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Analyzing the Economic and Environmental Performance of Residential PV-Battery Systems in Massachusetts

THOMAS ROSTAD

PV-BATTERY SYSTEMS OFFER A VIABLE TECHNOLOGICAL ALTERNATIVE TO INTERMITTENT, STAND-ALONE PV SYSTEMS. WHEN DEPLOYED AT THE RESIDENTIAL LEVEL, PV-BATTERY SYSTEMS ALLOW HOUSEHOLDS TO SIGNIFICANTLY REDUCE THEIR RELIANCE ON THE ELECTRIC GRID BY STORING EXCESS ELECTRICITY GENERATED FROM THEIR SOLAR PANELS FOR SELF-CONSUMPTION. THIS STUDY INVESTIGATES THE EXTENT TO WHICH RESIDENTIAL PV-BATTERY SYSTEMS OFFER ECONOMIC AND ENVIRONMENTAL BENEFITS TO MASSACHUSETTS HOMEOWNERS THROUGHOUT THEIR OPERATIONAL LIFETIME. USING SPREADSHEET MODELS, I REPRESENT THE ENERGY FLOWS, CASH FLOWS, AND GREENHOUSE GAS EMISSIONS ASSOCIATED WITH RESIDENTIAL PV-BATTERY SYSTEMS IN MASSACHUSETTS UNDER DIFFERENT ECONOMIC AND TECHNOLOGICAL ASSUMPTIONS. RESULTS INDICATE THAT THESE SYSTEMS ARE A VIABLE MEANS FOR HOMEOWNERS TO SAVE MONEY AND REDUCE THEIR CARBON FOOTPRINT. ECONOMIC PERFORMANCE OF RESIDENTIAL PV-BATTERY SYSTEMS IS DEEPLY IMPACTED BY FEDERAL AND STATE SUBSIDIES, AS WELL AS NET METERING OFFERINGS AND ELECTRICITY RATE STRUCTURES. SYSTEM SIZE ALSO OFFERS CERTAIN TRADEOFFS BETWEEN ECONOMIC AND ENVIRONMENTAL PERFORMANCE.

1. INTRODUCTION

According to the "U.S. Solar Market Insight – 2019 Year in Review", produced by Wood Mackenzie and the Solar Energy Industries Association (SEIA), the U.S. saw record-setting residential solar capacity added in 2019, with more than 2.8 GW installed (SEIA & Wood Mackenzie, 2020). In states with high retail electricity rates and robust incentives, installing solar can help homeowners save money on their electric bills. Others choose to install solar as a means of reducing their carbon footprint, thus helping to mitigate climate change.

An important limiting factor of solar power is its inherent intermittency. Photovoltaic (PV) cells are only able to generate electricity when the sun is shining, and homeowners who install solar are only able to use electricity generated from their system during the daytime (EnergySage, 2018a). One potential solution to this problem is to integrate a large lithium-ion battery with the PV system. By storing excess electricity produced from the solar panels throughout the day, homeowners can continue using electricity generated from their PV system even when the sun is no longer shining (see Figure 1). This comes with a few added benefits to the homeowner and society at large.

Unlike standalone PV systems, PV-battery systems can provide households with backup power in case of an outage. This has been a crucial driver of growth in California's residential solar-plus-storage market, where last year's wildfires, and subsequent public-safety power shutoff events, left hundreds of thousands of utility customers without electricity (Lazo & Carlton, 2019; St. John, 2020).

Residential PV-battery systems also have the potential to offer system-level benefits that improve the overall efficiency of the electric grid and reduce system-level costs. These benefits include the ability to offset generation from more expensive peaking units, reduce congestion on transmission and distribution lines, stabilize local electricity flows, control local voltage fluctuations, and defer transmission and distribution system upgrades. Electricity storage is critical for realizing these benefits and without it, high penetration of distributed solar may actually increase, not decrease, costs (Shlatz, Buch & Chan, 2013).

This analysis focuses on the use of PV-battery systems within Massachusetts from 2020-2050, a state that already offers robust incentives for its residential solar market. In addition to offering net metering at the full retail electricity rate, the state's Solar Massachusetts Renewable Target (SMART) Program requires utilities to pay solar owners for every kWh of electricity their PV system produces monthly. The SMART program also offers higher incentive payment rates to PV systems that include some form of energy storage (MassCEC, 2019).

This research will help to quantify the economic and environmental benefits accrued to households that install PV-battery systems in the state of Massachusetts. It will also shed light on the most important variables in determining this performance, allowing electricity consumers, policymakers, and utilities to make informed decisions on how to deploy the technology most effectively.

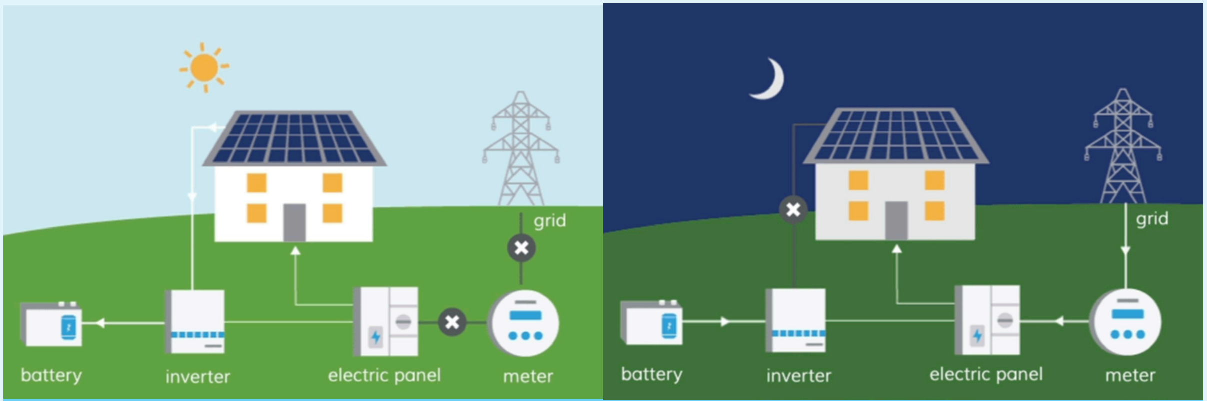

FIGURE 1: A VISUAL REPRESENTATION OF HOW PV-BATTERY SYSTEMS OPERATE DURING THE DAY VERSUS THE NIGHT (ENERGYSAGE, 2019)

2. LITERATURE REVIEW

2.1 Overview

Due to the nature of the article length in this journal, the Literature Review for this paper was removed to concentrate on the experiment and its conclusion.

This literature review highlights the current state of knowledge on PV-battery systems with a focus on studies that aimed to model the performance of these systems in a residential setting. Key findings from the literature review can be summarized as follows:

PV-battery systems have been extensively studied to quantify the benefits of deploying such systems at the residential level. Early research tended to focus on the application of these systems in countries that pioneered favorable policies for distributed generation. This often involved the simulation and optimization of residential PV-battery systems based on existing feed-in tariff (FiT) incentives and net metering programs. Most studies accounted for a similar variety of economic and technical parameters but used different model designs and assumptions to simulate energy flows and cash flows. Although many studies acknowledged the potential environmental benefits of increasing self-consumption of solar-generated electricity with a battery, few quantified those benefits.

3. METHODS

3.1 Research Questions

To quantify the economic and environmental performance of residential PV-battery systems in the state of Massachusetts, I created the following models to represent the operation of these systems on one-year and 30-year time scales:

- How effective are residential PV-battery systems at reducing a household's reliance on the electric grid?
- What is the expected payback period for a residential PV-battery system and how do government subsidies and net metering policies affect this timeline?
- How effective are residential PV-battery systems at mitigating GHG emissions throughout their lifetime?
- How does system size impact the economic performance of residential PV-battery systems?

For most of the questions, I additionally look at how standalone PV systems would perform in comparison as a technology alternative.

3.2 Model Descriptions

3.2.1 Overview

This section describes the models created for this study to represent the energy flows, cash flows, and GHG emissions associated with residential PV-battery systems in Massachusetts.

The "Year One Energy Flows" model quantifies a household's hourly energy flows over a year under three scenarios that use the same annual hourly electricity consumption profile: *Baseline* scenario represents a household with neither solar panels, nor battery system, *Standalone PV* scenario represents a household with solar panels, but no battery system, and *PV-battery* scenario represents a household with both solar panels and an integrated battery system. The *Standalone PV* and *PV-battery* scenarios pair the consumption profile with an annual hourly PV generation profile, then use a series of conditional statements to represent how each technology influences hourly energy flows.

The "Lifetime NPV" model calculates the NPV of both a standalone PV system and a PV-battery system in Massachusetts over 30 year. The year one calculation of NPV factors in outputs from the "Year One Energy Flows" model, the amount of electricity consumed on-site from the standalone PV or PV-battery systems, and the amount of electricity sent back to the grid for net metering. For subsequent years, deflationary pressure is applied to those values to reflect technological degradation. Retail electricity prices, net metering prices, and SMART incentive payment rates interact with these technological parameters to determine the annual revenues generated by the Standalone PV and PV-battery systems. Capital costs and operating and maintenance (O&M) costs associated with each technology are calculated as a function of system size and years in operation. After taking the difference between total system costs and revenues, a discount rate is applied to factor in the time value of money.

The "Lifetime Net Emissions" model calculates net GHG emissions from using a standalone PV system or a PV-battery system in a residential setting over a 30-year period. Net emissions are calculated by taking the difference between avoided emissions from using the standalone PV or PV-battery system, and the life cycle emissions associated with the technology itself. Avoided emissions factor in the amount of electricity consumed on-site from the standalone PV or PV-battery system over a 30-year period, a value drawn directly from the "Lifetime NPV" model. Lifetime emissions data for each technology are based on estimates from relevant academic papers and industry reports.

3.2.2 Year One Energy Flows

3.2.2.1 Baseline

In a household with neither solar panels nor energy storage system, all electricity demand is supplied directly from the grid: $E_{FromGrid_h} = E_{Load_h}$

where $E_{FromGrid_h}$ refers to electricity drawn from the grid during hour h, and E_{Load_h} refers to household electricity consumption during that same hour.

3.2.2.2 Standalone PV

This scenario represents the same household after installing a PV system without an associated battery storage system. The household's hourly demands for electricity from the grid are calculated using the following conditional statements:

$$E_{FromGrid_h} = \begin{cases} E_{Load_h} - E_{FromPV_h}, & E_{Load_h} > E_{FromPV_h} \\ 0, & E_{Load_h} \leq E_{FromPV_h} \end{cases}$$

where E_{FromPV_h} refers to electricity generated from the solar panels during hour h. Since Massachusetts utilities offer net metering credits to residential customers who send electricity to the grid, any excess electricity generated from the PV system must be accounted for:

$$E_{ToGrid_h} = \begin{cases} E_{FromPV} - E_{Load_h}, & E_{Load_h} < E_{FromPV_h} \\ 0, & E_{Load_h} \geq E_{FromPV_h} \end{cases}$$

where E_{ToGrid_h} represents electricity sent to the grid for net metering credits during hour h.

3.2.2.3 PV-Battery

In a household with both solar panels and an integrated battery, hourly demand for electricity from the grid is calculated using the following algorithm:

$$E_{FromGrid_h} = \begin{cases} E_{Load_h} - E_{FromPV_h} - B_{charge_h}, & E_{Load_h} - E_{FromPV_h} - B_{charge_h} > 0 \\ 0, & E_{Load_h} - E_{FromPV_h} - B_{charge_h} \leq 0 \end{cases}$$

where B_{charge_h} is the battery's level of charge at the end of hour h. The battery is charged and discharged in such a way as to maximize self-consumption. Figure 2 shows the decision tree that defines this process. Although, once the battery is fully charged, excess electricity is not merely "lost". Instead, it is sent to the grid for net metering.

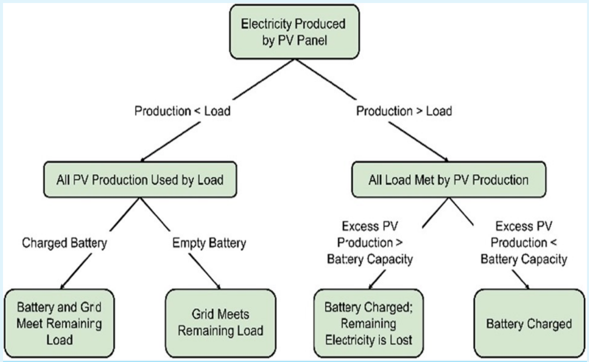

FIGURE 2: ALGORITHM FOR PV-BATTERY SYSTEM ENERGY FLOWS (TERO, ET AL., 2018)

If the solar panels generate excess power $(E_{Load_h} < E_{FromPV_h})$, that electricity first goes to charge the battery. If the battery is full, any excess electricity is sent to the grid for net metering credits:

$$B_{charge_h} = \begin{cases} B_{charge_{h-1}} + \eta_{bat}(E_{FromPV} - E_{load}), & B_{charge_{h-1}} + (E_{FromPV_h} - E_{Load_h}) < B_{max} \\ B_{max}, & B_{charge_{h-1}} + (E_{FromPV_h} - E_{Load_h}) \geq B_{max} \end{cases}$$

$$E_{ToGrid_h} = \begin{cases} B_{charge_{h-1}} + (E_{FromPV} - E_{Load_h} - B_{max}), & B_{charge_{h-1}} + (E_{FromPV_h} - E_{Load_h}) > B_{max} \\ 0, & B_{charge_{h-1}} + (E_{FromPV_h} - E_{Load_h}) \leq B_{max} \end{cases}$$

where $B_{charge_{h-1}}$ is the charge of the battery at the beginning of the hour, B_{max} is the battery's maximum capacity, and bat is the roundtrip efficiency of the battery.

If load exceeds PV production $(E_{Load_h} > E_{FromPV_h})$, the battery is discharged until either the excess load is met, or the battery reaches its minimum capacity:

$$B_{charge_h} = \begin{cases} B_{charge_{h-1}} - (E_{Load_h} - E_{FromPV_h}), & (E_{Load_h} - E_{FromPV_h}) < B_{charge_{h-1}} \\ B_{min}, & (E_{Load_h} - E_{FromPV_h}) > B_{charge_{h-1}} \end{cases}$$

where B_{min} is the minimum capacity of the battery. In this case, no electricity is sent to the grid for net metering.

3.2.3 Lifetime NPV

3.2.3.1 Standalone PV

The NPV of a grid-connected residential PV system after n years of operation is a function of the different costs and revenues it accumulates during those years. In Massachusetts, sources of revenue for these systems include avoided costs of electricity, incentive payments offered by the SMART program, and net metering credits:

$$Revenues_n = (E_{FromPV_n} \times P_{retail_n}) + (S_{SMART_n} \times [E_{PV_n}]) + (E_{ToGrid_n} \times P_{netmeter_n})$$

where P_{retail_n} is the retail price of electricity sold from the grid, S_{SMART_n} is the SMART program incentive payment rate, is the total amount of electricity produced by the PV system, and E_{PV_n} is the price of electricity sold back to the grid, all in the n^{th} year of operation. Costs for these systems include capital costs and operating and maintenance costs:

$$Costs_n = I_{PV_n} + OM_{PV_n}$$

where I_{PV_n} refers to the capital costs of the PV system, a function of system size, and OM_{PV_n} refers to the operating and maintenance costs, a function of system size and years in operation.

The NPV of the PV system is calculated as the difference between system costs and revenues that have accumulated after n years of operation, factoring in the time value of money:

$$NPV = \frac{\sum_{n=1}^{y} Revenues - \sum_{n=1}^{y} Costs}{(1+r)^n}$$

where y is the system lifetime in years, and r is the discount rate.

3.2.3.2 PV-Battery

The same aforementioned formulas are applied when calculating the NPV of the PV-battery system. The difference is that the battery adds an additional source of costs and revenues. Additional revenues come from an increase in avoided electricity costs:

$$Revenues_n = (E_{FromPV_n} + E_{FromBattery_n}) \times P_{retail_n} + (S_{SMART_n} \times E_{PV_n}) + (E_{ToGrid_n} \times P_{wholesale_n})$$

where $E_{FromBattery_n}$ is electricity supplied directly to the household from the battery in year n. Additional costs in this scenario come from the capital costs of the battery system, and its operating and maintenance costs over time:

$$Costs_n = I_{PV_n} + I_{battery_n} + OM_{PV_n} + OM_{battery_n}$$

where $I_{battery_n}$ equals the battery's capital costs, and $OM_{battery_n}$ equals the battery's operation and maintenance costs in year n of operation.

3.2.4 Lifetime Net Emissions

3.2.4.1 Standalone PV

The net GHG emissions for the Standalone PV scenario are calculated by taking the difference between the technology's expected lifetime emissions, and the emissions that would have been produced by the grid up until year n if the technology not been used at all. The system lifetime in years, referred to as y, acts as the upper limit for n.

$$Lifetime\ Net\ Emissions = \sum_{n=1}^{y} Emissions_{avoided_n} - Emissions_{lifetime_n}$$

The following equation represents the avoided emissions for a residential PV system without a battery component:

$$Emissions_{avoided_n} = E_{FromPV_n} \times CI_{grid}$$

where CI_{grid} refers to the average emissions intensity of the grid in metric tons of CO2e/kWh. Lifetime emissions of the PV system are calculated as follows:

$$Emissions_{lifetime} = PV_{cap} \times CI_{PV}$$

where PV_{cap} is the nameplate capacity of the PV system, and CI_{PV} is the life cycle emissions of the technology per kW of capacity.

3.2.45.2 PV-Battery

Similar formulas to the ones mentioned above are applied when calculating the net GHG emissions of the PV-battery system. In this case, the battery adds an additional source of avoided emissions and lifetime emissions:

$$Emissions_{avoided} = (E_{FromPV_n} + E_{FromBattery_n}) \times CI_{grid}$$

$$Emissions_{lifetime} = (PV_{cap} \times CI_{PV}) + (B_{max} \times CI_{battery})$$

where $CI_{battery}$ refers to the life cycle emissions of the battery per kWh of capacity.

3.3 DATA SOURCES

3.3.1 Technological Input Parameters

.3.1.1 Household Consumption Profile

The household consumption profile was sourced from the U.S. Department of Energy's OpenEI database. These data are calculated by the Office of Energy Efficiency and Renewable Energy (EERE) using residential building models and the EnergyPlus simulation software (Office of Energy Efficiency & Renewable Energy, n.d.). The profile predicts hourly electricity consumption for a household in Plymouth, MA, with an annual electricity demand of 8,853 kWh. This value was deemed reasonable given that the average New England household consumes 7,536 kWh of electricity per year (MassCEC, 2019). Figure 3 illustrates the average annual hourly load for the household consumption profile.

3.3.1.2 PV Generation Profile

The PV generation profile uses predicted values from the National Renewable Energy Laboratory's (NREL) PVWatts Calculator (National Renewable Energy Laboratory, 2016). The latitude and longitude of the profile are set to 41.97° N, 70.66° W, corresponding roughly to Plymouth, MA. The base case PV system size is set at 7 kW_{dc}, the average residential PV system size in Massachusetts (MassCEC, 2019). Other PV capacities tested in the analysis include a 3.5 kW_{dc} system and a 10.5 kW_{dc} system. The tool predicts AC system output in kilowatts for every hour of the year.

Technology specifications are set to standard modules in a fixed roof-mount array. The calculator assumes a 33° tilt angle since most homes in New England have roofs that are pitched at 33° or more to shed snow and ice (MassCEC, 2019). Ideally, a fixed roof-mounted PV array should be at an angle equal to the latitude of the location where it is installed to maximize exposure to sunlight over the year. However, adding tilt to a solar racking can increase installation costs and may lead to panels shading one another (EnergySage, 2018b).

Azimuth is set to 180°, implying a south-facing roof. A capacity factor of 15.3%, a DC to AC size ratio of 1.2, and an inverter efficiency of 96% are all used based on the calculator's recommendations. Figure 4 shows the average annual hourly PV generation profiles for the three PV capacities tested in this analysis.

3.3.1.3 Battery Storage

For the PV-battery base case, a maximum storage capacity of 13.5 kWh is used to reflect the capacity of the Tesla Powerwall 2, a market-leading product in the U.S. residential battery market. This analysis also tests the performance of 6.75 kWh and 20.25 kWh batteries, representing a 50% change in capacity from the base case. The round-trip efficiency of the batteries is assumed to be 87%, slightly less than the 90% figure Tesla advertises to be conservative (Tesla, 2019).

3.3.1.4 Yearly Degradation Rate

Since the "Lifetime NPV" model requires measuring the

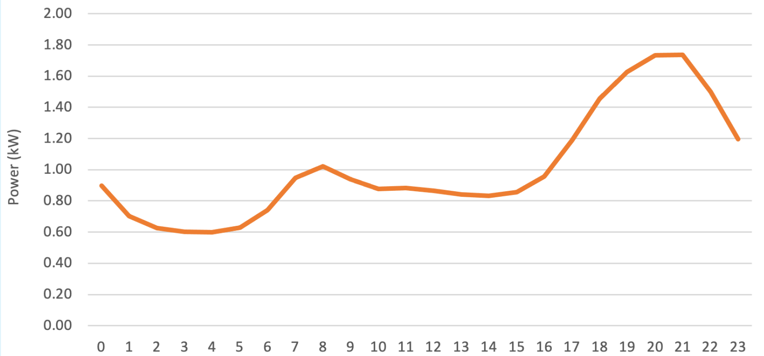

FIGURE 3: AVERAGE ANNUAL HOURLY ELECTRICITY CONSUMPTION PROFILE FOR A HOUSEHOLF IN PLYMOUTH, MA.

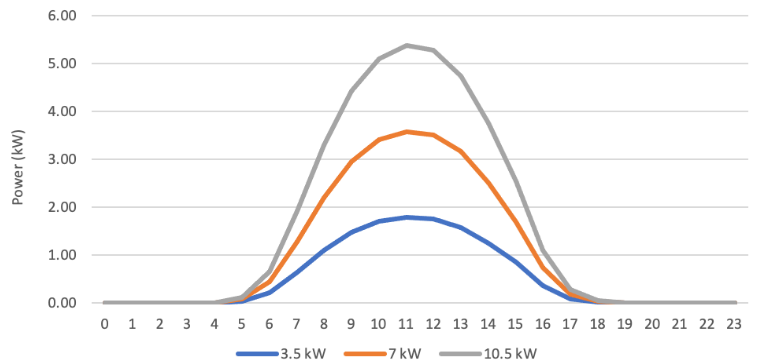

FIGURE 4: AVERAGE ANNUAL HOURLY GENERATION PROFILES PROJECTED FOR RESIDENTIAL PV SYSTEMS NEAR PLYMOUTH, MA.

value of these technologies over many years, it needs to account for losses of value due to technology degradation. Therefore, degradation rates are applied to both the PV and battery technologies. The PV degradation rate is based on an NREL study which found the median rate of degradation for solar panels to be 0.5% per year (Jordan & Kurtz, 2012).

Annual losses in maximum battery capacity and efficiency could either be a function of charge cycles or modeled using a fixed rate. I use a fixed rate derived from the 10-year warranty of Tesla's Powerwall 2 product. The warranty states that each Powerwall will retain 70% of its 13.5 kWh capacity, or 9.75 kWh, at 10 years following its initial installation date (Tesla, 2017). I use a 2% annual degradation rate, bringing the Powerwall's maximum capacity down to 11.26 kWh after 10 years.

3.3.2 Economic Input Parameters

3.3.2.1 Technology Costs

The capital cost of the PV system is assumed to be $2.84/$W_{dc}$ based on estimates for the national average residential system cost in the US before federal tax credits (SEIA, 2020). Operating and maintenance costs are based on the 2018 NREL O&M Cost Model which includes preventative maintenance, scheduled at regular intervals with costs increasing at an inflationary rate, and corrective maintenance to replace components. The model estimates annual O&M costs to be $22/$kW_{dc}$ (Fu, et al., 2018).

The capital cost of the battery system is assumed to be $800/kWh. This is based on pricing for the Tesla Powerwall 2 and includes estimates for system cost, installation costs, and additional hardware costs (Sendy, 2020). Operating and maintenance costs reflect the costs of replacing the battery at the end of its 10-year lifetime.

A price deflation rate of 0.02% is applied to the battery's capital cost value each year to account for future price decreases for lithium-ion battery products. Under these conditions, battery costs are projected to drop to $667/kWh by 2030, $545/ kWh by 2040, and $445/kWh by 2050. No price deflation rate is needed for the solar panels since this analysis assumes they are only installed once.

3.3.2.2 Retail Electricity Price

According to the U.S. Energy Information Administration, the average price of electricity in 2020 for residential consumers in Massachusetts is $0.22/kWh (U.S. Energy Information Administration, 2020). Prices are expected to increase in small increments over time given national trends in electricity rates over the past decade (U.S. Energy Information Administration, 2019). Therefore, a price inflation rate of 1% is applied annually.

3.3.2.3 Net Metering Price

Massachusetts utilities currently offer net metering credits to residential customers at the retail electricity rate. In this analysis, I test scenarios where net metering prices are either offered at 50% of retail electricity prices or not offered at all.

3.3.2.4 Government Subsidies

The federal ITC partly subsidizes capital costs for PV and PV-battery systems. In 2020, the federal ITC covers 26% of investment costs for both systems, so long as batteries are charged by the solar panels more than 75% of the time (National Renewable Energy Laboratory, 2017). Massachusetts also offers a personal income tax credit for 15% of total PV system capital costs, with a maximum credit of $1,000 (MassCEC, 2019). Both tax credits are applied to capital costs in the "Lifetime NPV" model.

Massachusetts' SMART Program offers incentive payments for a 10-year term to the owners of residential PV systems, with additional incentive payments provided to the owners of PV systems that integrate battery storage (MassCEC, 2019). A value of energy calculator is available on the program administrator's webpage to help calculate expected incentive payments based on solar capacity, storage capacity, and the duration of the storage. I used this calculator to find the appropriate 10-year incentive payments for various standalone PV and PV-battery system sizes tested in the "Lifetime NPV" model.

While the above mentioned subsidies all exist in reality, I decided to add one speculative subsidy into the "Lifetime NPV" model. If implemented, a carbon tax would increase the cost of electricity, thus incentivizing the use of standalone PV or PV-battery systems. Based on a 2015 study conducted by the Tax Policy Center, a $10/ton carbon tax would add about $0.05/kWh to the price of electricity generated from a typical fuel mix (Marron, et al., 2015). I account for a $40/ton carbon tax in 2035, which would cause retail electricity rates to increase by approximately $0.02/kWh from that year forward.

3.3.2.5 Discount Rate

Based on a review of previous studies, 4% is chosen as the nominal discount rate to be applied in the "Lifetime NPV" model (Hoppmann, et al., 2014).

3.3.3 Environmental Input Parameters

3.3.3.1 Life Cycle GHG Emissions

Through a meta-analysis of existing literature on PV life cycle assessments, Nian (2016) found the median value for the life cycle emissions of solar panels to be about 1,320 kg CO_2e/kW. Based on an extensive review of life cycle assessments for lithium-ion batteries, Peters et al. (2017) found the average value for the life cycle emissions of lithium-ion batteries to be 110 kg CO_2e/kWh. I apply each of these in the "Lifetime Net Emissions" model.

3.3.3.2 Grid Emissions Intensity (Annual)

Emissions data from ISO New England shows that its network's average GHG emission rate in 2017 was 682 lb. CO_2e /MWh (ISO New England, 2019a). This translates to 0.31 kg CO_2e/kWh and represents a 3.9% decrease from the 2016 average. Given the ambitious target set by New England states to reduce the region's GHG emissions by 80% from 1990 levels, we can expect this average to continue declining (Weiss et al., 2019). Therefore, I apply a 4% annual decrease in average emission rates for the "Lifetime Net Emissions" model.

4. RESULTS

4.1 Energy Flows

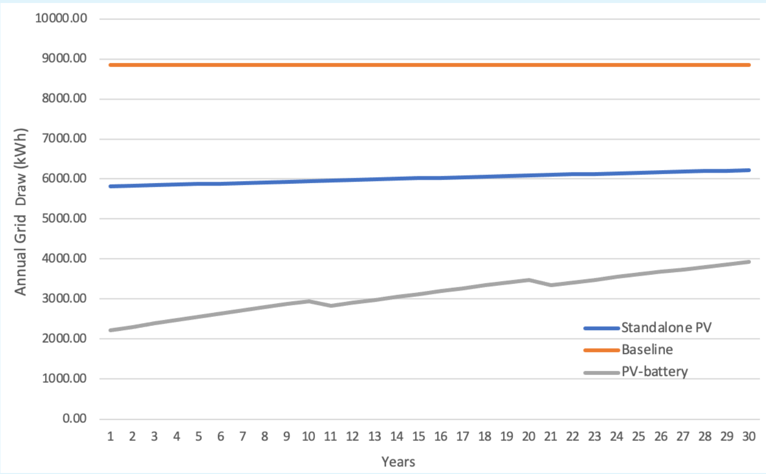

FIGURE 5: HOUSEHOLD GRID RELIANCE UNDER THE BASELIE, STANDALONE PV, AND PV-BATTERY SCENARIOS

Configuration	PV size (kW)	Battery size (kWh)	Self-Consumption (%)	
			Standalone PV	*PV-battery*
A	7	13.5	34	75
B	3.5	13.5	30	50
C	10.5	13.5	36	81
D	7	6.75	34	58
E	7	20.25	34	80

TABLE 1: SELF-CONSUMPTION LEVELS FOR VARIOUS PV-BATTERY SIZE CONFIGURATIONS

4.1.1 Comparing Standalone PV & PV-battery Systems

This analysis looks at how a Massachusetts household with an annual electricity load of 8,853 kWh can reduce reliance on the electric grid using standalone PV or PV-battery technologies. With neither of these systems installed, the grid supplies all of the household's electricity demands. After installing a 7 kW PV system, the household's annual grid draw drops to 5,811 kWh. By pairing a 13.5 kWh battery with the 7 kW PV system, annual grid draw drops to 2,216 kWh. It is useful to measure these differences in terms of self-consumption, or the percentage of total electricity consumption supplied on-site. In this case, the homeowner is able to meet 74% of total electricity consumption needs through self-consumption using a PV-battery system, compared to just 35% with solar panels and no battery. It is important to note that these values only represent each technology's first year of operation. Figure 5 demonstrates that grid reliance steadily increases in subsequent years as each technology degrades. Small dips in annual grid draw for the *PV-battery* scenario occur every 10 years when the battery is replaced, reflecting the gains in efficiency with a newly installed battery.

4.1.2 Effects of System Size

Through testing alternative size configurations for Standalone PV and PV-battery systems in the "Year One Energy Flows" model, we see different levels of self-consumption associated with each configuration for the first year of operation (see Table 1).

As represented by configurations B and C, changes in PV capacity have very little impact on self-consumption under any Standalone PV scenario. In these cases, the maximum difference in self-consumption resulting from a 50% change in PV capacity is just four percentage points. On the other hand, decreasing PV capacity has notable effects on self-consumption under the *PV-battery* scenario. Self-consumption levels for Configuration B are 25 percentage points lower than those of configuration A.

A 50% increase in battery capacity (upgrading configuration A to configuration E) only results in a five-percentage point increase in self-consumption. Decreasing battery capacity to 6.75 results in a 17 percentage point decrease in self-consumption which, although significant, is still less than the changes seen when the same amount decreases PV capacity.

Figures 6, 7, and 8 further illustrate how differences in battery size impact the energy flows of PV-battery systems. By contrasting the average annual hourly energy flows of configurations A, D, and E in their first year of operation, we can visualize differences in battery discharge, grid draw, and net metering. Amongst the three systems, configuration D demands the most electricity from the grid, and sends the most electricity back to the grid for net metering. Configuration E can continuously discharge electricity from its battery for long periods, and only demands small amounts of electricity from the grid throughout the night. Configuration A typically operates somewhere in between these two extremes.

4.2 CASH FLOWS

4.2.1 Comparing Standalone PV & PV-battery Systems

When making any large financial investment, one important consideration is the amount of time it will take for the investment to become profitable. Given that residential solar and solar-plus-storage installations can cost tens of thousands of dollars, homeowners would greatly benefit from knowing each technology's expected payback period. In this analysis, I calculate the expected payback period for PV and PV-battery systems in Massachusetts by determining when their NPV becomes positive in the "Lifetime NPV" model. Results show that after just five years, the base case standalone PV system attains a positive NPV, compared with the PV-battery system, which takes seven years to

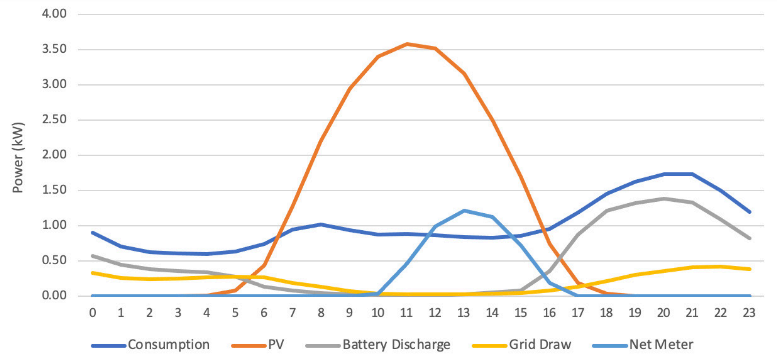

FIGURE 6. AVERAGE ANNUAL HOURLY ENERGY FLOWS (CONFIGURATION A).

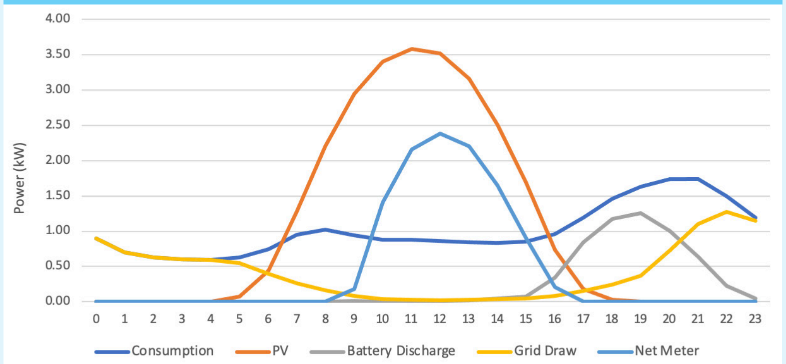

FIGURE 7. AVERAGE ANNUAL HOURLY ENERGY FLOWS (CONFIGURATION D).

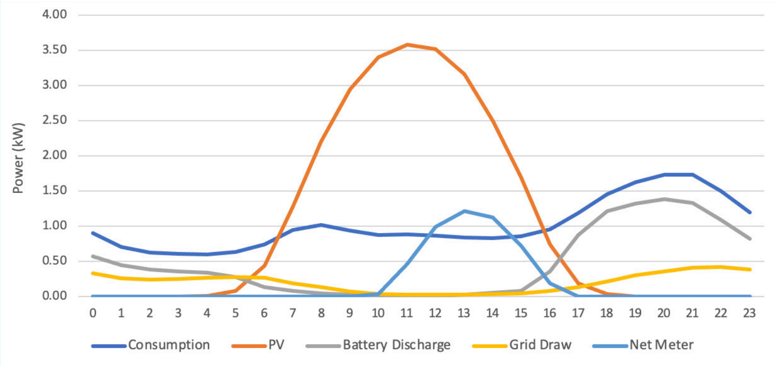

FIGURE 8. AVERAGE ANNUAL HOURLY ENERGY FLOWS (CONFIGURATION E).

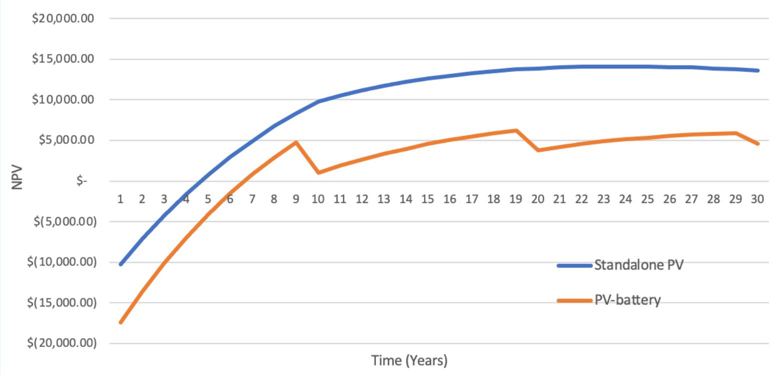

FIGURE 9. NPV FOR A STANDALONE PV SYSTEM AND PV-BATTERY SYSTEM.

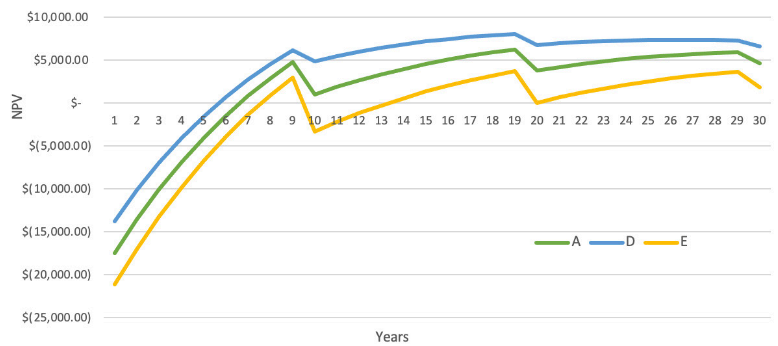

FIGURE 10. EFFECTS OF BATTERY CAPACITY ON PV-BATTERY NPV.

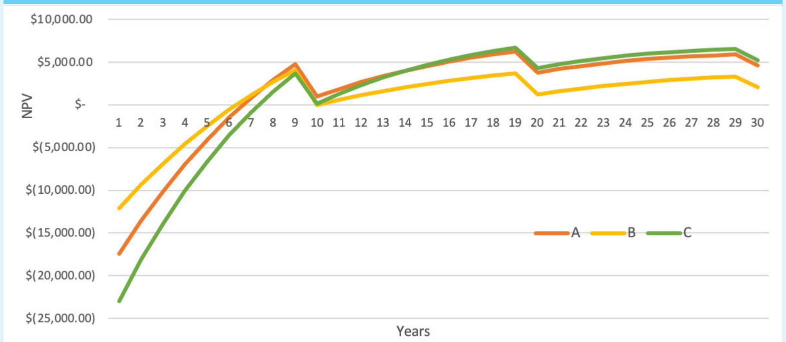

FIGURE 11. EFFECTS OF PV CAPACITY ON PV-BATTERY NPV.

break even. With higher capital costs at the outset of the study period, the PV-battery system's NPV experiences multiple dips throughout the 30-year period (see Figure 9). These dips can be attributed to the high costs of replacing the battery at the end of its lifetime which, in this analysis, is every 10 years. Homeowners may be able to continue using their battery past its intended lifetime. However, cost savings from not purchasing a replacement could be offset by losses in efficiency and maximum capacity as the battery continues to degrade. There may also be added safety risks when using large lithium-ion batteries past their lifetime.

4.2.2 Effects of System Size

When deciding whether to install a residential PV-battery system, homeowners should always consider a variety of system sizes to determine which may best suit their needs. In this analysis, I examine how the PV-battery size configurations listed in Table 1 compare in economic performance over a 30-year period. First, I measured differences in payback period between configurations A, D, and E, all of which share a 7 kW PV capacity but differ in battery size.

Figure 10 shows that configuration D, which has the smallest battery capacity, also has the shortest payback period. Although configuration E only has a slightly longer payback period than configurations A and D, replacing the battery after 10 years incurs high maintenance costs. Aside from higher replacement costs, other factors associated with battery size also contribute to differences in NPV over each configuration's lifetime. For example, larger batteries influence system revenues by increasing avoided electricity costs and, simultaneously, decreasing net metering revenues. The profitability of this tradeoff depends on factors such as the household's electricity consumption profile, net metering rates, and PV capacity.

Additionally, SMART incentive payments are partly influenced by battery capacity since the program's "Energy Storage Adder" is based on the ratio of PV capacity to battery capacity. As battery capacity increases relative to PV capacity, incentive payment rates increase, although the difference is quite small and payments only last for the first 10 years of operation.

Configuration	PV size (kW)	Battery size (kWh)	Payback Period (Years)	Maximum NPV
A	7	13.5	7	$6,230.82
B	3.5	13.5	7	$4,121.10
C	10.5	13.5	8	$6,704.74
D	7	6.75	6	$8,023.87
E	7	20.25	8	$3,688.56

TABLE 2. PAYBACK PERIOD AND MAXIMUM NPV FOR DIFFERENT PV-BATTERY SIZE CONFIGURATIONS.

I then repeated this process with configurations A, B, and C, all of which have a battery capacity of 13.5 kWh but differ in PV capacity. Although the changes in PV capacity do little to affect the payback period, the long-term effects on NPV are significant. Figure 11 shows that after 15 years of operation, configuration C surpasses configurations A and B in NPV. Interestingly, configuration B reaches its peak NPV in year nine, but fails to recover that value throughout the rest of its operational lifetime.

The payback period and maximum NPV for all of the PV-battery configurations mentioned above are summarized in Table 2. It becomes clear that configuration D has the best economic performance of all the PV-battery systems modeled in this analysis, both in terms of payback period and maximum NPV.

4.2.3 Effects of Government Subsidies

It remains to be seen whether residential solar-plus-storage markets can survive without the support of robust government incentives. By omitting certain subsidies from the "Lifetime NPV" model, I was able to visualize their effects on the expected payback of residential PV-battery systems in Massachusetts more clearly. For a 7 kW PV system paired with a 13.5 kWh battery (configuration A), certain subsidies have a significantly greater effect on NPV then others. The system's NPV fails to break even throughout the 30-year study period without any government subsidies. The Federal ITC plays an important role in improving the economics of the system by reducing initial investment costs. However, federal subsidies alone only bring the payback period down to 25 years. Figure 12 shows that Massachusetts' SMART program has the greatest effect on payback time out of any subsidy by substantially increasing system revenues throughout operation. Combining the Federal ITC and SMART incentive payments ultimately reduces the expected payback time to just seven years. Interestingly, implementing a $40/ton carbon tax in 2035, which would theoretically increase retail electricity prices, does virtually nothing to increase NPV in the following years.

4.2.4 Effects of Net Metering

Net metering has been proven to add significant value to

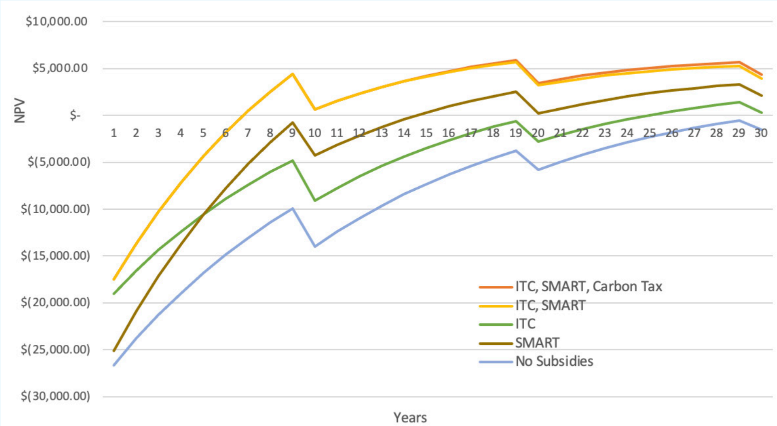

FIGURE 12. EFFECTS OF DIFFERENT GOVERNMENT SUBSIDIES ON PV-BATTERY NPV.

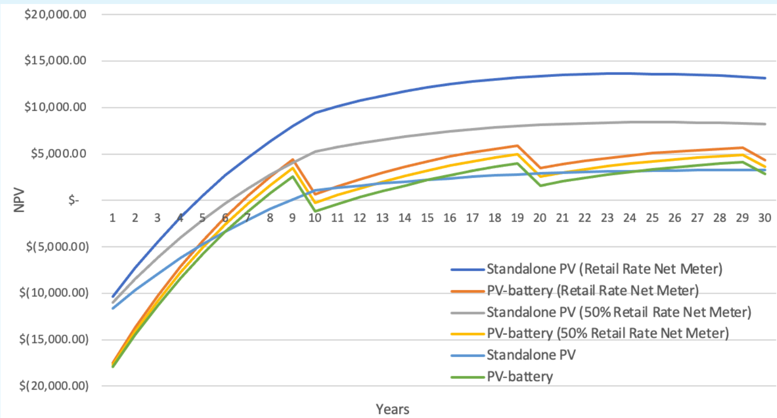

FIGURE 13. EFFECTS OF DIFFERENT NET METERING PRICES ON STANDALONE PV & PV-BATTERY NPV.

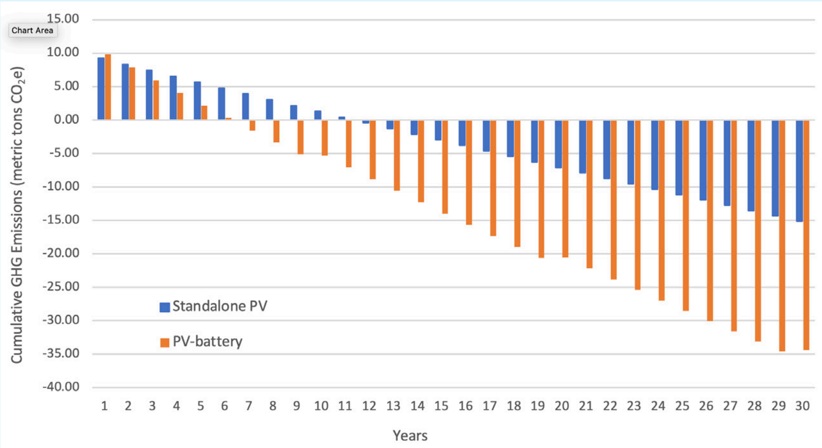

FIGURE 14. CUMULATIVE GHG EMISSIONS FOR STANDALONE PV AND PV-BATTERY SYSTEMS OVER A 30-YEAR PERIOD.

residential PV systems over time when offered at the full retail rate. In this analysis, I attempted to quantify that value by modeling scenarios where net metering is offered at a reduced rate, or not offered at all. I then looked at how these same changes would affect the economic performance of a PV-battery system. My findings suggest that reducing net metering rates by 50% raises the payback time of a standalone 7 kW PV system from five years to seven years, and eliminating net metering extends that payback period to nine years. Figure 13 shows just how little these changes affect PV-battery systems in comparison. Lowering the net metering rate by 50% only extends the payback period of the base case PV-battery system to eight years. After eliminating net metering, the payback period remains below nine years, shorter than the time needed to pay back the standalone PV system under the same circumstances. These findings reveal just how dependent standalone PV systems are on net metering revenues for economic viability. The expected payback period for PV-battery systems is barely impacted by these revenues.

4.3 GHG Emissions

4.3.1 Comparing Standalone PV and PV-battery Systems

In this study, I modeled the net GHG emissions associated with standalone PV systems and PV-battery systems over 30 years. My results indicate that the base case standalone PV system ends its 30-year lifetime with a net emissions value of -15.09 metric tons of CO2e while the base case PV-battery system has a net emissions value of -34.36 metric tons of CO2e. Figure 14 shows that the PV-battery system begins its lifetime with higher net emissions than the standalone PV system. This is due to the emissions that come with the production of the battery. However, as the PV-battery system continues through its operational lifetime, net emissions drop at a rapid pace unmatched by the standalone PV system. This can be attributed to the PV-battery system's enhanced ability to offset fossil fuel generation from the grid in favor of clean energy produced on-site. Replacing the battery every 10 years has little impact on offsetting these gains in emissions abatement.

It should be noted that this analysis assumes every kWh of electricity consumed from the grid results in the same amount of GHG emissions, regardless of the time of day or season. In reality, the emissions intensity of the electric grid changes hour by hour throughout the year.

5. DISCUSSION

Residential PV-battery systems have been proposed as a way for homeowners to reduce their reliance on the grid by storing excess power produced from their solar array for self-consumption. My analysis supports this claim, showing that PV-battery systems could increase a typical Massachusetts household's self-consumption percentage between 50% and 81%. In comparison, the standalone PV systems modeled in this study could only increase the same household's self-consumption percentage to a maximum of 36%. Although PV-battery configurations A, C, and E support self-consumption levels at or above 75%, this does not necessarily imply that the household in question could disconnect from the grid and meet its electricity needs for three quarters of the year. I cannot make this assertion because this model focuses on a battery's ability to meet a household's hourly energy demands without accounting for peaks in power usage. Low maximum power output is a common characteristic of lithium-ion batteries and, without the support of the grid, home battery systems may only be able to power a few small appliances at a time. This has long been one of the major weaknesses of residential PV-battery systems considering that many homeowners install these systems with hopes of disconnecting from the grid, or having total backup power in an outage (Cinnamon, 2019). Additionally, the household consumption profile used in this analysis does not represent all Massachusetts households. Future analysis should attempt to uncover how high and low estimates for household electricity consumption affect grid reliance and optimal system sizing.

Looking at Table 1, it is not surprising that the PV-battery configurations with the highest PV capacity and battery capacity, configurations C and E, respectively, also support the highest levels of self-consumption. However, in economic terms, these high-capacity systems do not perform as well as other configurations. In fact, Table 2 shows that configurations C and E have the longest payback periods of all the PV-battery configurations. The shortest payback period and maximum NPV belong to configuration D, a PV-battery system consisting of a 7 kW PV array and a 6.75 kWh battery. This enhanced performance is primarily driven by decreased capital costs and O&M costs associated with the smaller battery. One major shortcoming of the "Lifetime NPV" model is the assumption that capital costs for these technologies can be covered upfront without outside financing. While some homeowners may be able to afford these high upfront costs, many would struggle to afford them without a loan. Ideally, this analysis would be repeated for different financing scenarios. One innovative idea piloted in parts of the U.S. is to have utilities lease PV-battery systems to their customers for a monthly fee. Having access to thousands of customers' batteries would enable utilities to draw power when needed most, shaving peak demand and reducing peak system usage charges. For Green Mountain Power, Vermont's largest electric utility, this program resulted in increased reliability and lower overall costs for ratepayers (Mingle, 2019). In return, customers get to enjoy the benefits of their PV-battery system, without the high upfront costs, on the condition that they surrender control over their batteries during peak events which can occur several times a month for hours at a time.

The "Lifetime NPV" model makes it very clear that government subsidies still play a crucial role in supporting the economic viability of PV battery systems in Massachusetts. Without the federal ITC, the payback period for a 7 kW solar array paired with a 13.5 kWh battery jumps from seven to 15 years. By cutting Massachusetts' SMART incentive program on top of this, the same system fails to break even throughout its operational lifetime. Given that the federal ITC is set to phase out entirely for residential installations by 2022, Massachusetts policymakers may want to consider scaling up the state's personal income tax credit in compensation. On April 15, 2020, the Massachusetts Department of Energy Resources and Governor Charlie Baker's office released emergency regulations doubling the size of the SMART program, bringing the program's total capacity to 3.2 GW (Sylvia, 2020). With specific carve-outs for smaller projects, any new standalone PV or PV-battery installations will likely qualify for incentive payments in the near future.

Another key takeaway from the "Lifetime NPV" model is the impact of net metering on the economic performance of PV-battery systems in the state of Massachusetts. When offered at the full retail electricity rate, net metering seems to do more to hurt residential solar-plus-storage markets than to help them. Under these circumstances, it is much more profitable for homeowners to install standalone PV systems than installing PV-battery systems because any excess electricity they produce can quickly be sold back to the grid. Alternatively, if utilities were to forgo net metering entirely, owners of standalone PV systems would not be compensated for any of the excess electricity they produce. Therefore, storing the electricity in a battery for eventual self-consumption would become the only way solar owners can extract value from their excess electricity generation. This represents significant upside for residential solar-plus-storage markets, seeing that electric utilities across the nation are beginning to reconsider net metering offerings because of the way these programs shift costs to customers without solar (Trabish, 2019b).

Regarding environmental performance, my findings suggest that PV-battery systems have net negative GHG emissions and outperform standalone PV systems in cumulative lifetime net emissions. Compared to solar panels, the production of lithium-ion batteries contributes very little to net emissions. By offsetting a greater amount of electricity production from the grid, the base case PV-battery system helped abate 24.18 more metric tons of CO_2e than the standalone PV system after 30 years of operation.

It should be noted that this analysis only accounts for one particular measure of environmental performance. While net GHG emissions are certainly an important metric to consider, other environmental impact measures such as resource use and toxicity also deserve consideration.

6. CONCLUSION

Residential PV-battery systems have the potential to reduce homeowners' reliance on the electric grid, helping them to save money and lessen their carbon footprint. This study was designed to measure how well PV-battery systems achieve those objectives in the state of Massachusetts under various economic and technological assumptions. Using several spreadsheet models to represent the energy flows, cash flows, and GHG emissions of PV-battery systems, I was able to produce the following insights:

- Residential PV-battery systems are already a viable means for Massachusetts homeowners to reduce grid reliance, lower their electricity costs, and offset GHG emissions.

- Out of the six PV-battery system sizes considered, no one configuration stood out as the top performer across all categories of performance. For reducing grid reliance, PV-battery systems with high solar capacity are the best option. In terms of saving money and seeing those returns quickly, PV-battery systems with small batteries offer the most value.

- Government subsidies will continue to play a crucial role in supporting the economic viability of PV-battery systems in Massachusetts, especially the state's SMART program, which substantially increases system revenues throughout operation. If the federal ITC expires in 2022 as planned, the expected payback period for these systems will more than double.

- Net metering as it is currently offered in Massachusetts incentivizes the adoption of standalone PV systems considerably more than PV-battery systems. In cases where net metering credits are not offered to electricity customers, the payback period for PV-battery systems becomes slightly shorter than that of standalone PV systems.

Further research on this topic would benefit from analyzing a wider variety of household electricity consumption profiles, financing scenarios, modes of operation for home battery systems, and metrics of environmental performance. Additionally, increased penetration of residential PV-battery systems in society will demand more in-depth research on how these technologies impact day-to-day grid operations.

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