CHAPTER 14

Emerging Market of Household Batteries

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14.1 Why Household Batteries?

Solar photovoltaics (PV) was the most deployed generation technology in the years 2016 (72.4 GW) and 2017 (93.7 GW), reaching over 385 GW by the end of 2017.[1] This accelerated development is also characterised by rapid falling costs, and since 2010 the cost of new solar PV has declined by 70%.[2] Encouraging policies in the form of economic incentives such as feed-in tariffs (*e.g.*, in Germany and Italy) and renewable portfolio standards (*e.g.*, USA and China) has been a great mechanism to accelerate the deployment of PV technology. Feed-in tariffs (FiTs) are a guarantee for the owner of the PV system that the electricity injected into the main grid will be bought at a constant price for several years, which covers the investment costs, while renewable portfolio standards is a policy that ensures a minimum share of renewable generation for a region.[3]

Although economies of scale play a role in PV technology and the capital cost reduces with the system scale (*e.g.*, PV plants at the utility scale are

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50% and 60% cheaper than residential PV from an initial investment and life cycle cost perspective respectively[4]), PV is the most modular technology available in the market. Interestingly, the ratio between the levelised cost and capital expenditure remains constant with the scale since solar irradiance is scale independent (opposite to wind technology since power is proportional to the cubic of wind speed). As a consequence, small PV installations of a few kilowatts have largely been embedded into consumption centres. Making use of the available area on roofs, residential PV installations have been an important contributor to the massive deployment of PV installations. According to the National Renewable Energy Laboratory (NREL) in the USA, 67% of new PV installations with a nominal capacity lower than 2 MW were integrated into the residential sector.[5] This is also the case in Germany (with a current installed capacity of 75 GW, the second largest in the world after China) where PV rooftop plants contribute to more than 60% of the total installed capacity.[6] In Switzerland, 6317 and 834 PV systems were installed in individual and collective buildings in Switzerland in 2016, corresponding to 71% and 9% of the total of new grid connected PV systems.[7] These installations add 58 MW_p and 22 MW_p respectively, *i.e.* 22% and 9% of total capacity additions respectively. Following domestic driving forces, the second sector of the economy (*i.e.* industry and craftwork) is the main contributor in terms of capacity additions (111 MW_p in 2016) followed by farming with 40 MW.

After this successful deployment, policies have been adjusted and the value of FiTs has been reduced across many countries in the last few years in order to adapt it to the falling PV cost. For example, the FiT was divided by 3.5 from 2009 to 2016 in Germany, as shown in Figure 14.1, and its phase-out is expected in the coming years.[8] A similar trend has also been observed in other countries such as Switzerland, Italy, UK and Spain.[9] This reduces the profitability of residential PV installations but the electricity generated by residential PV installations can also be directly supplied to the local demand loads in the dwelling. In this case, PV generation avoids the purchase of retail electricity, the value of which is currently much higher (up to three times, as given in Figure 14.1) than the FiT across many geographies. In the case of Germany whose legislation has supported the massive penetration of renewable energy technologies and PV in particular together with the phase out of its nuclear plants, retail electricity prices increased by an average rate of 5.7% p.a. between 2010 and 2013.[10] Other European countries have experienced substantial increases in recent years including Spain (63% from 2008 to 2013, *i.e.* 10% p.a.) and UK (46% from 2007 to 2013, *i.e.* 6.5% p.a.) and in the European Union on average household electricity prices rose 4% p.a. between 2008 and 2012.

However, only a small fraction of the PV generation meets the electricity demand of dwellings due to its weather dependence, typically around 25–35% on an annual basis for a standard PV system in a region without important cooling needs throughout the year. In order to further increase PV self-consumption, electricity storage with residential batteries is a

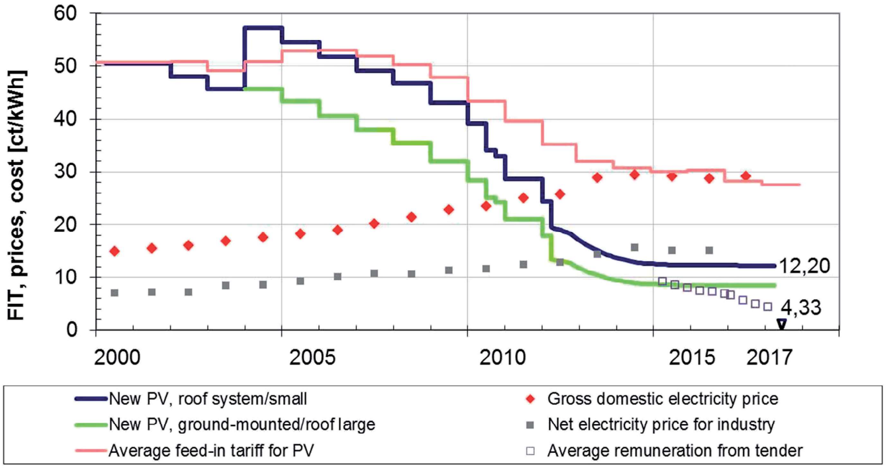

Figure 14.1 Feed-in tariff (FiT) for PV power as a function of the commissioning date, average remuneration of the bidding rounds of the Federal Network Agency in Germany. Reproduced with permission from the author of the following study: Recent Facts about Photovoltaics in Germany, Fraunhofer ISE, download from http://www.pv-fakten.de, version February 21, 2018.

becoming increasingly attractive for consumers with a PV system,[9,11] also referred to as prosumers. Adding a household battery can increase the PV self-consumption from around 30% (for direct PV self-consumption) to 60% approximately, but final values depend on the system configuration and dwelling.

Following the increase of retail prices, the reduction of PV cost and the reduction of FiT, household batteries have become a prime application for the energy storage industry (another important application is the use of frequency control). One of the world's most advanced residential storage markets is Germany, where around 50% of new PV installations include a battery system.[12] Other emerging markets are geographies such as Australia, California and United Kingdom. However, household batteries performing PV self-consumption are not profitable yet. In Germany, the motivation of consumers who invested in a household battery was not primarily based on profitability though; their decision responded to different criteria such as hedging against increasing electricity costs, sustainability and interest in energy storage.[12]

This chapter gives an overview of various factors that can contribute towards improving the techno-economic and environmental attractiveness of household batteries and therefore facilitate their acceptance among household owners and accelerate their deployment. Renewable energy and battery technologies for off-grid dwellings and communities are also an important niche[13] but this chapter focuses on household for batteries connected to a national grid. Topics such as various battery applications for consumers, different battery technologies and the community scale are covered. The overall cost, environmental and social implications of the massive deployment of a PV-coupled battery system are also discussed in Section 14.5. The final section is an interdisciplinary outlook including implications for various stakeholders such as consumers and utility companies as well as some policy recommendations.

14.2 A Household Battery System

Figure 14.2 is a schematic representation of the two different types of topologies that can be used for PV-coupled battery systems, namely a DC-coupled topology and an AC-coupled topology. The main difference lays in the electronics, namely DC/DC converters and DC/AC inverters, which enable the integration of the PV-coupled battery system into the dwelling and the national grid. A DC-coupled topology comprises a single power conversion to store electricity through a battery charge controller, whereas the AC-coupled

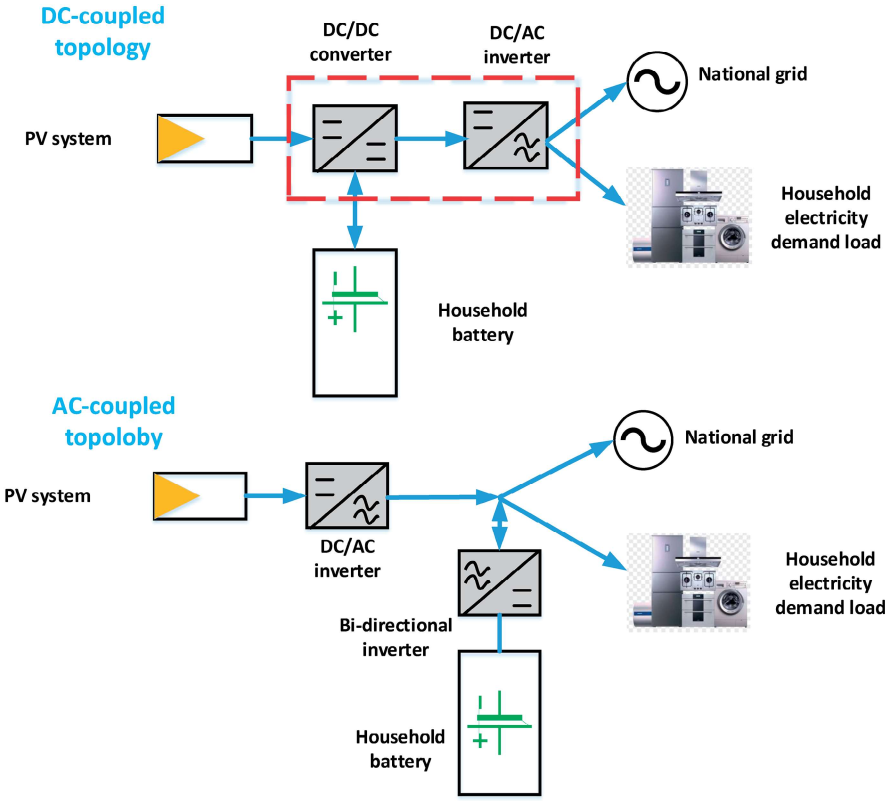

Figure 14.2 Two different topologies that can be applied for a PV-coupled battery system: DC-coupled topology (top) and AC-coupled topology (down).

topology requires two power conversions: firstly DC PV electricity to AC PV electricity through the PV inverter and then through a bi-directional inverter to the battery. An important implication is that the AC-coupled topology allows for the retrofitting of a PV system, *i.e.* the household battery could be installed after the PV system while the DC-coupled topology requires a joint installation together.

The DC-coupled topology is advantageous for installations that have a limited share of direct PV self-consumption from the PV system (*i.e.* much electricity is stored in the battery) since there is only one electricity loss across the battery charger between the PV system and the battery. The nominal efficiency of a DC/DC converter is around 98% and is higher than the nominal efficiency of an inverter (around 95%), which is used twice in the AC-coupled topology. Furthermore, the DC-coupled topology also allows the selection of a smaller inverter relative to the PV rating and to store otherwise clipped energy.[14] Likewise, the position of the battery upstream of the PV inverter (where the curtailment occurs) can prevent curtailment of PV electricity when a regulatory threshold is in place, as in Germany (see Section 14.3.4). In this case, PV electricity can be stored in the battery while this is not the case of the AC-coupled topology since the battery is downstream of the inverter.

14.3 Electricity Prices and Battery Applications for Consumers

This section introduces key applications for consumers in general (and residential consumers in particular) including their economic drivers. Consumer applications are those applications performed by a battery that have a direct positive impact on the electricity bill. Figure 14.3 is a schematic representation of the typical performance of a battery throughout a representative day when performing each consumer application, namely PV self-consumption, avoidance of PV curtailment, demand load-shifting and demand peak-shaving (only back-up power is not represented). Interestingly, the economic driver for each application is associated with the various components of an electricity bill. An electricity bill typically includes a single electricity price for the energy related component (P_e) of the electricity, as given by eqn (14.1). Here E_d refers to the electricity consumption in energy terms.

$$B_\mathrm{d} = E_\mathrm{d} P_\mathrm{e} \tag{14.1}$$

In addition to the profit margin, the energy price of the bill typically comprises three elements, namely wholesale electricity price, network charges and taxes or levies. The relative share of the wholesale electricity price, which used to be the main component, in the retail price of electricity has diminished over time across the European Union. Moreover, the network component increased 36.5% in average between 2008 and 2012. The reasons for

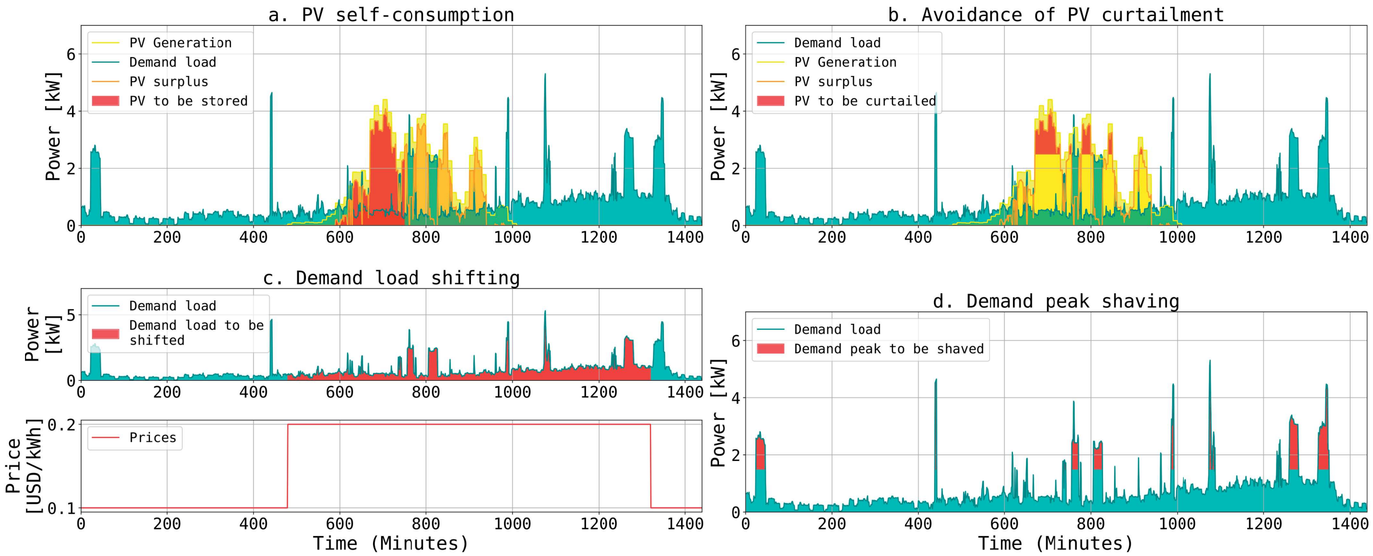

Figure 14.3 Schematic representation of the performance of a household battery when performing various consumer applications on a representative day: (a) PV self-consumption; (b) avoidance of PV curtailment; (c) demand load-shifting; and (d) demand peak-shaving. The horizontal axis gives the time throughout the day in minutes.

this may be related to network regulation and cost allocation practices but these are not always justified in detail by utility companies. Finally, taxes are also an important contributor to the final retail price across many European countries. European states usually include a tax *per se* (*e.g.*, VAT) as well as levies for financing energy and climate policies. For example, the cost of financing the feed-in tariff was around 15.5% of the final retail price in Germany[15] (similar in Spain).

There are many ongoing discussions about how electricity tariffs should evolve in order to, on the one hand, reflect real market prices and on the other hand give clear signals for energy efficiency and/or carbon savings to consumers.[16] Capacity-based tariffs are those in which the power component becomes relevant and are currently widely used for larger consumers (typically industrial) and small and medium enterprises (SMEs, with a typical consumption of 10 MWh per month) but not for small consumers.[9] This could change in the medium term and households could be charged also based on their maximum power capacity usage of the network regarding both import and export, in particular with the further penetration of PV systems, heat pumps and electric vehicles. A report commissioned by the Energy Supply Association of Australia concluded that capacity-based tariffs reflect best the real costs of power suppliers and are most effective for demand peak-shaving. Capacity tariffs would therefore allow utility companies to overcome profit losses due to PV self-consumption while consumers incorporating a PV-coupled battery system could also minimise the related expenses. The electricity bill would then also include an additional electricity price for the power related component $(P_{\mathrm{p}})m$ which applies to the maximum import from the grid in power terms (Π_{d}) as shown in the third term for the electricity imported from the grid of eqn (14.2).

Moreover, the price for the energy component can vary with time, *e.g.* having an off-peak peak (subscript 'off') and peak period (subscript 'p'), and if a PV-coupled battery system is installed on-site, the electricity exported to the grid is compensated for with a FiT but curtailed if exceeding a threshold (like in Germany).[17] Eqn (14.2) also includes these two extra components in the electricity bill, but the curtailment part is implicit within E_{PVgrid}. Here the subscript 'dgrid' denotes the part of the demand met with electricity imported from the grid (opposite to be supplied by local PV).

$$B_{\mathrm{d}} = E_{\mathrm{dgrid-off}}P_{\mathrm{e-off}} + E_{\mathrm{dgrid-p}}P_{\mathrm{e-p}} + \Pi_{\mathrm{dgrid}}P_{\mathrm{p}} - E_{\mathrm{PVgrid}}\mathrm{FiT} \qquad (14.2)$$

Household batteries can also contribute towards the stability and flexibility of the electricity network by performing other applications such as distribution upgrade deferral, frequency control, voltage control, power management, restoration and islanding capability.[18] However, the performance of these applications requires more complex management techniques and in some cases (*e.g.*, frequency control) the figure of an aggregator that pools many residential batteries to enter into a national market.[19] Therefore, this section only focuses on consumer applications when considering that they can also contribute indirectly to increase the flexibility and stability of the power system and reduce the likelihood of the stability issues of the power network.

14.3.1 PV Self-consumption

Household batteries can help to increase the amount of local PV generated and used on-site in a dwelling by charging and discharging when PV generation is higher and lower than the electricity demand load respectively.[20] Discharging a battery to supply local electricity demand only makes economic sense when the round trip efficiency of the battery (*i.e.* it includes all the energy losses within the battery system such as those associated with the storage medium and battery bi-directional inverter), η, is higher than the ratio between the price of the electricity sold (*i.e.* the FiT) and purchased (*i.e.* retail), as indicated by eqn (14.4), which is derived from eqn (14.3) to calculate the revenue obtained from performing PV self-consumption, $\mathrm{Rev}_{\mathrm{PVSC}}$. Here E_{PVbat} and E_{dbat} refer to the battery charge from the PV system and battery discharge to meet the local electricity demand load respectively. Therefore, the evolution of the ratio between retail price and FiT determines the revenue for this application together with the round trip efficiency of the battery. Without economic incentives, the FiT converges to the wholesale electricity price and this is expected to be the case for the energy transition once PV technology becomes fully mature. It is expected that at both levels electricity prices will increase across the energy transition but there is much uncertainty in specific trends, as indicated by Figure 14.4.

$$\mathrm{Rev}_{\mathrm{PVsc}} = E_{\mathrm{dbat}} \times P_{\mathrm{e}} - E_{\mathrm{PVbat}} \times \mathrm{FiT} \tag{14.3}$$

$$\mathrm{Rev}_{\mathrm{PVsc}} = E_{\mathrm{PVbat}} \times P_{\mathrm{e}} \times \left(\eta - \frac{\mathrm{FiT}}{P_{\mathrm{e}}} \right). \tag{14.4}$$

For economic sense, adding a battery to a PV system should be pursued when the levelised cost of the battery discharge throughout its lifetime is lower than the difference between the retail electricity price and the FiT. The levelised cost of battery systems is mostly sensitive to the capital expenditure (CAPEX) and the relationship is linear with a slope of 30–40% depending on the specific characteristics of the PV-coupled battery systems.[21] Another very important factor also reflected in Figure 14.4 is the amount of surplus annual PV generation, the annual electricity demand and its annual pattern. Current levelised cost values for household batteries performing PV self-consumption are still higher than 0.3 \$ kWh^{-1} for any battery technology, solar resource and demand profile but can approach this value for lithium nickel manganese cobalt oxide (NMC) technology (current cost 400 \$ kWh^{-1}) installed in dwellings with large PV generation and annual electricity demand.

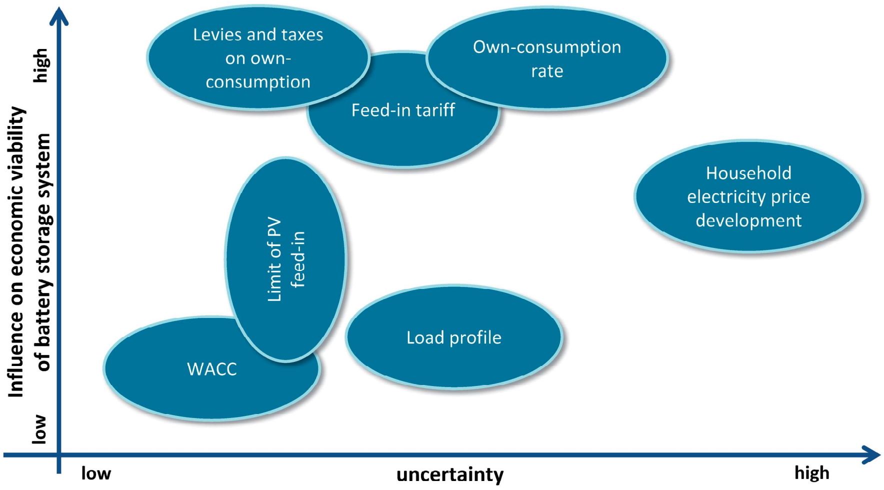

Figure 14.4 Factors impacting the economic viability of a PV-coupled battery system as a function of the importance and the associated uncertainty. This specific case was developed for the German market but could be in principle extended to other geographies. Reproduced from ref. 59 with permission from the author.

The performance schematically represented in Figure 14.1 maximises the economic revenue for a consumer when constant electricity prices apply for both electricity imported and exported and it is based on a simple schedule in which electricity is stored whenever PV generation is higher than the electricity demand. Table 14.1 gives some representative values for the distribution of PV generation and how the electricity demand is met for PV systems that integrate a battery depending on the type of building, namely domestic, commercial or industrial buildings. However, it has been argued that this basic control of a household battery performing PV self-consumption is not optimal from an energy system perspective, in particular for guaranteeing the stability of the electricity network.[22] For example, forecast of the PV electricity generation and the electricity demand can be used to relieve the electricity network with co-benefits to the distribution system operator while keeping the PV self-consumption share. Alternative control strategies to enhance the integration of PV-coupled battery systems include advanced battery management and a fully programmable PV production profile.[18]

The CAPEX reduction of lithium-ion batteries (see Section 14.3) is contributing to the reduction in the profitability gap of household batteries performing PV self-consumption but there is still no general economic case worldwide. Countries with high retail electricity prices such as Germany and Australia are examples of the most interesting markets at the moment but the amount of annual solar irradiance is also an important factor to be considered. Also in Germany there has been a market incentive programme since 2013 issued by the Germany Federal Government to stimulate the

Table 14.1 Upper part: annual distribution of PV electricity generation by PV-coupled battery systems integrated into buildings depending on the sector. The direct PV self-consumption is given by the column referred to as "to demand". Lower part: annual contribution to the electricity demand depending on the sector. The self-sufficiency is given by the column referred to as "from PV". Data refer to some representative values and but final values are greatly depend on the system configuration.

	To demand	To battery	To grid
Domestic[a]	30%	30%	40%
Commercial[b]	70%	10%	20%
Industrial[c]	30–70%	15–30%	15–40%
	From PV	**From battery**	**From grid**
Domestic	30%	30%	40%
Commercial	30%	5%	65%
Industrial	10–30%	5–30%	40–85%

[a] Based on a single dwelling. Direct PV self-consumption increases for block of flats (common buildings) due to rooftop constraints regarding the total demand.

[b] Based on a PV system with a size of 100 kW_p and a 40 kWh battery for a supermarket with a maximum load of 60 kW_p.

[c] Ranges based on the type of industry, namely continuous process or daily activity, *i.e.* lower or higher contribution of the PV and battery system to the demand (self-sufficiency).

market and boost the technology development of PV-coupled battery systems.[23] It is projected that the break-even point could occur around 2020 across several countries.[8,24]

Despite lithium-ion batteries being the benchmark technology, other electricity storage technologies have been proposed for PV self-consumption but only hot water tanks with heat pumps or electric heating make economic sense for the conversion of PV electricity into domestic hot water and/or heating, in particular if the dwelling already uses electricity for these purposes.[25] Other technologies such as hydrogen storage and flow batteries are significantly less attractive due to lower round trip efficiency and higher CAPEX.[26,27] These technologies would only make sense in a future scenario with important CAPEX reductions and large amounts of PV surplus electricity to be managed beyond a daily mismatch, *e.g.*, seasonal storage.

14.3.2 Avoidance of Renewable Energy Curtailment

Electricity curtailment is the most straightforward solution for a local network that cannot cope with high levels of PV export when the local electricity demand is low. It has been put into practice across many geographies (*e.g.*, Germany and UK) when weather conditions are very favourable and therefore renewable energy generation is high enough in a period with low demand to be able to destabilize the network frequency or the local voltage.[28] Germany was the first country to introduce curtailment capability as a new requirement for PV plants in 2009.[29] The curtailment capability refers a threshold relative to the installed PV capacity beyond which electricity cannot be exported into the grid. Therefore, the revenue of a household battery system avoiding PV curtailment (REVPVct) can be determined using eqn (14.5) where $[E_{\mathrm{PVbat}}]$ is the fraction of the stored PV electricity that would be otherwise curtailed. The threshold value has been revised since it was first adopted (equal to 70%) and currently the maximum value of the electricity injected into the grid should be lower than 40% of the nominal installed PV capacity in order to be eligible to receive a FiT scheme. Related regulations have also been ruled across other geographies, *e.g.* in Japan and California.

$$\mathrm{Rev}_{\mathrm{PVct}} = [E_{\mathrm{PVbat}}]_{\mathrm{Ct}} \times \eta \times P_{\mathrm{e}}. \tag{14.5}$$

The avoidance of PV curtailment is an application that is typically performed together with PV self-consumption but the value generated by a household battery avoiding PV curtailment is also substantially higher than for PV self-consumption since in this case there no alternative for the PV electricity generated opposite to PV self-consumption for which PV electricity could be exported and rewarded with the FiT. As a consequence, there are no conditions for the battery round trip efficiency to meet in order to perform the avoidance of PV curtailment. At the moment, the avoidance of PV curtailment is also referred to as a power application since periods when PV curtailment are required from a distribution system perspective are not so common yet. However, the frequency could increase throughout the energy transition and therefore this application may become an energy application from the discharge duration perspective (see Table 14.2).

14.3.3 Demand Load-shifting

Residential batteries can also be used to shift the electricity demand of a consumer without changing customer habits and this is the key advantage over demand-side-management technologies.[30] In this case, the economic driver for this application is related to time-varying electricity prices, which include peak and off-peak periods such as time-of-use tariffs or real time tariffs (RTPs) depending on the hour of the day, day of the week or month of the year. In terms of battery management, it consists of charging it whenever the price of electricity is low (off-peak period) and using the electricity stored when the price of the purchased electricity is higher later on (peak period), as stated by eqn (14.6):

$$\mathrm{Rev}_{\mathrm{DLS}} = E_{\mathrm{dbat}} \times P_{\mathrm{e-peak}} - E_{\mathrm{gridbat}} \times P_{\mathrm{e-off}} \tag{14.6}$$

$$\mathrm{Rev}_{\mathrm{DLS}} = E_{\mathrm{dbat}} \times P_{\mathrm{e-peak}} \times \left(\eta - \frac{P_{\mathrm{e-off}}}{P_{\mathrm{e-peak}}} \right). \tag{14.7}$$

In order to obtain some revenue from performing demand load-shifting, the round-trip efficiency of the battery should be higher than the ratio between the off-peak and the peak electricity price as derived from eqn (14.7).

Table 14.2 Comparison of various consumer applications that can be performed by household batteries. Some representative values are given for the battery discharge but they would finally depend on the system configuration and daily mismatch between the PV generation and the electricity demand load.

	Discharge duration	Classification	Economic driver	Value added
PV self-consumption	3 h	Energy application	Difference between retail electricity prices and feed-in tariff	Medium–high
Demand load-shifting	4 h	Energy application	Difference between peak and off-peak electricity prices	Low–medium
Avoidance of PV curtailment	0.2 h	Power application	Monetary losses associated with electricity curtailed	High
Demand peak-shaving	1 h	Power application	Capacity-based tariffs	Very high
Backup power	0.1–5 h	Energy application	Loss of value associated with the outage	Very high

Time-of-use tariffs have been offered, in particular to industrial consumers who are more sensitive to electricity prices, by utility companies across many geographies (*e.g.*, United Kingdom, United States and Australia) for the last 40 years because demand load-shifting also offers several benefits to the overall energy system such as better utilisation of the existing generation assets and reduction of the total cost and emissions.[31] At the same time, it is expected that real-time pricing becomes more relevant across the energy transition since new renewable generators such as solar and wind as well as new electricity demand loads such as heat pumps and, to a lesser extent, elective vehicles, show great spatiotemporal and inter-annual variability depending on weather conditions.

Off-peak prices are substantially higher than FiT values and therefore demand load-shifting is an application that significantly adds less value than PV self-consumption.[32] For example, the FiT and the off-peak price in Switzerland were equal to 10 \$ kWh^{-1} and 0.17 \$ kWh^{-1} respectively. On the other hand, a battery performing demand load-shifting is not limited by the PV surplus electricity (*e.g.*, on cloudy days) and it can reach high cycle activity. As a result, the levelised cost of batteries performing demand load-shifting is around 30% less than for PV self-consumption in regions with temperate climate.[21]

14.3.4 Demand Peak-shaving

Residential batteries can be used to meet peaks in the electricity demand curve (*e.g.*, the typical peaks during evenings) in the residential sector. For a household battery system, the logic is similar to demand load-shifting but some key differences are that the peak demand in a single dwelling may only last for a few minutes and the time at which it occurs is random. Therefore, demand peak-shaving is recognised as a power application characterised for discharges of a few minutes while demand load-shifting is referred to as an energy application with associated discharges of a few hours[9,21] (see Table 14.2). In the domestic sector, batteries can reduce the peaks during the afternoons and/or evenings by performing demand peak-shaving.

Regarding battery management, demand peak-shaving consists of having enough battery charge when the maximum peak occurs on a daily basis, therefore some forecast is necessary unless the peak electricity demand becomes predictable. The revenue associated with demand peak-shaving ($\mathrm{Rev}_{\mathrm{DPS}}$) is proportional to the reduction in the peak demand and the capacity-based component of the electricity bill as shown by eqn (14.8) (see also the third element of eqn (14.2) about the electricity bill). Demand charges are referred to the part of an electricity bill where charges are based on the power component but so far are more relevant for large consumers, *e.g.*, industrial consumers that use high intensive electrical demand loads. However, they usually pay for a maximum subscribed power that is not often used. Batteries can be used to smooth the grid import and even reduce the subscribed power, especially when the value of the maximum demand load can be forecasted. It is expected that the rolling out of smart meters will give more information about the consumer electricity demand profile and contribute towards the use of demand charges for residential consumers.

$$\mathrm{Rev}_{\mathrm{DPS}} = \max[\Pi_{\mathrm{dgrid}} - (\Pi_{\mathrm{dgrid}})_{\mathrm{bat}}] \times P_{\mathrm{p}}. \tag{14.8}$$

Being a power storage application, the value associated with demand peak-shaving has been reported to be the highest from all consumer storage applications[33] and, for example, the combination of PV self-consumption and demand peak-shaving has been reported to create a positive return of investment for household batteries in Germany assuming a hypothetical scenario with a market mechanism for this application.[9]

The reduction in the peak electricity demand brings several associated advantages to the energy system and contributes towards a reduction in the overall energy system cost. The peak demand is met by the most costly (and sometimes less efficient) generators that only run during peak time. For any utility company, the reduction in the peak power means purchasing less electricity when the price is higher. Typically the most expensive power plants in the "merit order" run the least just to meet the peak demand. In addition to this, it allows the use of less expensive equipment in the house (such as measurement and other auxiliary equipment) but also the deferral of investment in low voltage lines to increase its capacity, *e.g.*, transformers and voltage lines that are sized to meet the peak demand. Therefore, demand peak-shaving could be very effective for the further integration of electric heating (*i.e.* heat pumps) and electric mobility (*i.e.* electric vehicles) into the existing power network across the energy transition.

14.3.5 Back-up Power

Across geographies with power systems that are not very reliable and/or stable due to endogenous (ageing) or exogenous (storms and hurricanes) factors and in general for services or dwellings that must ensure a continuous power supply (*e.g.*, hospitals and hotels), batteries can also provide electricity for momentary outages. In this case, the economic revenue created by the battery ($\text{Rev}_{\text{back-up}}$) is in reality an avoided cost from the consumer in an alternative technology (*e.g.*, diesel generator) and/or the avoided loss of value related to the activity supplied by the electricity (*e.g.*, hotels and data centres).

14.3.6 Combination of Applications

Table 14.2 gives an overview of the five existing consumer applications for household batteries. Following the increase in retail prices, the reduction of PV cost and the reduction of FiTs, PV-coupled battery systems have emerged as a prime application for energy storage in addition to frequency control. This is already increasingly the case in Germany, one of the world's most advanced residential storage markets, where around 50% of new PV installations include a battery system.[23] However, the motivation of consumers who have invested in a PV-coupled battery system in Germany was not primarily based on profitability; their decision responded to different criteria such as hedging against increasing electricity costs, sustainability and interest in energy storage.

Household batteries can combine the various applications introduced above to increase the economic attractiveness, *i.e.* adding the various revenues introduced above, as shown in eqn (14.9). Current research shows that residential batteries would be close to economic viability if the four applications are combined within an appropriate regulatory framework. In particular, when the tariff structure includes a capacity tariff and a PV curtailment obligation. The combination of applications is always attractive, except for PV self-consumption and demand load-shifting for which dwellings should have a large annual demand. These are energy applications, and therefore charging from both the PV system and the grid makes economic sense when the PV generation is relatively low and/or the annual electricity demand is relatively high. For the combination of applications to become a reality, there are however some important developments to be accomplished. From the technology perspective, battery management systems should become more sophisticated, *e.g.*, communicate with smart meters and integrate forecasting techniques for balancing PV generation and electricity demand in real time considering various electricity prices. Furthermore, policy makers should upgrade market mechanisms for the various applications and avoid regulatory barriers.[34]

$$\text{Rev}_{\text{bat}} = \text{Rev}_{\text{PVsc}} + \text{Rev}_{\text{PVct}} + \text{Rev}_{\text{DLS}} + \text{Rev}_{\text{DPS}} + \text{Rev}_{\text{back-up}} \tag{14.9}$$

14.4 Different Lithium-ion Battery Technologies

Overall, lithium-ion battery technology has become the most widespread electrochemical technology for PV integration and household storage given its overall high round trip efficiency (90% approximately) and suitability for short-term and mid-term storage cycles. This success has been driven by a strong reduction in the cost of lithium-ion batteries. For example, the installed price per usable capacity reduced by half in 2017 from around 3000 € kWh^{-1} in 2013 in Germany.[35] Lithium-ion is however a family of various technologies based on a common material (*i.e.* lithium, in particular on the movement of lithium ions between the two electrodes during charging and discharge). Table 14.3 compares key characteristic of various existing lithium-ion technologies in the market, namely NMC, lithium nickel cobalt aluminium oxide (NCA), lithium iron phosphate (LFP) and lithium titanate (LTO). Moreover, other battery technologies such as lead-acid and vanadium redox are also given for comparison purposes.

Although the technology readiness of various lithium-ion batteries in Table 14.3 is already very high and they are already in the commercialisation phase,[36] it is still expected that the cost and performance will markedly improve through the energy transition. Some key drivers are the mass production of lithium-ion batteries for electric vehicles and/or renewable energy support and intense R&D efforts given their expected pivotal role in achieving a global low carbon energy system. Based on a thorough literature review and experts' opinions, The International Renewable Energy Agency (IRENA) provided improvement trajectories of various key performance indicators for different lithium-ion technologies taking the year 2030 as a reference, as shown in Figure 14.5. It is possible to see that CAPEX, equivalent full cycles and calendar life are the parameters for which greater improvements are projected across all technologies, while progress in other indicators such as energy density, depth of discharge and round trip efficiency seems to have already reached a plateau. In particular, CAPEX reductions between 50% and 60% are expected across all lithium-ion technologies by 2030.[37]

Table 14.3 Key characteristics of various lithium-ion battery technologies based on various sources.[37,58]

Technology family	Cathode material	Round trip efficiency (%)	Cycle life (EFC)	Calendar life (years)	Maximum discharge rate	CAPEX 2016 ($ kWh^{-1})
Li-ion	LFP	92	2500	12	2 C	580
	NMC	95	2000	12	0.4 C	420
	NCA	97	1000	12	1 C	350
	LTO	96	10 000	15	4 C	1050
Lead-acid	Traditional	91	1500	9	0.1 C	260
	Advanced	3000	3000	10	1 C	750
Flow	Vanadium redox	70	13 000	12	1 C	347

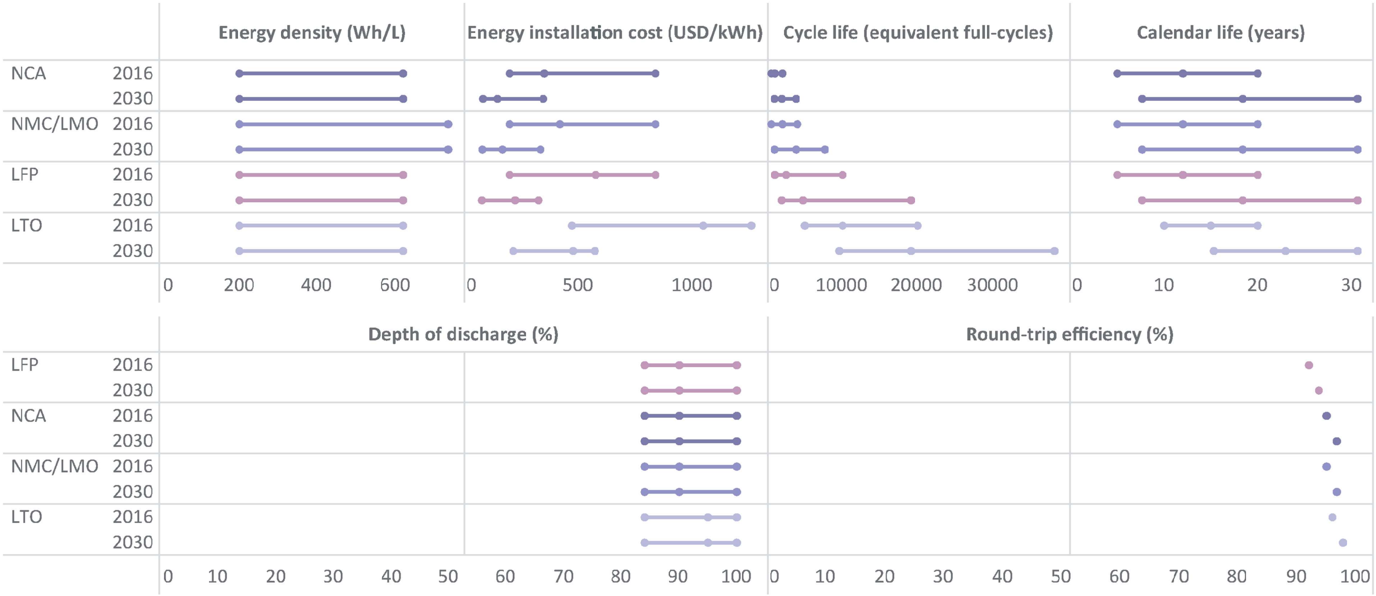

Figure 14.5 Properties of selected chemistries of lithium-ion battery electricity storage systems, 2016 and 2030. Figure created and provided by ©IRENA in the following report: IRENA (2017), Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi.

The technology choice should be made based on the application(s) to be performed and considering the optimal battery size and discharge rating. In the end, this decision is a trade-off considering that technologies that offer better performance in terms of number of equivalent full cycles and round trip efficiency (*e.g.*, LTO) have a higher CAPEX. However, the profitability of a household battery system is mostly sensitive to the CAPEX and this parameter is typically pivotal for the decision-making process of consumers. Interestingly, current research suggests that some technologies with higher CAPEX values are relatively more competitive when installed in dwelling with large demand and/or various applications are combined since they can provide more cycles.

Regarding other competitors, flow batteries are an attractive solution for mid-term storage applications (from four hours to daily storage) because of their unique characteristic of decoupled energy and power rating (this is not the case for lithium-ion batteries). However, their current main applications such as wind energy capacity firming correspond to systems of a few MWs installed at the distribution and transmission networks[38] and the household scale does not seem be the most appropriate for its deployment given some intrinsic cost dependence with the scale. When disregarding capacity tariffs, traditional lead-acid batteries are still competitive for demand load-shifting, which is the consumer application with the lowest power-to-energy ratio (*i.e.* longest discharge duration, as given in Table 14.2) since the battery capacity is sized according to the electricity demand load occurring during the peak period.[30] However, Li-ion batteries are much more interesting for PV self-consumption (with the battery sized according to surplus PV generation requirements) and demand peak-shaving.[32]

As the penetration of renewable energy and low carbon technologies increases during the energy transition, hybrid systems (comprising different types of electrochemical technologies, *e.g.*, supercapacitors, Li-ion batteries, flow batteries and/or hydrogen) may be required for some communities or districts in order to cover the full spectrum of applications and meet the associated storage cycles with different temporal scales (from seconds to weeks or months).[18,39]

14.5 The Community Scale

Considering that batteries installed in dwellings are not profitable yet, the concept of community energy storage (CES) as a battery system located near residential consumer points (at the edge of the grid) and able to develop several roles has been proposed.[40,41] Some basic differences between CES and a household battery are the number of dwellings to which the battery is connected to, the size and the number of applications which the battery system delivers. For the latter, CES is sometimes suggested under the smart grid concept[42] and delivering applications such as distribution network upgrade deferral and/or ancillary services (*e.g.*, frequency control), which are relevant for other stakeholders in addition to consumers.[40]

Community schemes create similar benefits as batteries implemented at the level of individual consumers but the advantages of CES are improved economies of scale (especially in aspects such as power electronics, communications and control technologies) and the option of professional management as well as system benefits at the level of the distribution grid. Moreover, the required power rating of the inverter of the community battery system and to a lesser extent the battery capacity reduces with the community size.[43] For example, Barbour *et al.* reported that the optimum CES requires a total storage capacity that is 65% of that at the level of individual households for a total amount of 4574 dwellings in Cambridge (USA).[42] Furthermore, community batteries are able to reduce significantly the interaction with the main grid in terms of imports and exports when connected into micro-grids despite the lower total installed capacity, in particular, improvement values in the range 64–94% were reported in the aforementioned study. Overall, lower CAPEX and operational expenditure (in particular maintenance) should be expected per kWh of installed capacity. Last, but not least, the community scale has proven to be a catalyst for the engagement of citizens in the energy transition in order to build a sustainable future, *i.e.* speed up renewable energy penetration, increase energy awareness and reduce the carbon footprint of communities.[18]

Given the currently increasing rates of battery adoption for individual dwellings and the further potential for widespread adoption, energy policies should prioritise the development of market mechanisms that facilitate the deployment of shared community-level storage. This is especially important given the limited and capital-expensive nature of the resources required for battery manufacture. Policy makers are already reacting to this evidence and community schemes are being suggested for PV owners without or with storage in some countries. For example in Switzerland, the current legislation allows the possibility of pooling self-consumers when the PV installed capacity is greater or equal to 10% of the maximum grid connection capacity. This would allow owners who share the same production site the opportunity to join together as one final consumer. This is called a “community of self-consumers” and they will be considered by the grid operator as one final consumer. The law also specifies that the costs of “joint PV self-consumption” are at the expense of the owners. In the ordinance, the production site should be a property of the owner, who could develop a joint project with the neighbours using the surrounding land (*e.g.*, another building) as long as the electricity network of the grid operator is not used between the production and the consumption. Then, the owner can also “force” the tenants to self-consume by writing it in the lease agreement of new buildings/apartments. If it is an existing lease agreement, the tenants cannot be “forced”. Furthermore, a community of “PV self-consumers” that has a demand of more than 100 MWh per year has no longer the obligation to purchase his electricity from the local utility and they have access to the electricity market. Battery storage is one of the technological options consumers have to increase the amount of local PV generation used by them.

14.6 Global Impact of Household Batteries

The effects of the massive penetration of PV-coupled battery systems located behind the meter are manifold including both positive and negative impacts, as summarized in Table 14.4. In particular, the coupling of battery storage to PV systems can help to mitigate some of the negative effects associated with the intermittency of PV generation. In this section, the impacts of PV-coupled battery systems installed behind the meter are assessed according to the following criteria: affordability, sustainability and energy security (these criteria also known as the energy trilemma). Finally, the impact on the wholesale electricity market is also discussed.

14.6.1 Energy System Cost

In the mid-term, the cost of the overall energy system should increase if relying heavily on PV-coupled battery systems. As discussed in Section 14.1, the capital cost of PV has fallen dramatically in recent years (by two thirds at the utility scale) and it is expected to reduce further up to 50% by 2040,[2] but its weather dependency prevents it from supplying larger fractions of demand. Despite operational cost savings compared to fossil supply, the levelised cost of PV systems is projected to remain higher due to low capacity factors. The typical annual capacity factor a PV installation located in central Europe (*e.g.*, Switzerland) is around 15%. Household batteries can increase the value of PV technology by providing high-value electricity on demand (*e.g.*, up to 250 € MWh^{-1} for consumers considering the difference between retail and wholesale prices in Germany) but as the cost of solar technology drops, the cost of batteries must also drop to continue to add value.[44] From the levelised cost perspective, the current levelised cost of batteries performing PV self-consumption still doubles the levelised cost of a small scale PV system across central Europe (slightly higher than 200 CHF MWh^{-1} for Switzerland). However, the price of battery storage has fallen more than four times for the last five years to reach 230 \$ kWh^{-1} in 2017 and, according to Panasonic, it may be half of 2016's price by 2025. Furthermore, several applications such as PV self-consumption and demand load-shifting can also be combined to reduce the levelised cost of batteries to below 300 \$ MWh^{-1}.[21]

However, if external costs are included to evaluate the attractiveness of PV technology, *e.g.*, health costs due to pollution and various climate change impacts, previous studies have proven that non-renewable energy technologies are more expensive than renewables. Moreover, the case becomes even more attractive if other macro-economic impacts such as jobs and GDP are considered within the balance. For example, several studies show the positive net employment and GDP effects of renewable energy expansion, in particular up to +3% in GDP and +1% in net jobs for Germany.[45] Although final impacts depend on the economic structure of the country, energy supply

Table 14.4 Various impacts of the penetration of PV and battery technologies across the energy transition. The impact could become more marked for higher penetration levels. Cost data for PV and battery refer to small scale installations in households. Data come from various sources introduced across Section 6.6 and mainly refers to the European context.

Parameter	Effect	Reason (s)	Current Data
Investment cost	Increase (negative)	More cost effective supply options, *e.g.*, natural gas	- PV: $2500\ \$\ \text{kW}_\text{p}^{-1}$ - Battery:[a] $500\ \$\ \text{kWh}^{-1}$ and $500\ \$\ \text{kW}_\text{p}^{-1}$
Operational cost	Decrease (very positive)	No fuel consumption	- PV: $35\ \$\ \text{kW}_\text{p}^{-1}$ - Battery: 0
Levelised cost[b]	Increase (very negative)	Low capacity factor and high investment cost	- PV: $210\ \$\ \text{kWh}^{-1}$ - Battery:[c] $400\ \$\ \text{kWh}^{-1}$
External cost	Decrease (very positive)	Reduction on emissions from fossil fuels	25–30% reduction
Externalities such as GDP and jobs	Increase (positive)	More distribution and labour-intensive jobs	+3% GDP +1% jobs
Environmental impacts	Decrease (positive)	Very low GHG emissions but metal depletion	- PV: 60 g CO_2 eq. kWh^{-1} - Battery: 250–350 g CO_2 eq. kWh^{-1}
Security of supply	Stable (neutral)	Trade-off between local supply and flexibly provided	n.a.
Social acceptance	Increase (very positive)	Easy integration in the built environment, quiet operation, safe and symbolic value	n.a.

[a] Includes the battery bidirectional inverter.
[b] Using a discount factor equal to 8%. PV lifetime is 30 years and battery calendar life 15 years.
[c] Based on a battery performing PV self-consumption.

alternatives and local manufacturing levels, the public funded UK Energy Research Centre (UKERC) has stated that solar PV creates at least twice the number of jobs per unit of electricity generated compared with natural gas.[46] It is expected that the retrofitting of PV systems with batteries and their combined installation further improves these values.

14.6.2 Environmental Impacts

The average life-cycle emissions depend on the selected battery chemistry, but are in general lower than 100 g CO_2 kWh^{-1} for PV self-consumption. It should be noted that the life cycle emissions can double for other applications based on electricity charging form the grid, in particular in geographies with high carbon intensity of the grid electricity such as Poland and

Australia.[47] To put these values into context, the life cycle GHG emissions of rooftop PV installations alone is around one tenth of natural gas CHP units, the latter ranging between 500 and 700 g CO_2 eq. kWh^{-1}.[48]

Another important challenge is to sustain growth in the production of lithium-ion batteries, since their manufacture is expected to grow as much as ten times the current size.[49] A recent perspective from Olivetti *et al.* concluded that most materials contained within lithium-ion batteries will likely meet the demand in the mid-term. However, cobalt used for the cathode of NMC and NCA batteries could become a critical material.[50] Current production is mainly located in countries such as the Democratic Republic of the Congo and Zambia in Africa.

14.6.3 Security of Energy Supply

The contribution of PV-coupled battery systems to security of supply can be assessed using three different criteria, namely resource supply, flexibility and availability, and it is therefore subject to trade-offs. Without a household battery, the PV contribution to these three criteria has been ranked as maximum, minimum and minimum respectively.[51] However, household batteries increase the flexibility of PV systems (*e.g.*, by extending the PV supply a couple of hours in the evening) while not impacting on their availability. Finally, the acceptance of PV by citizens worldwide has been demonstrated by various interviews, and people almost unanimously hold a strongly positive view of solar power.[52] This is also the case for household batteries but the concern about their environmental impact is higher based on the author's experience.

14.6.4 Wholesale Electricity Market

Wholesale electricity markets (also referred to as spot markets) are also being markedly affected by the penetration of renewable energy technologies such as PV and wind. Due to its zero marginal cost and/or privilege position in the merit order, PV shifts to the right the electricity supply curve and reduces the price considerably in the power spot market. In the short term, this creates savings from the demand side as well as reducing generator profits.[53] The spot market price reduced by 0.8–2.3 € MWh^{-1} in average per additional GW of renewable energy added in Germany between the years 2008 and 2012.[54] Furthermore, the spread between peak and off-peak prices is also being reduced, and this also impacts the benefits of hydropower plants. Despite solar PV penetration reducing the business case for conventional flexible generators such as hydro and gas in the spot market, new opportunities arise for battery and other storage technologies storing very cheap electricity and/or reducing renewable energy curtailment in the spot market and beyond. For example, batteries performing frequency control have been reported to be very close to economic viability at the moment. Although this application is more straightforward for utility batteries given the minimum size to enter into the market, there are business opportunities for household batteries to be aggregated and provide frequency response.[19]

14.7 Outlook

With some policy support (*e.g.*, FiT) and following the objective of maximising PV self-consumption, PV systems are already profitable across several geographies considering their lifetime of 30 years. However, this is not the case for household batteries yet, but a break-event point is projected to occur in the coming years (expected in the 2020s) in countries with high electricity prices and/or high solar resources (*e.g.*, Germany and Australia) due to the declining technology cost. However, assuming an interesting regulatory context for household batteries (*e.g.*, Germany), the decision whether to invest in them depends on many different socio-economic criteria such as available financial resources, space availability for installing a large PV system (*e.g.*, 5 kW_p or higher) and electricity demand consumption. Citizens, businesses and services who own the building where they live and/or operate respectively can be interesting targets for the PV and battery residential markets. Furthermore, direct PV self-consumption (including a battery system) will be much higher for activities that run throughout the whole year (*e.g.*, hotels, in contrast to schools). Similar to other low carbon technologies, the diffusion of battery storage will have a strong dependence on the regulatory context and their uptake can be enhanced through financial incentives and regulatory frameworks established by policymakers.

The remarkable success of PV and other renewable electricity coincides with the increase in electricity consumption in final energy demand—a trend that has been underway in parallel to the success of renewable energy technologies. Electrification is hence emerging as a key strategy for deep decarbonisation, supported by various catalytic technologies such as PV, batteries, heat pumps and electric vehicles. Across some countries, electricity is already being successfully used for space heating and for example heat pumps accounted in Switzerland for more than one third of the market share of heating systems by 2013, and with a share of already 12% of installed space heating in 2012.[55] Household batteries can be key to manage these new electricity demand loads such as heat pumps and electric vehicles together with PV generation if all different actors, including local authorities and the government, are on board.

Given the advantages of shared CES (*i.e.* shared batteries) over individual household batteries in terms of enhanced match of local PV generation and electricity demand per unit of installed storage, reduced battery capacity requirements for a given area and lower CAPEX and operational cost, energy policies should prioritise the development of market mechanisms that facilitate the deployment of shared community-level batteries. Regarding the ownership and related location of PV-coupled battery systems, different solutions may also coexist in addition to the conventional purchase and management by the consumer. PV-coupled battery systems can be offered by PV installers and/or house-builders and therefore installed in different households and communities (*e.g.*, block of buildings) and paid for by consumers. Alternatively, they can be operated and/or provided by utility companies and distribution system operators while being connected to the PV plants and demand loads of the residential sector. The low voltage side of the utility transformers is already being used for installing batteries in USA. Regardless of the type of ownership model, investments should be profitable but also associated business models should develop win–win solutions for different stockholders involved in the project and avoid free riders. This is an important subject of future research.

Two examples of win–win solutions are: (a) electricity tariffs with capacity components for both electricity import and export, which promote household batteries to combine applications such as PV self-consumption and demand peak-shaving and therefore help them to become profitable; and (b) shared business and/or ownership models (including both CAPEX and maintenance) when the value propositions include applications that benefit different stakeholders. For example, the optimum management of local PV generation benefits both the consumer (*e.g.*, self-consumption is driven by the difference between the import and export electricity prices), and the utility company and/or distribution system operators (*e.g.*, the deferral of distribution network investment). Moreover, utility companies and/or aggregators could also benefit from optimising the performance of PV-coupled battery systems for the electricity network and/or wholesale markets. Likewise, hierarchical control techniques including both the household/community level, upper level (*e.g.* distribution network and/or wholesale market) and maintenance should be applied by the utility company (or aggregator). Some scholars are now even suggesting that peer-to-peer energy-trading platforms may be a better market mechanism than a top-down approach managed by utility companies and/or aggregators to assure social welfare.[56,57]

Some of the various impacts related to the penetration of PV and battery systems may create conflict with other elements of the energy system and some particular stakeholders. Downstream of the power sector, consumers who generate their own electricity with PV systems and who increase the amount of PV-self consumption with batteries reduce substantially their electricity bills. This implies that they save not only the wholesale electricity component of the bill but also network fees and taxes that together account for more than 50% of the bill for some European countries. However, they do still rely on the utility company and distribution grid for meeting maximum peak demand and/or during days with low solar irradiance. Overall, the benefits of utility companies are decreasing while they still need to operate the distribution network system or even upgrade it. The transition from an old centralised to a more distributed energy system brings new opportunities for new actors such as aggregators, IT companies as well as municipal utilities. Utility companies already have a privilege position and therefore they could engage prosumers and propose solutions (*e.g.*, new tariff design) that are win–win for the consumer and (in terms of electricity bills) for the society (in terms of carbon footprint), and for their own profitability. Otherwise, prosumers may collaborate with new stakeholders such as aggregators or even organise themselves to extract as much value as possible our of their PV-coupled battery systems.

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