A Prototype Model for Pumped Hydro Storage of Off-Grid <10KW Photovoltaic and Wind-Energy

Citation

Wikman, Jason M. 2019. A Prototype Model for Pumped Hydro Storage of Off-Grid <10KW Photovoltaic and Wind-Energy. Master's thesis, Harvard Extension School.

A Prototype Model for Pumped Hydro Storage of Off-Grid <10KW Photovoltaic and Wind-Energy

Jason M. Wikman

A Thesis in the Field of Sustainability
for the Degree of Master of Liberal Arts in Extension Studies

Harvard University
November 2019

Abstract

With over 1 billion people world-wide without access to electricity, small-scale alternative energy systems have the potential to lessen this need. Through hands-on experimentation and Excel spreadsheet modeling, this project examined the potential of pumped-hydro storage of renewable energy sources as potentially being more cost effective than standard lead-acid and lithium-ion battery storage systems.

The research question addressed was: is a gravity fed water storage system a more cost effective and sustainable storage solution for small (<10kW) photovoltaic and wind renewable off-grid energy hybrid systems in comparison to more traditional battery storage systems? I hypothesized that with adequate sizing, an uphill gravity storage system would be more cost effective over a 30-year period, than a lead-acid battery (or other battery) storage system for an off-grid hybrid solar and wind energy production system.

After calculating the energy requirements for my 20-acre off-grid homestead in north-east Washington state, experiments were conducted to determine the most cost effective and energy efficient means of solar and wind renewable energy production. A 700-watt fixed mount PV solar array and 1KW residential wind turbine were installed as an energy production system. The experiments examined three different renewable energy storage systems including lead-acid battery, lithium-ion battery and pumped-hydro storage (PHS). Each storage system was constructed and tested by changing variables such as wiring size and lengths, along with calculating system maintenance

times for each renewable energy storage system. Water storage equipment and piping was established on site, and a Pelton wheel water-generator was built and perfected with a hand-built 12V alternator for optimal efficiency. These system tests and equipment efficiencies were used in the cost-benefit modeling to determine the most cost effective and energy efficient means of energy storage.

Through my cost-benefit analysis (CBA), I determined that a gravity fed pumped-hydro storage system for renewable energies is 95% cheaper than a traditional battery storage system over a 30-year period. In addition, it was only 27% of the initial connection charge of tying into the traditional local utility grid system due to the remoteness of my homestead location, not including the 30 years of grid-connected utility charges.

This spreadsheet model has the potential to be used on a situational basis to determine the potential cost-effectiveness of government subsidized renewable energy projects in lieu of standard grid connectedness for remote communities. Any site that has the topography of at least 100 feet of elevation available for water storage, along with adequate wind and solar access and no or overly expensive electrical grid access, could be suitable for this pumped-hydro storage system. The spreadsheet model can be adapted by others to evaluate the cost-effectiveness of different scenarios by substituting site-specific parameter values for different variables and energy generation and storage system sizes.

Acknowledgements

Thank you, Dr. Mark Leighton for the introduction to and mentorship through spreadsheet modeling. Its power of study has amazed me through Atlantic fisheries analysis, Tuscany lumber production and biochar financial modeling, my personal future homestead plans and this renewable energy production modeling. Your encouragement of hands-on experimentation within my thesis as well as biochar production, on-site sustainable rural farming practice evaluation in Italy, and lumber valuation has been exciting and rewarding in this program. Thank you to my extended family for holding the bar high and encouraging me along this journey. Thank you to my wife Karrie and son Thor, who inspire me everyday to be a better person and always support my path.

Table of Contents

List of Tables

List of Figures

Definition of Terms

AC	Alternating current (standard 120-volt electricity)
CBA	Cost benefit analysis
DC	Direct current (12-volt electricity)
DOD	Depth of Discharge
ESS	Energy-storage systems
GPM	Gallons per minute
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilo-watt hours (measurement of watts used in 1 hour)
PHS	Pumped-hydro storage
PV	Photo-voltaic (solar panel)
RES	Renewable energy storage
ROI	Return on Investment

Chapter I

Introduction

The World Bank (2013) estimates that more than 1.2 billion people worldwide do not have access to electricity. Nearly 80% of those without electricity live in rural areas with no grid connectedness in the foreseeable future due to high infrastructure costs (IEA, 2014). In countries such as Mozambique and Tanzania, it is estimated that less than 5% or the rural population has access to electricity (Ahlborg & Hammar, 2014). The IEA (2014) foresees 350 million of these people worldwide gaining access to electricity via off-grid systems by the year 2040. Due to climate change pressure, costs of handling grid peak demand, and grid infrastructure inconsistency, implementation of renewable energies is expanding. A 2014 International Renewable Energy Agency report outlined that in most scenarios it is more cost-effective to invest in alternative energies for electricity than to use fossil fuels (IRENA, 2015).

Renewable Energy Storage (RES) systems have a unique opportunity to fill this need more sustainably but still require research (Zidar, Georgilakis, Hatziargyriou, Capuder, & Skrlec, 2016). The demand and use of renewable energies have increased in recent decades but are regarded as inconstant; solar panels only produce energy when the sun is out, and wind generators only produce energy when the wind blows. Energy-storage systems (ESS) limit these uncertainties (Zidar et al., 2016). Wang, Mae, Lu and Wang (2013) determined that combining an ESS with wind-power and solar has increased renewable energy penetration into the market; however, the limiting factor of its implementation is the correct sizing of the ESS and its economic feasibility.

Common ESS include stand-alone battery storage systems, although pumped-hydro may be a more sustainable RES alternative. Pumped-hydro storage (PHS) is a means of energy storage where water is pumped uphill during excess energy times and then released downhill by means of gravity to turn electricity producing turbines during times of energy demand. Evaluating the potential of this technology for rural RES systems requires financial feasibility modeling.

Research Significance & Objectives

My research evaluated the feasibility of a prototype model of PHS as an effective means of energy storage for renewable energy sources in impoverished non-grid connected areas. The feasibility depended on the appropriate technology selected, the scale and capacity to meet energy demands as well as the cost effectiveness of installing and managing the system. This evaluation also compared typical battery storage systems to the prototype model to determine if this constitutes a sustainable and more economical means for energy storage where the costs of grid-connectedness are high.

My objectives were:

- To build a model that will serve as a blueprint for future PHS of renewable energy installations, with a focus on low environmental and health impact, efficient energy acquisition and storage system design

- To choose appropriate technology for system needs in energy capacity, water storage, and turbine sizing by conducting return on investment (ROI) sensitivity analysis in comparison to similarly sized battery storage systems
- To develop and evaluate a prototype model of water stored uphill that is released as needed to power small turbines to store renewable energy sources on my 20-acre property in Curlew, WA

Background

In 2007, the UN Secretary General Ban Ki-Moon stated whether we examine climate change from an economic, social or environmental viewpoint, it is the "defining challenge of our age". In 2014, the Intergovernmental Panel on Climate Change (IPCC) attempted to draw attention to this point by referring to the challenge as being "irreversible" and urged global policy makers to take immediate action to reduce current and future greenhouse gas emissions.

These impacts have already started according to the NASA Global Climate Change report (2017) with loss of sea ice, accelerated sea-level rise, and longer, more intense heat waves. IPCC scientists predict a possible temperature increase between 2.5 to 10 degrees Fahrenheit over the next century. Greenhouse gas (GHG) emissions, mainly carbon dioxide, are the most vigorous anthropogenic factors driving climate change. Carbon dioxide readings (a direct correlative to global warming) in certain northern sites throughout the world have been recorded at 406 ppm (NASA, 2017). With the dawn of the Industrial Revolution, human activities have contributed significantly to rising concentrations of GHGs in the atmosphere, and electricity production comprises approximately 29% of U.S. greenhouse gas emissions (EPA, 2017).

Renewable Energies Expand

In 2010, the USA ranked second in the world in energy consumption following China (Barr, 2011). The United States is making great changes in its current energy development. US oil production is the highest it has been in the last eight years while imports are at their lowest in more than a decade (Mullaney, 2012). The US currently produces more natural gas and uses less coal to produce electricity (EIA, 2017). Non-hydro renewable energy has more than tripled in the past decade while reducing US carbon pollution (2017, EIA). Furthermore, according to Kevin Bullis of the MIT Technology Review (2012), the US could get 80% of its energy from renewables by 2050. A new renewable energy market is emerging powered by geothermal, solar and wind energy (Block, 2012). Global cumulative wind and solar renewable capacity is expected to continue to expand (Figure 1) (Powerweb, 2018).

With climate and global instability being tied to the concerns of the future availability and healthiness of oil and coal, our nation needs to embrace clean energy on a scale and pace that has never been seen before.

Each day enough solar energy strikes the earth’s surface to provide energy to power the world’s yearly needs many times over (Botkin & Keller, 2011). While the build-up of CO2 and global warming are becoming a concern due to fossil fuel use, direct solar energy can become a valuable energy source to help protect our planet. Development in solar cells in the US has exploded since 2010, reaching an astonishing

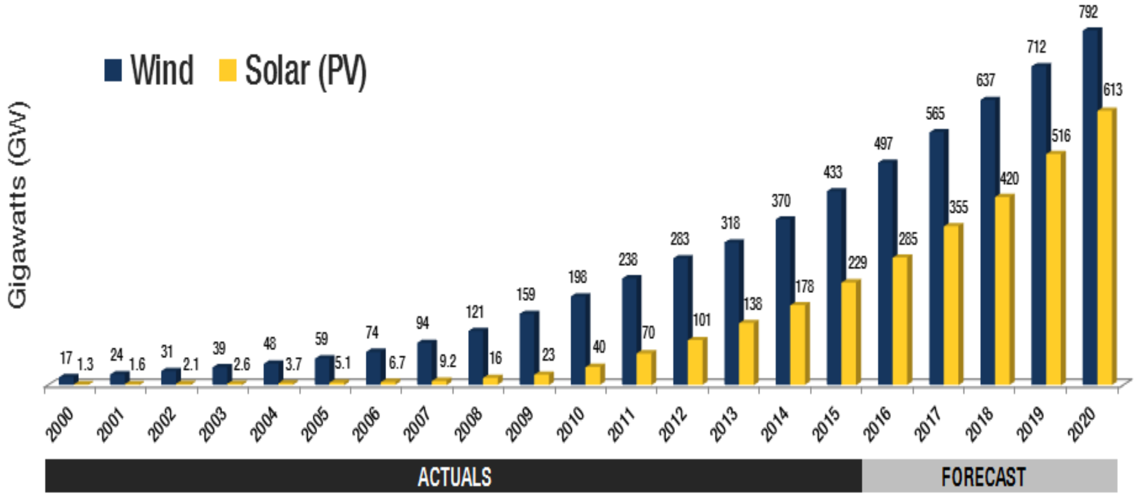


Figure 1. Cumulative global wind and solar installations in gigawatts (GW). Forecast included for future global installations through 2020 (Powerweb, 2018).

14,626 megawatts of solar PV installed in 2016, a 95% increase from the previous year (Munsell, 2017). Solar panels are large arrays of silicon wafers mounted beneath glass connected in series that collect photons from the sun and convert them to DC electrical power. By five years ago there were more than 303 gigawatts of photovoltaic installations operating world-wide (IEA, 2016).

Nearly 80% of the more than 1.2 billion people worldwide do not have access to electricity (World Bank, 2013) live in rural areas with no grid connectedness in the foreseeable future due to high infrastructure costs (IEA, 2014). In countries such as Mozambique and Tanzania, it is estimated that less than 5% or the rural population has access to electricity (Ahlborg & Hammar, 2014). The IEA (2014) foresees 350 million of these people worldwide gaining access to electricity via off-grid systems by the year 2040. This points to a great need for small-scale, cost-effective, rural energy storage systems.

Renewable Energy Storage

One of the main difficulties facing renewable energies, including solar and wind, is storage options when peak demand does not coincide with peak availability (Trainer, 2017). Trainer (2017) reviews several case studies where batteries have been used in small-scale operations at high costs financially and environmentally. Europe's largest renewable energy operation with battery storage is the 10-megawatt German Feldheim Project at a cost of $1420/kWh, with the calculations not accounting for Lithium-ion (Li-ion) battery life expectancy at approximately 10-15 years (Steel, 2015).

At the non-grid connected individual household level, Garimella and Nair (2009) concluded using optimized HOMER models that on a small scale (<5kW) lead acid batteries are the most cost-effective means of PV storage in comparison with NiCd, NiMH and Li-ion batteries. However, within most renewable energy efficiency studies, no consideration is being given to the entire life-cycle of these battery storage systems (Sullivan & Gaines, 2010). Garimella and Nair (2009) only considered initial capital cost and cost of operation within their analysis and did not account for replacement costs over the long term. Furthermore, some of the current recycling methods of these used batteries have proven deadly (Haefliger et al., 2009).

Pumped Hydro Storage

The highest capacity of Renewable Energy Storage (RES) worldwide is Pumped Hydro Storage (PHS) (Berrada, Loudiyi, & Zorkani, 2017). While large scale PHS in the form of hydro-electric dams efficiently generate power world-wide (Trainer, 2017), no small-scale site specific PHS systems have been identified as a RES. The major problem with PHS is the storage capacity of the system, which is a function of the height of the descending water and volume storage of the system as these two main factors lead to limits on site selection (Evans, Strezov, & Evans, 2012). One study in France attempted to use an open-air water tank on an apartment building roof in a small-scale PHS system connected to electricity generating turbines but determined the size was inadequate for the building's electrical demand (Libre de Bruxelles, Université, 2016).

Pumped Hydro Storage with Solar and Wind Renewable Energies

One feasibility study was performed in a remote Hong Kong island of a pumped hydro storage RES fed by wind and solar renewable energies; however, the system was 250+KWh, and optimization factors were not identified (Figure 2) (Ma, Yang, Lu, & Peng, 2014). With this type of hybrid wind-solar PHS system, PV panels and wind generators supply electricity, with these renewable energies' electricity converted from DC to AC for immediate use with the inverter (Figure 2). Excess electricity is used to pump water uphill for storage reserve for autonomous periods requiring non-renewable energy (Figure 2). This stored water is released during these autonomous times to produce electricity via water turbines (Figure 2). Multiple factors such as PV, wind, and water turbine sizing, output efficiencies, equipment costs, site variables, labor costs, and ongoing maintenance costs would affect the cost effectiveness of such a system. These factors need to be analyzed and compared to a traditional battery system for renewable energy storage to determine the cost effectiveness of such an endeavor on a small scale.

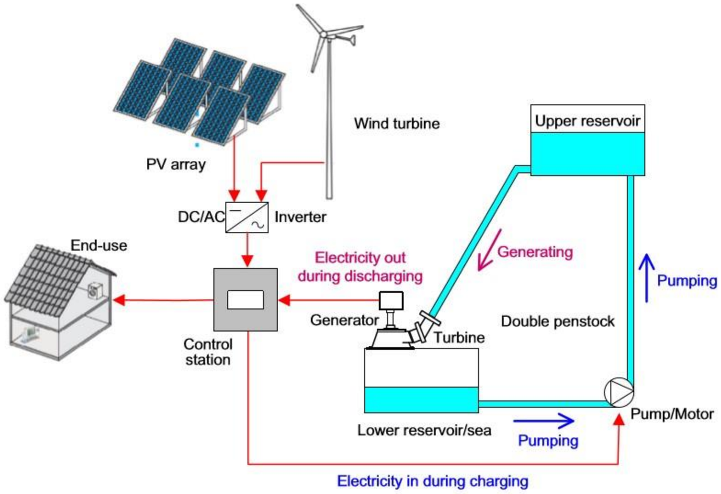


Figure 2. A combined solar and wind RES with pumped hydro storage (Ma, Yang, Lu, & Peng, 2014).

Ma, Yang, Lu and Peng (2014) determined the reservoir needs for a PHS to be calculated by the equation:

$$V = \frac{E_c}{\eta_t \cdot \rho \cdot g \cdot h} \qquad E_c = n_{day} \cdot E_{load} = \eta_t \cdot \rho \cdot V \cdot g \cdot h$$

where V is the volume of the of the PHS reservoir (m^3); E_c is the energy storage capacity of the reservoir measured in Joules calculated by the n_{day} number of autonomous days x E_{load} daily energy consumption (Joules); p is the density of water (kg/m^3); g is the gravitational acceleration (9.81 m/s^2); h is the total head (m); η_t is the efficiency of the turbine determined by the turbine wheel efficiency rating * electrical generator efficiency rating * the water piping drag efficiency rating. Proper turbine sizing and efficiency rating was determined to be vital in increasing the overall PHS system efficiency along with determining the days of autonomy (consecutive days without renewable energy supply) for the entire system (Ma, Yang, Lu, & Peng, 2014).

Prototype Model Site Location

Over 188,000 households (Davidson, 2006) in the United States are estimated to not be connected to the electrical grid. In Ferry county, WA, the location for the prototype model upon which this research is based, more than 20% of the homes are not connected to the electrical grid due to high initial connecting costs (John Friederichs, personal communication, January 16 2018). Ferry county is a rugged hilly area of the Kettle River Range on the eastern edge of the Okanagan Highland. Most of these homes are using small scale wind and solar RE with lead-acid battery storage in combination with fossil fuel generators (John Friederichs, personal communication, January 16 2018).

The 20-acre site for the prototype has an elevation gain of over 400 ft within the property, which is typical in this hilly area, so was well suited as a site to study small-scale gravity-fed PHS with solar and wind renewable energies as an alternative to typical battery storage systems for renewable energies.

Multiple studies, including Hoppmann, Volland, Scmidt and Hoffmann's (2014) meta-analysis of the economic viability of battery storage for residential PV systems, and Kohle's (2009) techno-economic optimal battery sizing for PV study, were used for the battery types baseline comparisons. These studies provided detailed analysis that take into account solar radiation, PV array efficiency, load energy requirements, daily energy availability, daily efficiency of the PV system, maximum load fraction, storage sizing and storage roundtrip efficiency, guiding modeling included in the system economics calculations.

Research Question, Hypothesis and Specific Aims

This research specifically addresses this question: Is a pumped hydro storage (PHS) system a feasible, more cost effective and sustainable storage solution for small (<10kW) photovoltaic and wind renewable off-grid energy hybrid systems in comparison to more traditional battery storage systems?

In attempting to answer this question, I hypothesized that with adequate sizing, an uphill gravity storage system will be more cost effective over a 30-year period, than a lead-acid battery (or other battery) storage system for an off-grid hybrid solar and wind energy production system.

Specific Aims

To test this hypothesis, I completed the following steps:

- Determined the system capacity needed for this off-grid location
- Determined the size of the water storage system needed for adequate reserve needs
- Determined the size of water turbines required for the reserve electricity generation
- Constructed this prototype model on my 20-acre property in Curlew, WA
- Calculated if various battery-type storage systems or the prototype water storage is more cost-effective over a 30-year investment
- Conducted a sensitivity analysis to evaluate the effects of different variables on cost effectiveness

Chapter II

Methods

To evaluate the feasibility and cost effectiveness of the prototype model of PHS as an effective means of energy storage in impoverished non-grid connected areas, compared to typical battery storage for renewable energy sources, I created cost benefit models comparing each type of renewable energy storage systems. The baseline model was constructed with the setup costs and long-term operating costs for a primary PV solar system, redundant wind system and lead-acid battery RES system. The baseline model was comprised of "best-performing" data gleamed from on-site testing of each renewable energy storage (RES) system.

The model was based on providing 150% of daily electricity needs for the home I expected to build on the site, as well as three and five (150%) days of autonomy in each RES scenario. The alternative scenarios were evaluated by comparing their respective Return on Investment (ROI) over a duration of 30 years.

Although the baseline model used variable costs appropriate for my specific site and location with additional options added for comparison, the spreadsheet model was set up so that simple changes in parameter values for variables such as daily power needs, autonomous days and solar panel cost could create site-specific analyses for any user. The various storage system tabs in the Excel spreadsheet identify which variable had the most impact on net present value (NPV) based on a sensitivity analysis.

Modeling Categorization and Organization

The modeling methods weres based on the type of RES and consequent accumulation of autonomous days for each RES. Categories of different scenarios were:

- Lead-Acid Battery – Zero Autonomous Days (Baseline Model)
- Lead-Acid Battery – Three Autonomous Days
- Lead-Acid Battery – Five Autonomous Days
- Lithium-Ion Battery Storage – Zero Autonomous Days
- Lithium-Ion Battery Storage – Three Autonomous Days
- Lithium-Ion Battery Storage – Five Autonomous Days
- Pumped Hydro Storage – Zero Autonomous Days
- Pumped Hydro Storage – Three Autonomous Days
- Pumped Hydro Storage – Five Autonomous Days

Baseline Model Scenario

A prototype model for the gravity-fed water storage system was constructed in the field using large capacity 1500-gallon cisterns both up hill and downhill connected with both up hill and downhill 1” diameter piping runs on my 20-acre property in north-eastern Washington state. Water was pumped uphill with renewable energy sources (solar and wind) using a Rural Power System 400 Solar / Wind Well Pump and allowed to flow downhill during the renewable non-producing times (night) through small electricity generating pelton-wheel water turbines (Figure 3). The feasibility of this model was analyzed by examining efficiencies in storage of this system compared to various types of battery storage tested on site.

Figure 3. Pelton wheel encased in housing to trap water and gravity feed lower storage tank (photo by author, 2018).

Determining System Size

Electrical load calculations were first conducted to determine the daily electrical load with ample reserve in kwh and amp/hr. A typical inverter has an 85-90% efficiency of transforming 12-volt power to 120-volt (Bowman, 2010). Therefore, the home on the property was designed to run on a 12-volt system that does not invert the 12-volt energy produced off-grid. This allowed a 20% reduction in the systems size (the extra 5% not needed for allowances). The total estimate of electrical draw on the 12-volt system was based on estimates of average time used in a typical 24 hr period (Table 1).

Table 1. Electricity daily uses calculated in 12-volt kwh and amp/hrs per day.

Appliance	Quantity	Draw/hr (amps)	Hours/day	Total Amps/Day
Circulation Pumps (radiant flooring)	4	0.83	12	39.84
Ceiling Fan (low setting)	1	0.27	8	2.16
Refrigerator (compressor running)	1	1.2	11	13.2
Composting Toilet	1	0.16	24	3.84
Lighting (Kitchen: Recessed)	6	0.58	3	10.44
Lighting (Kitchen: strip)	2	0.33	4	2.64
Lighting (Living: Recessed)	4	0.58	4	9.28
Lighting (Bath: Recessed)	2	0.58	2	2.32
Lighting (Bath: Spot)	2	0.33	2	1.32
Lighting (Bath: Strip)	1	0.33	2	0.66
Lighting (Loft: Recessed)	2	0.58	4	4.64
Lighting (Loft: Spot)	2	0.33	2	1.32
Lighting (Bedroom: Recessed)	2	0.58	2	2.32
Lighting (Bedroom: Spot)	2	0.33	2	1.32
Circulation Pump (domestic hot water)	1	3.16	12	38
	Max Draw Total (Amps):	10.17	Total Energy (Amps)/Day:	133.3

The basic energy for essential systems was calculated to be approximately 133 (12-volt) amp hours per day, with a max hourly load of 10.17 amps (122-Watts) (Table 1). As some minor items might need to be plugged into a 12-volt at times (i.e., computer or cell-phone chargers), the daily energy load was increased to 200 amp hours/day for an adequate margin, with a max hourly load of 14 amps (170-Watts). This provided a considerable back-up source (150% of daily need) of amp-hours per day/hour. The number of solar panels and wind generator size was determined based on these calculations.

Days of Autonomy

One important determining factor in calculating battery storage systems, cistern sizing, elevation requirements, and water turbine output is based on system reserve needs during non-solar and non-wind producing times (days of autonomy). Three to five days of autonomy (the storage system’s ability to function without charging) is a typical threshold for most off-grid solar systems (IEEE, 2008). Both three and five-day scenarios were examined, along with zero days, with alterations to all cost factors due to larger solar bank sizes. Cost per ampere was calculated for these different scenarios as well.

Baseline Site Requirements

Initially I determined what would be required for energy production for the needs for my family's off-grid home, based on these considerations:

- Daily Power Needs: 200 amps maximum daily draw was determined for our home's low energy use (Table 1). The use of the sun's energy through the design, orientation and construction of our structure was utilized through a passive solar design. This design allowed for fewer or smaller-scale active equipment to provide the remainder of the heating and lighting needs. According to the EPA (2016), continuing energy costs can be appreciably reduced by exploiting the use of passive solar practices before adding active technologies because the sun's energy has no cost. Typically, the climate control of a typical residence constitutes 54% of a utility bill (Energy.gov, 2018). The use of passive solar design to heat and cool a home can lower the home's embodied energy and carbon, as well as harnessing sustainable, natural operating energy.
- Peak Sun-Hours: the number of hours in a day in which the sunlight intensity is at least 1,000 watts per square meter (WWO, 2019). This is an average day over the year for the site location in Curlew, WA and may be higher or lower depending on the season and solar angle of incidence.

- Average Daily Wind Speed: the average wind speed for the Curlew, WA area, which may be lower or higher at different times during the year (WWO, 2019).

Baseline Solar Energy Production

Based on the expected household energy needs, a 700-watt fixed mount solar panel system was installed that produces an average of 3.5 kW of power throughout the day. The line items and variables entering into the Excel cost-benefit model are defined below:

- Solar Panel Requirements: Each 12V Monocrystalline Renogy solar panel is rated at 100 watts or 6.1 amps. This determined the minimum number of panels required for the Daily Power needs. This was calculated by taking the daily power needs (cell B4 of the spreadsheet model, see Results) divided by the 6 amp output of the panels multiplied by peak sun-hours (cell B5) year-round for Curlew, WA.
- Individual Solar Panel Cost: Each 100-watt Renogy solar panel costs $110.
- Total Solar Panel Costs: the individual solar panel cost (cell B10) multiplied by the number of solar panels required (cell B9).
- Solar Charge Controller: The RENOGY 40 Amp Rover PG MPPT charge controller was used to block reverse current, electrical overload and to protect against battery overcharge.
- Solar Wiring Length: As the solar panels were run in a parallel circuit, approximately 6 ft of 10-gauge wire was used per panel. The Excel function was 6ft multiplied by the number of solar panels required (cell B9).

- Solar Wiring Cost: This was solar wiring length (cell B13) multiplied by $0.30 / ft of 10-guage wire.
- Solar System Setup Labor Cost: This system was a do-it-yourself (DIY) setup by the researcher which took 6 hr multiplied by a $12/hr labor cost; for consistent, accurate modeling, no matter who is performing the work, all production cost hours need to be accounted for unbiased cost-benefit analysis (Wiswall, 2009). The value of $12/hr might seem low, but approximates handyman pay scale for rural WA.
- Solar Maintenance Labor: The solar panels need to be checked for individual voltage testing, wiring health and cleaning on a monthly basis. This was estimated to take 0.15 hours per month at a labor cost of $12/hr.
- Amps Produced Per Hour: During peak sun-hours, the solar panels should produce 6.1 amp; this calculation is the total panels (cell B9) multiplied by the peak amps 6.1 per panel.
- Amps Produced Per Day: peak sun-hours (cell B5) multiplied by total amp/hrs (cell B16).
- Total Amps Produced to Date: total amps produced in a year, multiplied by the number of years the panels have produced energy.
- Total Baseline Solar Energy Expenditures Per Year: the sum of the total dollars spent each year for the solar system.
- Total Baseline Solar Energy Expenditures to Date: total sum of dollars spent at the end of each year, including previous years.
- Total Solar System Expenditures over 30 Years: total cost of entire solar system over 30 years.

- Average Yearly Baseline Solar Energy Costs Over Time: total dollars spent to date (cell B21), divided by the number of years the system has been running (cell B2).
- Cost Per Amp Produced to Date: the total baseline solar energy expenditures to date (cell B21) divided by the total amps produced to date (cell B19).

Baseline Wind Energy Production

Due to possible days with little to no sun, a 1KW residential wind turbine was installed on a 30ft tower. The average wind speed throughout the year in Curlew, WA is 6.2 mph (WWO, 2019). The line items in the spreadsheet and other relevant variables in the model were:

- 1KW Residential Wind Turbine: A GudCraft WG1000 1KW 1000W Residential 12V Wind Turbine that produces an average of 375 Watts or 31 amps at 6 mph wind speed was used simultaneously with the solar array for non-solar times; this formula is a function of the daily power needs (cell B4) divided by the amps produced per day by the wind generator (cell B34) rounded up to the nearest whole number multiplied by the price of one 1KW residential wind turbine ($575).
- Wind Charge Controller with Water Heater Diversion Dump Load: This controller was used to block reverse current, electrical overload and to protect against battery overcharge along with a water heater diversion dump load circuit to protect the wind turbine at high speeds as well as excess energy output.
- Wind Wiring Length: The GudCraft wind turbine was mounted on a 30ft tower, 45 ft from the battery bank using 150 ft of 6-guage wire to prevent voltage drop for positive and negative runs.

- Wind Wiring Costs: total length of wire required (cell B29) multiplied by $1/ft of 6-guage wire, the smallest gauge of wire tested with minimal resistance for the load requirements.
- Wind System Setup Labor Cost: This system and tower was a DIY setup by the researcher with a 15000lb truck winch which took 9 hr at $12/hr labor, plus the tower and support system.
- Wind Maintenance Labor: The wind turbine needs to be checked for voltage testing, wiring and blade health on a 3-month basis. This is estimated to take 0.15 hours per month at a cost, for consistency, of $12/hr.
- Amps Produced Per Hour: The GudCraft wind turbine produces 31 amps at 6 mph, the average daily windspeed for Curlew, WA.
- Amp/hrs Produced Per Day: amps/hr (cell B33) multiplied by 24hr.
- Total Amps Produce to Date: total amps produced in a year multiplied by the number of years the wind system has produced energy.
- Total Baseline Wind Energy Expenditures Per Year: total dollars spent at the end of each year.
- Total Baseline Wind Energy Expenditures to Date: total dollars spent at the end of each year, including previous years.
- Total Wind System Expenditures over 30 years: Total cost of entire wind system over 30 years.
- Average Yearly Baseline Wind Energy Cost Over Time: total dollars spent to date (cell B37), divided by the number of years the system has been running (cell B2).

- Cost Per Amp Produced to Date: total baseline wind energy expenditures to date (cell B37) divided by the total amps produced to date (cell B35).

Baseline Lead-Acid Battery Storage System

The Baseline model included a flooded lead-acid battery storage system, the typical storage system for off-grid solar/wind energy production systems, as it is relatively inexpensive and readily available. The life expectancy is about three years or 1200 cycles at 50% depth of discharge (DOD) if properly maintained (IEEE, 2008). The other line items and variables in this section of the spreadsheet model were:

- Battery Bank Capacity: based on the daily power needs (cell B4) doubled, as lead-acid batteries should not be depleted past 50% DOD (IEEE, 2008).
- Number of Batteries Needed: The TROJAN T605 SOLAR 6Volt 214 Amp-hr battery was used in pairs (to produce 12 volts). The total number needed was determined by battery bank capacity (cell B43) divided by the 214-amp-hr capacity of the battery, rounded up to the nearest whole battery multiplied by 2, as two 6 Volt batteries are needed to produce 12 Volts. The typical life of this type of battery is three years and will be replaced at these intervals (IEEE, 2008).
- Battery Bank Daily Available Usage: Due to lead-acid batteries 50%DOD the amp-hrs available is the battery bank capacity (cell B43) divided by 2.
- Battery Bank Cost Lead-Acid: the lead-acid battery cost of $127 multiplied by the number of batteries needed (cell B44).
- Battery Bank Wiring Length: As the 6V batteries were run in a combined series and parallel circuit to increase the volts and amperage of the battery bank, approximately

5 ft of 1-gauge wire was used per battery. Therefore, 5ft was multiplied by the number of batteries needed (cell B44).

- Battery Bank Wiring Costs: battery bank wiring length (cell B47) multiplied by $2.75/ft of 1-guage wire, the smallest gauge of wire tested with minimal resistance for the load requirements.
- Battery System Setup Labor Cost: This system was a DIY setup by the researcher, which took 4 hr multiplied by $12/hr labor.
- Battery Maintenance Labor: The batteries should be checked for individual voltage testing, correct fluid levels, terminal corrosion and cleaning to be continued monthly. This was estimated to take 2 hr per month multiplied by 12 months in the year multiplied by the cost of labor.
- Battery Maintenance Supplies: This included testing equipment, fluid replacement, and battery terminal cleaning supplies.
- Total Amps Produce to Date: total amps produced in a year, multiplied by the number of years the battery bank has produced energy.
- Total Baseline Lead-Acid Battery Storage Expenditures Per Year: total dollars spent at the end of each year.
- Total Baseline Lead-Acid Battery Storage Expenditures to Date: total dollars spent at the end of each year including previous years.
- Total Lead-Acid Battery Storage Expenditures over 30 years: total cost of entire lead-acid battery system over 30 years.

- Average Yearly Baseline Lead-Acid Battery Storage System Cost Over Time: total dollars spent to date (cell B51), divided by the number of years the system has been running (cell B2).
- Cost Per Amp Produced to Date: total baseline lead-acid battery system expenditures to date (cell B54) divided by the total amps produced to date (cell B52).

Baseline Cost of Energy Production

The costs were determined for each renewable energy production system as well as the baseline lead-acid battery storage system in dollars per 12V-amp as a means for comparison:

- Solar Energy Production Cost: total solar system costs (cell B22) divided by the average solar Amp/hrs produced per day (cell B18).
- Wind Energy Production Cost: total wind system costs (cell B38) divided by the average wind Amp/hrs produced per day (cell B34).
- Lead-Acid Battery Energy Storage Production Cost: total lead-acid battery system costs (cell B55) divided by battery bank daily available usage (cell B45).

Baseline Lead-Acid Battery Days of Autonomy

- Days of Autonomy: number of days the system will run without recharging.
- Battery Bank Capacity: based on the daily power needs (cell B4) doubled for DOD multiplied by the days of autonomy (cell B65)

- Number of Batteries Needed: The TROJAN T605 SOLAR 6Volt 214 Amp-hr battery was used in pairs (to produce 12 volts). Total battery needed was battery bank capacity (cell B66) divided by the 214-amp hr capacity of the battery rounded up to the nearest whole battery multiplied by 2, as two 6 Volt batteries are needed to produce 12 Volts. The typical life of this type of battery is three years and will be replaced at these intervals (IEEE, 2008).
- Amps/hr Available per Autonomous Time Period: the battery bank capacity (cell B66) divided by 2 due to 50% DOD.
- Battery Bank Cost Lead-Acid: the lead-acid battery cost of $127 multiplied by the number of batteries needed (cell B67).
- Battery Bank Wiring Length: As the 6V batteries were run in a combined series and parallel circuit to increase the volts and amperage of the battery bank, approximately 5 ft of 1-gauge wire was used per battery so 5ft was multiplied by the number of batteries needed (cell B67).
- Battery Bank Wiring Costs: battery bank wiring length (cell B70) multiplied by $2.75/ft of 1-guage wire.
- Battery System Setup Labor Cost: This system was a DIY setup by the researcher which took 6 hr multiplied $12/hr labor cost.
- Battery Maintenance Labor: The batteries were checked for individual voltage testing, correct fluid levels, terminal corrosion and cleaning which will be continued on a monthly, estimated to take four hr per month at $12/hr.
- Battery Maintenance Supplies: This included testing equipment, fluid replacement, and battery terminal cleaning supplies.

- Total Amps Produced to Date: total amps produced in a year multiplied by the number of years the battery bank produced energy.
- Total Baseline Lead-Acid Battery Storage Expenditures Per Year: total dollars spent at the end of each year.
- Total Baseline Lead-Acid Battery Storage Expenditures to Date: total dollars spent at the end of each year including previous years.
- Total Lead-Acid Battery Storage Expenditures over 30 years: total cost of entire lead-acid battery system over 30 years.
- Average Yearly Baseline Lead-Acid Battery Storage System Cost Over Time: total dollars spent to date (cell B77), divided by the number of years the system has been running (cell B2).
- Cost Per Amp Produced to Date: total baseline lead-acid battery system expenditures to date (cell B77) divided by the total amps produced to date (cell B75).
- Lead acid battery energy storage production cost: total lead-acid battery system costs over 30 years (cell B**7**8) divided by battery bank available amp usage (cell B68).

The calculations for the baseline lead-acid battery costs for three vs. five days of autonomy are identical except for the number of days the system will run without recharge, and the added hours of labor for initial setup and maintenance labor of the system due to its larger size.

Alternative Storage System Scenarios

Within the various renewable energy storage system scenarios, many of the values are inherently the same as the baseline model. The key changes were those of alternative energy storage systems, detailed below.

Lithium-Ion Battery Storage System

Lithium-ion batteries are more expensive but maintenance free, and have a much longer life expectancy of up to 10,000 cycles at 100% DOD. The Relion LFP Battery-12V (RB100) 100 amp-hr battery was borrowed and tested on site; this spreadsheet model is for a ROI comparison to a traditional lead-acid battery system that was also tested.

- Battery Bank Capacity: the battery bank capacity is based on the daily power needs (cell B4). The 100% DOD allows for full usage of the battery's capacity; therefore, a smaller capacity bank was possible.
- Number of Batteries Needed: The Relion LFP Battery-12V (RB100) is a 100 amp-hr battery. The total batteries needed is a function of battery bank capacity (cell B43) divided by the 100-amp hr capacity of the battery rounded up to the nearest whole battery at 100% DOD. The typical life of this type of battery is up to 10,000 full 100% DOD cycles; therefore, this battery bank should last at least 16 years, which will be the replacement cycle.
- Battery Bank Daily Available Usage: Due to lithium-ion batteries 100% DOD, the amp-hrs available is the battery bank capacity (cell B43).

- Battery Cost Lithium-ion: The Relion LFP Battery-12V (RB100) costs $1054 each multiplied by number of batteries needed (cell B44).
- Battery Bank Wiring Length: As these are 12V batteries, they were run in a parallel circuit needing approximately 2ft of 1-gauge wire per battery multiplied by the number of batteries needed (cell B44).
- Battery System Setup Labor Cost: This system was a DIY setup by the researcher which took 2 hr at $12/hr labor.
- Battery Maintenance Labor/Supplies: These batteries are maintenance free and, therefore, would require no battery maintenance labor or supplies.
- Total Amps Produced to Date: total amps produced in a year, multiplied by the number of years the battery bank has produced energy.
- Total Baseline Lithium-Ion Battery Storage Expenditures Per Year: total dollars spent at the end of each year.
- Total Baseline Lithium-Ion Battery Storage Expenditures to Date: total dollars spent at the end of each year including previous years.
- Total Lithium-Ion Battery Storage Expenditures over 30 years: cost of entire lead-acid battery system over 30 years.
- Average Yearly Baseline Lithium-Ion Battery Storage System Cost Over Time: total dollars spent to date (cell B54), divided by the number of years the system has been running (cell B2).
- Cost Per Amp Produced to Date: total baseline lithium-ion battery system expenditures to date (cell B54) divided by the total amps produced to date (cell B52).

Lithium-Ion Battery Cost of Energy Production

The costs were determined for each renewable energy production system as well as the lithium-ion battery storage system in dollars per 12V-amp as a means for comparison in the same manner as they were on the Baseline Lead-Acid Battery Storage System.

All calculations for the lithium-ion battery storage system costs for both three and five days of autonomy were identical to the calculations to those of the lead-acid battery storage system except for specific lithium-ion values. The cost of energy production for each autonomous scenario was calculated the same as the baseline model.

Pumped Hydro Storage System

THE PHS system was tested on site using two 1500-gallon tank cisterns, placed uphill at 100 ft of head pressure (Figure 4) resulting in 43 psi at the bottom. A solar/wind powered pump was used to pump water up during the day when renewable energies were readily available and stored for later use when they were not. Water flowed through 1" polyethylene 100psi pipe with the Pelton wheel (Figure 3) attached at the bottom of the down-hill run and exiting into the bottom storage tank. A 1kW generator was first attached to the Pelton wheel; however, with further testing a 100-amp automotive alternator was identified to use the least amount of water (4.25 gpm), while producing a steady 30-amps of current. The line items and variables in this section of the spreadsheet model were:

- Hours of Operation Per Day: total number of non-solar hours the system is expected to produce power, equal to 24 hr day minus the peak sun-hours of the location (cell

Figure 4. Uphill 1500-gallon water tank with bottom tank downhill in picture to the right of buildings (photo by author, 2018).

B5) when the solar and wind systems will provide the daily power needs.

- Gallons of Water Needed Per Day / Pelton Wheel Requirements: 4.25 gpm multiplied by 60 min first, then multiplied by the hours of operation per day (cell B43).
- Total Water Storage Tank Capacity Upper and Lower: gallons of water needed per day for the Pelton Wheel (cell B44), doubled for two cisterns, rounded up to the nearest 1000, as the tanks are available in 1000 gallon increments up to 10,000 gallons.
- Water Storage Tank Cost: total water storage tank capacity (cell B45) multiplied by \$0.46/gallon, the price of the storage tank.

- Piping Length to Maintain Minimum of 100’ of Head: the amount of 1” polyethylene pipe required to achieve 100’ of head pressure and 43psi of water pressure entering the Pelton wheel.
- Total Piping Needs: piping length to maintain minimum of 100’ of head (cell B47) doubled for both the uphill and downhill runs.
- Piping Cost: total piping needs (cell B48) rounded up to the nearest 100 ft roll multiplied by $0.19/ ft piping cost.
- Piping Fittings Cost: total piping needs (cell B48) rounded up to the nearest 100 ft roll multiplied by $5 fittings cost per roll.
- Solar Water Pump Capacity 100 ft of Head: The RPS Solar 800V consistently pumped a minimum of 990 gallons/hr.
- Solar Water Pump Cost: The RPS Solar 400V water pump costs $880.
- Solar Water Pump Wiring Length: 10 ft of 6-gauge wire was required.
- Solare Water Pump Wiring Cost: The wiring required length (cell B54) multiplied by $1/ft of 6-gauge wire.
- Solar Panel Requirements for Water Pump: number of 100W solar panels required to run the solar pump. This power requirement was kept separate from the baseline solar requirements for calculation purposes but should not be needed due to the redundant solar and wind systems.
- Total Solar Panel Costs: the individual 100W Reonogy solar panel cost (cell B10) multiplied by the number of solar panels required (cell B56).

- Solar Wiring Length: As the solar panels will be run in a parallel circuit approximately 6 ft of 10-gauge wire will be used per panel so 6ft was multiplied by the number of solar panels required (cell B56).
- Solar Wiring Cost: solar wiring length (cell B58) multiplied by $0.30/ft of 10-guage wire.
- Pelton Wheel Cost: the total cost of the Pelton wheel construction with case, nozzles and greased fittings.
- Alternator and Coupling Cost: the total cost of the 100-amp automotive alternator and flex coupling used to connect to the Pelton wheel.
- Alternator Wiring Length: the total length of 1-gauge wire needed to run from the Pelton wheel to the solar/wind controller.
- Alternator Wiring Cost: alternator wiring length (cell B62) multiplied by $2.75/ft of 1-guage wire.
- PHS System Setup Labor Cost: This system was a DIY setup by the researcher which took 26 hours over multiply days multiplied $12/hr labor.
- PHS Maintenance Labor: The PHS was checked for individual current production (Amps), water storage tank levels, piping leaks, wiring connections and cleaning which will be continued on a monthly. This is estimated to take 1/2 hour per month at $12/hr.
- Alternator Continuous Output: The 100-amp alternator continually produced 30amps at a rate of 4.25 gpm through the Pelton wheel.
- Amps Produced Per Day: The alternators continuous output (cell B66) multiplied by the hours of operation per day cell (B43).

- Potential Total Amps Produced to Date: total amps produced in a year, multiplied by the number of years the battery bank has produced energy.
- Total Baseline PHS Expenditures Per Year: total sum of dollars spent at the end of each year.
- Total Baseline PHS Expenditures to Date: total sum of dollars spent at the end of each year including previous years.
- Total PHS Expenditures over 30 years: total cost of entire PHS system over 30 years.
- Average Yearly Baseline PHS Cost Over Time: total dollars spent to date (cell B70), divided by the number of years the system has been running (cell B2).
- Cost Per Amp Produced to Date: the total baseline PHS system expenditures to date (cell B70) divided by the potential total amps produced to date (cell B67).

Pumped Hydro Storage System Cost of Energy Production

The costs were determined for each renewable energy production system as well as the pumped hydro storage system in dollars per 12V-amp as a means for comparison in the same manner as they were on the Baseline Lead-Acid Battery Storage System and Lithium-Ion Battery Storage Systems.

All calculations for the PHS system costs for both three and five days of autonomy are identical to the calculations to those of the lead-acid and lithium-ion battery storage systems except for specific PHS values. However, it was determined that with the larger volume of water needed for the autonomous days, the construction of upper and lower ponds would be cheaper then multiple large storage tanks. Therefore, water storage pond construction was determined per gallon of pond size (cell B89) and the cost of construction (cells B88 & B131) and liner costs (cells B87 & B130) for both upper and lower reservoirs were factored in with the variable cost of setup labor based on total water storage capacity needed for both the three and five day autonomous scenarios. The cost of construction was factored at 10 hr per pond at $12/hour labor, $50 of diesel fuel and $250 2-day bulldozer rental.

The cost of energy production for each autonomous scenario was calculated the same as for the baseline model.

Chapter III

Results

The goal of my experimentation was to see if creating a PHS was in fact feasible on my 20-acre property and to determine its cost effectiveness, in cost per amp produced, compared to a standard lead-acid battery storage system and lithium-ion battery storage system. More specifically, this would allow a financial decision to be made for future purchases for energy acquisition and storage for our future off-grid 20-acre homestead. Through sensitivity analysis, I also wished to reveal which variables had the greatest effect on long-term costs for each type of RES.

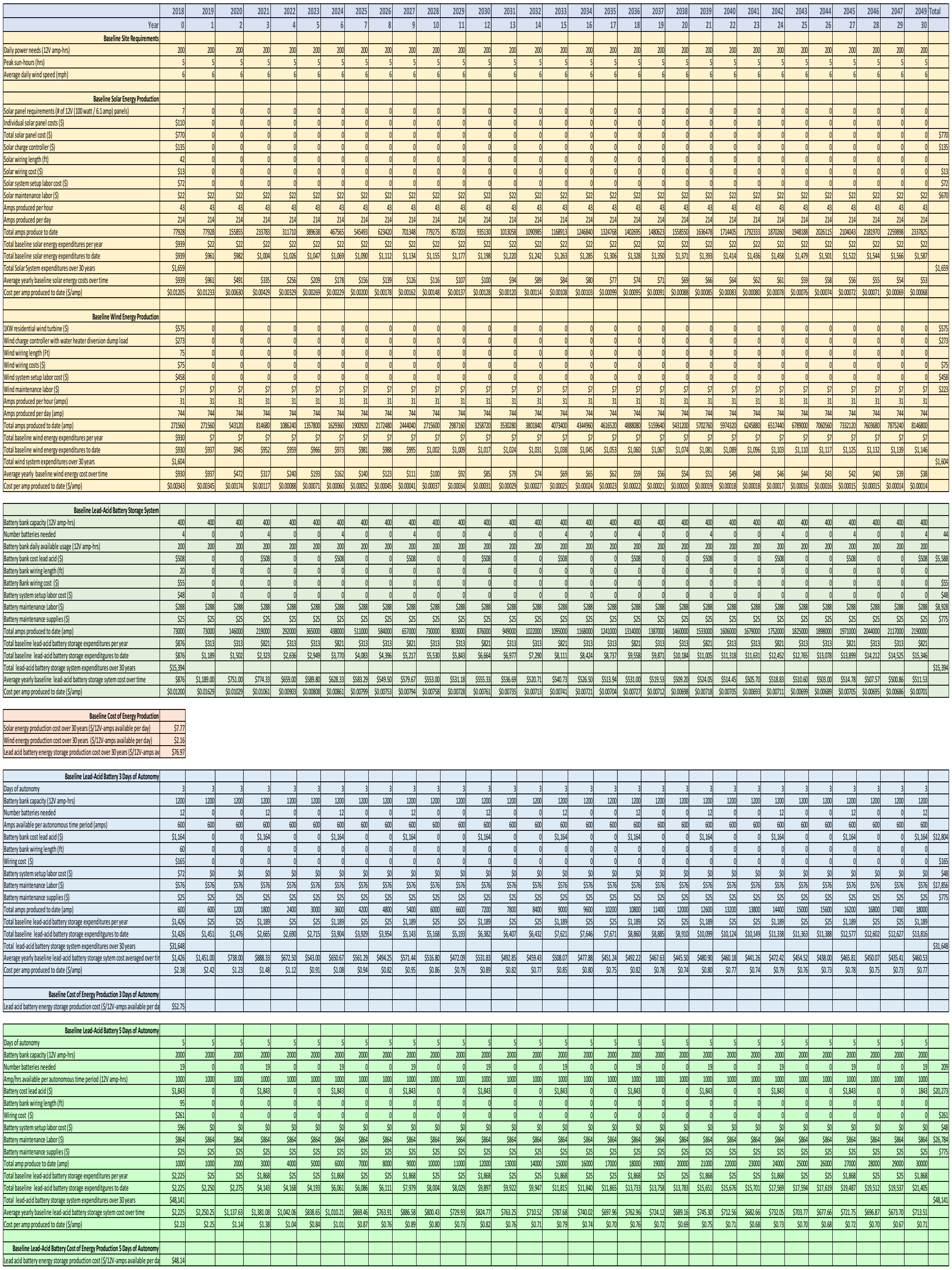
Baseline Model Spreadsheet

The goal of the baseline modeling was to determine the requirements for energy production of the solar RES as well as the redundant wind RES. Furthermore, each data point in column B of the spreadsheet model (Tables 2, 3 & 4) is linked so that any user can input their specific parameters into the spreadsheet model for their own specific site analysis. Each line item is explained in the Methods section.

The typical storage system for most off-grid RES systems is lead-acid batteries. I created a model that is based on experimentation on my property, and included 1, 3 and 5-day autonomous reserves with their associated costs over a 30-year period (Table 2).

The total cost of my specific sized system for our energy needs over 30-years for the solar PV system was $1,659, and the redundant wind system was $1,604. The 1-day

Table 2. Baseline model of lead-acid battery RES.



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2049	Total
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Baseline Site Requirements																																
Daily power needs (12V amp-hrs)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	
Peak sun-hours (hrs)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	
Average daily wind speed (mph)	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	
Baseline Solar Energy Production																																
Solar panel requirements (# of 12V (100 watt / 6.1 amp) panels)	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Individual solar panel costs ($)	$110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Total solar panel cost ($)	$770	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$770
Solar charge controller ($)	$135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$135
Solar wiring length (ft)	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar wiring cost ($)	$13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$13
Solar system setup labor cost ($)	$72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$72
Solar maintenance labor ($)	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$670
Amps produced per hour	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	
Amps produced per day	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	
Total amps produce to date	77928	77928	155855	233783	311710	389638	467565	545493	623420	701348	779275	857203	935130	1013058	1090985	1168913	1246840	1324768	1402695	1480623	1558550	1636478	1714405	1792333	1870260	1948188	2026115	2104043	2181970	2259898	2337825	
Total baseline solar energy expenditures per year	$939	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	
Total baseline solar energy expenditures to date	$939	$961	$982	$1,004	$1,026	$1,047	$1,069	$1,090	$1,112	$1,134	$1,155	$1,177	$1,198	$1,220	$1,242	$1,263	$1,285	$1,306	$1,328	$1,350	$1,371	$1,393	$1,414	$1,436	$1,458	$1,479	$1,501	$1,522	$1,544	$1,566	$1,587	
Total Solar System expenditures over 30 years	$1,659																															$1,659
Average yearly baseline solar energy costs over time	$939	$961	$491	$335	$256	$209	$178	$156	$139	$126	$116	$107	$100	$94	$89	$84	$80	$77	$74	$71	$69	$66	$64	$62	$61	$59	$58	$56	$55	$54	$53	
Cost per amp produced to date ($/amp)	$0.01205	$0.01233	$0.00630	$0.00429	$0.00329	$0.00269	$0.00229	$0.00200	$0.00178	$0.00162	$0.00148	$0.00137	$0.00128	$0.00120	$0.00114	$0.00108	$0.00103	$0.00099	$0.00095	$0.00091	$0.00088	$0.00085	$0.00083	$0.00080	$0.00078	$0.00076	$0.00074	$0.00072	$0.00071	$0.00069	$0.00068	
Baseline Wind Energy Production																																
1KW residential wind turbine ($)	$575	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$575
Wind charge controller with water heater diversion dump load	$273	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$273
Wind wiring length (Ft)	75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Wind wiring costs ($)	$75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$75
Wind system setup labor cost ($)	$458	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$458
Wind maintenance labor ($)	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$223
Amps produced per hour (amps)	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	
Amps produced per day (amp)	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	
Total amps produced to date (amp)	271560	271560	543120	814680	1086240	1357800	1629360	1900920	2172480	2444040	2715600	2987160	3258720	3530280	3801840	4073400	4344960	4616520	4888080	5159640	5431200	5702760	5974320	6245880	6517440	6789000	7060560	7332120	7603680	7875240	8146800	
Total baseline wind energy expenditures per year	$930	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	
Total baseline wind energy expenditures to date	$930	$937	$945	$952	$959	$966	$973	$981	$988	$995	$1,002	$1,009	$1,017	$1,024	$1,031	$1,038	$1,045	$1,053	$1,060	$1,067	$1,074	$1,081	$1,089	$1,096	$1,103	$1,110	$1,117	$1,125	$1,132	$1,139	$1,146	
Total wind system expenditures over 30 years	$1,604																															$1,604
Average yearly baseline wind energy cost over time	$930	$937	$472	$317	$240	$193	$162	$140	$123	$111	$100	$92	$85	$79	$74	$69	$65	$62	$59	$56	$54	$51	$49	$48	$46	$44	$43	$42	$40	$39	$38	
Cost per amp produced to date ($/amp)	$0.00343	$0.00345	$0.00174	$0.00117	$0.00088	$0.00071	$0.00060	$0.00052	$0.00045	$0.00041	$0.00037	$0.00034	$0.00031	$0.00029	$0.00027	$0.00025	$0.00024	$0.00023	$0.00022	$0.00021	$0.00020	$0.00019	$0.00018	$0.00018	$0.00017	$0.00016	$0.00016	$0.00015	$0.00015	$0.00014	$0.00014	

Baseline Lead-Acid Battery Storage System																																
Battery bank capacity (12V amp-hrs)	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	
Number batteries needed	4	0	0	4	0	0	4	0	0	4	0	0	4	0	0	4	0	0	4	0	0	4	0	0	4	0	0	4	0	0	4	44
Battery bank daily available usage (12V amp-hrs)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	
Battery bank cost lead acid ($)	$508	0	0	$508	0	0	$508	0	0	$508	0	0	$508	0	0	$508	0	0	$508	0	0	$508	0	0	$508	0	0	$508	0	0	$508	$5,588
Battery bank wiring length (ft)	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Battery Bank wiring cost ($)	$55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$55
Battery system setup labor cost ($)	$48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$48
Battery maintenance Labor ($)	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$288	$8,928
Battery maintenance supplies ($)	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$775
Total amps produced to date (amp)	73000	73000	146000	219000	292000	365000	438000	511000	584000	657000	730000	803000	876000	949000	1022000	1095000	1168000	1241000	1314000	1387000	1460000	1533000	1606000	1679000	1752000	1825000	1898000	1971000	2044000	2117000	2190000	
Total baseline lead-acid battery storage expenditures per year	$876	$313	$313	$821	$313	$313	$821	$313	$313	$821	$313	$313	$821	$313	$313	$821	$313	$313	$821	$313	$313	$821	$313	$313	$821	$313	$313	$821	$313	$313	$821	
Total baseline lead-acid battery storage expenditgures to date	$876	$1,189	$1,502	$2,323	$2,636	$2,949	$3,770	$4,083	$4,396	$5,217	$5,530	$5,843	$6,664	$6,977	$7,290	$8,111	$8,424	$8,737	$9,558	$9,871	$10,184	$11,005	$11,318	$11,631	$12,452	$12,765	$13,078	$13,899	$14,212	$14,525	$15,346	
Total lead-acid battery storage system expenditures over 30 years	$15,394																															$15,394
Average yearly baseline lead-acid battery storage sytem cost over time	$876	$1,189.00	$751.00	$774.33	$659.00	$589.80	$628.33	$583.29	$549.50	$579.67	$553.00	$531.18	$555.33	$536.69	$520.71	$540.73	$526.50	$513.94	$531.00	$519.53	$509.20	$524.05	$514.45	$505.70	$518.83	$510.60	$503.00	$514.78	$507.57	$500.86	$511.53	
Cost per amp produced to date ($/amp)	$0.01200	$0.01629	$0.01029	$0.01061	$0.00903	$0.00808	$0.00861	$0.00799	$0.00753	$0.00794	$0.00758	$0.00728	$0.00761	$0.00735	$0.00713	$0.00741	$0.00721	$0.00704	$0.00727	$0.00712	$0.00698	$0.00718	$0.00705	$0.00693	$0.00711	$0.00699	$0.00689	$0.00705	$0.00695	$0.00686	$0.00701	

Baseline Cost of Energy Production	
Solar energy production cost over 30 years ($/12V-amps available per day)	$7.77
Wind energy production cost over 30 years ($/12V-amps available per day)	$2.16
Lead acid battery energy storage production cost over 30 years ($/12V-amps av	$76.97

Baseline Lead-Acid Battery 3 Days of Autonomy																																
Days of autonomy	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	
Battery bank capacity (12V amp-hrs)	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	
Number batteries needed	12	0	0	12	0	0	12	0	0	12	0	0	12	0	0	12	0	0	12	0	0	12	0	0	12	0	0	12	0	0	12	
Amps available per autonomous time period (amps)	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	
Battery bank cost lead acid ($)	$1,164	0	0	$1,164	0	0	$1,164	0	0	$1,164	0	0	$1,164	0	0	$1,164	0	0	$1,164	0	0	$1,164	0	0	$1,164	0	0	$1,164	0	0	$1,164	$12,804
Battery bank wiring length (ft)	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Wiring cost ($)	$165	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$165
Battery system setup labor cost ($)	$72	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$48
Battery maintenance Labor ($)	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$576	$17,856
Battery maintenance supplies ($)	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$775
Total amps produced to date (amp)	600	600	1200	1800	2400	3000	3600	4200	4800	5400	6000	6600	7200	7800	8400	9000	9600	10200	10800	11400	12000	12600	13200	13800	14400	15000	15600	16200	16800	17400	18000	
Total baseline lead-acid battery storage expenditures per year	$1,426	$25	$25	$1,189	$25	$25	$1,189	$25	$25	$1,189	$25	$25	$1,189	$25	$25	$1,189	$25	$25	$1,189	$25	$25	$1,189	$25	$25	$1,189	$25	$25	$1,189	$25	$25	$1,189	
Total baseline lead-acid battery storage expenditgures to date	$1,426	$1,451	$1,476	$2,665	$2,690	$2,715	$3,904	$3,929	$3,954	$5,143	$5,168	$5,193	$6,382	$6,407	$6,432	$7,621	$7,646	$7,671	$8,860	$8,885	$8,910	$10,099	$10,124	$10,149	$11,338	$11,363	$11,388	$12,577	$12,602	$12,627	$13,816	
Total lead-acid battery storage system expenditures over 30 years	$31,648																															$31,648
Average yearly baseline lead-acid battery storage sytem cost averaged over tir	$1,426	$1,451.00	$738.00	$888.33	$672.50	$543.00	$650.67	$561.29	$494.25	$571.44	$516.80	$472.09	$531.83	$492.85	$459.43	$508.07	$477.88	$451.24	$492.22	$467.63	$445.50	$480.90	$460.18	$441.26	$472.42	$454.52	$438.00	$465.81	$450.07	$435.41	$460.53	
Cost per amp produced to date ($/amp)	$2.38	$2.42	$1.23	$1.48	$1.12	$0.91	$1.08	$0.94	$0.82	$0.95	$0.86	$0.79	$0.89	$0.82	$0.77	$0.85	$0.80	$0.75	$0.82	$0.78	$0.74	$0.80	$0.77	$0.74	$0.79	$0.76	$0.73	$0.78	$0.75	$0.73	$0.77	
Baseline Cost of Energy Production 3 Days of Autonomy																																
Lead acid battery energy storage production cost ($/12V-amps available per da	$52.75																															

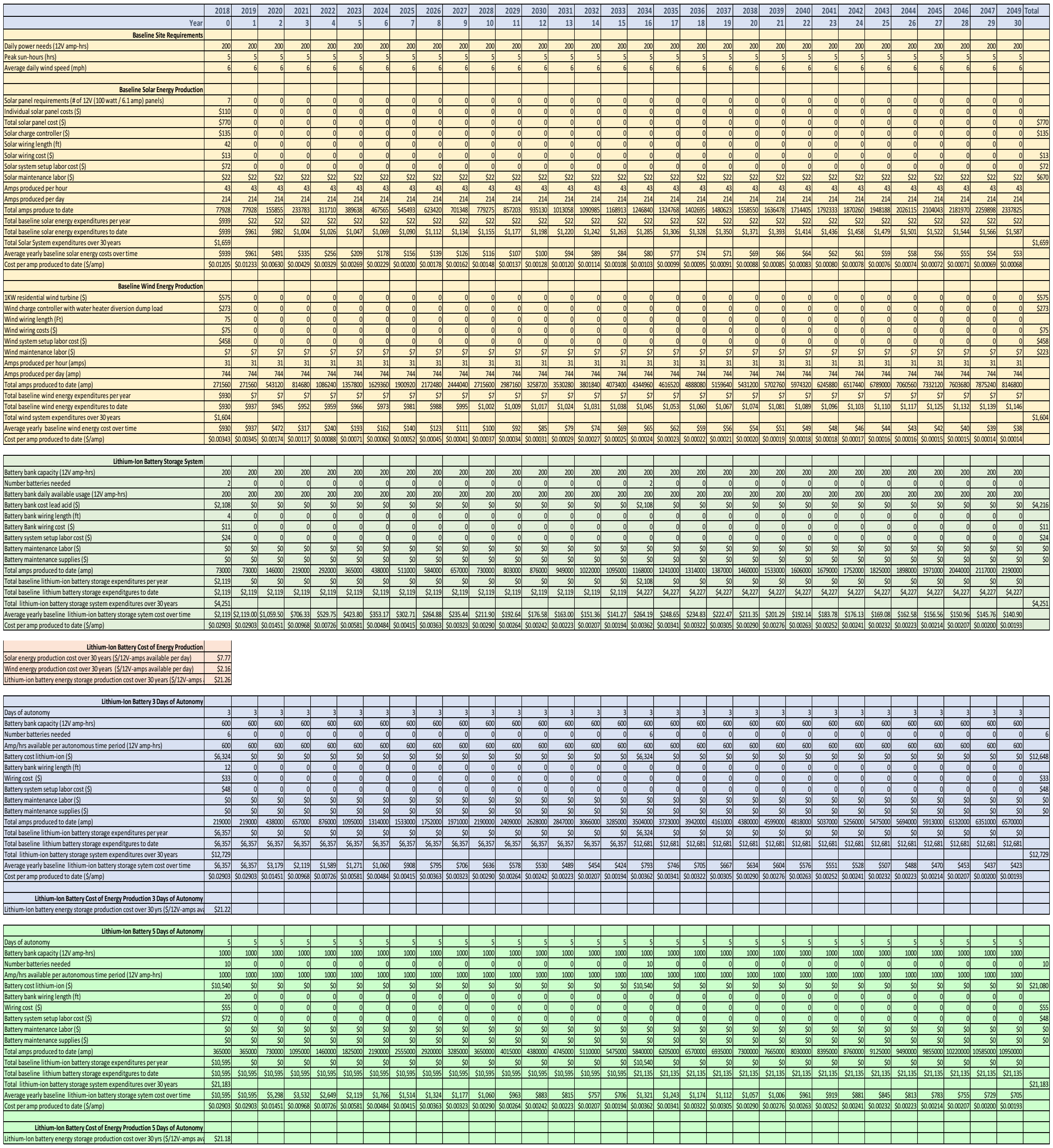
Baseline Lead-Acid Battery 5 Days of Autonomy																																
Days of autonomy	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	
Battery bank capacity (12V amp-hrs)	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	
Number batteries needed	19	0	0	19	0	0	19	0	0	19	0	0	19	0	0	19	0	0	19	0	0	19	0	0	19	0	0	19	0	0	19	209
Amp/hrs available per autonomous time period (12V amp-hrs)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	
Battery cost lead acid ($)	$1,843	0	0	$1,843	0	0	$1,843	0	0	$1,843	0	0	$1,843	0	0	$1,843	0	0	$1,843	0	0	$1,843	0	0	$1,843	0	0	$1,843	0	0	1843	$20,273
Battery bank wiring length (ft)	95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Wiring cost ($)	$261	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$261
Battery system setup labor cost ($)	$96	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$48
Battery maintenance Labor ($)	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$864	$26,784
Battery maintenance supplies ($)	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$25	$775
Total amp produce to date (amp)	1000	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	14000	15000	16000	17000	18000	19000	20000	21000	22000	23000	24000	25000	26000	27000	28000	29000	30000	
Total baseline lead-acid battery storage expenditures per year	$2,225	$25	$25	$1,868	$25	$25	$1,868	$25	$25	$1,868	$25	$25	$1,868	$25	$25	$1,868	$25	$25	$1,868	$25	$25	$1,868	$25	$25	$1,868	$25	$25	$1,868	$25	$25	$1,868	
Total baseline lead-acid battery storage expenditgures to date	$2,225	$2,250	$2,275	$4,143	$4,168	$4,193	$6,061	$6,086	$6,111	$7,979	$8,004	$8,029	$9,897	$9,922	$9,947	$11,815	$11,840	$11,865	$13,733	$13,758	$13,783	$15,651	$15,676	$15,701	$17,569	$17,594	$17,619	$19,487	$19,512	$19,537	$21,405	
Total lead-acid battery storage system expenditures over 30 years	$48,141																															$48,141
Average yearly baseline lead-acid battery storage sytem cost over time	$2,225	$2,250.25	$1,137.63	$1,381.08	$1,042.06	$838.65	$1,010.21	$869.46	$763.91	$886.58	$800.43	$729.93	$824.77	$763.25	$710.52	$787.68	$740.02	$697.96	$762.96	$724.12	$689.16	$745.30	$712.56	$682.66	$732.05	$703.77	$677.66	$721.75	$696.87	$673.70	$713.51	
Cost per amp produced to date ($/amp)	$2.23	$2.25	$1.14	$1.38	$1.04	$0.84	$1.01	$0.87	$0.76	$0.89	$0.80	$0.73	$0.82	$0.76	$0.71	$0.79	$0.74	$0.70	$0.76	$0.72	$0.69	$0.75	$0.71	$0.68	$0.73	$0.70	$0.68	$0.72	$0.70	$0.67	$0.71	
Baseline Lead-Acid Battery Cost of Energy Production 5 Days of Autonomy																																
Lead acid battery energy storage production cost ($/12V-amps available per da	$48.14																															

autonomous lead-acid battery RES was $15,394, 3- day autonomous lead-acid battery RES was $31,648, and 5-day autonomous lead-acid battery RES was $48,141.

Alternative Storage System Scenarios

The lithium-ion battery RES (Table 3) and PHS (Table 4) have been included on separate tabs of the spreadsheet model. They are organized and color coded exactly like the baseline model with 1, 3 and 5-day autonomous calculations.

Table 3. Lithium-ion battery RES spreadsheet.



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2049	Total
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Baseline Site Requirements																																
Daily power needs (12V amp-hrs)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	
Peak sun-hours (hrs)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	
Average daily wind speed (mph)	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	
Baseline Solar Energy Production																																
Solar panel requirements (# of 12V (100 watt / 6.1 amp) panels)	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Individual solar panel costs ($)	$110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Total solar panel cost ($)	$770	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$770
Solar charge controller ($)	$135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$135
Solar wiring length (ft)	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar wiring cost ($)	$13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$13
Solar system setup labor cost ($)	$72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$72
Solar maintenance labor ($)	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$670
Amps produced per hour	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	
Amps produced per day	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	
Total amps produce to date	77928	77928	155855	233783	311710	389638	467565	545493	623420	701348	779275	857203	935130	1013058	1090985	1168913	1246840	1324768	1402695	1480623	1558550	1636478	1714405	1792333	1870260	1948188	2026115	2104043	2181970	2259898	2337825	
Total baseline solar energy expenditures per year	$939	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	
Total baseline solar energy expenditures to date	$939	$961	$982	$1,004	$1,026	$1,047	$1,069	$1,090	$1,112	$1,134	$1,155	$1,177	$1,198	$1,220	$1,242	$1,263	$1,285	$1,306	$1,328	$1,350	$1,371	$1,393	$1,414	$1,436	$1,458	$1,479	$1,501	$1,522	$1,544	$1,566	$1,587	
Total Solar System expenditures over 30 years	$1,659																															$1,659
Average yearly baseline solar energy costs over time	$939	$961	$491	$335	$256	$209	$178	$156	$139	$126	$116	$107	$100	$94	$89	$84	$80	$77	$74	$71	$69	$66	$64	$62	$61	$59	$58	$56	$55	$54	$53	
Cost per amp produced to date ($/amp)	$0.01205	$0.01233	$0.00630	$0.00429	$0.00329	$0.00269	$0.00229	$0.00200	$0.00178	$0.00162	$0.00148	$0.00137	$0.00128	$0.00120	$0.00114	$0.00108	$0.00103	$0.00099	$0.00095	$0.00091	$0.00088	$0.00085	$0.00083	$0.00080	$0.00078	$0.00076	$0.00074	$0.00072	$0.00071	$0.00069	$0.00068	
Baseline Wind Energy Production																																
1KW residential wind turbine ($)	$575	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$575
Wind charge controller with water heater diversion dump load	$273	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$273
Wind wiring length (Ft)	75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Wind wiring costs ($)	$75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$75
Wind system setup labor cost ($)	$458	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$458
Wind maintenance labor ($)	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$223
Amps produced per hour (amps)	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	
Amps produced per day (amp)	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	
Total amps produced to date (amp)	271560	271560	543120	814680	1086240	1357800	1629360	1900920	2172480	2444040	2715600	2987160	3258720	3530280	3801840	4073400	4344960	4616520	4888080	5159640	5431200	5702760	5974320	6245880	6517440	6789000	7060560	7332120	7603680	7875240	8146800	
Total baseline wind energy expenditures per year	$930	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	
Total baseline wind energy expenditures to date	$930	$937	$945	$952	$959	$966	$973	$981	$988	$995	$1,002	$1,009	$1,017	$1,024	$1,031	$1,038	$1,045	$1,053	$1,060	$1,067	$1,074	$1,081	$1,089	$1,096	$1,103	$1,110	$1,117	$1,125	$1,132	$1,139	$1,146	
Total wind system expenditures over 30 years	$1,604																															$1,604
Average yearly baseline wind energy cost over time	$930	$937	$472	$317	$240	$193	$162	$140	$123	$111	$100	$92	$85	$79	$74	$69	$65	$62	$59	$56	$54	$51	$49	$48	$46	$44	$43	$42	$40	$39	$38	
Cost per amp produced to date ($/amp)	$0.00343	$0.00345	$0.00174	$0.00117	$0.00088	$0.00071	$0.00060	$0.00052	$0.00045	$0.00041	$0.00037	$0.00034	$0.00031	$0.00029	$0.00027	$0.00025	$0.00024	$0.00023	$0.00022	$0.00021	$0.00020	$0.00019	$0.00018	$0.00018	$0.00017	$0.00016	$0.00016	$0.00015	$0.00015	$0.00014	$0.00014	

Lithium-Ion Battery Storage System																																
Battery bank capacity (12V amp-hrs)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	
Number batteries needed	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Battery bank daily available usage (12V amp-hrs)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	
Battery bank cost lead acid ($)	$2,108	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,108	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$4,216
Battery bank wiring length (ft)	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Battery Bank wiring cost ($)	$11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$11
Battery system setup labor cost ($)	$24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$24
Battery maintenance Labor ($)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Battery maintenance supplies ($)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total amps produced to date (amp)	73000	73000	146000	219000	292000	365000	438000	511000	584000	657000	730000	803000	876000	949000	1022000	1095000	1168000	1241000	1314000	1387000	1460000	1533000	1606000	1679000	1752000	1825000	1898000	1971000	2044000	2117000	2190000	
Total baseline lithium-ion battery storage expenditures per year	$2,119	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,108	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
Total baseline lithium battery storage expenditgures to date	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$2,119	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	$4,227	
Total lithium-ion battery storage system expenditures over 30 years	$4,251																															$4,251
Average yearly baseline lithium-ion battery storage sytem cost over time	$2,119	$2,119.00	$1,059.50	$706.33	$529.75	$423.80	$353.17	$302.71	$264.88	$235.44	$211.90	$192.64	$176.58	$163.00	$151.36	$141.27	$264.19	$248.65	$234.83	$222.47	$211.35	$201.29	$192.14	$183.78	$176.13	$169.08	$162.58	$156.56	$150.96	$145.76	$140.90	
Cost per amp produced to date ($/amp)	$0.02903	$0.02903	$0.01451	$0.00968	$0.00726	$0.00581	$0.00484	$0.00415	$0.00363	$0.00323	$0.00290	$0.00264	$0.00242	$0.00223	$0.00207	$0.00194	$0.00362	$0.00341	$0.00322	$0.00305	$0.00290	$0.00276	$0.00263	$0.00252	$0.00241	$0.00232	$0.00223	$0.00214	$0.00207	$0.00200	$0.00193	

Lithium-Ion Battery Cost of Energy Production	
Solar energy production cost over 30 years ($/12V-amps available per day)	$7.77
Wind energy production cost over 30 years ($/12V-amps available per day)	$2.16
Lithium-ion battery energy storage production cost over 30 years ($/12V-amps	$21.26

Lithium-Ion Battery 3 Days of Autonomy																																
Days of autonomy	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	
Battery bank capacity (12V amp-hrs)	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	
Number batteries needed	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
Amp/hrs available per autonomous time period (12V amp-hrs)	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	
Battery cost lithium-ion ($)	$6,324	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$6,324	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$12,648
Battery bank wiring length (ft)	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Wiring cost ($)	$33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$33
Battery system setup labor cost ($)	$48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$48
Battery maintenance Labor ($)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Battery maintenance supplies ($)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total amps produced to date (amp)	219000	219000	438000	657000	876000	1095000	1314000	1533000	1752000	1971000	2190000	2409000	2628000	2847000	3066000	3285000	3504000	3723000	3942000	4161000	4380000	4599000	4818000	5037000	5256000	5475000	5694000	5913000	6132000	6351000	6570000	
Total baseline lithium-ion battery storage expenditures per year	$6,357	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$6,324	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
Total baseline lithium battery storage expenditgures to date	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$6,357	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	$12,681	
Total lithium-ion battery storage system expenditures over 30 years	$12,729																															$12,729
Average yearly baseline lithium-ion battery storage sytem cost over time	$6,357	$6,357	$3,179	$2,119	$1,589	$1,271	$1,060	$908	$795	$706	$636	$578	$530	$489	$454	$424	$793	$746	$705	$667	$634	$604	$576	$551	$528	$507	$488	$470	$453	$437	$423	
Cost per amp produced to date ($/amp)	$0.02903	$0.02903	$0.01451	$0.00968	$0.00726	$0.00581	$0.00484	$0.00415	$0.00363	$0.00323	$0.00290	$0.00264	$0.00242	$0.00223	$0.00207	$0.00194	$0.00362	$0.00341	$0.00322	$0.00305	$0.00290	$0.00276	$0.00263	$0.00252	$0.00241	$0.00232	$0.00223	$0.00214	$0.00207	$0.00200	$0.00193	
Lithium-Ion Battery Cost of Energy Production 3 Days of Autonomy																																
Lithium-Ion battery energy storage production cost over 30 yrs ($/12V-amps ava	$21.22																															

Lithium-Ion Battery 5 Days of Autonomy																																
Days of autonomy	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	
Battery bank capacity (12V amp-hrs)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	
Number batteries needed	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
Amp/hrs available per autonomous time period (12V amp-hrs)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	
Battery cost lithium-ion ($)	$10,540	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$10,540	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$21,080
Battery bank wiring length (ft)	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Wiring cost ($)	$55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$55
Battery system setup labor cost ($)	$72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$48
Battery maintenance Labor ($)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Battery maintenance supplies ($)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total amps produced to date (amp)	365000	365000	730000	1095000	1460000	1825000	2190000	2555000	2920000	3285000	3650000	4015000	4380000	4745000	5110000	5475000	5840000	6205000	6570000	6935000	7300000	7665000	8030000	8395000	8760000	9125000	9490000	9855000	10220000	10585000	10950000	
Total baseline lithium-ion battery storage expenditures per year	$10,595	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$10,540	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
Total baseline lithium battery storage expenditgures to date	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$10,595	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	$21,135	
Total lithium-ion battery storage system expenditures over 30 years	$21,183																															$21,183
Average yearly baseline lithium-ion battery storage sytem cost over time	$10,595	$10,595	$5,298	$3,532	$2,649	$2,119	$1,766	$1,514	$1,324	$1,177	$1,060	$963	$883	$815	$757	$706	$1,321	$1,243	$1,174	$1,112	$1,057	$1,006	$961	$919	$881	$845	$813	$783	$755	$729	$705	
Cost per amp produced to date ($/amp)	$0.02903	$0.02903	$0.01451	$0.00968	$0.00726	$0.00581	$0.00484	$0.00415	$0.00363	$0.00323	$0.00290	$0.00264	$0.00242	$0.00223	$0.00207	$0.00194	$0.00362	$0.00341	$0.00322	$0.00305	$0.00290	$0.00276	$0.00263	$0.00252	$0.00241	$0.00232	$0.00223	$0.00214	$0.00207	$0.00200	$0.00193	
Lithium-Ion Battery Cost of Energy Production 5 Days of Autonomy																																
Lithium-Ion battery energy storage production cost over 30 yrs ($/12V-amps ava	$21.18																															

Table 4. Pumped-hydro storage RES spreadsheet.

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2049	Total
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Baseline Site Requirements																																
Daily power needs (12V amp-hrs)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	
Peak sun-hours (hrs)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	
Average daily wind speed (mph)	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	
Baseline Solar Energy Production																																
Solar panel requirements (# of 12V (100 watt / 6.1 amp) panels)	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Individual solar panel costs ($)	$110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Total solar panel cost ($)	$770	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$770
Solar charge controller ($)	$135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$135
Solar wiring length (ft)	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar wiring cost ($)	$13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$13
Solar system setup labor cost ($)	$72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$72
Solar maintenance labor ($)	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$670
Amps produced per hour	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	
Amps produced per day	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	214	
Total amps produce to date	77928	77928	155855	233783	311710	389638	467565	545493	623420	701348	779275	857203	935130	1013058	1090985	1168913	1246840	1324768	1402695	1480623	1558550	1636478	1714405	1792333	1870260	1948188	2026115	2104043	2181970	2259898	2337825	
Total baseline solar energy expenditures per year	$939	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	$22	
Total baseline solar energy expenditures to date	$939	$961	$982	$1,004	$1,026	$1,047	$1,069	$1,090	$1,112	$1,134	$1,155	$1,177	$1,198	$1,220	$1,242	$1,263	$1,285	$1,306	$1,328	$1,350	$1,371	$1,393	$1,414	$1,436	$1,458	$1,479	$1,501	$1,522	$1,544	$1,566	$1,587	
Total Solar System expenditures over 30 years	$1,659																															$1,659
Average yearly baseline solar energy costs over time	$939	$961	$491	$335	$256	$209	$178	$156	$139	$126	$116	$107	$100	$94	$89	$84	$80	$77	$74	$71	$69	$66	$64	$62	$61	$59	$58	$56	$55	$54	$53	
Cost per amp produced to date ($/amp)	$0.01205	$0.01233	$0.00630	$0.00429	$0.00329	$0.00269	$0.00229	$0.00200	$0.00178	$0.00162	$0.00148	$0.00137	$0.00128	$0.00120	$0.00114	$0.00108	$0.00103	$0.00099	$0.00095	$0.00091	$0.00088	$0.00085	$0.00083	$0.00080	$0.00078	$0.00076	$0.00074	$0.00072	$0.00071	$0.00069	$0.00068	
Baseline Wind Energy Production																																
1KW residential wind turbine ($)	$575	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$575
Wind charge controller with water heater diversion dump load	$273	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$273
Wind wiring length (Ft)	75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Wind wiring costs ($)	$75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$75
Wind system setup labor cost ($)	$458	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$458
Wind maintenance labor ($)	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$223
Amps produced per hour (amps)	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	
Amps produced per day (amp)	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	
Total amps produced to date (amp)	271560	271560	543120	814680	1086240	1357800	1629360	1900920	2172480	2444040	2715600	2987160	3258720	3530280	3801840	4073400	4344960	4616520	4888080	5159640	5431200	5702760	5974320	6245880	6517440	6789000	7060560	7332120	7603680	7875240	8146800	
Total baseline wind energy expenditures per year	$930	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	
Total baseline wind energy expenditures to date	$930	$937	$945	$952	$959	$966	$973	$981	$988	$995	$1,002	$1,009	$1,017	$1,024	$1,031	$1,038	$1,045	$1,053	$1,060	$1,067	$1,074	$1,081	$1,089	$1,096	$1,103	$1,110	$1,117	$1,125	$1,132	$1,139	$1,146	
Total wind system expenditures over 30 years	$1,604																															$1,604
Average yearly baseline wind energy cost over time	$930	$937	$472	$317	$240	$193	$162	$140	$123	$111	$100	$92	$85	$79	$74	$69	$65	$62	$59	$56	$54	$51	$49	$48	$46	$44	$43	$42	$40	$39	$38	
Cost per amp produced to date ($/amp)	$0.00343	$0.00345	$0.00174	$0.00117	$0.00088	$0.00071	$0.00060	$0.00052	$0.00045	$0.00041	$0.00037	$0.00034	$0.00031	$0.00029	$0.00027	$0.00025	$0.00024	$0.00023	$0.00022	$0.00021	$0.00020	$0.00019	$0.00018	$0.00018	$0.00017	$0.00016	$0.00016	$0.00015	$0.00015	$0.00014	$0.00014	

Pumped Hydro Storage System																																
Hours of operation per day	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	
Gallons of water needed per day / pelton wheel requirements	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	4845	
Total water storage tank capacity upper and lower (gallons)	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	
Water storage tank cost ($)	$4,600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$4,600
Piping length to maintain minimum of 100' of head (ft)	187	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Total piping needs (ft)	374	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Piping cost ($)	$71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$71
Piping fittings cost ($)	$20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$20
Solar water pump capacity 100 ft of head (gallons/hr)	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	
Average gallons pumped per day (gallons)	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	
Solar water pump cost ($)	$880	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$880
Solar water pump wiring length (ft)	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar water pump wiring cost ($)	$10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$10
Solar panel requirements for water pump (# of 12V (100 watt / 6.1 amp) panels)	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Total solar panel cost ($)	$440	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$440
Solar wiring length (ft)	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar wiring cost ($)	$7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$7
Pelton wheel Cost	$255	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$255
Alternator and coupling cost ($)	$108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$108
Alternator wiring length (ft)	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Alternator wiring cost ($)	$55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$55
PHS system labor setup cost ($)	$312	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$312
PHS system maintenance labor ($)	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$2,232
Alternator continuous output (12v amps)	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	
Amps produced per day	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	570	
Potential total amps produced to date (amp)	208050	208050	416100	624150	832200	1040250	1248300	1456350	1664400	1872450	2080500	2288550	2496600	2704650	2912700	3120750	3328800	3536850	3744900	3952950	4161000	4369050	4577100	4785150	4993200	5201250	5409300	5617350	5825400	6033450	6241500	
Total baseline PHS expenditures per year	$6,830	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	
Total baseline PHS expenditgures to date	$6,830	$6,902	$6,974	$7,046	$7,118	$7,190	$7,262	$7,334	$7,406	$7,478	$7,550	$7,622	$7,694	$7,766	$7,838	$7,910	$7,982	$8,054	$8,126	$8,198	$8,270	$8,342	$8,414	$8,486	$8,558	$8,630	$8,702	$8,774	$8,846	$8,918	$8,990	
Total baseline PHS expenditures over 30 years	$8,990																															$8,990
Average yearly baseline PHS cost over time	$6,830	$6,902	$3,487	$2,349	$1,780	$1,438	$1,210	$1,048	$926	$831	$755	$693	$641	$597	$560	$527	$499	$474	$451	$431	$414	$397	$382	$369	$357	$345	$335	$325	$316	$308	$300	
Cost per amp produced to date ($/amp)	$0.03283	$0.03318	$0.01676	$0.01129	$0.00855	$0.00691	$0.00582	$0.00504	$0.00445	$0.00399	$0.00363	$0.00333	$0.00308	$0.00287	$0.00269	$0.00253	$0.00240	$0.00228	$0.00217	$0.00207	$0.00199	$0.00191	$0.00184	$0.00177	$0.00171	$0.00166	$0.00161	$0.00156	$0.00152	$0.00148	$0.00144	

Pumped Hydro Storage System Cost of Energy Production	
Solar energy production cost over 30 years ($/12V-amps available per day)	$7.77
Wind energy production cost over 30 years ($/12V-amps available per day)	$2.16
PHS energy storage production cost over 30 years ($/12V-amps available per day)	$15.77

Pumped Hydro Storage System 3 Days of Autonomy																																
Days of autonomy	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	
Hours of operation per day	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	
Total hours of operation capacity	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	
Gallons of water needed per day / pelton wheel requirements	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	14535	
Total water storage tank capacity upper and lower (gallons)	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	29000	
Water storage pond liner cost ($)	$1,015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Water storage pond construction cost ($)	$540	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$540
Water storage pond construction cost per gallon ($/gallon)	$0.0186																															
Piping length to maintain minimum of 100' of head (ft)	$187	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$187
Total Piping needs (ft)	374	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Piping cost ($)	$71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$71
Piping/ Fittings Cost ($)	$20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$20
Solar water pump capacity 100 ft of head (gallons/hr)	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	
Average gallons pumped per day (gallons)	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	4950	
Solar water pumps needed	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar water pump Cost ($)	$880	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$880
Total solar water pumps cost ($)	$5,280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$5,280
Solar water pumps wiring length (ft)	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$60
Solar water pump wiring cost ($)	$60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$60
Solar panel requirements for water pump (# of 12V (100 watt / 6.1 amp) panels)	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Individual solar panel Cost ($)	$110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$110
Total solar panel cost ($)	$2,640	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$2,640
Solar wiring length (ft)	144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar wiring cost ($)	$43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$43
Pelton Wheel Cost	$255	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$255
Altenator cost ($)	$108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$108
Alternator Wiring length (ft)	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Wiring Cost ($)	$55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$55
PHS system setup cost ($)	$120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$120
PHS system maintenance labor ($)	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$2,232
Altenator continuous output (12v amps)	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	
Amps available per autonomous time period (12V amp-hrs)	1710	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Potential total amps produced to date (amps)	624150	624150	1248300	1872450	2496600	3120750	3744900	4369050	4993200	5617350	6241500	6865650	7489800	8113950	8738100	9362250	9986400	10610550	11234700	11858850	12483000	13107150	13731300	14355450	14979600	15603750	16227900	16852050	17476200	18100350	18724500	
Total PHS storage expenditures per year for 3 days of autonomy	$11,346	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	
Total PHS expenditgures to date for 3 days of autonomy	$11,346	$11,418	$11,490	$11,562	$11,634	$11,706	$11,778	$11,850	$11,922	$11,994	$12,066	$12,138	$12,210	$12,282	$12,354	$12,426	$12,498	$12,570	$12,642	$12,714	$12,786	$12,858	$12,930	$13,002	$13,074	$13,146	$13,218	$13,290	$13,362	$13,434	$13,506	
Total PHS expenditures over 30 years for 3 days of autonomy	$12,661																															$12,661
Average yearly PHS cost over time for 3 days of autonomy	$11,346	$11,418	$5,745	$3,854	$2,909	$2,341	$1,963	$1,693	$1,490	$1,333	$1,207	$1,103	$1,018	$945	$882	$828	$781	$739	$702	$669	$639	$612	$588	$565	$545	$526	$508	$492	$477	$463	$450	
Cost per amp produced to date ($/amp)	$0.01818	$0.01829	$0.00920	$0.00617	$0.00466	$0.00375	$0.00315	$0.00271	$0.00239	$0.00214	$0.00193	$0.00177	$0.00163	$0.00151	$0.00141	$0.00133	$0.00125	$0.00118	$0.00113	$0.00107	$0.00102	$0.00098	$0.00094	$0.00091	$0.00087	$0.00084	$0.00081	$0.00079	$0.00076	$0.00074	$0.00072	
Pumped Hydro Storage System Cost of Energy Production 3 days of Autonomy																																
PHS storage production cost over 30 yrs ($/12V-amps available per day)	$7.40																															

Pumped Hydro Storage System 5 Days of Autonomy																																
Days of autonomy	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	
Hours of operation per day	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	
Total hours of operation capacity	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	
Gallons of water needed per day / pelton wheel requirements	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	24225	
Total water storage tank capacity upper and lower (gallons)	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	48000	
Water storage pond liner cost ($)	$1,680	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$1,680
Water storage pond construction cost ($)	$894	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$894
Piping length to maintain minimum of 100' of head (ft)	$187	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$187
Total Piping needs (ft)	374	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Piping cost ($)	$71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$71
Piping/ Fittings Cost ($)	$20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$20
Solar water pump capacity 100 ft of head (gallons/hr)	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	
Average gallons pumped per day (gallons)	19800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar water pumps needed	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar water pump Cost ($)	$880	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$880
Total solar water pumps cost ($)	$2,640	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$2,640
Solar water pumps wiring length (ft)	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar water pump wiring cost ($)	$30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$30
Solar panel requirements for water pump (# of 12V (100 watt / 6.1 amp) panels)	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Individual solar panel Cost ($)	$110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$110
Total solar panel cost ($)	$1,320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$1,320
Solar wiring length (ft)	72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Solar wiring cost ($)	$22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$22
Pelton Wheel Cost	$255	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$255
Altenator cost ($)	$108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$108
Alternator Wiring length (ft)	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Wiring Cost ($)	$55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$55
PHS system setup cost ($)	$120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$120
PHS system maintenance labor ($)	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$2,232
Altenator continuous output (12v amps)	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	
Amps available per autonomous time period (12V amp-hrs)	2850	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Potential total amp produced to date (amps)	1040250	1040250	2080500	3120750	4161000	5201250	6241500	7281750	8322000	9362250	10402500	11442750	12483000	13523250	14563500	15603750	16644000	17684250	18724500	19764750	20805000	21845250	22885500	23925750	24966000	26006250	27046500	28086750	29127000	30167250	31207500	
Total PHS storage expenditures per year for 5 days of autonomy	$8,495	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	$72	
Total PHS expenditgures to date for 5 days of autonomy	$8,495	$8,567	$8,639	$8,711	$8,783	$8,855	$8,927	$8,999	$9,071	$9,143	$9,215	$9,287	$9,359	$9,431	$9,503	$9,575	$9,647	$9,719	$9,791	$9,863	$9,935	$10,007	$10,079	$10,151	$10,223	$10,295	$10,367	$10,439	$10,511	$10,583	$10,655	
Total PHS expenditures over 30 years for 5 days of autonomy	$10,623																															$10,623
Average yearly PHS cost over time for 5 days of autonomy	$8,495	$8,567.45	$4,319.73	$2,903.82	$2,195.86	$1,771.09	$1,487.91	$1,285.64	$1,133.93	$1,015.94	$921.55	$844.31	$779.95	$725.50	$678.82	$638.36	$602.97	$571.73	$543.97	$519.13	$496.77	$476.55	$458.16	$441.37	$425.98	$411.82	$398.75	$386.65	$375.41	$364.95	$355.18	
Cost per amp produced to date ($/amp)	$0.00817	$0.00824	$0.00415	$0.00279	$0.00211	$0.00170	$0.00143	$0.00124	$0.00109	$0.00098	$0.00089	$0.00081	$0.00075	$0.00070	$0.00065	$0.00061	$0.00058	$0.00055	$0.00052	$0.00050	$0.00048	$0.00046	$0.00044	$0.00042	$0.00041	$0.00040	$0.00038	$0.00037	$0.00036	$0.00035	$0.00034	
Pumped Hydro Storage System Cost of Energy Production 5 days of Autonomy																																
PHS storage production cost over 30 yrs ($/12V-amps available per day)	$3.73																															

The total cost of my specific sized system for our energy needs over 30-years for the 1-day autonomous lithium-ion battery RES was $4,251, for the 3-day autonomous lithium-ion battery RES was $12,729, and 5-day autonomous lithium-ion battery RES was $21,183. In contrast, the total cost for the PHS 1-day RES was $5,911, 3-day autonomous PHS RES was $8,267 and 5-day autonomous PHS RES was $10,623.

Variable Analysis

Supplementary calculations to adjust 30-year costs of the solar and wind systems and RES systems were needed, and included total expenditures per year, average yearly baseline costs over time, as well as total expenditures to date, cumulative as successive year passed for each system. These were combined to calculate cumulative amps produced, allowing cost per amps to be calculated yearly (Figure 5).

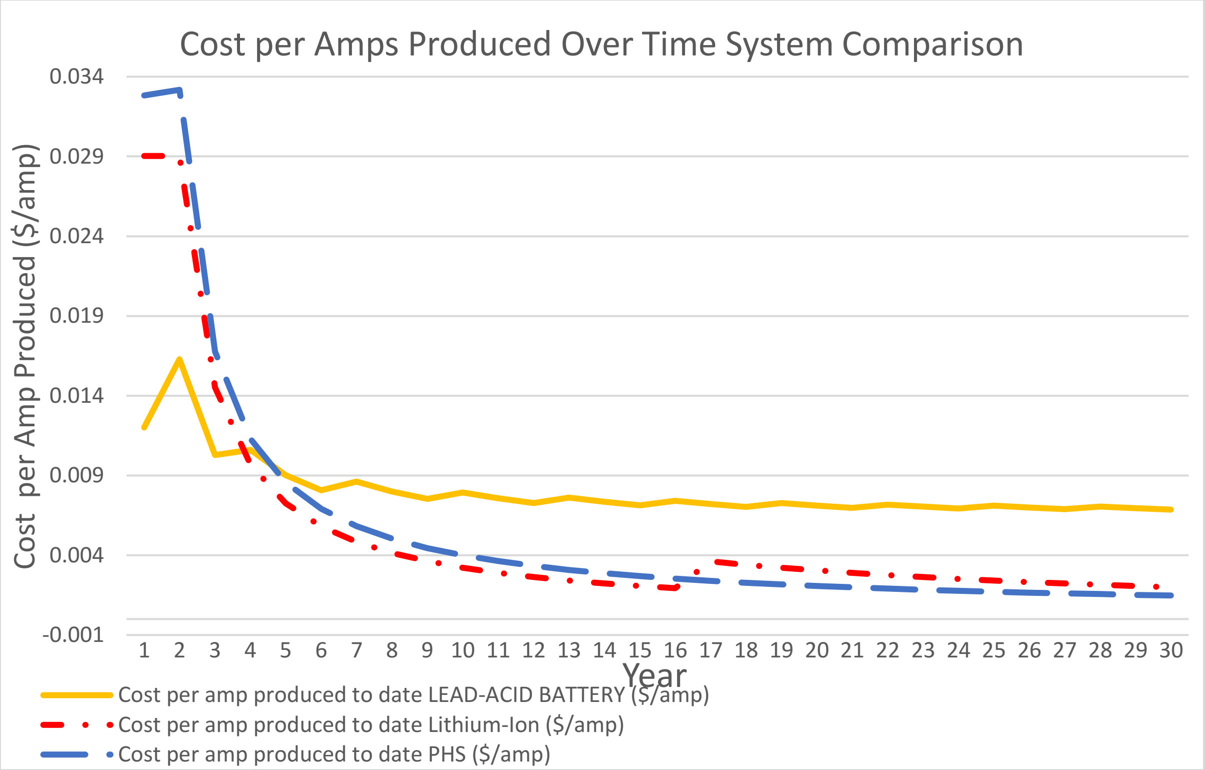


Figure 5. Cost per amps produced over time for different RES systems.

Costs per amp produced over time for each RES was performed for each set system for 1, 3 and 5 days of autonomy (Figures 6, 7 & 8).

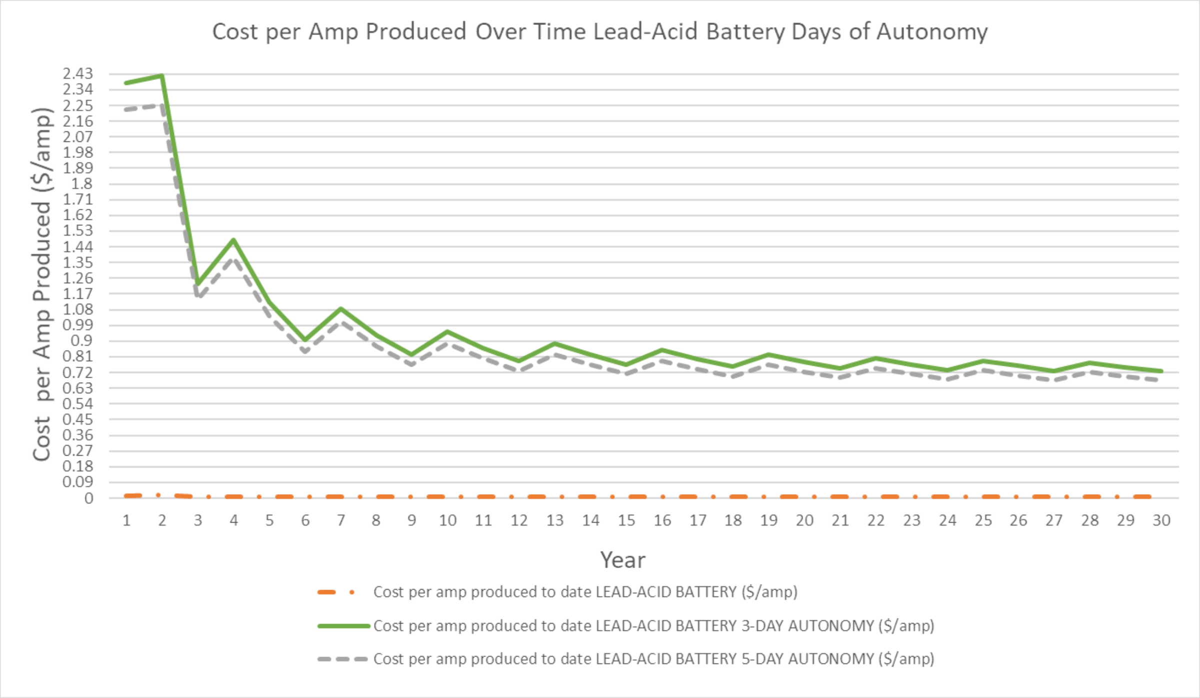


Figure 6. Cost per amp produced over time for lead-acid days of autonomy.

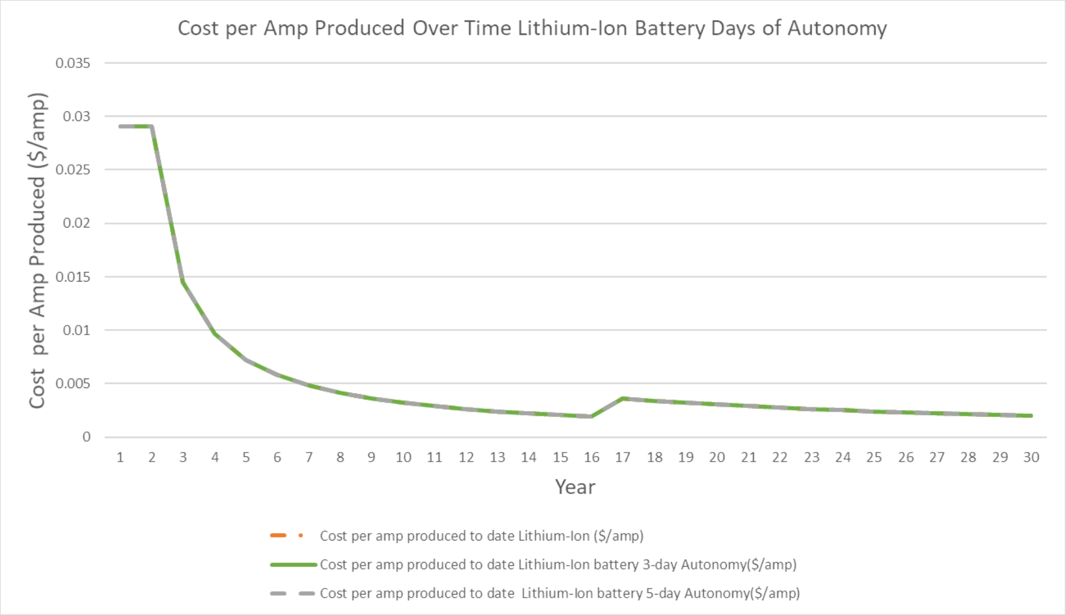


Figure 7. Cost per amp produced over time for lithium-ion days of autonomy.

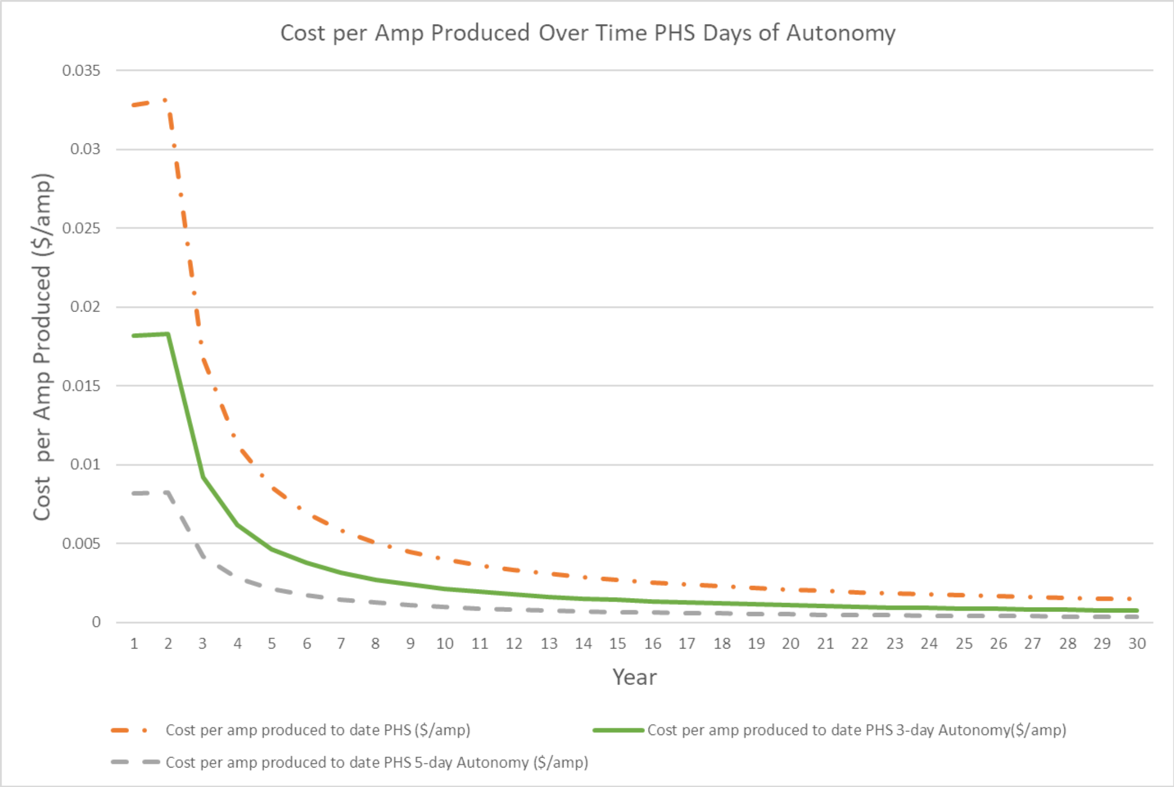


Figure 8. Cost per amp produced over time for PHS days of autonomy.

Each energy producing and storage system had set categories of costs that led to unique comparative analysis. These categories included: 1) setup equipment costs, 2) setup labor costs, 3) ongoing equipment costs, 4) ongoing maintenance labor, and 5) ongoing maintenance supplies. Figures 9, 10, 11, 12 and 13 show each systems' categorical cost breakdown.

Setup equipment costs were similar for energy generated by the solar and wind systems, but setup costs were high for the wind system (Figure 10), whereas ongoing maintenance costs were high for the solar system (Figure 9). The PHS system was spared from ongoing equipment costs with costs dominated by initial equipment purchases (Figure 13). Lead-acid battery storage required high ongoing maintenance labor and supplies (Figure 11), whereas the lithium-ion batteries were expensive (Figure 12).

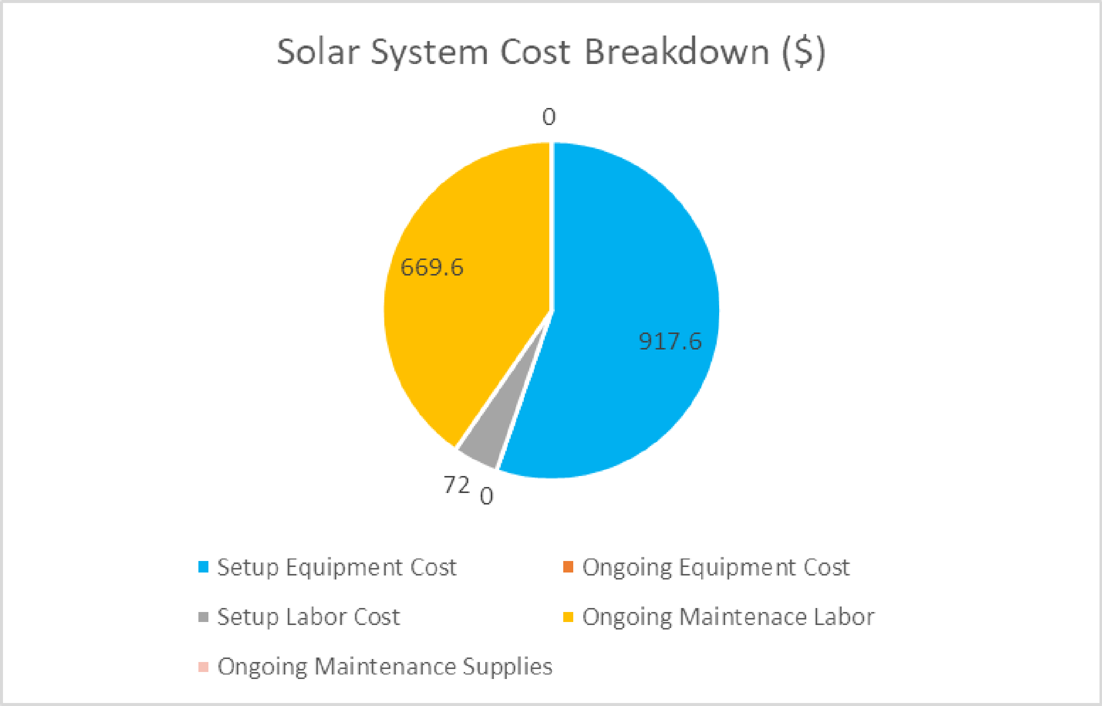


Figure 9. Solar system cost breakdown ($).

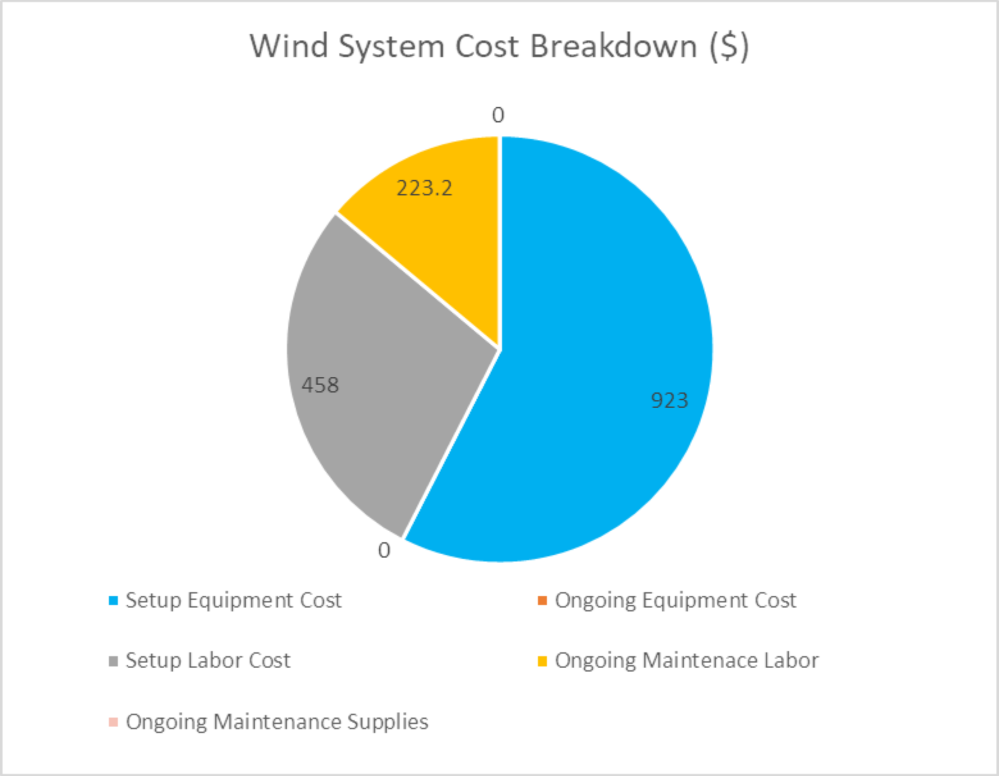


Figure 10. Wind system cost breakdown ($).

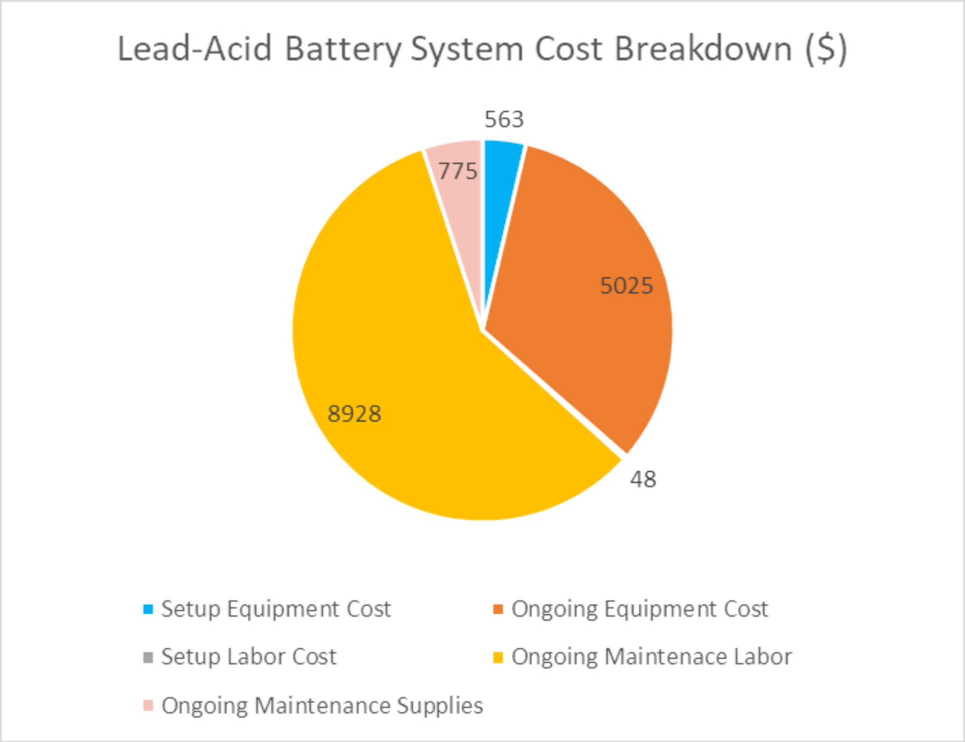


Figure 11. Lead-acid battery system cost breakdown ($).

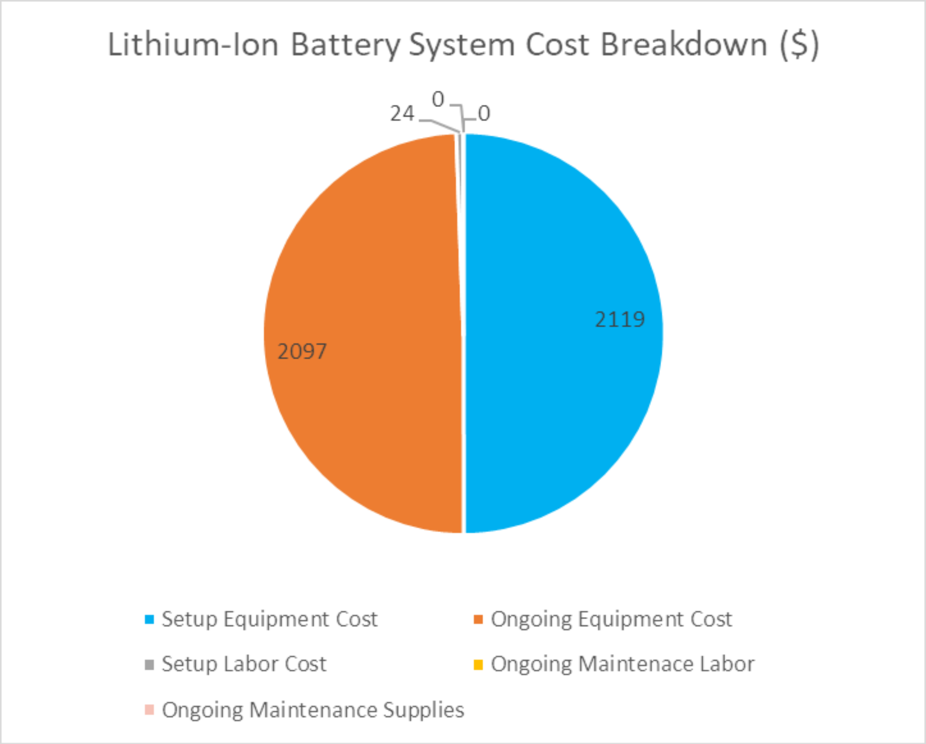


Figure 12. Lithium-ion battery system cost breakdown ($).

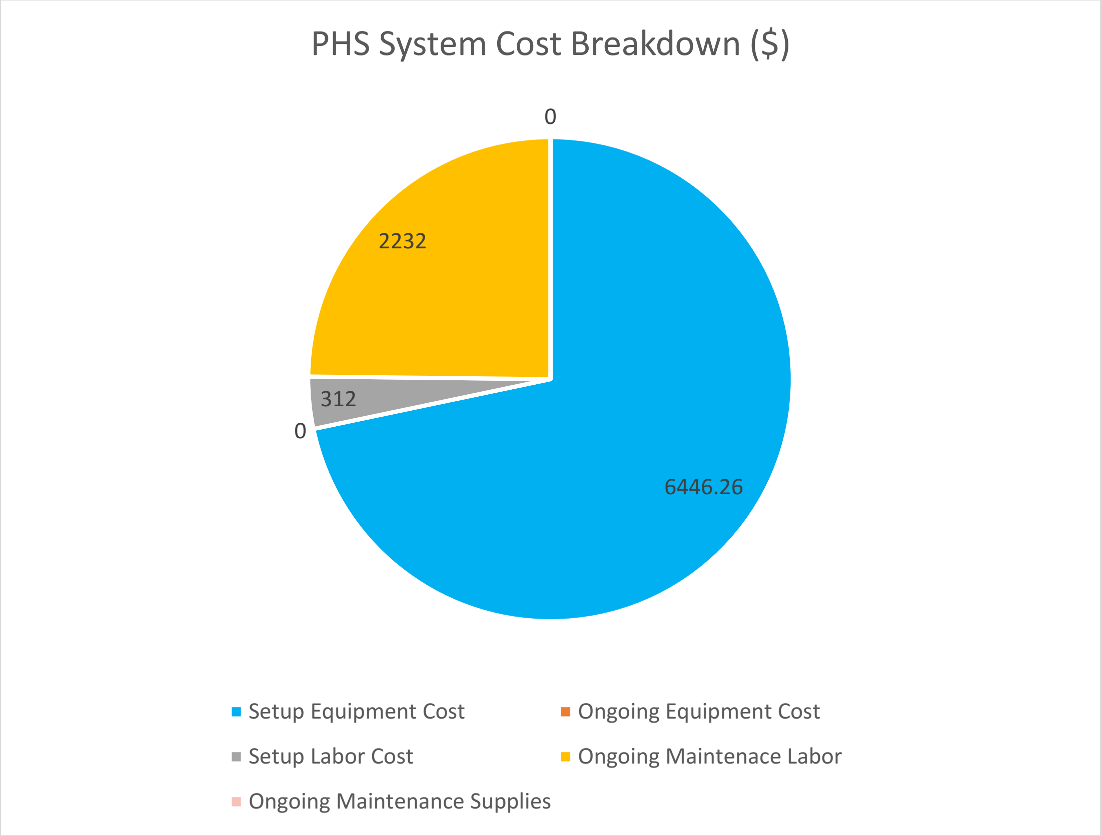


Figure 13. PHS system cost breakdown ($).

Chapter IV

Discussion

Analyzing the data gathered from the modeling based on these experiment, at these specific system sizes, an uphill gravity storage system (PHS) is more cost effective than a lead-acid battery storage system at 1, 3 or 5 days of autonomy for an off-grid hybrid solar and wind energy production system over a 30-year period. Although the lithium-ion RES is less expensive then the PHS for 1-day autonomy, the PHS becomes significantly more cost effective at increasing days of autonomy. The PHS system is half the cost of the lithium-ion RES and one-fifth the cost of the lead-acid battery RES at 5 days of autonomy. Similar differences in system costs continued when modeling scenarios up to 14 days of autonomy calculations.

Significant Variables

In examining the cost per amps produced over time between the various energy producing and energy storage systems, it was surprising to discover that the PHS had some of the highest initial cost per amp production although the lowest of each RES storage system by the end of the 30-year period (Figure 5). The fact that the lead-acid battery storage system had the lowest initial cost per amp produced is more than likely a major factor in its popular and continued use in rural RES systems, although over the 30-year analysis period its cost per amp produced remains somewhat constant while the other RES systems significantly decrease over time. Many off-grid homesteaders do not consider the significant ongoing equipment and maintenance needed for such a system. Figure 11 visually depicts how low the upfront costs of lead-acid batteries are in comparison to the rest of the costs over the 30-years. Furthermore, a 5 day autonomous lead-acid battery storage system would need 132 of the 60 lb lead-acid batteries over the 30-year period, as the batteries are replaced every three years. This would have a significant impact on the environment and human health if the entire life-cycle of the lead-acid battery was taken into consideration.

The PHS system cost breakdown (Figure 13) was very similar to both the solar (Figure 9) and wind (Figure 10) renewable energy productions systems. It features large initial setup costs with little ongoing costs, with the PHS system having an even smaller percent of total costs as ongoing costs.

Additional Scenarios

Days of autonomy had a significant effect on both overall costs and cost per amp hour produced for each renewable energy storage system. Figure 14 graphs the overall 30-year costs of each renewable energy producing and storage system for 1, 3, 5, 8, 11 and 14 days of autonomy. The percent of cost growth rate for the PHS was significantly lower than that of the lithium-ion battery storage system as well as the lead-acid battery storage system (compare PHS in blue with lithium-ion in red and lead-acid in yellow).

After experimenting with the use of cisterns and calculating the per gallon costs of setup ($0.46/gal for a cistern and $0.0186/ gallon for pond construction), it became immediately apparent that water storage in ponds as upper and lower reservoirs would be significantly more cost effective. The modeling spreadsheet allows for the rental of a

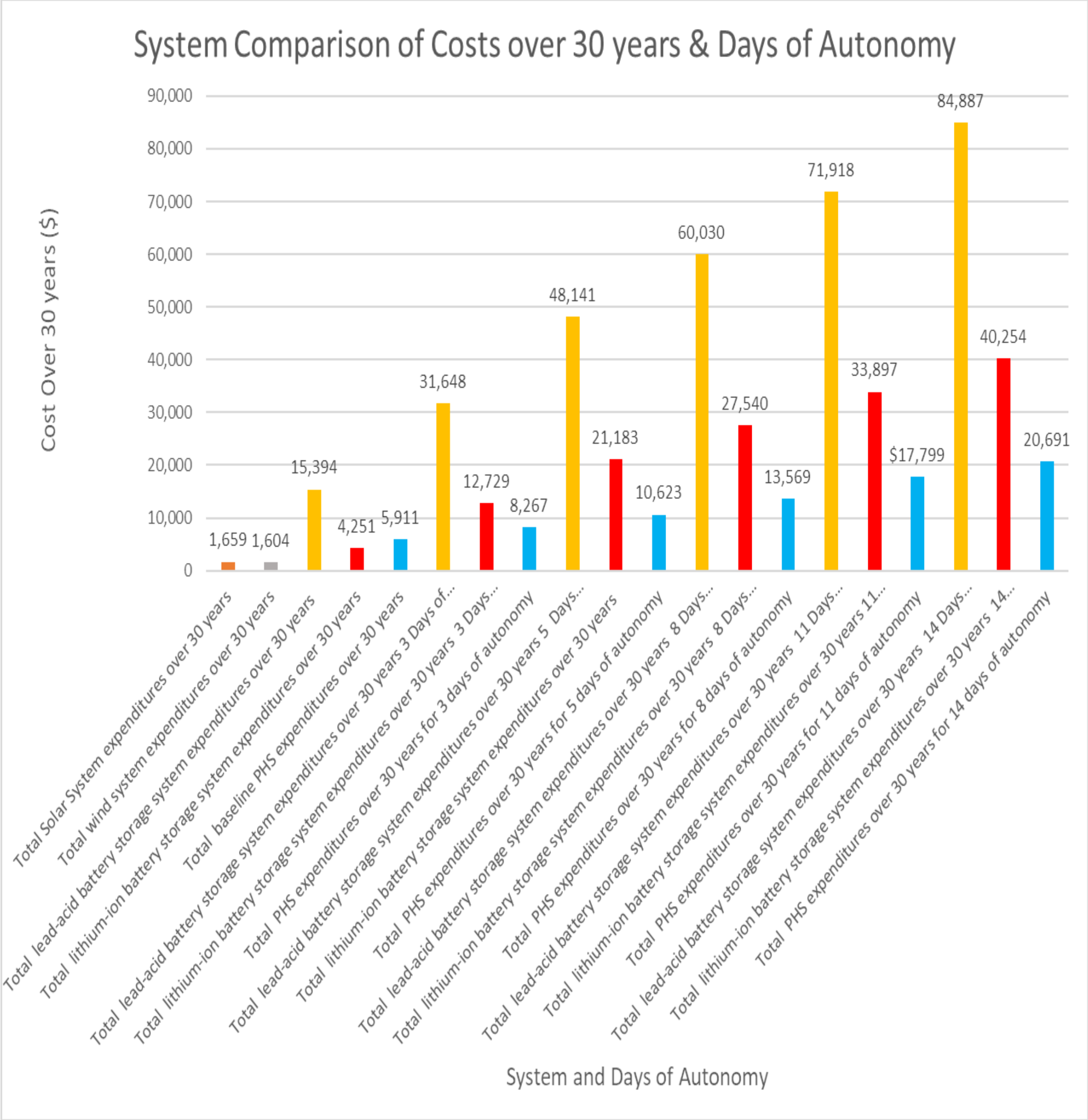


Figure 14. System comparison of costs over 30 years with 14 days of autonomy. Solar and wind far left, then from left to right, costs for 1, 3, 5, 8, 11 and 14 days of autonomy, organized in groups of three for lead-acid (gold), lithium-ion (red) and PHS (blue).

bulldozer and diesel fuel although I used my own to calculate the time needed for construction. This experiment was conducted by me and could be a DIY setup for any person with adequate prior research into each system, as well as electrical wiring knowledge. However, although my own labor costs were factored in to each modeling scenario, hired laborers could be used and labor rate inputs changed.

Each system produces or has available to be consumed different amounts of amps per day. I compared the cost of each system's energy production based on the cost of the system over 30-years for the amount of energy that is available per day or total available over the 1, 3 and 5 day autonomous periods (Figure 15).

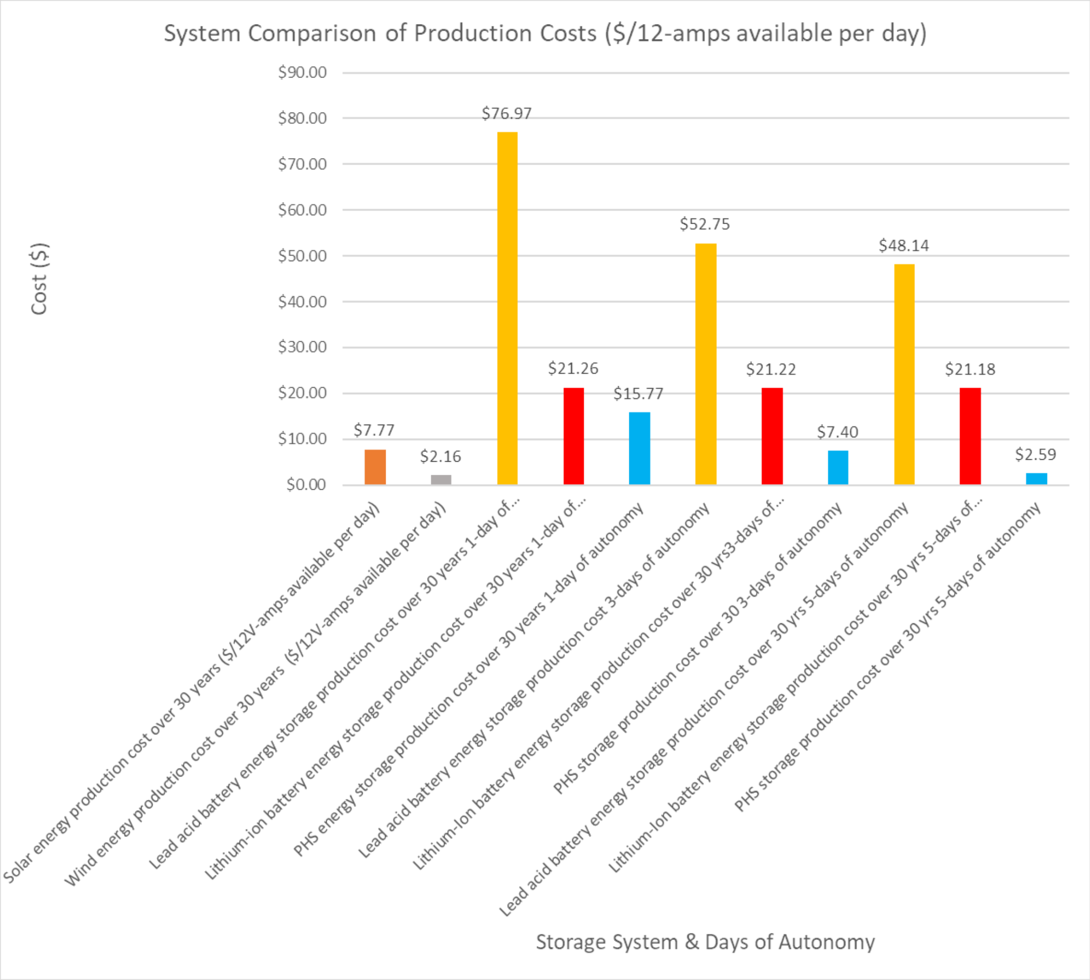


Figure 15. System comparison of productions costs over a 30-year period compared to the amount of energy that is available per day or total available over 1, 3 and 5 day autonomous periods. Color coding as in Figure 14.

Conclusions

The impetuous for this analysis for my 20-acre homestead in north-east Washington state was that it is off-grid and eight miles from the nearest electrical pole. According to the local Ferry county Public Utilities Department (PUD) at a cost near \$11,000 dollars per mile of electrical wire and pole installation, the \$88,000 price tag seemed outrageous. Once connected to the local utilities, there will still be monthly \$20 service charge as well as a \$0.08798 per KWH energy charge. With a total 30-year cost with 5-days of autonomy the solar, redundant wind and PHS systems would cost \$23,954. This site-specific solar and PV RES with PHS storage is 27% of the initial connection charge to the grid not including the 30 years of grid-connected utility charges.

In situations where local governments are paying to run utilities to a limited number of rural isolated residents, it would make more sense to subsidize off-grid solar and wind renewable energy systems with pumped-hydro storage.

I started a small solar system with lead-acid batteries a few years ago although with the extreme summer to winter temperature fluctuation, the lead-acid battery performance quickly diminished to non-functioning within just a few years. This experimentation and subsequent spreadsheet modeling allowed for long-term financial analysis of the best system for my combination of parameters.

Others may alter these parameters values for their specific site location to make best choices for themselves or policy makers. Nearly, 1.2 billion people worldwide do not have access to electricity (World Bank, 2013); this spreadsheet model allows for variables to be altered depending on-site parameters and household needs to quantify off-grid RES production systems.

References

Ahlborg, H., & Hammar, L. (2014). Drivers and barriers to rural electrification in Tanzania and Mozambique – Grid-extension, off-grid, and renewable energy technologies. *Renewable Energy*, *61*, 117-124.

Berrada, A., Loudiyi,K., & Zorkani, I. (2017). System design and economic performance of gravity energy storage. *Journal of Cleaner Production*, *156*, 317-326.

Barr, R. (2011). China surpasses US as top energy producer. In Business - Oil & Energy on MSNBC- NBC News. Retrieved October 15, 2017, from http://www.msnbc.msn.com/id/43327793/ns/business-oil_and_energy/t/chinasurpasses- us-top-energy-consumer/#.UJrwBIWd7Od

Block, B. (2012), U.S. Renewable Energy Growth Accelerates. In Worldwatch Institute. Retrieved October 1, 2017, from http://www.worldwatch.org/node/5855

Botkin, D., & Keller, E. (2011). *Environmental Science: Earth as a Living Planet*. (8th ed., p. 336-340). Hoboken, NJ: John Wiley & Sons, INC.

Bowman, J. (2010). Inverter modeling For accurate energy predictions Of tracking HCPV installations. *AIP Conference Proceedings*, *1277*, 320-323.

Bullis, K. (2012). The US could run on 80-percent renewable electricity by 2050. In *MIT Technology Review*. Retrieved October 15, 2017, from http://www.technologyreview.com/view/428284/the-us-could-run-on-80-percentrenewable-electricity-by-2050/

Davidson, P. (2006). Off the grid or on, solar and wind power gain. April 12. USA Today. Retrieved January 12, 2018 from https://usatoday30.usatoday.com/tech/news/techinnovations/2006-04-12-off-the-grid_x.htm

Energy.gov. (2018) Tips: heating and cooling. Retrieved August 2, 2018 from http://energy.gov/energysaver/articles/tips-heating-and-cooling

EIA (2016). U.S. energy facts explained. Retrieved September 24, 2017 from https://www.eia.gov/energyexplained/?page=us_energy_home

EPA. (2016). *Green Building.* Retrieved August 2, 2018 from http://www.epa.gov/greenbuilding/pubs/about.htm

EPA. (2017). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015*. Retrieved October 2, 2017, from https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015

Evans, A., Strezov, V., & Evans. T. (2012). Assessment of utility energy storage options for increased renewable energy penetration, In *Renewable and Sustainable Energy Reviews*, *16*, 4141-4147. Retrieved on December 11 2017, from http://www.sciencedirect.com/science/article/pii/S1364032112002316

Garimella, N. & Nair, N. (2009). Assessment of battery energy storage systems for small-scale renewable energy integration. in *Proc. IEEE Reg. 10 Conf. (TENCON),* Singapore, Jan. 2009, pp. 1–6. Retrieved on February 1, 2018 from http://ieeexplore.ieee.org.ezp-prod1.hul.harvard.edu/stamp/stamp.jsp?tp=&arnumber=5395831&isnumber=5395786

Haefliger, P., Mathieu-Nolf, M., Lociciro, S., Ndiaye, C., Coly, M., Diouf, A., & Neira, M. (2009). Mass Lead Intoxication from Informal Used Lead-Acid Battery Recycling in Dakar, Senegal. *Environmental Health Perspectives*, *117*, 1535–1540.

Hoppmann J., Volland J., Schmidt T.S., & Hoffmann V.H. (2014). The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems - A Review and a Simulation Model. *Renewable and Sustainable Energy Reviews, 39*, 1101–1118.

IEA. (2014). The International Energy Agency's World Energy Outlook. Retrieved on February 3, 2018 from https://www.iea.org/publications/freepublications/publication/WEO2014.pdf

IEA. (2016). The International Energy Agency's Snapshot of Global Photovoltaic Markets 2016. Retrieved on October 12, 2017 from http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_-_A_Snapshot_of_Global_PV_-_1992-2016__1_.pdf

IEA. (2017). Electric Power Monthly with Data for July 2017. Retrieved October 2, 2017 from https://www.eia.gov/electricity/monthly/current_month/epm.pdf

IEEE. (2008). Guide for Optimizing the Performance and Life of Lead-Acid Batteries in Remote Hybrid Power Systems. *1561*, 1-25.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IRENA (2015). *Renewable Power Generation Costs in 2014*. Retrieved on December 28, 2017 from http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf

Kolhe, M. (2009). Techno-economic optimum sizing of a stand-alone solar photovoltaic system. *IEEE Trans. Energy Convers*., *24*, 511–519.

Libre de Bruxelles, Université. (2016). Is energy storage via pumped hydro systems is possible on a very small scale?. *ScienceDaily*. Retrieved December 11, 2017 from www.sciencedaily.com/releases/2016/10/161024090454.htm

Ma T, Yang H, Lu L, & Peng J. (2014). Technical feasibility study on a standalone hybrid solar–wind system with pumped hydro storage for a remote island in Hong Kong. *Renew Energy*, *69,* 7–15.

Melillo, J.M., Richmond, T.C., & Yohe. G. W. (2015). 2014*: Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Munsell, M. (2017). US solar market grows 95% in 2016, smashes records. Retrieved on October 3, 2017 from https://www.greentechmedia.com/articles/read/us-solar-market-grows-95-in-2016-smashes-records#gs.gV2XwTM

NASA (2017). *Global Climate Change*. Retrieved on October 14, 2017 from http://climate.nasa.gov

Powerweb (2018). *Renewable Energy*. Retrieved on January 11, 2018 from http://www.fi-powerweb.com/Renewable-Energy.htm

Steel, W. (2015) Europe's largest battery energy storage project opens In Feldheim, Germany. *Clean Technol*. Retrieved on October 1st, 2017 from https://cleantechnica.com/2015/09/21/new-10-mw-storage-plant-opened-feldheim-germany-europes-largest/

Sullivan, J. L., & Gaines, L. (2010). A review of battery life-cycle analysis : state of knowledge and critical needs. *Argonne Technical Report, ANL/ESD/10-7*, Argonne National Laboratory, Argonne, IL.. Retrieved on November 2nd, 2017 from http://www.ipd.anl.gov/anlpubs/2010/11/68455.pdf

Trainer, T. (2017). Some problems in storing renewable energy. *Energy Policy*, 110, 386-393.

Wang, W., Mao, C., Lu, J., & Wang, D. (2013). An energy storage system sizing method for wind power integration. *Energies*, 6(7), 3392-3404.

Wiswall, R. (2009). *The Organic Farmer's Business Handbook: A Complete Guide to Managing Finances, Crops and Staff-and Making a Profit.* White River Junction, VT: Chelsea Green Publishing Co.

World Bank. (2013). First Set of Global Data on Energy Access, Renewable Energy and Energy Efficiency Released. Retrieved January 12, 2018, from http://www.worldbank.org/en/news/press-release/2013/05/28/first-set-of-global-data-on-energy-access-renewable-energy-and-energy-efficiency-released

WWO. (2019). Curlew Monthly Climate Averages, World Weather Online. Retrieved October 13, 2018, from https://www.worldweatheronline.com/lang/en-us/curlew-weather-averages/washington/us.aspx

Zidar, M., Georgilakis, P. S., Hatziargyriou, N. D., Capuder, T., & Škrlec, D. (2016). Review of energy storage allocation in power distribution networks: applications, methods and future research. *IET Generation, Transmission & Distribution*, *10*, 645-652.