UHERO
THE ECONOMIC RESEARCH ORGANIZATION
AT THE UNIVERSITY OF HAWAI'I

Residential Battery Systems and the Best Time to Invest
A case study of Hawaii

BY

Aida D. Arik

Working Paper No. 2017-9
December 11, 2017

UNIVERSITY OF HAWAI'I AT MANOA
2424 MAILE WAY, ROOM 540 • HONOLULU, HAWAI'I 96822
WWW.UHERO.HAWAII.EDU

Residential Battery Systems and the Best Time to Invest
A case study of Hawaii

UHERO Working Paper

Aida D. Arik
Ph.D. Student
Department of Urban and Regional Planning
University of Hawaiʻi at Mānoa
aarik@hawaii.edu

Abstract

Battery storage is a complementary technology to intermittent renewable energy sources. In particular, it pairs well with solar photovoltaic (PV) systems to capture excess solar generation during daylight hours and to draw energy from it when needed. Technological advancements and rapidly declining costs have made batteries more economically feasible for households, especially in the state of Hawaiʻi, which faces the highest cost of electricity in the U.S. With the sunset of net energy metering (NEM) in 2015, and technical limitations from interconnecting additional PV systems capable of exporting energy to the grid, non-exportable PV systems are increasingly a viable option for residential customers in Hawaiʻi. This paper analyzes whether the installation of a PV plus battery system is economically compensatory for households on Oahu, with the power grid as a back-up option. Given the importance of state and federal tax incentives in reducing capital costs, this paper compares household savings in the decision to invest now or later, given that the federal tax credit of 30% is set to decline in 2020 and expire by 2022. Installing a PV plus battery system in 2019 could increase net savings by 17-32% in Oahu compared to installing the same system in 2017.

Acknowledgements

This paper was completed to fulfill the Master Degree requirements for the University of Hawaiʻi at Mānoa Department of Economics. The topic was inspired by a project led by Dr. Makena Coffman as the Principal Investigator. The project received financial support from the State of Hawaii Division of Consumer Advocacy. I thank Dr. Coffman for her input on this paper, as well as my other capstone committee member, Dr. Kimberly Burnett. I also thank Dr. Sherilyn Wee for her thoughtful feedback.

1. Introduction

The "grid of the future" is being shaped by household adoption of technological innovation, most recently in distributed solar photovoltaic (PV) and electrified transportation. This paper focuses on what is perhaps the next stage of household energy technology adoption: the residential battery. Batteries pair well with PV systems to store energy that might otherwise be curtailed during times when the solar energy generated is greater than the household demand for electricity. With the highest electricity prices in the U.S. and the lowest electricity consumption rates (EIA 2016), Hawai'i serves as a test-bed for the adoption of household batteries. That is, if batteries are viable in Hawai'i, it is a positive indication of imminent prospects elsewhere. A study of the economic viability of residential solar PV by Hagerman et al. (Hagerman, Jaramillo, and Morgan 2016) found that Hawai'i was the only state in the U.S. where energy from solar PV can be generated at a cost equivalent to the retail electricity rate. Rocky Mountain Institute similarly published a study that found Honolulu to be the first to reach economic viability for grid-connected PV+battery systems out of five major U.S. cities (Bronski et al. 2015). Hawai'i is rich and geographically varied in solar resources and is a national leader in adoption of clean energy technology and policy (Clean Edge 2015). Until 2015, electricity customers wishing to install PV could enroll in net energy metering (NEM), a program where excess electricity sent to the grid would be credited on the electricity bill at the full retail rate (Hawaiian Electric 2015). Challenged with technical limitations of interconnecting additional PV systems capable of exporting energy to the grid (i.e. grid-supply), other systems such as non-exportable PV systems (i.e. self-supply) are a prospective option for residential customers (Hawaiian Electric Company 2017). Batteries thus represent the next step in household electricity self-sufficiency.

In this analysis, I focus on the City & County of Honolulu, which is the island of Oahu. Relative to the rest of the counties within Hawai'i, Oahu supports the largest population center and the lowest electricity prices in the state (DBEDT 2017), as well as ranks first in the nation for PV installed per capita (Norman, Sargent, and Fanshaw 2016). Rate structures for residents in Oahu include a monthly fee for grid connection. Electricity used from the grid is assessed a per kilowatt-hour (kWh) charge that is intended to include both the "fixed costs" of grid infrastructure and an average marginal cost of utility electricity generation. Although the state of Hawai'i has a Renewable Portfolio Standard (RPS) in place to reach 100% renewable energy sales by 2045, the current electricity generation portfolio is still largely tied to oil. Policy incentives have played an important role in adoption of PV (Timilsina, Kurdgelashvili, and Narbel 2012) and will likely be an important component in household battery adoption, particularly for newly installed PV systems. Thus, I explore the household financial payback of installing battery systems as well as the net savings gained by optimally timing installation, given the declining prices of batteries and the scheduled phase-out of the federal tax rebate.

2. Levelized Cost Applied to Electricity Storage

With batteries becoming a rapid reality to solving intermittency issues inherent with renewable energy generation, there has been a recent effort in the literature to develop levelized cost of energy (LCOE) methods that can be applied to electricity storage for a solar PV system. Typically, levelized cost is a measure used to compare lifetime cost of different energy generating technologies by dividing the total lifetime energy generated by the net lifetime costs adjusted for interest. The measure of LCOE is best used for actively controlled power generators out of which it was developed, and does not capture a true levelized cost for intermittent renewable energy technology where energy generated might be curtailed. Levelized cost literature as applied to batteries build on foundational work in developing levelized measures for solar PV summarized in a review paper by Branker et al. (2011). Lai and McCulloch (2017) provide a literature review of methods of levelized cost calculations for both PV systems and battery storage systems, as well as propose a method of levelized cost of delivery to separate value for storage systems alone. They find that vanadium redox flow batteries have a lower cost of delivery when compared with lithium-ion battery technology. Specific to utility-scale application, Obi et al. (2017) provide a generalized LCOE algorithm for calculating electricity-specific energy storage systems for utility application assuming an annual output. Their methodology expands on methodology detailed by Pawel (2014) to include tax incentives.

Several studies based in Germany offer outlooks to investment in residential PV+battery systems. Hoppmann et al. (Hoppmann et al. 2014) use a simulation model to find that investments in lead-acid battery storage for residential PV were already economically viable in 2013. Whereas, Jülch et al. (2015) find PV+battery systems will likely be economically attractive by 2020. This paper also develops a methodology for levelized cost of storage combined with a life cycle analysis, finding lithium-ferrophosphate having the lowest costs when compared to lead-acid and lead-gel batteries. Naumann et al. (2015) found that lithium-ion battery investment would be profitable in 2015 under a modeled scenario of increasing electricity prices and strongly decreasing storage prices, with the prediction of positive return on investment in the near future.

In this analysis, I modify the levelized cost metric to account for the actual usage of electricity per source (i.e., PV or battery), and refer to this as "effective cost." Fundamental to my analysis of effective cost for PV+battery systems is a household temporal usage simulation that takes into account seasonality of solar resources and household demand. Similar to the levelized cost methodology, I normalize system cost, except by actual system electricity usage rather than the electricity generated by source as traditionally defined. This method of normalizing by usage gives better understanding of the value added by battery storage in its effectiveness to capture otherwise curtailed energy when solar PV generation exceeds household demand. I also apply a similar concept to calculate an effective savings as a comparison value. As calculated within, effective savings is the avoided electricity costs associated with using self-generated rather than grid-supplied electricity.

2.1 Effective cost/savings methodology

For this analysis, I compare present value calculations by normalizing present value costs and savings by the amount of electricity used per system. *Effective costs* (EC), for PV systems (PV) or combined PV+battery systems ($PV, batt$) are given by:

$$EC_{PV} = \frac{C_{0,PV}}{\sum_{t=0}^{T} U_{t,PV}}$$

$$EC_{PV,batt} = \frac{C_{0,PV} + C_{0,batt}}{\sum_{t=0}^{T}\left(U_{t,PV} + U_{t,batt}\right)}$$

where C_0 is the initial capital investment taking into account subsidies, U_t is the annual electricity usage from the technology source in kWh, and T is the lifetime of analysis in years. It is assumed that there are no annual maintenance costs.

Similarly, *effective savings* (ES) are calculated by normalizing present value avoided electricity costs by the amount of electricity used per system over the specified timeframe:

$$ES_{PV} = \frac{\frac{\sum_{t=0}^{T} S_{t,PV}}{(1+r)^t}}{\sum_{t=0}^{T} U_{t,PV}}$$

$$ES_{PV,batt} = \frac{\frac{\sum_{t=0}^{T}(S_{t,PV}+S_{t,batt})}{(1+r)^t}}{\sum_{t=0}^{T}\left(U_{t,PV} + U_{t,batt}\right)}$$

where S_t is the present value annual avoided electricity costs, also calculated from source usage. This set-up takes into account the seasonal variation of solar irradiation, the efficiency degradation of PV panels, the loss of battery capacity, and electricity price forecasts as detailed further in sections 2.2 and 2.3. Figure 1 is a conceptual sketch of the temporal usage electricity usage simulation. At an hourly resolution, the simulation uses average household demand and solar irradiation to estimate the amount of solar electricity produced that can be directly used per season, where August produces the most solar electricity and November produces the least.

From the unutilized solar electricity, the simulation calculates the amount of electricity that can be stored and then how much of the stored energy can be used based on demand during non-solar times. These calculations take into account the capacity loss of the battery and the PV panel efficiency loss. Thus, the average amount of electricity used directly from PV and from battery storage is determined for each season over the specified timeframe. The savings can then be calculated according to the electricity forecast based on the total avoided grid electricity usage from having a household PV+battery system. Economic viability, as defined in this analysis, occurs when $LS \geq LC$.

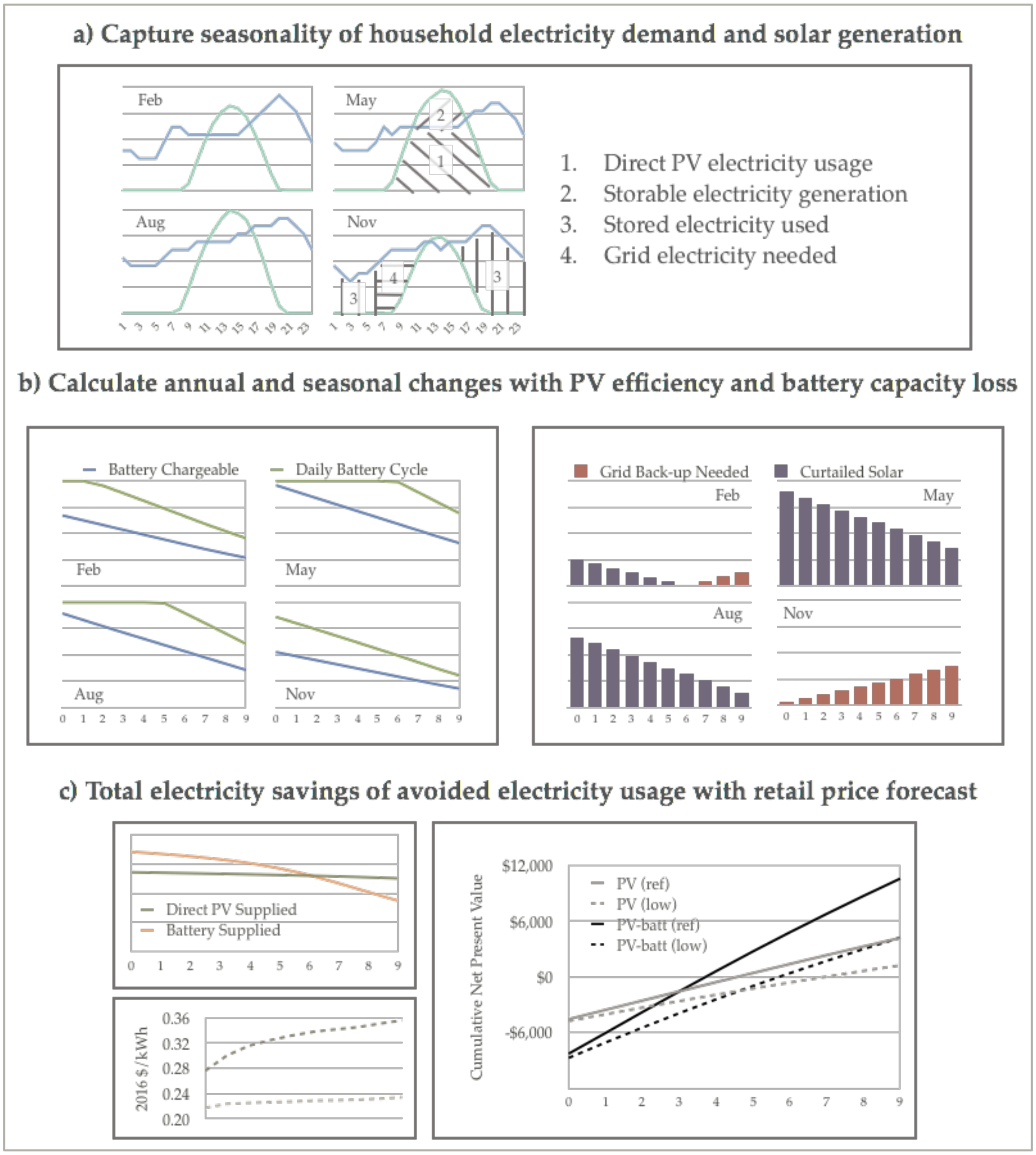

Figure 1. Conceptual process of simulating energy savings per year as aggregated over season and the total electricity drawn from each source. a) The hourly household electricity demand curve and the hourly solar irradiation is used to calculate the amount of PV generated electricity that can be directly used or stored. Based on the demand, the amount of stored electricity that can be used and the amount of grid back-up needed is calculated seasonally. b) With PV panel efficiency loss and loss of battery depth of discharge capacity, the seasonal and annual changes are captured to calculate what electricity source will cover household demand. Curtailment occurs during the spring and summer months, while Grid back-up is always needed during the fall and winter is transitions to needing grid back-up as the PV+battery degrades with time. c) Using the retail electricity price forecast, the annual net present value of the PV only and PV+battery system are calculated.

Table 1. Parameter values used in household temporal usage simulation and effective cost analysis.

Household Characteristics	
Daily household load curve, 2014 (aggregate divided number of residential customers) (Navigant Consulting 2015)	Customer average daily totals [kWh] Feb: 18.5 May: 19.0 Aug: 21.4 Nov: 19.1
PV Characteristics	
Household system size	5 kW
Initial PV cell efficiency rating (National Renewable Energy Laboratory (NREL) 2017)	22%
Panel degradation (Jordan and Kurtz 2013)	0.5% per year
Inverter efficiency, for direct use	95%
Solar irradiance at Honolulu International Airport (Giambelluca et al. 2014)	Average daily max [W/m^2] Feb: 673 May: 797 Aug: 818 Nov: 607
Household Battery Characteristics	
Usable capacity (Tesla 2016)	13.5 kWh
Capacity loss (Dubarry, Devie, and McKenzie 2017)	6% per 250 cycles
Roundtrip efficiency (Tesla 2016)	90%
Financial Parameters	
Interest rate (U.S. Treasury 2017)	3%
PV cost, inclusive of install (Fu et al. 2016)	$3/W
Battery cost inclusive of install (Tesla 2016)	$500/kWh
State subsidy (HI Rev Stat § 235-12.5 2012)	$5,000
Federal tax credit (“H.R. 6 — 109th Congress: Energy Policy Act” 2005; “H.R. 2029 — 114th Congress: Consolidated Appropriations Act” 2016)	30% until 2020 26% in 2020 22% in 2021 Set expiration in 2022 for residential
Electricity price forecast (Coffman, Bernstein, and Wee 2017)	Reference & low

2.2 Household temporal usage simulation & financial parameters

In my analysis, I use a representative household, based on average household electricity consumption patterns, to simulate the interaction between PV generation over time and the cycling of a battery system. Table 1 summarizes the parameters used in the simulation. A constant demand curve over a 10-year horizon for an average household is assumed, based on 2014 Oahu data[1] for an average day in February, May, August, and November (Navigant Consulting 2015). These months were used as a proxy of demand for the entire season. Similarly, average daily solar irradiation at the Honolulu International Airport was used for the respective months to calculate average solar energy generation per season (Giambelluca et al. 2014). The insolation estimates are based on modeled clear sky radiation, cloud frequency estimates, and terrain shading. Although PV panels last much longer than 10 years, the timeframe was chosen as a reasonable expected lifetime of a household battery. It would be expected that if the usable life of either a household battery or PV panels is greater than 10 years, this would serve to increase savings.

PV panel efficiency is assumed to be 22%, which represents panels available on in the current market on the most-efficient end (NREL 2017). Based on an analytical review by Jordan and Kurtz (2013), a half percent decline in efficiency per year is applied to the panels. It is also assumes that there is a 95% inverter efficiency for direct PV electricity usage. These values were chosen as ideal technological parameters for a new PV installation. Degradation of panel efficiency and battery capacity loss is taken into account at each season, such that the amount of solar energy generation and usable battery storage changes at each interval, even though the demand and solar irradiation remains constant over the full ten years. The PV system size is based on average size reported for both Hawai'i and the U.S, but rounded to 5 kW for ease of calculation[2] of the state subsidy offered. The price of PV panels is assumed to be $3.00/W (Fu et al. 2016), inclusive of hardware and installation costs.

Table 2. Comparison of two major market contenders for lithium-ion household battery technology. Source: Tesla (Tesla 2016), Blue Planet Energy (Blue Planet Energy 2017)

Tesla Powerwall 2 (14 kWh)	**Blue Ion 2.0 (8/12/16 kWh)**
Battery cost: $5,500	Battery + install: $10,000[3]
Installation: ≥$1,000	Chemistry: lithium-ferrophosphate
Usable battery capacity: 13.5 kWh	Usable depth of discharge: 99%
Roundtrip efficiency: 90%	Roundtrip efficiency: 95%
7 kW peak/5 kW continuous	9 kW max/8.6 kW continuous[4]
10-year warranty	Lifetime: 8000 cycles

Lithium-ion battery systems are an emerging market in household applications, therefore little data is available on tested performance. Data used for this analysis includes information

[1]Aggregate residential demand curves for were estimated using Graphclick software, then divided by 266,900 (DBEDT 2017), representing the average number of residential customers for 2014.
[2]The Hawai'i State tax credit is 35% of costs of equipment and installation, capped at $5,000 per PV system
[3]Based on phone conversations with local PV installation companies. It might be assumed that this value represents the company's maximum quote and could be negotiated down.
[4]Calculated using reported 180 Amps continuous maximum system current and nominal system voltage of 48Vdc.

from sales specification sheets combined with tested data in the electric vehicle (EV) literature. Table 2 shows technical specifications of two major household batteries on the market, the Tesla Powerwall 2 and the Blue Planet Energy Blue Ion 2.0. While it is critical that battery performance in this analysis be grounded in realistic performance parameters, this analysis assumes an idealized battery system. Therefore, I use an initial battery capacity of 13.5 kWh at a cost of $500/kWh[5] with 90% efficiency based on the Tesla Powerwall 2 specifications, and assume a linear capacity loss of 6% per 250 cycles based on EV battery testing (Dubarry, Devie, and McKenzie 2017). A timeframe of ten years was chosen based on the warranty limit on the Powerwall 2. This timeframe was thought to be a reasonable assumption for the length of time a household lithium-ion battery might be expected to last, even though the technology has not been widely tested in household application, however, it does not reflect the longer lifetime of a PV system installation. Battery performance and lifetime will be dependent on many factors, including usage and temperature. Although the Blue Ion reports specifications for a more efficient and longer lasting battery, I did not use these parameters since the chemistry is different from most tested EV batteries. It is further assumed that the current and voltage of this idealized battery would accommodate the timing of charging and discharging needed.

Finally, the interest rate is assumed to be 3% (U.S. Treasury 2017). For simplicity, it is assumed that all the capital costs and subsidies or tax credits take place in the first year, and that there is no maintenance cost over the ten years of analysis. The State of Hawaiʻi offers a maximum of $5,000 rebate for a newly installed PV system (HI Rev Stat § 235-12.5 2012), coupled with a 30% federal tax credit that can be applied to both PV panels and batteries installed concurrently ("H.R. 6 — 109th Congress: Energy Policy Act" 2005; "H.R. 2029 — 114th Congress: Consolidated Appropriations Act" 2016). The final system cost is reflective of current prices given by major companies selling solar PV and battery systems. Moreover, the sensitivity of system specifications was tested to understand the effect of the assumptions on overall values.

2.3 Electricity price forecast

The electricity price forecast methodology is from Coffman et al. (2017) and updated for Oahu based on historical retail electricity prices and its correspondence to oil prices (DBEDT 2017). Forecasts are based on a simple regression analysis of oil prices related to electricity prices. Electricity is currently heavily dependent on oil-fired sources, thus electricity prices are known to track oil prices in Hawaiʻi. The forecast, however, does not take into account the Renewable Portfolio Standard (RPS) that the state of Hawaiʻi has in place, which includes decisive goals for replacing fossil fuel-based energy with renewables. Currently, Hawaiʻi has 70% oil-powered generation in its electricity portfolio, with a goal to reach 30% renewable sources by 2020 (DBEDT 2017). Estimating the influence renewable sources will have on electricity prices is a difficult task, because of the uncertainty in future fixed costs embedded in the volumetric fuel charge. For the purposes of this analysis, the timeframe of the forecast is 2017-2026, thus the electricity portfolio will still be heavily influenced by oil prices over the next 10 years. The forecast includes a reference and low

---

[5]Although this battery cost reflects the price given by Tesla for their Powerwall 2, it could be optimistic. In conversations with several local solar installers, they say there is a premium closer to $11,000 to $12,000.

forecast trajectory in order to bracket some of the uncertainty in electricity price forecasting, and are reported in 2016 dollars per kWh (Figure 2).

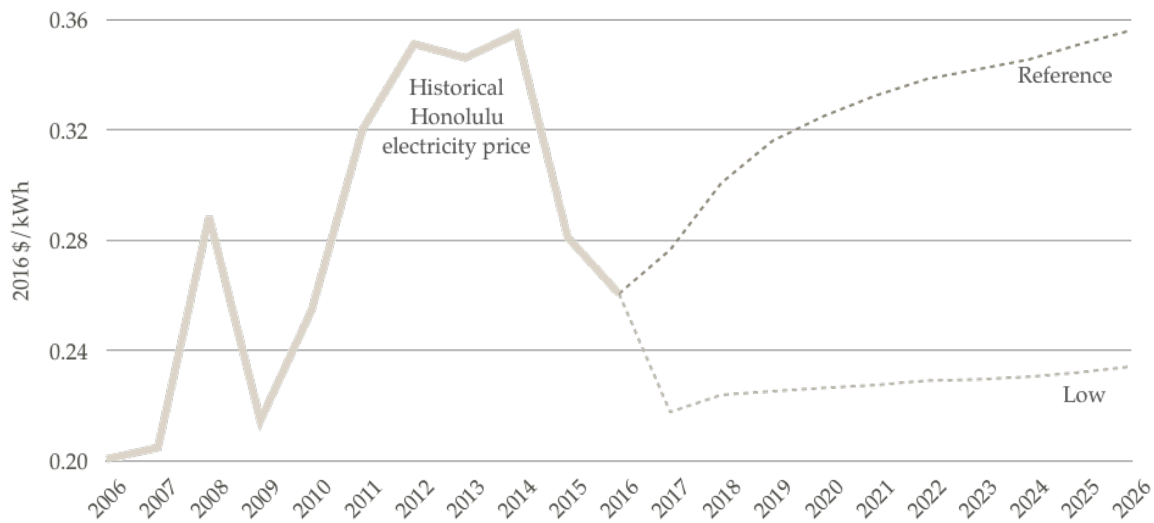

Figure 2. Oahu retail rate electricity price forecast in 2016$/kWh. Solid line shows historical prices, dotted lines show forecasted prices for reference (upper line) and low (lower line).

3. The optimal timing of investment

A seminal paper by McDonald and Siegel (1986) explores the optimal timing to invest in a project when faced with uncertainty and irreversibility. The concept of real option value of waiting to invest has been applied in evaluation of renewable energy project investment (Martínez-Ceseña and Mutale 2011; Fernandes, Cunha, and Ferreira 2011; Reuter et al. 2012), hybrid vehicle investment (Avadikyan and Llerena 2010), energy-savings investment (Ansar and Sparks 2009), as well as to evaluate supportive renewable energy policies (Boomsma, Meade, and Fleten 2012). In the realm of batteries, Bakke et al. (2016) apply a real options approach to evaluate investment in a utility-scale lithium-ion battery bank in the United Kingdom and Germany.

Real options methodology offers a value to waiting to make an irreversible investment, which is applicable to installing a PV+battery system. A household deciding whether to install a PV+battery system is faced with the uncertainty of electricity prices and interest rates into the future, but would expect with certainty for technology to improve with falling costs for both PV and battery technologies. A sensitivity analysis conducted by Ren et al. (2009) finds that interest rate has the largest impact on effective cost of a PV system, followed by capital cost and panel efficiency. Moreover, households would certainly want to take advantage of financial incentives while they are available if their electricity usage patterns would categorize the household investment of PV+battery as cost-effective.

3.1 Optimal timing methodology

At its core, understanding the optimal timing of investment requires identifying a number of uncertainties, particularly of future prices. Solar PV technology has seen major improvements in efficiency since the 1970s (NREL 2017). PV prices have declined rapidly over the last decade, but have leveled off in recent years (Fu et al. 2016). Battery prices, as tracked in the EV market, are decreasing rapidly coupled with an increase energy density (Nykvist and Nilsson 2015). Electricity prices also offer uncertainty into the mix, especially with increased renewable energy penetration. For a description of uncertainties associated with electricity price forecasting, see Section 2.3.

Government incentives play a large role in the reduction of capital costs for PV+battery systems, and have been an important factor in the cost-effectiveness of solar PV (Hagerman, Jaramillo, and Morgan 2016). The federal tax rebate for residential solar PV systems is currently scheduled to phase out, with a planned decline from 30% to 26% in 2020, and from 23% in 2021 to complete expiration in 2022. With the federal incentive schedule, I analyzed four scenarios to determine the change in net savings as compared to installing a PV+battery system in 2017. In surveying all reported lithium-ion EV battery prices, Nykvist and Nilsson (2015) found that battery prices of market leaders declined at an annual rate of 8%, and 14% for all reported values. It has been found that the price of batteries may in fact be falling at a faster rate, however, and the choice of these numbers are conservative. Thus, I chose to analyze both the low and reference electricity price forecasts with a conservative 8% and 14% decline in battery prices from the original simulation setup described in Section 2.2. I examine the net savings change from 2018 to 2022 as compared to 2017.

Each year is analyzed according to the effective cost method described in Section 2, and brought to present value according to the formula:

$$NPV_t = C_0 - \frac{\sum_{t=0}^{T} S_t}{(1+r)^t}$$

NPV_t = Net Present Value in year *t*
C_0 = Initial capital investment
S_t = Electricity savings in year *t*
r = Interest rate

3.1 Analysis Scenarios

There are twelve total scenarios used to compare potential outcomes of effective costs and savings for an average household in Honolulu. The first aspect of comparison is between installing a PV only system or a PV+battery system. Under the grid as a back-up which is assumed in this analysis, storage reduces curtailed energy, or energy that would otherwise go unused when there is no possibility to export to the grid. In such a set-up, it is not assumed that the household would go off-grid, but rather that the household would use the grid as a back-up electricity system. Analyzing the grid as back-up allows for comparison of effective costs and savings without running a system size optimization exercise. The second aspect of comparison is the low and reference electricity price forecasts, which allows for an understanding of a reasonable bracket for future ranges in prices. Finally, I analyze how net costs are affected by subsidies by analyzing scenarios with both the state and federal subsidies, no subsidies, and only the federal subsidy. All of these scenarios hold demand constant annually.

In the analysis of best time to invest, I concentrate on the subsidized PV+battery system. There are four scenarios analyzed over a six-year investment timeframe. Again, I compare a low and reference electricity forecast. With both of these scenarios, I further look at the savings that would be experienced in the circumstance that battery costs decrease by 8% or 14%. These set of scenarios give a range of possible outcomes for an average household wanting to invest in a PV+battery system given future uncertainties.

4. Results and Discussion

4.1 Effective cost calculations

Assuming the average Oahu household demand and solar resources, a solar PV system without a battery would reduce grid-supplied electricity by about half over a 10-year span, taking seasonality into account. Installing a battery nearly doubles the amount of usable self-generated electricity (assuming non-export). There is a cost associated with staying on-grid, which is a minimum of $25 per month for Oahu households. Costs associated with staying on-grid are not taken into account in this analysis. August exhibits the most energy generated by solar, and thus without changing the demand curve, this results in some curtailment of energy even with storage. Whereas November has the least amount of energy generated, with the most amount of electricity needed to be drawn from the grid. This analysis was not an exercise in optimizing PV and battery size, instead, it is meant to get a sense of whether under battery systems could be cost-effective under average household circumstances.

Table 3. Effective costs compared with effective savings for the reference and low electricity forecasts. Values are normalized based on estimated electricity used by technology source.

10-year period	Costs [per kWh usage]	Savings [per kWh usage] (reference)	Savings [per kWh usage] (low)
Subsidized			
PV only	$0.16	**0.29**	**0.20**
PV + Battery	$0.14	**0.29**	**0.20**
Unsubsidized			
PV only	$0.44	0.29	0.20
PV + Battery	$0.27	**0.29**	0.20
Federal Subsidy Only			
PV only	$0.31	0.29	0.20
PV + Battery	$0.21	**0.29**	0.20

Table 3 shows the present value (in 2016 $) of costs compared with savings normalized by electricity used by the installed system. With both state and federal subsidies applied to capital costs, savings exceed costs of a "PV only" system over ten years of usage, as well as the PV paired with a battery. Installing a battery reduces costs per kWh of electricity used by $0.02. Net savings for a PV+battery system range from $0.06 to $0.15 per kWh over the 10-year period. Without the subsidies in place, a PV+battery system saves $0.02 per kWh in the scenario where electricity prices increase into the future. Accordingly, the federal tax credit decreases capital cost by $0.07 per kWh usage and the state credit accounts for $0.06, totaling $0.13 reduction in capital cost for every generated kWh used. As the system is used beyond a 10-year period, this would serve to increase net savings.

Assumption sensitivities indicate that the PV system size and battery capacity is best optimized according to average demand, such that a household does not pay for an oversized system that provides no further benefit, especially with grid-supply as a backup. In other words, oversizing the PV system or battery raises costs without increasing savings. A household with the goal of going completely off-grid might be faced with a different optimization problem, needing to adjust and take into account the interactions between PV supply, battery storage, and household demand. Initial PV panel efficiency has no discernable effect on the net savings within a realistic range of values, whereas the annual efficiency loss has a significant effect. On the other hand, net savings has little sensitivity to battery capacity loss. A realistic usable lifetime of the battery is an important factor, however, and it is a critical assumption that there is no significant lifetime underperformance or failure of the battery. The usable lifetime of PV panels will likely outlast a household lithium-ion battery system and more than the 10 years of this chosen analysis. A PV+battery system that lasts beyond 10 years would increase the total net benefit of a household system. As expected, effective savings are sensitive to real interest rate, with increased savings as real interest rates decrease.

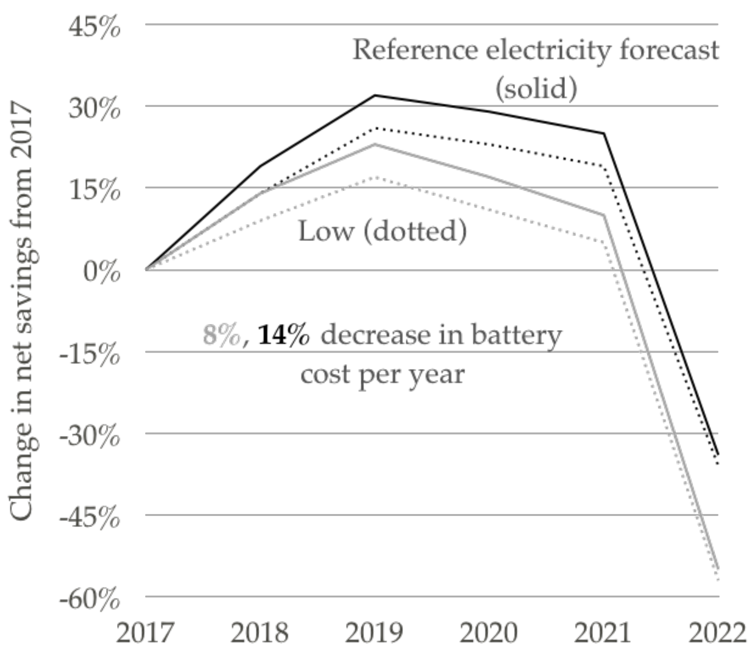

Figure 3. Potential change in net savings compared with 2017. Solid lines reflect reference electricity prices and dotted lines reflect the low electricity price forecast. The upper dark lines correspond to a 14% decrease in battery cost per year, and the lower gray lines reflect an 8% decrease.

4.2 Optimal time to invest

The results of the effective cost analysis show that financial incentives are important to the economic viability of PV+battery systems. An analysis seeking to determine the best time to install a PV+battery system shows that even with the declining cost in battery costs, the federal subsidy is still a key driver in the net present value costs of a PV+battery system. I find that the best time to install a PV+battery system to maximize potential savings for an average household would be 2019 while the 30% federal subsidy level is still offered, as Figure 3 shows. This might save a household 17-32% compared to installation in 2017. If the federal subsidy is not extended by 2022, the expiration of the federal incentive might lead to loss of economic viability of PV+battery systems.

5. Conclusions

Over a 10-year time-frame, PV becomes more economical when paired with battery storage. Large upfront costs increase when installing a battery, but over the long run, the ability to increase the usage of solar energy generated brings down the per kWh usage costs with the ability to use most of the PV-generated electricity. As systems become cost-effective and increasing numbers of customers adopt grid-connected PV+battery systems, Bronski et al. (2015) predicts that the grid will evolve for many years to come as more electricity customers install PV+battery systems and use the grid as back-up. For the purposes of this analysis, I assumed this option, however, other options available for households installing PV or PV+battery systems include grid-export or timed grid-export. Creative solutions for how customers interact with the grid will be increasingly critical as smart technologies become more prevalent.

In Oahu, financial incentives still play an important role in the economic viability of PV+battery systems. Higher electricity rates serve to bring households closer to economic viability, which would be the case for a household on time of use (TOU) rates, or for the other Hawaiʻi counties which face higher flat-rates. With the set expiration of the federal tax credit for residential PV installations, the onus may fall on the state or local level to set policies that encourage cost-effectiveness of PV+battery systems. This will likely be the case across the U.S. Similar to other jurisdictions (Borenstein 2016), Oahu faces a conundrum of recovering fixed costs exacerbated by customers with PV not paying the per kWh charge to the utility where the "fixed costs" are incorporated. A policy change that would encourage PV+battery system adoption might therefore be to employ pricing schemes that reflect true costs of electricity generation, such as real-time-pricing, which would serve to increase net savings from installing a PV+battery system. Further research would provide insight on how the federal and state subsidies affect social efficiency with respect to PV+battery adoption, and the social benefit provided by switching from fossil fuel-sourced energy to renewables, which is not captured in this analysis. Subsequent research is also needed to understand the optimization of system size and effective costs under various grid-export options.

References

Ansar, Jasmin, and Roger Sparks. 2009. "The Experience Curve, Option Value, and the Energy Paradox." *Energy Policy* 37 (3): 1012–20. doi:10.1016/j.enpol.2008.10.037.

Avadikyan, Arman, and Patrick Llerena. 2010. "A Real Options Reasoning Approach to Hybrid Vehicle Investments." *Technological Forecasting and Social Change* 77 (4). Elsevier Inc.: 649–61. doi:10.1016/j.techfore.2009.12.002.

Bakke, I, S-E Fleten, L I Hagfors, V Hagspiel, B Norheim, and S Wogrin. 2016. "Investment in Electric Energy Storage under Uncertainty: A Real Options Approach." *Computational Management Science* 13 (3). Springer Berlin Heidelberg: 483–500. doi:10.1007/s10287-016-0256-3.

Blue Planet Energy. 2017. "Blue Ion 2.0 Tech Specs."

Boomsma, Trine Krogh, Nigel Meade, and Stein Erik Fleten. 2012. "Renewable Energy Investments under Different Support Schemes: A Real Options Approach." *European Journal of Operational Research* 220 (1). Elsevier B.V.: 225–37. doi:10.1016/j.ejor.2012.01.017.

Borenstein, Severin. 2016. "The Economics of Fixed Cost Recovery by Utilities." EI @ Haas WP 272. http://ei.haas.berkeley.edu.

Branker, K, M J M Pathak, and J M Pearce. 2011. "A Review of Solar Photovoltaic Levelized Cost of Electricity." *Renewable and Sustainable Energy Reviews* 15 (9). Elsevier Ltd: 4470–82. doi:10.1016/j.rser.2011.07.104.

Bronski, Peter, Jon Creyts, Mark Crowdis, Stephen Doig, John Glassmire, Leia Guccione, Peter Lilienthal, et al. 2015. "The Economics of Load Defection: How Grid-Connected Solar-plus-Battery Systems Will Compete with Traditional Electric Service, Why It Matters, and Possible Paths Forward." *Rocky Mountain Institute*. doi:10.1002/0471755621.ch15.

Clean Edge. 2015. "2015 US Clean Tech Leadership Index."

Coffman, Makena, Paul Bernstein, and Sherilyn Wee. 2017. "Integrating Electric Vehicles and Residential Solar PV." *Transport Policy* 53. Elsevier: 30–38. doi:10.1016/j.tranpol.2016.08.008.

Department of Business Economic Development & Tourism (DBEDT). 2017. "Monthly Energy Trends."

Dubarry, Matthieu, Arnaud Devie, and Katherine McKenzie. 2017. "Durability and Reliability of Electric Vehicle Batteries under Electric Utility Grid Operations: Bidirectional Charging Impact Analysis." *Journal of Power Sources* 358: 39–49.

Fernandes, Bartolomeu, Jorge Cunha, and Paula Ferreira. 2011. "The Use of Real Options Approach in Energy Sector Investments." *Renewable and Sustainable Energy Reviews* 15 (9). Elsevier Ltd: 4491–97. doi:10.1016/j.rser.2011.07.102.

Fu, Ran, Donald Chung, Travis Lowder, David Feldman, Kristen Ardani, and Robert Margolis. 2016. "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016." doi:10.7799/1325002.

Giambelluca, T W, X Shuai, M L Barnes, R J Alliss, R J Longman, T Miura, Q Chen, et al. 2014. "Evapotranspiration of Hawai'i. Final Report Submitted to the U.S. Army Corps of Engineers—Honolulu District, and the Commission on Water Resource Management, State of Hawai'i."

"H.R. 2029 — 114th Congress: Consolidated Appropriations Act." 2016. https://www.gpo.gov/fdsys/pkg/PLAW-114publ113/html/PLAW-114publ113.htm.

"H.R. 6 — 109th Congress: Energy Policy Act." 2005. https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf.
Hagerman, Shelly, Paulina Jaramillo, and M Granger Morgan. 2016. "Is Rooftop Solar PV at Socket Parity without Subsidies?" *Energy Policy* 89. Elsevier: 84–94. doi:10.1016/j.enpol.2015.11.017.
Hawaiian Electric. 2015. "Net Energy Metering." https://www.hawaiianelectric.com/clean-energy-hawaii/producing-clean-energy/net-energy-metering.
Hawaiian Electric Company. 2017. "Customer Self-Supply and Grid-Supply." https://www.hawaiianelectric.com/clean-energy-hawaii/producing-clean-energy/customer-self-supply-and-grid-supply-programs.
HI Rev Stat § 235-12.5. 2012. "Renewable Energy Technologies; Income Tax Credit." http://www.capitol.hawaii.gov/hrscurrent/Vol04_Ch0201-0257/HRS0235/HRS_0235-0012_0005.HTM.
Hoppmann, Joern, Jonas Volland, Tobias S. Schmidt, and Volker H. Hoffmann. 2014. "The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems - A Review and a Simulation Model." *Renewable and Sustainable Energy Reviews* 39. Elsevier: 1101–18. doi:10.1016/j.rser.2014.07.068.
Jordan, D. C., and S. R. Kurtz. 2013. "Photovoltaic Degradation Rates-an Analytical Review." *Progress in Photovoltaics: Research and Applications* 21 (1): 12–29. doi:10.1002/pip.1182.
Jülch, Verena, Thomas Telsnig, Maximilian Schulz, Niklas Hartmann, Jessica Thomsen, Ludger Eltrop, and Thomas Schlegl. 2015. "A Holistic Comparative Analysis of Different Storage Systems Using Levelized Cost of Storage and Life Cycle Indicators." *Energy Procedia* 73: 18–28. doi:10.1016/j.egypro.2015.07.553.
Lai, Chun Sing, and Malcolm D. McCulloch. 2017. "Levelized Cost of Electricity for Solar Photovoltaic and Electrical Energy Storage." *Applied Energy* 190. Elsevier Ltd: 191–203. doi:10.1016/j.apenergy.2016.12.153.
Martínez-Ceseña, E. A., and J. Mutale. 2011. "Application of an Advanced Real Options Approach for Renewable Energy Generation Projects Planning." *Renewable and Sustainable Energy Reviews* 15 (4): 2087–94. doi:10.1016/j.rser.2011.01.016.
McDonald, Robert L, and Daniel Siegel. 1986. "The Value of Waiting to Invest." *The Quarterly Journal of Economics* 101 (4): 707–27.
National Renewable Energy Laboratory (NREL). 2017. "Best Research-Cell Efficiencies." Golden, CO. https://www.nrel.gov/pv/assets/images/efficiency-chart.png.
Naumann, Maik, Ralph Ch Karl, Cong Nam Truong, Andreas Jossen, and Holger C Hesse. 2015. "Lithium-Ion Battery Cost Analysis in PV-Household Application." *Energy Procedia* 73. Elsevier B.V.: 37–47. doi:10.1016/j.egypro.2015.07.555.
Navigant Consulting. 2015. "Demand Response Potential for Hawaiian Electric Companies. Final Draft Report. Prepared for Hawaiian Electric Companies. Docket 2015-0412 Exhibit A."
Norman, Kim, Rob Sargent, and Bret Fanshaw. 2016. "Shining Cities: How Smart Local Polies Are Expanding Solar Power in America."
Nykvist, Bjorn, and Mans Nilsson. 2015. "Rapidly Falling Costs of Battery Packs for Electric Vehicles." *Nature Climate Change*, no. February.
Obi, Manesseh, S M Jensen, Jennifer B Ferris, and Robert B Bass. 2017. "Calculation of Levelized Costs of Electricity for Various Energy Storage Systems." *Renewable and Sustainable Energy Reviews* 67. Elsevier: 908–20. doi:10.1016/j.rser.2016.09.043.
Pawel, Ilja. 2014. "The Cost of Storage - How to Calculate the Levelized Cost of Stored

Energy (LCOE) and Applications to Renewable Energy Generation." *Energy Procedia* 46. The Authors: 68–77. doi:10.1016/j.egypro.2014.01.159.

Ren, Hongbo, Weijun Gao, and Yingjun Ruan. 2009. "Economic Optimization and Sensitivity Analysis of Photovoltaic System in Residential Buildings." *Renewable Energy* 34 (3). Elsevier Ltd: 883–89. doi:10.1016/j.renene.2008.06.011.

Reuter, Wolf Heinrich, Jana Szolgayová, Sabine Fuss, and Michael Obersteiner. 2012. "Renewable Energy Investment: Policy and Market Impacts." *Applied Energy* 97. Elsevier Ltd: 249–54. doi:10.1016/j.apenergy.2012.01.021.

Tesla. 2016. "Tesla Press Information." https://www.tesla.com/presskit.

Timilsina, Govinda R., Lado Kurdgelashvili, and Patrick A. Narbel. 2012. "Solar Energy: Markets, Economics and Policies." *Renewable and Sustainable Energy Reviews* 16 (1). Elsevier Ltd: 449–65. doi:10.1016/j.rser.2011.08.009.

U.S. Energy Information Administration (EIA). 2016. "Electric Power Monthly: With Data for September 2016." *U.S. Energy Information Administration*. Washington, DC.

U.S. Treasury. 2017. "Daily Treasury Yield Curve Rates." https://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/TextView.aspx?data=yield.