Available Online at http://www.journalajst.com

ASIAN JOURNAL OF
SCIENCE AND TECHNOLOGY

ISSN: 0976-3376

Asian Journal of Science and Technology
Vol. 10, Issue, 07, pp.9796-9803, July, 2019

REVIEW ARTICLE

REVIEW OF SOLAR PHOTOVOLTAIC INTEGRATION WITH RESIDENTIAL BUILDINGS

[*,1]Magnanil Goswami, [2]Narasimha Siva Chary, [2]Jahnavi Mulinti, [2]Navya Gade and [2]Sumalatha, K.

[1]CL Educate Ltd, A-45, Mohan Cooperative Industrial Area, Near Mohan Estate Metro Station,
New Delhi 110044, India
[2]Department of Electrical and Electronics Engineering, University College of Engineering,
Kothagudem, Kakatiya University, Telangana, India

ARTICLE INFO

Article History:
Received 27th April, 2019
Received in revised form
26th May, 2019
Accepted 10th June, 2019
Published online 28th July, 2019

Key words:

EV, Grid export, Load control,Load Pull, Output push, PV.

ABSTRACT

Batteries and load control devices can increase the value of distributed solar photovoltaics (PV) from multiple perspectives end-user, utility, and social. This review paper summarizes the end-user economics of battery and load control technologies that increase the value of PV by controlling and temporally shifting PV output, an approach referred to as "solar plus." Solar plus can increase on-site PV use. The literature shows that these values justify the incremental costs of solar plus devices for a wide variety of technologies, geographies, and customer load profiles, especially for customers in three rate structure contexts: where PV is sold to the grid at a lower value than the customer's retail rate, in time-of-use rates where peak periods do not coincide with PV output, and in demand charge rates where load peaks do not coincide with PV output. Rate structure and policy reform may be necessary to ensure that increasing solar plus deployment provides both end-user and system-level benefits.

Citation: Magnanil Goswami, Narasimha Siva Chary, Jahnavi Mulinti, Navya Gade and Sumalatha, K. "Review of solar photovoltaic integration with residential buildings", *Asian Journal of Science and Technology*, 09, (07), 9796-9803.

INTRODUCTION

Grid-connected solar photovoltaic (PV) output can either be consumed on-site or exported to grid. Self-use may be instantaneous or by storing and discharging PV output through energy storage system. Energy storage systems include batteries and load control devices that use the inherent storage capabilities of certain home appliances to store PV output. A lack of low-cost energy storage options has limited the ability of customers to self-use PV output (1–5). Further, PV export compensation in most major markets reduces customer incentives to invest in technologies to increase self-use (2), (6–8). Both of these paradigms are eroding due to falling battery costs (9–11), the emergence of low-cost load control devices (12–16), and falling compensation rates for grid export (6), (17). These trends suggest that future PV systems will be increasingly integrated with batteries and load control devices that optimize PV system through increased self-use. The term "solar plus" refers to technological applications that increase the value of PV by controlling and temporally shifting PV output, as shown in Fig. 1. In this discourse, we explore the end-user economics of solar plus applications in residential buildings. Solar plus systems comprise of an open-ended list of battery and load control technologies. Batteries may be stationary, such as a wall-mounted lithium-ion battery, or mobile in an electric vehicle (EV). Load control refers to devices that add control capabilities to home appliances. Any deferrable customer load can theoretically be controlled to increase self-use. Water heating and air conditioning (AC) are illustrative examples of deferrable loads. With a "smart" domestic water heater (DWH) upgrade, the electric unit in an electric DWH can be configured to pre-heat water with PV output then defer, as much as possible, re-heating water after sunset. Similarly, smart thermostats can be configured to pre-cool a home with PV output then defer, as much as possible, re-cooling the home after sunset. In both cases, the end-user reduces grid use costs by deferring loads until PV output is available. Other examples of deferrable loads include heat pumps, dishwashers, washing machines, dryers, refrigerators, and freezers. Devices with thermal storage capabilities such as DWH, AC, and heat pumps have the potential to significantly increase self-use, while other home appliances have relatively modest potential impacts (18), (19). Three trends contribute to the rise of solar plus. First, battery costs are falling, bringing both stationary and EV storage within financial reach for more customers (9–11), (20–22). Second, customers have increasing access to low-cost, practical load control devices (13), (16). Recent developments in machine-to-machine communication, the near ubiquity of smart phones, and falling costs have driven a proliferation of load control products and increasing adoption (15), (16), (23–25).

Corresponding author: Magnanil Goswami
CL Educate Ltd, A-45, Mohan Cooperative Industrial Area, Near Mohan Estate Metro Station, New Delhi 110044, India.

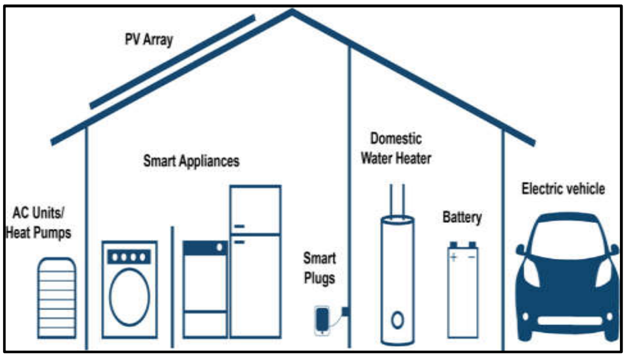

Fig. 1. The solar plus home [1]

Third, grid export compensation rates are falling in major PV markets around the world, incentivizing customer investments in solar plus technologies (26–30). Other retail rate reforms incentivize solar plus by increasing the value of arbitraged PV output, such as time-of-use (TOU) rates and demand charges (5), (6), (31–35). The technical ability of solar plus to increase self-use is reviewed in (4). A logical follow-up question is whether and under what circumstances increased self-use provides enough end-user value to sustain a scalable solar plus market. Apart from meeting the primary objective of summarizing residential end-user economics of solar plus, the factors that drive the solar plus value proposition is explored by answering the following key concerns:

- What are the incremental end-user benefits of solar plus, relative to standalone PV?
- What are the incremental end-user costs of solar plus? What are the economics of solar plus for end-users?
- How do technology costs affect the economics of solar plus? How do customer electricity rate structures affect the end-user economics of solar plus?
- How do customer load profiles affect the end-user economics of solar plus?

End user value of solar plus: Solar plus devices convert variable PV into a partially-dispatchable resource. Dispatchability may improve the end-user value of PV whenever that value varies over time (36), (37). The residential end-user value of PV output varies over time if (a) the customer's retail electricity rate is higher than the grid export compensation rate, (b) the customer is on a terms of use (TOU) volumetric rate schedule, or (c) the customer is on a demand charge ($/kW) rate schedule. If self-use is more valuable than grid export, then the value of solar increases with the volume of self-use (2), (3), (6), (8), (19), (33), (38). Further, if the value of self-use varies over time in a TOU or demand charge rate structure, then the value of solar increases with the correlation between PV output use and peak-price periods (5), (6), (31), (32). Solar plus devices can increase self-use in two ways. First, solar plus devices can re-shape customer load profiles so that more load is "pulled" into PV output periods. Second, some solar plus devices (predominantly batteries) can be charged with PV output and discharged to meet customer loads outside of the PV output period, effectively "pushing" PV output into later time periods. Fig. 2 illustrates a load pull scenario for a customer between 5 pm-10 pm in a peak pricing period based on the TOU structure. Fig. 3 illustrates an output push scenario. The battery can be configured to charge with excess PV output, increasing self-use and reducing grid exports. The battery is then discharged after the PV output period to reduce the customer's peak demand. The key difference between load pull in Fig. 2 and output push in Fig. 3 is that the customer's load profile is not necessarily re-shaped in the latter. Solar plus systems with multiple battery and load control devices can simultaneously offer load pull and output push capabilities to maximize PV end-user value in terms of electricity cost reduction. This article focuses on the value of load pull and output push in solar plus systems. However solar plus devices can provide additional values independent from PV output (39). Batteries and load control devices can be configured to perform TOU arbitrage (13), (16), (39).

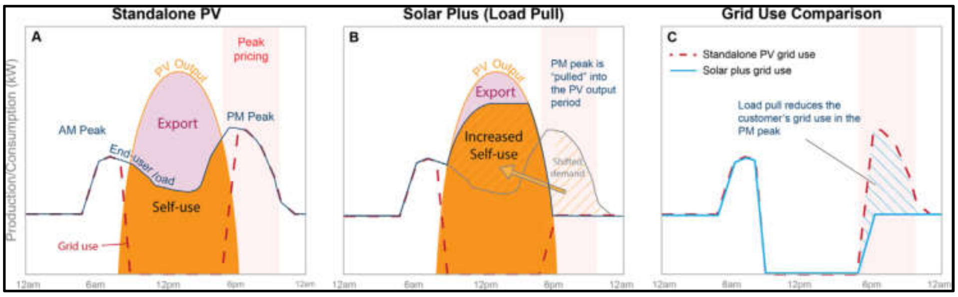

Fig. 2. Load pull: re-shaping customer load profiles with solar plus devices. (A) Some PV output is exported to the grid and unavailable to reduce the customer's PM peak. (B) Load control devices "pull" the customer's PM peak into the PV output period, reducing grid exports and reducing the customer's grid use during peak pricing hours. (C) Comparison of grid use in the two scenarios

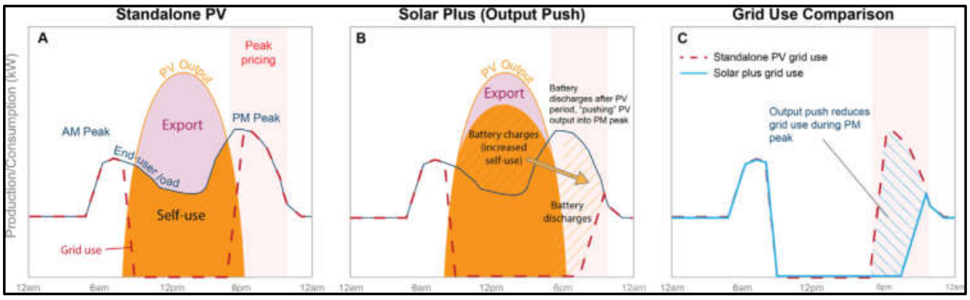

Fig. 3. Output push: charging and discharging batteries with PV output. (A) Some PV output is exported to the grid and unavailable to meet the customer's PM peak. (B) A battery charges with PV output, reducing grid exports. The battery is then discharged to meet the customer's PM peak, reducing on-peak electricity use (if applicable). (C) Comparison of grid use in the two scenarios

For instance, a smart DWH can be programmed to pre-heat water overnight when TOU rates tend to be lower, ensuring a low-cost hot water supply for the morning peak. Similarly, batteries can charge with off-peak grid electricity then discharge to reduce grid use during peak hours. Some solar plus batteries, may also provide fewer tangible benefits such as backup power (39–41).

Costs of solar plus

Battery Costs: Battery costs are often normalized by power ($/kW) and energy ($/kWh) capacity for comparison purposes. The appropriate metric depends on the application of the battery and optimal sizing. Customer load profiles with high peaks may require higher power capacity (kW) but may not require a deep discharge (kWh). Customers with relatively flat load profiles may require deeper discharges (kWh) relative to power capacity (kW). As a result, customer load profiles with high peaks may generally aim to minimize costs relative to power capacity ($/kW), while flat load customers may aim to minimize costs relative to energy capacity ($/kWh) (42), (43). The useful lifetime of batteries, generally measured in the number of expected useful cycles and depth-of-discharge for lithium-ion chemistry, must also be accounted for in cost comparisons across different technologies. For instance, lead-acid batteries are generally lower cost than lithium-ion batteries, however lithium-ion battery lifetimes are on the order of two to three times longer than lead-acid batteries (44), (45). Technological progress to improve the useful lifetime of battery chemistries has been slow (46), (47). Lithium-ion has emerged as the most practical current technology with suitable performance characteristics for a variety of applications, including energy management in grid-connected and off-grid buildings (44), (45), (48).

Numerous studies report battery costs for residential energy storage systems, typically for lithium-ion systems, the most common technology for residential storage. Several studies assume battery hardware costs of €500/kWh (□$600/kWh).2 (7), (8), (38). Most studies use installed costs, meaning the final cost paid for the installed system including non-hardware costs like installation labor. Installed costs do not necessarily correlate with hardware costs. Indeed, battery hardware costs fell by about 50% per year from 2014 to 2016 (22), while installed costs remained relatively stable (49). Fares and Webber (2) cite a range of $700–1800/kWh for installed costs. Lorenzi and Silva (5) assume a total installed battery cost of $5185 for a 6.4 kWh system, or roughly $810/kWh. Linssen *et al.* (44) use a higher installed cost of €1000/kWh (∼$1200/kWh). Finally, Ardani *et al.* (43) estimate an installed cost of $8559 for a 3 kW/6 kWh system, or about $1427/kWh. Battery cost assumptions are difficult to compare across studies, as different studies use different approaches and system size assumptions. Nonetheless the literature generally suggests a range on the order of $700–1500/kWh for current installed battery costs. These hardware costs do not account for the round-trip efficiency losses that occur from the multiple direct to alternating current conversions involved in battery storage. Several studies have explored levelized cost metrics to account for round-trip efficiency losses and other use-phase factors that affect battery costs (50–54). One study includes balance of system costs such as energy management systems and fire suppression (55), while others include non-hardware cost parameters related to financing and operations when calculating the levelized cost of storage (56). Increasingly, non-hardware costs related to installation and regulatory compliance are being included in cost benchmarking methodologies (57), which can lead to higher reported system prices compared to technology providers. Battery costs have fallen significantly in recent years (22) and are projected to continue to decline on the order of 5% per year (10), (23). Given projections for 5% annual reductions in PV system prices (58), installed prices for PV plus battery systems should decline at a similar rate.

Load Control Costs: Load control devices leverage home appliances that most residential customers already own (13), (16). The incremental costs of load control are therefore small relative to batteries (14), (16), (24), (25), (59). Incremental costs entail hardware added to the home appliances and any software needed to configure the system. For instance, a smart thermostat can convert the home's thermal mass into an energy storage system without replacing the existing heating and AC infrastructure. The incremental cost is the cost of the thermostat hardware and installation, which is on the order of hundreds rather than thousands of dollars (14), (24), (25). However, for DWH and space heating, the hardware cost will be higher for customers that use gas rather than electricity for water and space heating, given that customers must electrify these loads in order to leverage solar plus. Load control device consumer prices have declined over time (23), though not as quickly as projected by industry experts (24). Strother and Lawrence (23) project annual price declines for various load control devices ranging from 3.5%/year for smart thermostats to 7%/year for smart plugs from 2016 to 2026. Table 1 summarizes load control cost estimates from various literature.

Economic analysis: Economic analysis of solar plus evaluates whether the incremental lifetime value of solar plus devices justifies the incremental lifetime costs. The six metrics used for solar plus economic analysis are summarized in Table 2. Simple cost savings comparison is the most common approach, possibly due to the relatively easy interpretation of the results. The levelized cost of electricity (LCOE) is rarely used in the literature, perhaps due to the added complexity of calculating annual output with energy storage and load control. Several studies have developed metrics for the levelized cost of storage that could be extended to estimate LCOE in the context of solar plus (50–54). All of the metrics identified in Table 2 require some estimate of complex and uncertain cost savings. To quantify these cost savings, the economic analysis must establish (1) the type of solar plus devices, (2) the size of solar plus devices, (3) how those devices are operated with respect to the load and the utility tariff under consideration, and (4) the lifecycle performance of those devices. These factors affect both capital and operating cost, as well as the ability to offset utility costs. Balance of these four items is critical to establishing the cost-effectiveness of any solar plus configuration.

All studies use models with empirical or simulated customer load profiles to estimate potential cost savings based on customer rate structures. The basic approach is to model customer electricity costs at each time step in a study period, ensuring that the customer load is met while enabling the model to choose what device(s) are meeting the load. Models vary in terms of what technologies are considered, how technical operating constraints are modeled, customer rate structures considered, etc., but their analytic approach generally falls into three categories: simultaneous optimization

Table 1. Load control device cost assumptions

Study	Cost	Assumptions
Dyson etal. [60]	AC: $225 DWH: $200 Electric dryer: $500 EV charging: $100	Costs for AC and electric dryer reflect incremental costs for smart device upgrades, DWH represents capital and installation costs, EV charging cost reflects costs of hardware and software controls for remotely-controlled charging
Iwafune etal. [31]	Heat pump water heater: $300–400	Incremental cost of communication control function device, including installation
Lorenzi etal. [5]	DWH: $200	Incremental cost of controller
Kemper etal. [14]	Smart plug: $65 Thermostat: $247	Incremental product costs
O'Shaughnessy etal.[6]	AC: $200 DWH: $250	Incremental product costs, cost of DWH assumes additional cost for mixing valve to prevent scalding
Parra etal. [61]	DWH: $700 (£500)	Market price of DWH controller

Table 2. Economic metrics used in solar plus studies

Metric	Description	Objective
Cost savings	Present value of lifetime electricity cost savings.	Maximize
Internal rate of return (IRR)	Discount rate at which the investment becomes economical.	Maximize
Levelized cost of electricity (LCOE)	Levelized annual electricity and capital costs divided by system output ($/kWh).	Minimize
Net present value (NPV)	Present value of lifetime electricity cost savings less system capital costs.	Maximize
Simple payback time	Time period after which the investment yields economic returns (does not consider cost of money).	Minimize
Total cost of ownership (TCO)	Present value of electricity and system capital costs.	Minimize

Table 3. Summary of solar plus research methodologies

Approach	Description
Simultaneous optimization of system type, size, operation	Typically formulated as mixed-integer linear programs for computational tractability while considering decision variables on both system size and dispatch.
Optimal system control considering a range of system configurations/sizes	Approaches to optimal control include: linear programming, non-linear programming, dynamic programming. Some studies evaluate impact of forecast uncertainty. Often shorter time horizons are evaluated.
Heuristic or algorithmic controls while considering a range of system configurations/sizes	A focus on algorithmic or real-time control approaches. Can include testing on actual hardware.

of system sizing and operation, optimized control evaluated over a range of system sizes/types/configurations, or heuristic controls evaluated over a range of system sizes/types/configurations; summarized in Table 3. In terms of lifecycle performance, typical PV degradation rates are on the order of 0.5–1% per year (66), yielding useful lifetimes for PV systems of around 20 years accounting for degradation (7), (8), (61). Useful lifetimes and lifecycle performance for batteries and load control devices vary based on technology and cycling frequency (4), (5), (38), (46), (61), (67). Battery lifetimes are commonly assumed on the order of 10 to 15 years (2), (5), (31), though specific duty cycles, maintained states of charge, and temperature may extend or reduce estimated lifetimes (38), (65), (68). Some studies account for battery degradation and battery replacement costs within the study period (6), (8), (17), (61), (63), (69). Operation and maintenance costs are marginal relative to capital costs for solar plus devices (6–8), (17), (38), (69).

Empirical data

Role of Technology Costs: Luthander *et al.* (4) found that batteries increase PV self-use by 13–24 percentage points while load control strategies increase self-use by 2–15 percentage points. Batteries are more flexible than load control, capable of charging and discharging PV output to meet any electrical load in the home. However, the increased flexibility of batteries comes at a premium; full installation cost of batteries is currently in the order of thousands of dollars, while load control devices are increasingly available in the order of hundreds of dollars per device. The cost advantages of load control dominate the technological advantages of batteries at current battery costs. Several studies find that load control devices are cost-effective in solar plus systems whereas batteries are not (5), (31), (61), (64), (65), (74), (75). Batteries may only currently be cost-effective in limited cases, such as customers with residential demand charges (6), (35), (38). Battery hardware costs are falling (9–11), (20), (21), (48), (61) and should continue to decline (9), (10), (20), (21), (49), though falling hardware costs do not necessarily translate to falling installed costs. Kittner *et al.* (20) find that residential PV plus battery storage could be cost-competitive by as early as 2020, especially with policy support for battery research and development. Fares and Webber (2) found that installed battery costs would need to fall to below $100/kWh to be economically viable. Similarly, Quoilin *et al.* (17) find that costs would need to fall below €214/kWh (□$260/kWh),4 and Johann and Madlener (75) find that costs would need to fall below €300/kW (~$370/kW) to be economically viable. Schmidt *et al.* (9) project that installed residential battery costs could fall to about $520/ kWh if 1 TWh of cumulative capacity is installed by 2030, well above the cost-effectiveness thresholds from the literature. In Fig. 4, we illustrate a range of projected potential battery costs based on current battery cost estimates and assumed annual cost reductions of 5% per year, consistent with projections in (10). Under these assumptions, battery costs do not reach the cost-effectiveness thresholds estimated in the literature by 2030. Even allowing for more rapid cost reductions, batteries may only be cost-effective under a limited range of scenarios for the foreseeable future. Despite these results, consumers are increasingly interested in and adopting residential battery systems (57), (76), (77). The apparent disparity between the relatively weak economics of and high demand for batteries stems partly from incentives that improve the cost-

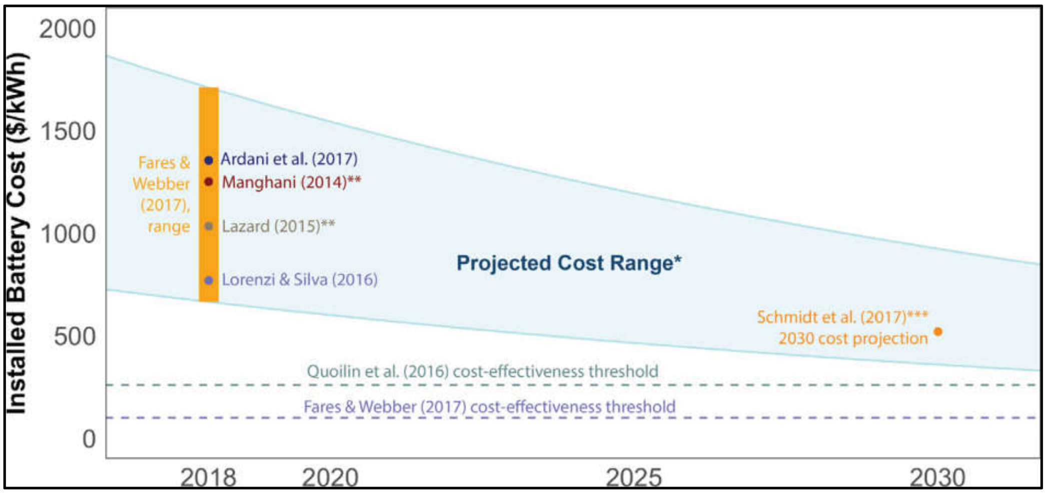

Fig. 4. Current battery cost estimates, projected cost range, and cost-effectiveness thresholds from the literature. *Based on 5%/year reduction. **Normalized estimates presented in [43], based on 3 kW/6 kWh system. ***Based on study's 2030 learning-based cost projection, assuming 1 TWh of cumulative capacity

effectiveness of batteries (49), (77). But the disparity may also indicate that solar plus analyses do not accurately account for the co-benefits of batteries, especially backup power. Co-benefits such as backup power reduce the effective costs of solar plus devices, such that solar plus economic analyses which do not include economic benefits for energy resiliency may yield results that do not accord with real customer behavior. As costs for stationary batteries fall, so do the costs of EVs (9), (11). EV owners can increase PV self-use and the value of PV systems by synchronizing EV charging with PV output periods (38), (78–80). Indeed, EV owners generally face incentives to coordinate EV charging with PV output in order to reduce charging costs (81), (82). Further, EV owners may be able to use bidirectional chargers to store PV output in the EV battery and use the PV output later in the day (38), (80), (83–85). Hence EVs can provide both load pull (synchronized charging) and output push (bidirectional charging) values to end users. These potential values are significant: a typical EV battery has a storage capacity on the order of 30 kWh (78), far larger than conventional stationary battery models. Increasing EV adoption could result in a growing role for EVs in solar plus applications.

Role of Rate Structures: For the purposes of this section, rate structure refers to the full suite of PV customer electricity payments and revenues, including volumetric rates ($/kWh), demand charges ($/kW), and grid export compensation ($/kWh). The customer's volumetric rate determines the value of PV self-use. The grid export rate determines the value of excess PV output delivered to the grid. The magnitude of these values and the proportion of self-used PV output determine the overall value of the PV system. The incremental value of solar plus is proportional to the difference between the customer's volumetric rate and the grid export rate. This general assertion is borne out across many studies (2), (3), (6), (8), (19), (26), (31), (33), (38), (63). In a sensitivity analysis, O'Shaughnessy *et al.* (6) show that solar plus improves system NPV in a case study in Hawaii by about 3% at full retail rate net metering, but that solar plus improves system NPV by about 53% when the gap between the customer's retail rate and grid export rate increases to $0.20/ kWh. Fares and Webber (2) demonstrate a similar relationship for the incremental value of solar plus in a series of case studies in Fig. 5. Beck *et al.* (7) find similar results, but show that the incremental value of solar plus does not necessarily correlate with solar plus deployment when grid export compensation is very low. In their study, optimal solar plus capacity increases as feed-in tariffs fall from 100% of the retail rate to 30% of retail, given the increasing value of self-use under lower feed-in tariff rates. At feed-in tariffs below 30% of the retail rate, the value of self-use continues to increase, but the overall value of PV is relatively low due to the low value of exported output. The optimal PV system size is so diminished at low feed-in tariff rates that there is less PV output to store and shift through solar plus devices. As a result, the value of solar plus exhibits a non-monotonic relationship, initially increasing then decreasing in relation to the feed-in tariff rate.

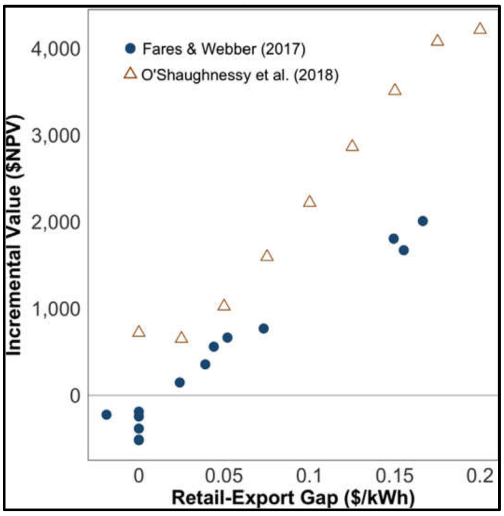

Fig. 5. Relationship between retail-export gap - difference in $/kWh between volumetric rate and grid-export rate - and the incremental value of solar plus relative to standalone PV ($NPV)

These results imply that the future trajectory of solar plus deployment depends on national and sub-national policies for grid export compensation. Grid export compensation rates are falling by policy design in major PV markets around the globe (26–30). These reductions in grid export compensation increase the value of self-use relative to grid export and signal increasing incentives for solar plus technologies. In TOU rate structures, solar plus can provide additional value through arbitrage between peak- and off-peak grid electricity use (5), (6), (31–34), (62), (63). Solar plus devices perform this arbitrage by pushing PV output into the on-peak period or pulling on-peak load under the PV output curve or into off-peak periods. The highest arbitrage value is achieved by shifting PV output to reduce on-peak electricity use. Therefore, the value of solar plus is higher under rate structures where the peak rate period occurs outside of the peak PV output period (6). Demand charges ($/kW) can significantly reduce the PV value proposition (6), (87). Standalone PV is largely ineffective at reducing demand charges for typical residential customers with late afternoon or early evening demand peaks, and the variability of a standalone PV system may limit the ability to mitigate demand charges in general. In addition, customers on demand charge schedules generally pay lower volumetric rates, further undermining the PV value proposition. Solar plus offers significant incremental value for customers on demand charge schedules (6), (35), (38), (63). Customers can use solar plus devices to temporally shift PV output into peak use periods to reduce peak demand and demand charges. Alternatively, customers can use the same devices to shift grid electricity and smooth their load profile to achieve the same result. Demand charges are currently uncommon for residential rate schedules though common for commercial customers. To summarize the findings of this section, the role of rate structure in determining the value of solar plus can be expressed in three relationships:

- The value of solar plus is higher for customers with lower grid export rates, all else equal, up to a critically low export rate beyond which PV adoption becomes economically unattractive.
- The value of solar plus is higher for customers on TOU rates where the peak period does not coincide with PV output, all else equal.
- The value of solar plus is higher for customers that pay demand charges, especially if peak demand occurs outside of the PV output period, all else equal.

Role of Customer Load Profiles: Total quantity of electricity demand positively correlates with the value of solar plus and optimal solar plus capacity (6–8), (26), (31), (38). Customers with larger electricity demands tend to install larger PV systems, which results in more PV output available for storage and load shifting. Further, TOU or demand charge customers with larger demands have increased opportunities for load shifting of grid electricity. Electric heating and EV ownership can therefore significantly increase the value of solar plus systems, even if heating and EV charge/discharge cycles are not configured to optimize PV self-use (26), (38). The shape of customer load profiles determines incentives for load shifting and the value of potential arbitrage opportunities. All else equal, customers with a higher proportion of demand occurring outside of PV output hours face greater incentives to invest in solar plus to implement load shifting. For TOU customers, the coincidence of load profiles with TOU schedules further influences the value of solar plus. Climate dictates the optimal selection of solar plus technologies by determining the types of loads shifted by solar plus devices: warm climates result in more cooling load control capacity (AC), while cool climates result in more heating load control capacity. Iwafune *et al.* (31) analyzes heat pumps. O'Shaughnessy *et al.* (6) includes smart AC and DWH but no space heating. Regional selection of solar plus candidate technologies reflects underlying assumptions on which technology could actually fit in a particular geography.

Conclusion

A growing body of literature demonstrates the value of PV integration with batteries and load control, the approach referred to as "solar plus." Solar plus provides value by using batteries and load control devices to increase PV self-use or temporally shift that use to provide end-user benefits. Solar plus can increase the value of residential PV systems, increase end-user electricity bill savings in a variety of rate structures, and may provide system-level benefits. The literature demonstrates several key factors that determine the economics of solar plus:

- Low-cost load control options are generally more cost-effective than higher-cost batteries, though batteries may be deployed in the near term because of co-benefits such as backup power.
- Rate structures determine the end-user value of solar plus.
- Customers using more electricity above PV output periods face higher incentives to invest in solar plus. Falling technology costs, the increasing availability of load control devices, and falling grid export rates all suggest that PV systems will be increasingly integrated with batteries and load control systems. Rate structure and policy reforms may be necessary to ensure that increasing solar plus deployment provides both end-user and system-level benefits.

REFERENCES

Agnew, S. and Dargusch, P. 2015. Effect of residential solar and storage on centralized electricity supply systems. *Nat Clim Change,* 5(4):315–318.

Ardani, K., *et al*., 2017. Installed costs and deployment barriers for residential solar photovoltaics with energy storage. Golden (CO): *National Renewable Energy Laboratory.*

Asakura, K., Shimomura, M. and Shodai, T. 2003. Study of life evaluation methods for Li-ion batteries for backup applications. *J Power Sources,* 119:902–905.

Beaudin, M. and Zareipour, H. 2015. Home energy management systems: a review of modelling and complexity. *Renew Sustain Energy Rev.,* 45:318–35.

Beck, T, *et al*., 2017. Optimal operation, configuration and sizing of generation and storage technologies for residential heat pump systems in the spotlight of self-consumption of photovoltaic electricity. *Appl Energy*, 188:604–19.

Belderbos. A, *et al*., 2017. Levelized cost of storage – introducing novel metrics. *Energy Econ.,* 67:287–99.

Bertsch, V., Geldermann, J. and Luhn, T. 2017. What drives the profitability of household PV investments, self-consumption and self-sufficiency? *Appl Energy*, 204:1–15.

Bhatti, AR., *et al*., 2016. A critical review of electric vehicle charging using solar photovoltaic. *Int J Energy Res*., 40(4):439–461.

Bhatti, AR., *et al*., 2016. Electric vehicles charging using photovoltaic: status and technological review. *Renew Sustain Energy Rev*., 54:34–47.

Braff, W., Mueller, J. and Trancik, J. 2016. Value of storage technologies for wind and solar energy. *Nat Clim Change,* 6:964–969.

Bruce, PG, *et al*., 2012. Li-O-2 and Li-S batteries with high energy storage. *Nat Mater,* 11(1):19–29.

Burns, JC., *et al.*, 2013. Predicting and extending the lifetime of Li-ion batteries. *J Electrochem Soc.,* 160(9):A1451–A1456.

Cao, S., Hasan, A. and Sirén, K. 2013. Analysis and solution for renewable energy load matching for a single-family house. *Energy Build.,* 65:398–411.

Castillo-Cagigal, M, *et al.*, 2011. PV self-consumption optimization with storage and active DSM for the residential sector. Sol Energy, 85:2338–2348.

Ceran, B., *et al.*, 2016. An analysis of hybrid power generation systems for a residential load. Energy and fuels conference, Cracow, Poland.

Coffman, M., Bernstein, P. and Wee, S. 2017. Integrating electric vehicles and residential solar PV. Transp Policy, 53:30–38.

Curry, C. 2017. Lithium-ion battery costs and market. *Bloomberg New Energy Finance*.

Darghouth, N, *et al.*, 2017. Exploring demand charge savings from residential solar. Berkeley (CA): Lawrence Berkeley National Laboratory.

De la Fuente, DV., *et al.*, 2013. Photovoltaic power system with battery backup with gridconnection and islanded operation capabilities. *IEEE Trans Ind Electron.,* 60(4): 1571–1581.

De Oliveira e Silva, G. and Hendrick, P. 2017. Photovoltaic self-sufficiency of Belgian households using lithium-ion batteries, and its impact on the grid. *Appl Energy*, 195:786–799.

De Schepper, E., Van Passel, S. and Lizin, S. 2015. Economic benefits of combining clean energy technologies: the case of solar photovoltaics and battery electric vehicles. *Int J Energy Res.,* 39(8):1109–1119.

Dehamma, A., Eller, A. and Asmus, P. 2015. Energy storage for renewables integration. *Navigant Research*.

Dyson, M, *et al.*, 2015. The economics of demand flexibility. Boulder (CO): Rocky Mountain Institute.

Eller, A. and Dehamna, A. 2016. Residential energy storage. Navigant Research.

Energy Sage, 2018. Solar installer survey 2017 results.

Erdinc, O. 2014. Economic impacts of small-scale own generating and storage units, and electric vehicles under different demand response strategies for smart households. *Appl Energy*, 126:142–150.

Fares, R. and Webber, M. 2017. The impacts of storing solar energy in the home to reduce reliance on the utility. *Nat Energy*, 2:17001.

Fischer, D/, *et al.*, 2016. Impact of PV and variable prices on optimal system sizing for heat pumps and thermal storage. *Energy Build.,* 128:723–733.

Fitzgerald, G., *et al.*, 2016. The economics of battery energy storage. Boulder (CO): Rocky Mountain Institute.

Fu, R., *et al.*, 2017. U.S. solar photovoltaic system cost benchmark: Q1 2017. Golden (CO): National Renewable Energy Laboratory.

Gallagher, B. 2017. PV system pricing H1 2017: breakdowns and forecasts. GTM Research.

Green, R. and Staffell, I. 2017. "Prosumage" and the British electricity market. *Econ Energy Environ Policy*, 6(1):33–49.

GTM Research. 2018. U.S. energy storage monitor 2017 year in review and Q1 2018.

GTM, Research. 2017. US energy storage monitor: Q4 2017 full report.

Hirth, L. 2013. The market value of variable renewables.The effect of solar wind power variability on their relative price. *Energy Econ.,* 38:218–236.

Hoppmann, J., *et al.*, 2014. The economic viability of battery storage for residential solar photovoltaic systems – a review and simulation model. *Renew Sustain Energy Rev.,* 39:1101–1118.

IEA. Photovoltaic power systems annual report. Photovoltaic Power Sys. Tech. Collaboration Programme; 2017.

Iwafune, Y., Kanamori, J. and Sakakibara, H. 2017. A comparison of the effects of energy management using heat pump water heaters and batteries in photovoltaic-installed houses. *Energy Convers Manage,* 148:146–160.

Jaffe, S. 2016. Balance of systems economics and functions. Boulder (CO): Carin ERA.

Jäger-Waldau, 2017. A. PV status report 2017. Luxembourg: Joint Research Centre.

Johann, A. and Madlener, R. 2014. Profitability of energy storage for raising self-consumption of solar power: analysis of different household types in Germany. International conference on applied energy, ICAE2014, 2206–2210.

Jordan, DC/, *et al.*, 2016. Compendium of photovoltaic degradation rates. *Progr Photovolt*., 24(7):978–989.

Joskow, PL. 2011. Comparing the costs of intermittent and dispatchable electricity generating technologies. *Am Econ Rev.,* 101(3):238–241.

Julch, V. 2016. Comparison of electricity storage options using levelized cost of storage (LCOS) method. *Appl Energy*, 183:1594–1606.

Kaschub, T., Jochem, P. and Fichtner, W. 2016. Solar energy storage in German households: profitability, load changes and flexibility. *Energy Policy,* 98:520–532.

Kemper, E, *et al.*, 2015. Opportunities for home energy management systems (HEMS) in advancing residential energy efficiency programs. Northeast Energy Efficiency Partnerships.

Kittner, N., Lill, F. and Kammen, DM. 2017. Energy storage deployment and innovation for the clean energy transition. *Nat Energy,* 2:17125.

Krieger, EM., Cannarella, J. and Arnold, CB. 2013. A comparison of lead-acid and lithium-based battery behavior and capacity fade in off-grid renewable charging applications. *Energy,* 60:492–500.

Kuzlu, M/, Pipattanasomporn, M. and Rahman, S. 2012. Hardware demonstration of a home energy management system for demand response applications. IEEE Trans Smart Grid, 3(4):1704–1711.

Lai, CS. and McCulloch, MD. 2017. Levelized cost of electricity for solar photovoltaic and electrical energy storage. *Appl Energy,* 190:191–203.

Lazard, 2017. Lazard's levelized cost of storage analysis version 3.0. New York (NY).

Leuschner, P. and Strother, N. 2016. Smart thermostats. Navigant Research.

Leuschner, P., Strother, N. and Callaway, L. 2015. Navigant Research leaderboard report: home energy management. *Navigant Research*.

Linssen, J., Stenzel, P. and Fleer, J. 2017. Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles. *Appl Energy*, 185:2019–2025.

Lorenzi, G. and Silva, CAS. 2016. Comparing demand response and battery storage to optimize self-consumption in PV systems. *Appl Energy*, 180:524–35.

Luthander, R., *et al.*, 2015. Photovoltaic self-consumption in buildings: a review. *Appl Energy,* 142:80–94.

MacGill, I. and Watt, M. 2015. Economics of solar PV systems with storage, in main grid and mini-grid settings. In: Sorensen B, editor. Solar energy storage. Academic Press.

Manghani, R. 2014. The future of solar-plus-storage in the U.S. Boston (MA): GTM Research.

Marnay, C., *et al*., 2008. Optimal technology selection and operation of commercialbuilding microgrids. *IEEE Trans Power Syst.,* 23(3):975–982.

Masa-Bote, D., *et al*., 2014. Improving photovoltaics grid integration through short time forecasting and self-consumption. *Appl Energy.,* 125:103–113.

N.C.C.E.T.C, 2018. Database of state incentives for renewables & efficiency.

Nema, P., Nema, RK. and Rangnekar, S. 2009. A current and future state of art development of hybrid energy system using wind and PV-solar: a review. *Renew Sustain Energy Rev.,* 13(8):2096–2103.

Niyato, D., Xiao, L. and Wang, P. 2011. Machine-to-machine communications for home energy management system in smart grid. *IEEE Commun Mag.,* 49(4):53–9.

Nunes, P., Farias, T. and Brito, MC. 2015. Enabling solar electricity with electric vehicles smart charging. *Energy,* 87:10–20.

Nyholm, E., Odenberger, M. and Johnsson, F. 2017. An economic assessment of distributed solar PV generation in Sweden from a consumer perspective – the impact of demand response. *Renew Energy,* 108:169–78.

Nykvist, B. and Nilsson, M. 2015. Rapidly falling costs of battery packs for electric vehicles. *Nat Clim Change*, 5(4):329–32.

Obi, M., *et al*., 2017. Calculation of levelized costs of electricity for various electrical energy storage systems. *Renew Sustain Energy Rev.*, 67:908–920.

Oliva, HS. and MacGill, I. 2014. Value of net-FiT PV policies for different electricity industry participants considering demand-side response. *Progr Photovolt.,* 22(7):838–850.

O'Shaughnessy, E, *et al*., 2018. Solar plus: Optimization of distributed solar PV through battery storage and dispatchable load in residential buildings. *Appl Energy*, 213:11–21.

Pang, C., Dutta, P. and Kezunovic, M. 2012. BEVs/PHEVs as dispersed energy storage for V2B uses in the smart grid. IEEE Trans Smart Grid, 3(1):473–482.

Parra, D. and Patel, MK. 2016. Effect of tariffs on the performance and economic benefits of PVcoupled battery systems. *Appl Energy,* 164:175–187.

Parra, D., Walker, G. and Gillott, M. 2016. Are batteries the optimum PV-coupled energy storage for dwellings? Techno-economic comparison with hot water tanks in the UK. *Energy Build.,* 116:614–621.

Poruschi, L., Ambrey, CL. and Smart, JCR. 2018. Revisiting feed-in tariffs in Australia: a review. *Renew Sustain Energy Rev.,* 82:260–270.

Quoilin, S., *et al*., 2016. Quantifying self-consumption linked to solar home battery systems: statistical analysis and economic assessment. *Appl Energy*, 182:58–67.

Ranaweera, I. and Midtgard, OM. 2016. Optimization of operational cost for a grid-supporting PV system with battery storage. *Renew Energy,* 88:262–272.

Ratnam, EL., Weller, SR. and Kellett, CM. 2015. An optimization-based approach to scheduling residential battery storage with solar PV: assessing customer benefit. *Renew Energy*, 75:123–134.

Ren, ZG., Grozev, G. and Higgins, A. 2016. Modelling impact of PV battery systems on energy consumption and bill savings of Australian houses under alternative tariff structures. *Renew Energy,* 89:317–330.

Richardson, DB. 2013. Electric vehicles and the electric grid: a review of modeling approaches, Impacts, and renewable energy integration. *Renew Sustain Energy Rev.,* 19:247–254.

Salpakari, J. and Lund, P. 2016. Optimal and rule-based control strategies for energy flexibility in buildings with *PV. Appl Energy.,* 161:425–436.

Schill, WP., Zerrahn, A. and Kunz, F. 2017. Prosumage of solar electricity: pros, cons, and the system perspective. *Econ Energy Environ Policy*, 6(1):7–31.

Schmidt, O., Hawkes, A. and Staffell, I. 2017. The future cost of electrical energy storage based on experience rates. *Nat Energy,* 2.

Schuller, A., Flath, CM. and Gottwalt, S. 2015. Quantifying load flexibility of electric vehicles for renewable energy integration. *Appl Energy,* 151:335–344.

Smith, K, *et al*., 2017. Life prediction model for grid-connected li-ion battery energy storage system. American control conference (ACC), Seattle, WA.

Strother, N. and Lawrence, M. 2016. Market data: IoT for residential customers. *Navigant Research*.

Timilsina, G., Kurdegelashvili, L. and Narbel, P. 2015. A review of solar energy: markets, economics and policies. In: Adaramola M, editor. Solar energy: application, economics, and public perception. Oakville (ON): Apple Academic Press.

Truong, N/, *et al*., 2016. Economics of residential photovoltaic battery systems in Germany: the case of Tesla's powerwall. Batt-Basel, 2:2.

Widén, J. 2014. Improved photovoltaic self-consumption with appliance scheduling in 200 single-family buildings*. Appl Energy,* 126:199–212.

Zakeri, B. and Syri, S. 2015. Electrical energy storage systems: a comparative life cycle cost analysis. *Renew Sustain Energy Rev.,* 42:569–596.

Zhou, B., *et al*., 2016. Smart home energy management systems: concept, configurations, and scheduling strategies. *Renew Sustain Energy Rev.,* 61:30–40.

****