver (red), and Nuremberg (green). Calculations include curtailment of 1% of the overall yield. Also shown is the first derivative of this curve, below, with the maximum being used to mark sensible battery capacities used in this analysis.

obtained battery capacities are overestimations and will be affected in practice by sector coupling. As mentioned before, there are no physical necessities for how much storage is needed to achieve a certain contribution of renewables. The numbers found here are between 3 and 4 kWh/kW$_P$. A more detailed scenario by Bogdanov et al.[20] for a global power system uses battery storage with a capacity of 2.2 kWh/kW$_P$. A study by the Energy Watch group cites 1.2 kWh/kW$_P$ when considering only coupling between power and heat,[5] whereas a PV prosumer study focusing options for residential applications finds a 2 kWh/kWp economic threshold for batteries.[10] A detailed scenario for Singapore was presented in the study by Reindl et al.[21] The study confirms our finding that even a small amount of support can notably extend the contribution of PV to the power grid. It suggests that by 2050, 43% of the island's electricity could be generated by solar cells with battery support.

Why does it matter?

The key takeaway from this analysis is that there is a window of opportunity for batteries to maximize their effect on the extension of PV capacity. The window lies at capacities of below 3 to 4 kWh/kW$_P$ depending on the location. This conclusion can be drawn even from a simple analysis like the one presented here, and the finding is supported and refined by more detailed studies. However, a simple analysis also requires careful interpretation. In the discussion about the transition toward high fractions of renewable energy, there are reports that use simplified scenarios with outrageous conclusions. For example, batteries alone will not enable solar PV modules to balance seasonal variations that are relevant at high latitudes, outside the sunbelt. Modeling such a scenario will conclude that there is a need for battery capacities that are neither economically nor ecologically sensible or feasible. In one internet discussion, we found a figure of 4 trillion dollars of battery investment for the state of Colorado alone.

ECONOMIC CONSIDERATIONS

One of the biggest concerns about battery storage is the cost that it adds to electricity production. Cost implications are dominated by the amount of battery storage considered. As discussed in the previous section, we consider a capacity of below 4 kWh/kW$_P$ to be sensible from a system architecture viewpoint.

Installed costs are the most important economic factor. These costs limit the amount of storage that is economically feasible. It is important here to point out that installed costs (c_{ins}) include the costs for the battery pack (c_{bat}) and balance of systems (*BOS*) costs, which sometimes are also referred to as balance of plant (*BOP*) costs in \$. BOS costs per kWh are then not constant but depend on power rating (*rat*) in kW and duration (*dur*) in hours. Following Fu et al.,[22] installed costs can be approximated by

$$c_{ins} = c_{bat} + \frac{BOS}{rat} \cdot \frac{1}{dur} \quad \text{(Equation 4)}$$

An example for a grid-scale battery system is the Hornsdale Power Reserve large battery storage in Australia. With an updated capacity of 185 MWh, a power rating of 70 MW/10 min and 30 MW/3 h, and construction costs quoted at 66 million USD[23] for the initial capacity of 129 MWh, the installed costs are just above 500 US\$/kWh. With the increased adoption of electric vehicles (EVs), battery prices are projected to continue to decrease over the next years. Studies do not agree on the extent of cost reduction that is possible for full systems. Vartiainen et al.[24] projects 130 US\$/kWh for 2030, based on past learning rates. A report by NREL[25] states a range of between 125 and 300 US\$/kWh for 2030. A cautioning remark about projections based on learning rates was made by Hsieh et al.[26] This study points out practical limitations to cost reductions for lithium-ion (Li-ion) batteries and concludes that costs (c_{bat}) are unlikely to drop below 124 US\$/kWh by 2030, translating to installed costs of about 225 US\$/kWh for a utility scale system and 4 kWh/kW$_P$ capacity. To explore economic implications of battery storage, we will use two values here: 350 US\$/kWh, which according to projections is a conservative estimate for installed costs in 2020, and 200 US\$/kWh, which is a value that could be achievable within the next decade.

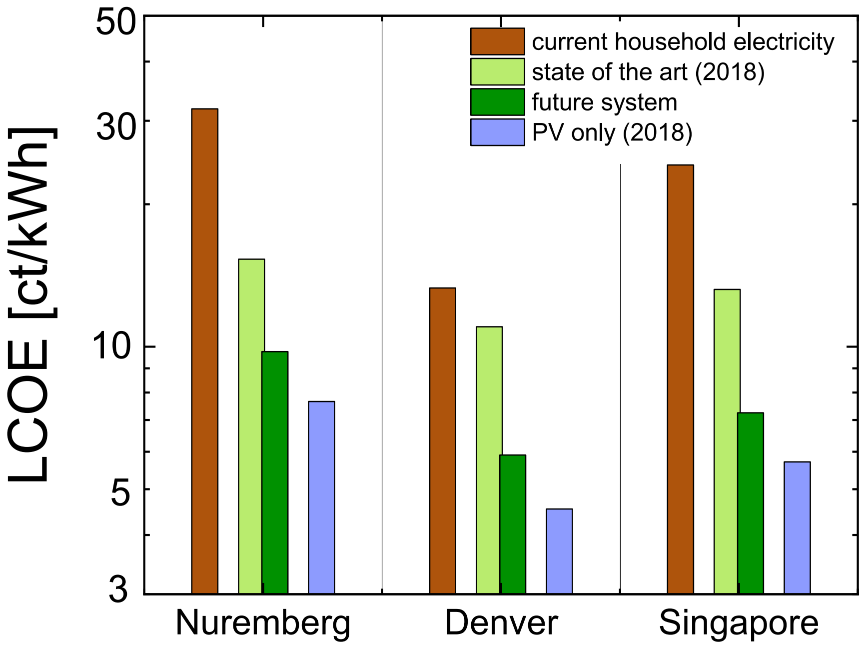


Figure 2. LCOE of PV-battery installations for the three considered cities

Brown bars indicate current local household electricity prices, green bars are the modeling results for PV-battery systems, and blue bars mark reference LCOEs for PV installations without batteries in 2018. For PV-battery systems, two scenarios were modeled, a 2018 state-of-the-art scenario using 350 US$/kWh installed cost and 15-year battery lifetime and a future scenario using 200 US$/kWh installed cost, 30-year battery lifetime, and reduced PV costs. Note the logarithmic scale.

A second important factor for the economic performance is battery lifetime. Battery lifetime determines the rate at which batteries have to be replaced in a system, which has ecological implications as well. For current battery technology, Cole et al.[25] summarize several studies that state lifetimes between 10 and 20 years and approximately one full cycle per day. We will use two values here: 15 year corresponding for current technology and 30 years for future batteries.

We calculated levelized cost of energy (LCOE) by using the NREL System Advisor Model.[27] Results are shown in Figure 2 using the sensible battery capacities for each city from Figure 1, 200 US$/kWh and 350 US$/kWh installed costs and 15 and 30 years lifetime. Also shown are the calculated LCOE values for utility scale PV-only installations for each city in blue and the current household electricity costs in brown.[28–30] The latter are included to set the increases in generation cost owing to batteries into perspective. PV system costs were modeled according to numbers for utility installations given in Fu et al.[31] and using local irradiance data. Lifetime costs are accounted for on a discounted cash-flow basis, calculated once annually. For the future systems, PV panel costs were reduced to meet the SunShot 2030 goal of 3 USct/kWh for Denver.

Batteries will inevitably increase the cost of electricity. For the state-of-the-art scenario (350 US$/kWh, 15 years lifetime[32]), LCOE approximately doubles compared with a PV-only system. In Denver, the value for this scenario is 11 USct/kWh, similar to where a PV system without batteries was in late 2013.[31] Note here that we used the same cost for battery installation and battery replacement. As battery costs will come down and as replacement costs will be lower than initial installation costs, LCOEs for the state-of-the-art scenario are slightly exaggerated. For the future scenario (200 US$/kWh, 30-year lifetime), the increase in LCOE compared with the 2018

PV-only system is on average 28%. In Denver, LCOE for this scenario is 5.9 USct/kWh, corresponding to a PV-only system in mid-2017.[10] This figure would also meet the SunShot targets for 2030 PV-battery systems. To set the cost increases into perspective, we compare the cost for solar electricity with and without batteries with the current household electricity prices (shown in brown in Figure 2).

Why does it matter?

The key takeaway from this section is that the extension of PV capacities through battery storage is economically feasible today and will be even more feasible in the future. Compared with PV-only systems, batteries increase the cost of electricity, yet projected costs are still similar to those of a natural gas plant (4.2–7.8 USct/kWh) and are below those of a coal-fired power plant (6.0–14.3 USct/kWh).[33] Following Xcel energy's net-zero carbon plan, the addition of batteries will aid the retirement of 660 MW of coal-fired power units and their replacement with 1,131 MW of wind, 707 MW of solar, and 275 MW of battery storage.[34] Median bids in late 2017 for solar-battery systems in Colorado were at 3.6 USct/kWh and for solar alone at 2.95 USct/kWh.[35] Because of these low costs of solar + battery electricity, transitioning toward renewables might even reduce the overall cost of electricity. These figures stand in stark contrast to some numbers circulating in the internet that claim additional annual household costs for batteries of 100,000 US$ or more.

ECOLOGICAL CONSIDERATIONS

In addition to adding costs, batteries will also increase the ecological impact of PV systems. Battery production requires energy and resources, and used batteries produce waste. These aspects should also be considered when adding battery capacity. Here, we look at how the addition of batteries affects the global warming potential (GWP) (a metric that is similar to the carbon footprint) and the energy payback (EP) time of PV-battery systems. These metrics are relevant for the goal of decarbonizing electricity productions, although they do not fully capture the ecological implications of introducing large battery capacities into the energy infrastructure.

The GWP describes how much carbon dioxide equivalent is released during the production of the PV-battery system. In this analysis, we follow the method outlined in Leccisi et al.[36] to calculate the GWP given in kg $CO_{2\text{-eq}}$ per kW_P. We also take from this analysis the GWP for a PV system. Representatively, PV modules made in China by using multicrystalline silicon solar cells with a module efficiency of 18.0% and an average performance of 85% are used. CO_2 emissions for battery production were taken from Arvidsson et al.[37] for the example of a Li-ion battery. Local irradiance was taken from the global solar atlas.[38] The obtained GWP is shown in Figure 3, in the upper half. Battery capacities are taken from Figure 1; we again show two scenarios, one with no battery replacements (battery life of 30 years) and one with one battery replacement (battery life of 15 years). Also shown are figures of the emission intensities for Germany and Colorado for 2019 and for Singapore for 2018.[39–41] Although batteries increase the GWP of a PV system, PV-battery systems in this example still have a much lower emission intensity than the current energy mixes in the respective areas. It should also be noted that GWP depends on the source of energy used to fabricate an asset. By only using carbon-neutral energy for production, PV-battery systems will become completely carbon neutral themselves.

The EP time describes how long a system needs to generate energy before the amount used for its production is recovered. Typical EP times for PV systems are in the range of one-half to 2 years, depending on technology and location. In the example here, we have again used numbers for multicrystalline silicon PV modules

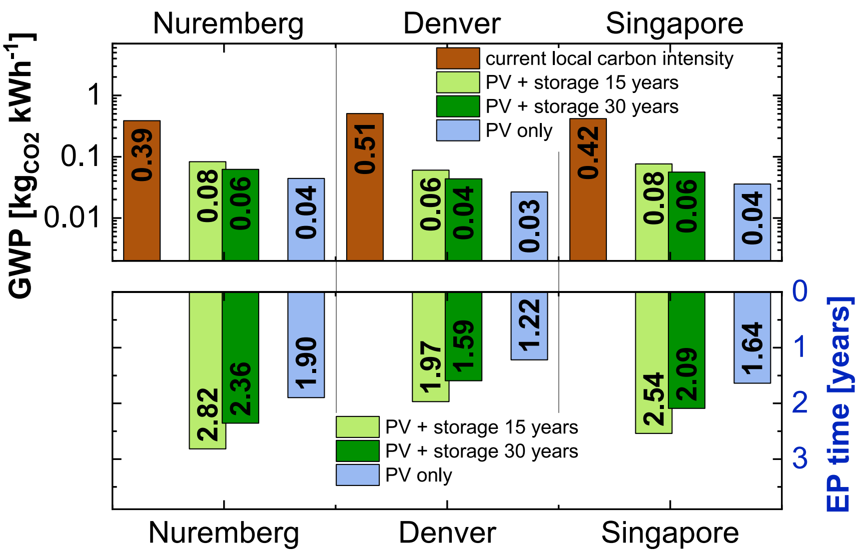


Figure 3. Global warming potential (top) and energy payback time (bottom)

Shown are results for PV-only systems in blue and PV-battery systems with one battery replacement (light green) and no battery replacement (dark green) over the 30-year lifetime of the overall system. Also shown are the carbon intensities of the energy mixes in Germany and Colorado 2019 and Singapore 2018 in brown [35-41]. Note the logarithmic scale at the top.

from Leccisi et al.[36] Energies required for producing a battery were taken from Larcher et al.,[42] and typical insolation values were taken from Leccisi et al.[36] Results are shown in the lower part of Figure 3 for PV-only systems and PV-battery systems with 15-year and 30-year battery lifetime, that is, no and one replacement during the life of the system. The addition of batteries in this example increases EP times by between 25% and 60% compared with PV-only systems.

The analysis shown here is simplistic, as mentioned earlier. For example, we have not considered battery recycling explicitly, which would reduce the energy intensity of battery production.[43] In addition, energy learning in manufacturing is not considered, but well documented.[44] However, our main intention was to contribute to the discussion about the use of batteries to support terawatt photovoltaics by assessing a limiting scenario. For the battery capacities used in this study, we observe only moderate increases in GWP and EP time compared with PV-only systems. Because the GWPs of PV-battery systems are much lower than those of current energy mixes and because batteries enable extending the adoption of PV, limited battery capacities can be effective in reducing our overall carbon footprint. Ecological and societal concerns remain. Apart from the need to ensure environmentally friendly recycling,[45] mining of materials and battery fabrication cause a number of issues. Lithium mining is water intensive, and the withdrawal of water affects the surrounding regions, especially farming.[46] Cobalt mining is an even bigger concern with social, ethical, and environmental issues being mentioned.[46] For stationary applications, cathodes without cobalt, such as $LiFePO_4$ and LMO, are a potential alternative.

Why does it matter?

Ecological considerations are frequently missing in the discussion about battery adoption to support renewable energies, yet in our opinion they should be an essential part. The transition to renewable energies has multiple, partially conflicting goals. Achieving carbon neutrality is one, sustainability another, and low cost a third. As any additional component will affect all of these goals, careful analysis of these

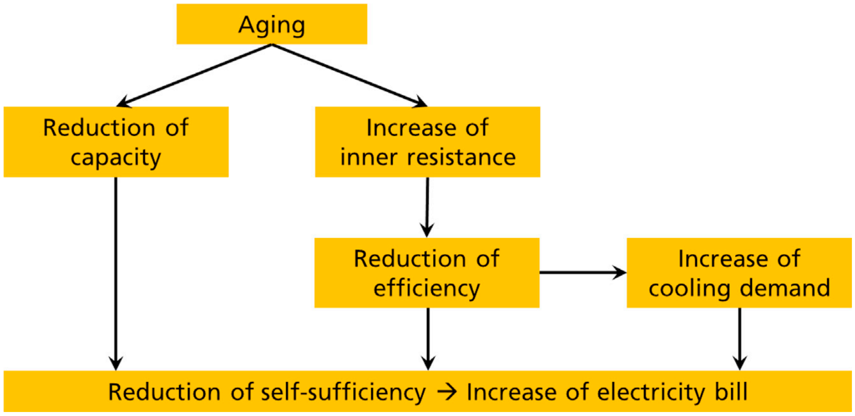


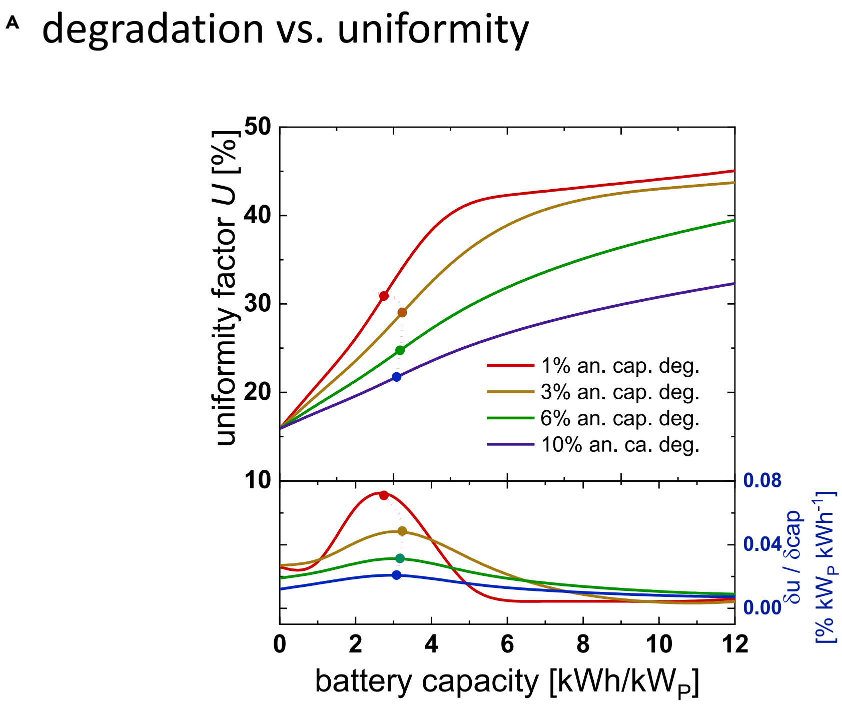
Figure 4. Influence of aging on self-sufficiency for behind-the-meter PV-battery systems
Please see Vetter.[47]

impacts is necessary. Batteries will increase the carbon footprint of a PV system, and a too large increase would defeat the systems' very purpose. Batteries should be assessed against other options such as pumped hydro, synthetic fuels, and transmission. Ecological arguments might be decisive when designing the complex energy infrastructure of the future.

EFFECT OF BATTERY AGING

Battery aging is a complex process that results in a capacity fade and an increase of inner resistance. How aging affects battery self-sufficiency is sketched out in Figure 4; we implemented a simple capacity degradation model with a constant annual degradation rate between 0% and 10% over a 30-year lifetime. In our considered used cases, batteries are only operated with low C rates and/or moderate currents. Therefore, we assume only a minor impact of inner resistance increase in the following considerations.

The degradation rate of a Tesla Powerwall is given at 3%[48] annually. Values for capacity degradation in scientific literature are typically given as a function of cycles and over several temperatures. Assuming one cycle per day, results presented by Preger et al. translate to between 1% and 4% annual degradation for $LiFePO_4$-based batteries.[49] Results of our degradation model are shown in Figure 5. As degradation rates increase, the uniformity factor decreases (Figure 5A, upper part), as well as the rate of change in uniformity factor with additional battery capacity (Figure 5A, lower part). The reduction in uniformity is indicative of the severe consequences of fast capacity degradation. Although the reference capacity is not much affected, the ability of the battery to shift power over its lifetime is strongly affected and with it the ability to support renewable energies in the grid. To make this characteristic more descriptive, we plotted battery capacity and uniformity factor for different fade rates in Figure 5B. The reference capacity is again given by the maximum change of uniformity factor with battery capacity and is marked by dots in Figure 5A. For small degradation rates, capacity reductions can be compensated by using larger batteries and uniformity, largely, can be retained. Once degradation rates exceed 2% to 3%, this compensation is no longer possible and uniformity starts to drop, whereas reference capacities stay constant or even decrease for very large degradation rates. This characteristic shape translates to the impact of battery degradation on LCOE, GWP, and EP time. Although uniformity can be maintained, all three quantities increase with capacity degradation, as larger batteries compensate for capacity loss. The



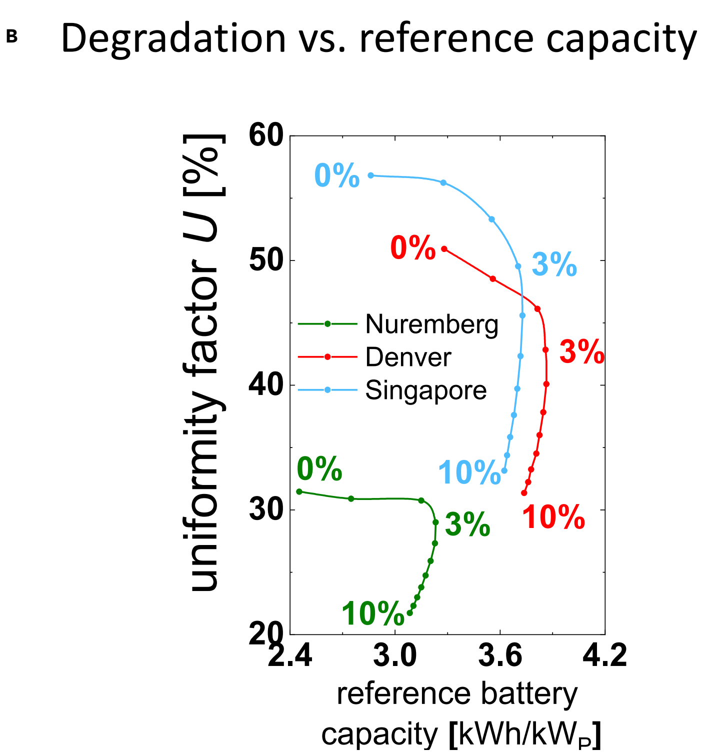


Figure 5. Impact of capacity degradation

(A) Relation between battery capacity and effective uniformity factor over the 30-year lifetime as a function of capacity degradation rate (above) and derivative to obtain the reference value (below) on the example of Nuremberg.

Figure 5. ***Continued***
(B) Reference battery capacity versus uniformity factor as a function of battery capacity degradation for the three cities.
(C) Levelized cost of energy (LCOE), global warming potential (GWP), and energy payback time (EPT) as a function of capacity degradation rate.

relative increase is largest for Singapore and smallest for Denver. In the rapid degradation regime, LCOE, GWP, and EP time peak and then start to decrease as battery capacities are not increasing further.

POSSIBLE BARRIERS TO ADOPTION

In the previous sections, we discussed the potential of batteries to support increased supply uniformity and resulting electricity generation associated with the installation of TW levels of PV. We found that installing moderate battery capacities enables increasing PV adoption at costs that are comparable with or lower than conventional, fossil fuel combustion, and enables reducing the GWP of our energy infrastructure. In this section, we will briefly discuss possible barriers to adopting stationary battery storage.

TECHNOLOGICAL BARRIERS

Batteries available today are technologically capable of supporting even utility PV installations and providing reliable and stable power to the grid. A prominent example is the Hornsdale Power Reserve installed by Tesla in Australia with an updated capacity of 185 MWh.[50] The battery is capable of supporting grid stability and by May 2018 provided 55% of frequency control and ancillary services in South Australia, reducing their cost by 90%.[51]

Although there are no fundamental technological barriers to adoption, performance of stationary battery storage can still be improved, on component and system level. Most relevant for a reliable and high-performance support of renewable energies are aging behavior over life time—capacity degradation[52] and increase of inner resistance—and round trip efficiency[53] for daily cycling, whereas high efficiencies at partial load conditions are crucial owing to the typical operating conditions. Trendsetting for battery development will be the continued electrification of transportation. This trend will guarantee and accelerate further development of battery technology and the expansion of Li-ion battery production capacity[54,55] (Figure 6, left). This trend holds both opportunities and challenges for stationary storage. The availability of large battery capacities is an opportunity, especially if second-life applications are considered[56] and should be a motivation to explore synergies between electro mobility and battery storage to support renewable energies[57] further. One much-noticed option here is also the grid-interaction of batteries integrated into EVs, also called vehicle to grid or V2G. This option is attractive because the targets for EV fleets would provide a very significant battery capacity. Bloomberg New Energy Finance estimates the global EV fleet in 2030 to exceed 100 million vehicles.[58] IEA has published a scenario with 250 million.[59] The same report projects the 2030 energy storage potential in EV batteries to be 16 TWh in China, the EU, India, and the US alone. Because these batteries would predominantly be paid for for providing mobility, the value proposition and economic scenarios also differ from batteries used for stationary storage only. V2G integration faces a number of challenges of its own that exceed the scope of this work and have been discussed, for example, in Noel et al.[60]

A challenge for stationary battery storage is that it is a niche market with a market share below 10% of the total battery market and will likely stay that way for the

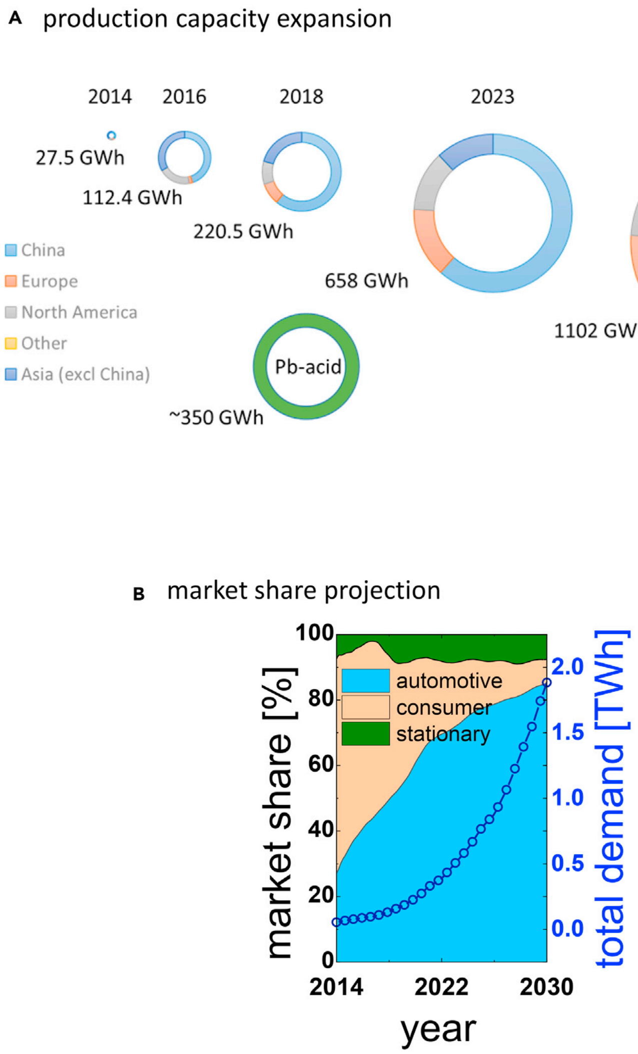


Figure 6. Li-ion battery market projections

(A) History and projections of the manufacturing capacity and locations for Li-ion batteries between 2014 and 2028.[54,55]

(B) Historic and projected market shares for batteries in the automotive industry, consumer electronics, and for stationary storage.[61]

coming years[61] (Figure 6, right). By not building a battery market specifically to service variable power from solar and wind, we risk being left with devices that are not optimized for the application, which could compromise cost targets and reliability. Stationary batteries differ, for example, in charge and discharge rate and in thermal management from EV batteries. Establishing such a market may require exploring how to incentivize battery manufacturing specifically for renewable energies. Besides high-temperature sodium batteries (NaS and NaNiCl[62]), emergent flow batteries area candidate to resolve this challenge.[63] Their structure is inherently suited for stationary storage and resolves the self-discharging issue. Low cost options for flow batteries are currently explored.[64]

ECONOMIC BARRIERS

Battery system costs will determine how large their contribution to extending PV capacity will be. Even at today's costs, batteries are commercially viable and are

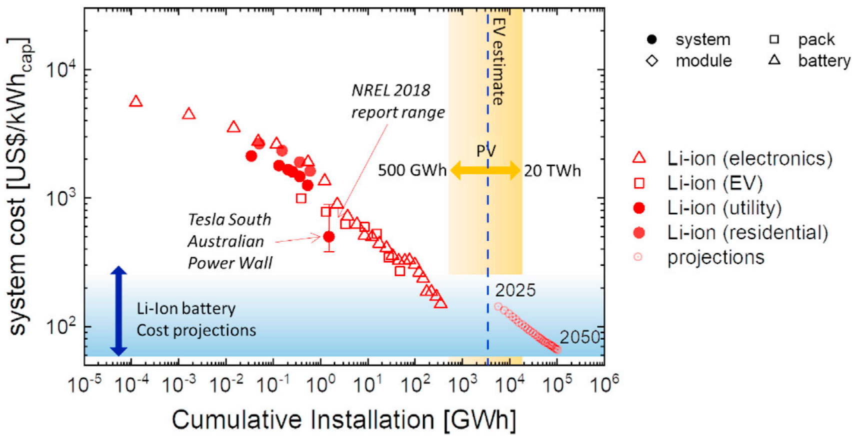


Figure 7. Learning curves for Li-ion batteries
Different configurations ranging from just the battery (open triangles) to full systems (colored circles) are included.[4,24,66–69]

installed alongside PV installations. The largest current project is the FPL Manatee Storage Centre in Florida, featuring a 409 MW/900 MWh battery and being charged with existing PV installations.[65] Battery system cost reductions will further improve the competitiveness of PV-battery systems and result in a greater number of battery storage projects or combined PV-battery projects.

Figure 7 shows the learning curves of different storage technologies. Data shown in this figure were compiled from previous studies.[4,66–69] The yellow band marks a capacity range of between 500 GWh and 20 TWh, sufficient for supporting multiple TW of PV for several hours. Projections for a battery system learning curve were adapted from Vartianen et al.[24] The blue band shows a projection range from industry experts and academics. As previously mentioned, some studies point out physical limitations of cost reductions.[26] These studies expect the learning curve to converge toward a technology-specific minimum value.

To achieve the projected low costs of PV-battery systems, reductions are necessary not only for the battery pack but also for BOS/BOP contributions. Although battery packs will become cheaper as a result of the adoption of EVs, cost reductions on the BOS/BOP side lack a similar drive from industry. To ensure fast enough cost reductions for battery systems, additional efforts are needed. We propose to develop targeted programs for cost reduction in battery BOS costs, similar to comparable efforts to lower the BOS costs for PV installations.[70]

Resource availability is an additional factor that could limit the adoption of batteries. Lithium availability is a topic of controversial discussion. Although total resources are estimated at 53 million metric tons by the 2018 US geological survey,[71] only a fraction of this amount, estimated by the same source at 16 million tons, is economically extractable. In 2017, Li-ion batteries used approximately half of the world's 43.000 metric tons production in lithium, and demand is projected to rise quickly. Lithium prices have risen accordingly and have almost quintupled between 2010 and 2018.[72] Although there is enough lithium on Earth to support TW levels of PV, rising demand and increasing difficulty in mining the material could become economic barriers to battery adoption. Similar concerns also apply to other metals, especially Co and Cu, which is another motivator for alternative material systems.[73]

BARRIERS FROM POLICY AND REGULATIONS

A future energy infrastructure based on renewable energies benefits strongly from synergies of different technologies and multiple uses of its components. Interlocking of generation, management, and storage mechanisms marks a difference to our past and current energy infrastructure in which one structure is largely responsible for one task. The transition from single to multi-use is further complicated by policies and regulations that are sometimes missing and sometimes hindering the process.

In a survey in Germany, 86% of all companies stated that they perceived the regulatory framework as the largest barrier for the entry of new battery storage concepts and technologies. Project developers face legal challenges that they can only resolve with professional legal help. As a result, in Germany, only two business cases for battery storage (small home-based systems <10 kWp and storage for supporting the operating reserve) have been financially viable until now. Especially harmful market barriers include the restriction of innovative and multi-use applications, long approval procedures, and the lack of transparency of legal provisions. Restriction of innovative and multi-use applications obstruct the energy transition, not only technologically but also because it prevents the development of new business cases . One specific example that was discussed in Müller et al.[74] is regulatory barriers for a shared storage unit used by multiple households.

Although regulations are regionally specific, similar trends can be observed across many regions. For example, policy barriers and lack of rules and regulations for batteries to provide multiple services in the United States were discussed in Forrester et al.[75] and Bowen et al.[76] In other regions, a lack of regulations or incoherent policies is the main barrier because it results in financial uncertainties, as was pointed out, for example, in Lane et al.[77] and Monyei et al.[78] A challenging regulatory environment is not unusual for energy technologies deployed at an increasing rate, and the situation for batteries reflects that of photovoltaics.[79]

SUMMARY AND DISCUSSION

The terawatt challenge for photovoltaics has become an infrastructure challenge. As we transition to a majority of renewable energy sources, choices lie ahead about how to design our future energy system. Several paths are available for reaching carbon neutrality, and various technologies are involved—power generation is supplemented by transmission, storage, and load management. Although no concept or technology is without alternatives, each comes with unique strengths and weaknesses that will shape its role. Batteries introduce a mechanism to distribute energy over time and match supply and demand even on a local, decentralized level. In addition, batteries are modular in nature and can be ubiquitously deployed and capacity can be scaled freely. This feature sets batteries apart from pumped hydro energy storage. Other beneficial characteristics of batteries are their ability to support grid stability and react quickly to fluctuation and outages.

Because of the highly coupled nature of our electricity grid, there is no definite amount of required battery storage, but rather a window of opportunity in which batteries optimally support the extension of installed PV capacity. This window is determined by efficiency in matching supply and demand, by cost, and by environmental impact. We argue that a capacity of a few (our simple model suggests 3 to 4 kWh/kW_P) constitutes a sensible amount, depending on the location. We illustrate our argument using three exemplary locations: Nuremberg, Denver, and Singapore. For these locations, our model suggests that battery storage in the aforementioned range is most efficient in transitioning the PV generation profile toward uniformity. The same capacities result in electricity costs that, today, are about twice and in 2030 are projected to be approximately 1.3 times those of PV-only electricity today. Carbon footprints of the corresponding PV-battery systems are two to three times higher than PV-only systems but are still between five and ten times lower than those of the current energy mixes and would further reduce as cleaner energy is used for productions. EP times increase by approximately 50% compared with PV-only systems. Capacity degradation is important for all three figures and should be as low as possible. In addition, batteries should be assessed on efficiency of transforming generation, cost, and environmental impact against alternatives like pumped hydro energy storage, transmission, and synthetic fuels.

Large-scale stationary battery adoption also faces challenges. Although the growing EV market will ensure battery pack cost reductions, those batteries will be optimized for mobility and not for stationary storage. In addition, BOS costs for stationary batteries are still high. Concentrating research efforts on these topics will be significant for the future of stationary battery storage. In particular, batteries with very long lifetime (30 years) are beneficial for stationary battery performance. Batteries also face further environmental challenges. Three topics here are sustainable recycling and the mining of raw materials and research in the field of alternative materials and technologies. Mining for metals, including lithium and cobalt, entail environmental and social challenges. Continuous improvements should be implemented and monitored. Finally, regulatory barriers currently prevent a wider adoption of stationary batteries. Simpler rules, planning reliability and a removal of barriers for innovative and multi-use applications are primarily needed here. Cheap and durable stationary batteries with a strong supporting regulatory framework are a potent companion for photovoltaics in meeting the terawatt challenge.

FINAL THOUGHTS

This study originated from discussions among the authors about how a future energy infrastructure with very high renewable contribution could look like and how stationary batteries would fit into the picture. Stationary batteries are attractive because they provide a straightforward solution to the need for added flexibility in a world powered by sun and wind. However, as mentioned, batteries are but one of many solutions to provide this flexibility. So how will our future energy system look like? Likely, it will be diverse and use a portfolio of technologies to complement power generation. This portfolio might include different types of electricity and other energy storage, demand response, and transmission. The mix of these technologies will depend on their techno-economic performance and local geographic, political, economic, and climatic conditions. Our intention with this study was to point where the strengths and opportunities for stationary batteries lie and under which conditions they can provide a valuable contribution to the energy transition.

DATA AVAILABILITY STATEMENT

All data used in this work are available from the sources mentioned in the references. All data and used codes are available upon request from I.M. Peters. Please send an email to im.peters@fz-juelich.de.

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AUTHOR CONTRIBUTIONS

Conceptualization, methodology, validation, investigation, and resources, I.M.P.; C.B., S.A.J., S.K., T.R., R.S., and M.V.; writing original draft, I.M.P.; writing review and editing, I.M.P.; visualization, I.M.P. and M.V. All authors reviewed and approved the manuscript.

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