Battery Storage in Renewable Energy Systems

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I. Introduction

THIS article investigates the deployment of energy storage to facilitate the adoption of renewable energy. A review of renewable generating systems operating under net metering agreements is supplied to illustrate the storage requirements associated with renewable energy. An electrified residential load profile is considered to include heating loads. The levelized cost of energy resulting from renewable systems without net metering is calculated to assess viability in displacing fossil fuel energy.

II. A Review of Net Metering

Net metering is an accounting practice which allows renewable generating sites to feed into the grid at times of surplus generation and redeem energy credit when load is unmet by the renewable generation. This practice allows net metering participants to generate and consume net equal sums of energy on an annual basis. While individual users offset their grid imports with renewables, the participants are highly reliant on firm (often fossil fuel) generation from the grid. Net metering encourages the adoption of renewables but has limitations at scale. Grids operating with a significant share of net metering must still maintain peak capacity of fossil fuel generators due to the intermittency of renewables. The upper limit of load that could be met by net metering is that which occurs when renewable resource is available, such as loads on days with clear skies for photovoltaic systems.

A residential load profile with PV generation is examined to demonstrate the operation of net metering [1]. Generation data is localized to the site of loads, which includes both electricity usage and facility heating. The data is detailed further in the appendix. The numbers discussed are specific to the load profile and climate of the data set, but are considered as estimates of residential systems in temperate climates. The operation of a PV system and residential load with net metering is illustrated in figure 1. Energy quantities are expressed per unit of the annual load for the system under consideration.

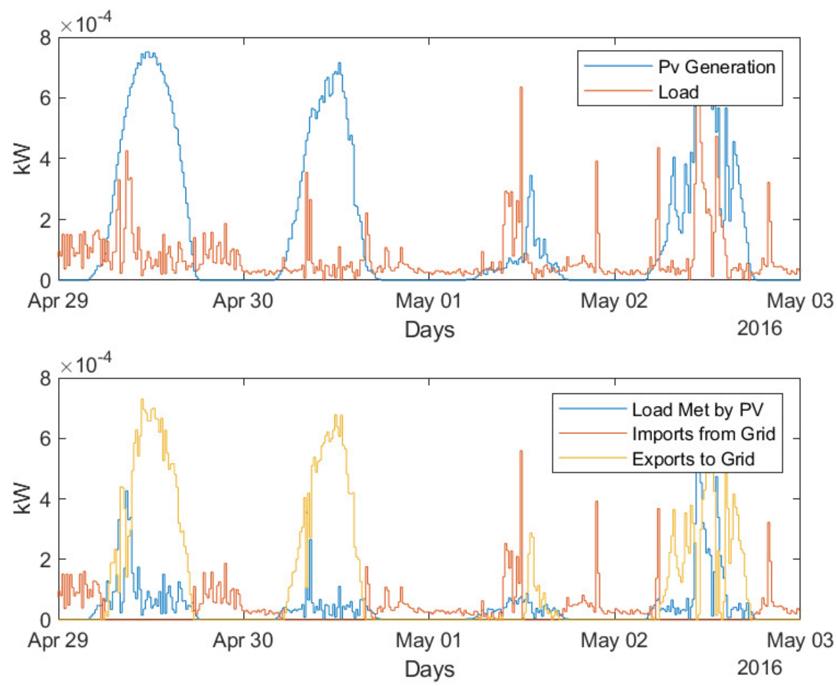


Fig. 1: Net Metering AY Data: Early May

Some PV generation coincides with the loads but most is exported and later imported. An upper estimate of 34% of the generation coincides with load over a year for this data set, but the grid is still relied on to export and reimport over 65% of the energy. The cumulative effect of this import and expert service provided by the grid over a year is illustrated in figure 2.

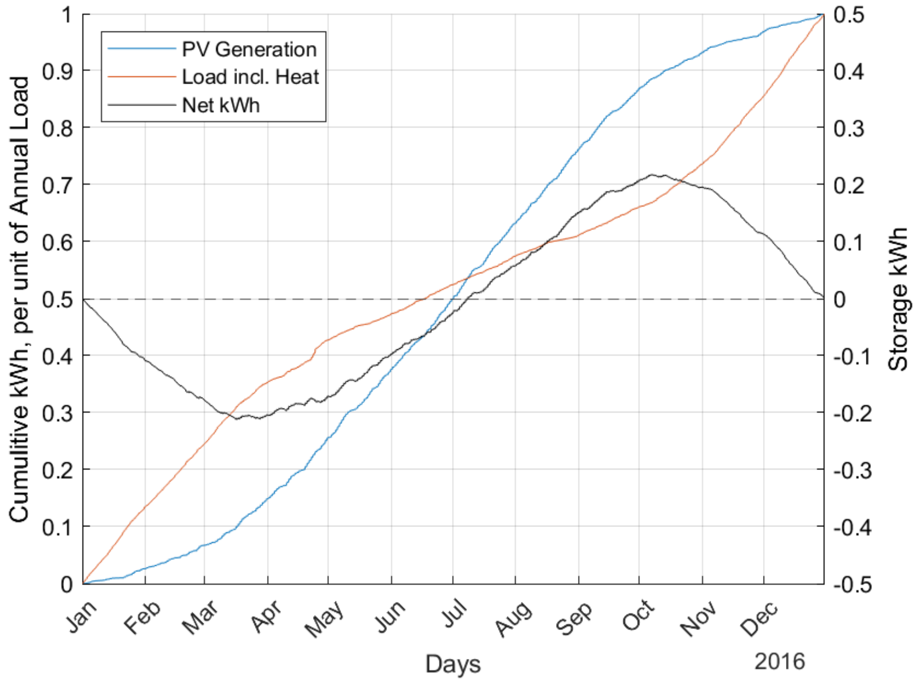


Fig. 2: Net Metering AY

Figure 2 shows that, for this particular data set, the grid handles a seasonal imbalance of 43% of the annual load. It may be inferred that 22% of load occurs during nighttime and inclement weather periods during the seasons of excess PV generation. Customers practicing net metering receive the benefit of overnight storage for much of the year, which combined with renewable generation meets 56% of energy needs, and an equivalent to long-term storage amounting to 43% of annual energy usage. These numbers will vary with climate and load profile.

III. Battery Storage

Introducing energy storage allows renewables to directly meet a greater portion of annual load. Battery storage is not the only energy storage technology available to be studied, however it is considered for its relative maturity and independence of geography. A small amount of storage can greatly increase the amount of load met directly by renewables. This system is operated such that energy use is prioritized from the renewable system, followed by the storage, and grid is relied on to meet deficiencies when the battery is depleted. A system operated with a battery sized to 0.001 of annual load is applied to the data. This ratio is sized such that this simulation is equivalent to providing a 10 kWh battery to a small household with an annual load of 10,000 kWh. This battery size is comparable to that of installing a commercially available battery in a small residence. Battery charging curves are neglected for simplicity, but are unlikely to significantly impact results due to the large portion of curtailment. Figure 3 applies battery storage to the segment shown in figure 1.

The figure demonstrates the operation of battery storage. In weather with surplus renewable generation, a small storage installation handles most of the overnight loads. The seasonal trend, however, is identical to figure 2. The important questions to consider are: how much fossil fuel energy can renewables with storage displace, and what does it take for deployment of storage to become a viable alternative to net metering.

The performance of renewables and storage is unique to a specific climate and load profile, however the systems are simulated on the data to provide insight to this question. Varying sizes of PV and storage are simulated in figure 4. Units are expressed as a ratio to annual load. A PV system at coordinate 1.0 is sized for net metering, greater than 1 indicates a system sized for curtailment. The storage is expressed such that a point at 10^{-3} corresponds to the battery size demonstrated in figure 3. The vertical axis is the ratio of load met relative to the total annual load. A point at a vertical coordinate of 1.0 would indicate the renewables and storage met all energy needs without importing from the grid. This surface demonstrates that introducing a small amount of storage to a renewable generating system allows renewables to meet a greater share of the load. With sufficient generation and storage, the remaining unmet load largely constitutes seasonal deficits and adverse weather events. Increasing the PV system size reduces the necessary seasonal storage from about 48%, to as low as 15% in this figure. The cost of increasing generation and storage sizes must also be considered.

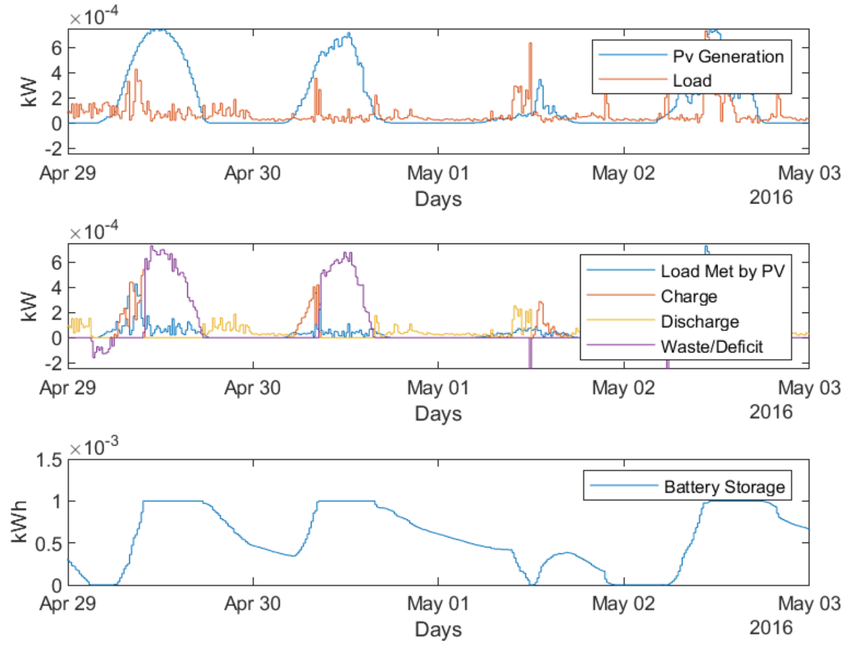
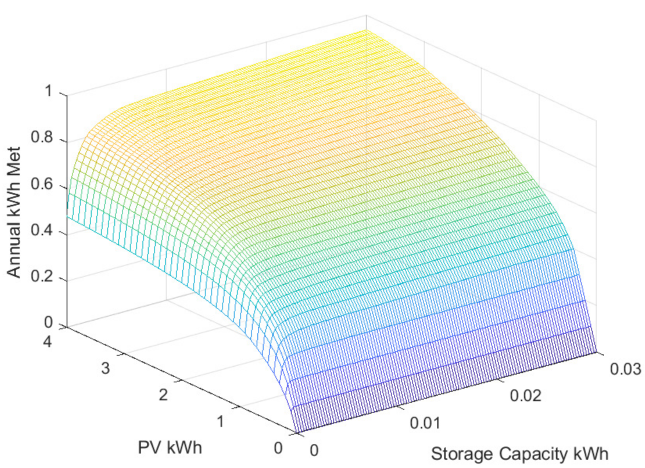
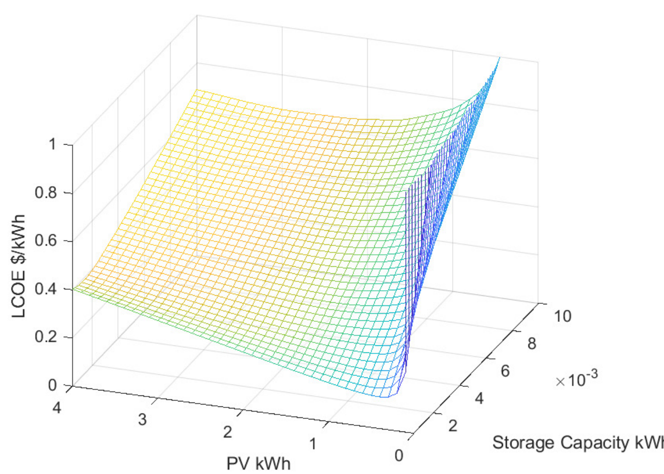


Fig. 3: Battery Operation

The costs of the renewable system scale with the size of the PV and LI components, however, figure 4 showed that the energy useful for non-export consumption does not scale linearly. The resulting LCOE of useful energy on a non-export basis is illustrated in figure 5. A PV LCOE of $0.06/kWH is assumed [2], and a battery cost of $380/kWh [3] levelized over a 10 year lifetime [4] is approximated as $38/storage kWh. On the battery size axis, with PV size of 0, there is no energy generated so costs have no yield. Moving away from the origin the surface asymptotically approaches the linearly increasing system cost as energy returns diminish. A region is priced under $0.20, indicating that solutions exist for adopting storage in favor of net metering at competitive cost. Consumers able to adopt renewables at the cited price points are able to offset a portion of their energy usage behind the meter at grid parity. The plot only accounts for the cost of renewables, neglecting associated costs of maintaining the grid and generation. It must be noted that, at a utility scale, significant reductions in conventional energy usage will increase the cost per kWh required to maintain resilience. The partial penetration of renewables does not negate the need for full fossil fuel capacity to meet power requirements in adverse weather. The cost surface is therefore an underestimate at higher rates of renewable penetration.



(a) Fig. 4 Annual load met by PV - Storage sizes



(b) Fig. 5 LCOE of PV - Storage sizes

The minimum cost of introducing renewables is found by minimizing cost given a renewable penetration target. The results are plotted in figure 6, roughly mapping the path to renewables as a function of cost. The axes indicate relative system size. Points are labeled with percentage of renewable energy (complement of the remaining fossil fuel requirement) and LCOE. Renewable penetration at 15% costs \$0.10/kWh, with only nominal curtailment and a storage size ratio 0.0002. The costs increase significantly beyond 35% penetration, even with generation sized multiples larger than the annual load.

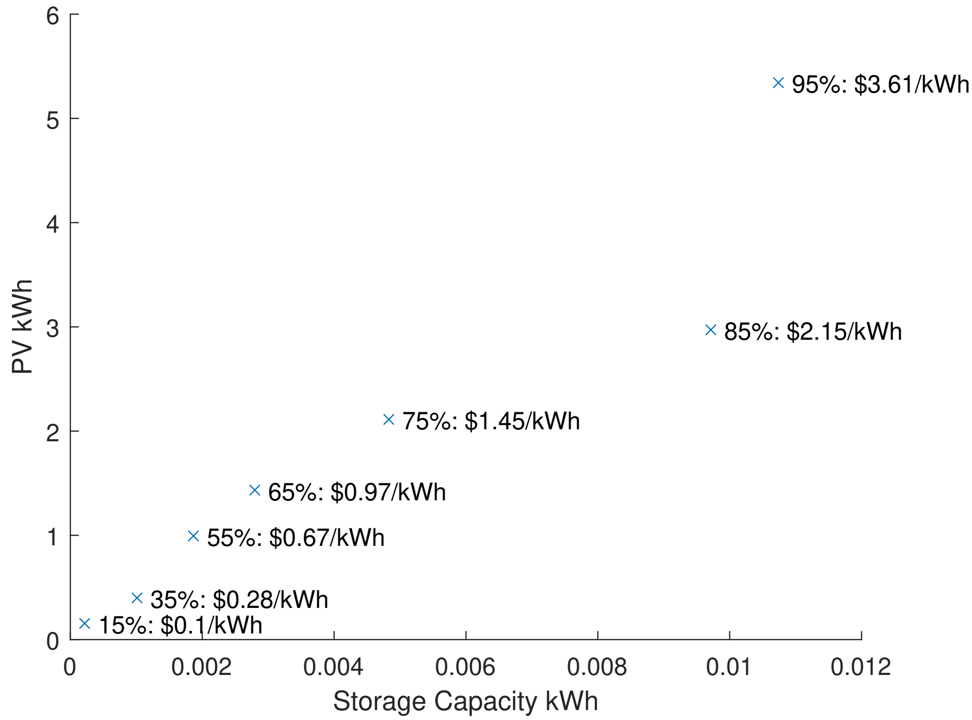


Fig. 6: Renewable Penetration: LCOE

IV. Conclusions

Deploying batteries to operate renewable generation without net metering exports can allow greater penetration of renewables on residential load profiles. At low rates of renewable penetration without export credit, the minimum cost system design is approximately a linear combination of PV and storage. At rates of renewable penetration under 15%, renewables with storage may be competitive with retail energy prices. Storage with renewables could be cost effetive for commercial customers, residential customers would need utility-scale installation costs to access the price point demonstrated. The adoption of renewable energy may be accelerated by incentivizing battery installation as an alternative to net metering. This analysis considered electrified loads including electric heating, therefore the results are an underestimate of market viability when heating loads are excluded. Value to utilities, and consumers on variable-rate pricing, accompanied by the adoption of storage needs to be investigated further. Short-term and limited capacity energy storage has diminishing returns after nightly cycles are met. Technology for seasonal storage requires a cost per unit of storage significantly below that of LI batteries.

V. Appendix: Data

Energy usage data has been made available by Open Power Systems Data (website). The data used for this is a year of 15-minute interval energy data for a residential facility in Germany from January 1, 2016 to December 30, 2017, selected to capture the pv generation and corresponding residential load profile resulting from weather in a temperate climate. It is assumed that the customer has made no effort to shift loads to occur during periods of peak PV generation. The residence heat system is electric, thus the entirety of stationary energy demand is electrical. Heating in the original data constitutes approximately 48% of the annual kWh load. No implementation of cogeneration heat is considered in this analysis.

The data provides cumulative summations of kWh, plotted in the figure. Power in kW is estimated from the data by taking a first forward difference of kWh and multiplying to correct the scale. This is a zeroth order approximation of power for 15-minute intervals. Systems in this report are assumed to be grid-tied, instantaneous power demand spikes within the time intervals are not a concern. The relative value at each data point is used to yield a per-unit generation and per-unit load based on the area under the estimated annual kW curve. While both renewable generation and consumer loads can be highly variable on a sub-minute time span for small scale systems, storage is again assumed to reduce this discussion to an analysis of net kWh over the sampling period.

Total load is found by subtracting export from PV and adding import. Electrical load is found by subtracting heat from total load. Anomalies, such as export exceeding PV, account for less than 0.4% of the total load and are corrected prior to analysis.

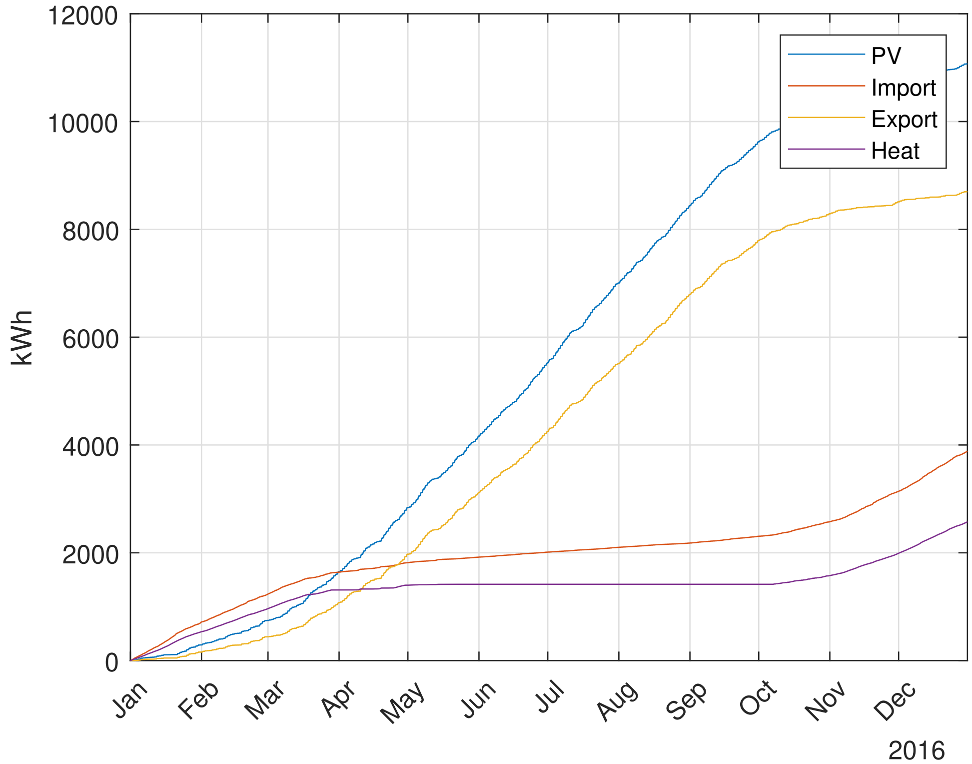


Fig. 7: Imported Data

References

[1] "Open Power System Data. 2020. *Data Package Household Data.* Version 2020-04-15. https://data.open-power-system-data.org/household_data/2020-04-15/. (Primary data from various sources, for a complete list see URL)

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[3] Cole, Wesley, and A. Will Frazier. 2019. Cost Projections for Utility-Scale Battery Storage. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-73222.

[4] Tesla Powerwall 2 Datasheet, Tesla Inc., 2019. https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall_2_AC_Datasheet_EN_NA.pdf