The Environmental Impacts of Utility-Scale Battery Storage in California

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As authors of this Group Project report, we archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

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The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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LIST OF ABBREVIATIONS

ALCA	Attributional Life-Cycle Assessment
AB 32	Assembly Bill 32
AC	Alternating current
BAU	Business as usual
BESS	Battery energy storage systems
CAISO	California Independent System Operator
CEC	California Energy Commission
CO2	Carbon dioxide
CO2e	Carbon dioxide-equivalent
DB	Dichlorobenzene
DB eq.	Dichlorobenzene-equivalent
DC	Direct current
DoD	Depth of discharge
E3	Energy and Environmental Economics
EIA	U.S. Energy Information Administration
GHG	Greenhouse gas
GWP	Global warming potential
ILR	Inverter loading ratio
ISO	International Organization for Standardization
kg	Kilogram
kVA	Kilovolt-ampere
LCA	Life-cycle assessment
Li-ion	Lithium-ion
MW	Megawatt
MWh	Megawatt-hour
NO_X	Nitrogen Oxide
No_X eq.	Nitrogen Oxide-equivalent
P	Phosphorus
P eq.	Phosphorus-equivalent
PG&E	Pacific Gas and Electric
PM	Particulate matter
PM eq.	Particulate matter-equivalent
PV	Photovoltaic
RPS	Renewable Portfolio Standard
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
SO_2	Sulfur Dioxide
SO_2 eq.	Sulfur Dioxide-equivalent
ts	ThinkStep
Wh	Watt-hour

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ABSTRACT

As California's population and economy continue to grow, so will electricity demand and the strain it places on natural resources. Renewable energy is the fastest-growing electricity source, displacing fossil fuel-electricity and transitioning towards more sustainable electricity production. Though solar and wind offer low-carbon electricity generation, their electricity generation is not always available to meet electricity demand. Battery storage is an emerging solution to increase renewable penetration to the grid. However, more information is needed to determine the environmental impacts of large-scale battery storage. The objectives of this study were: 1) conduct a life-cycle assessment to determine the environmental impacts of utility-scale battery storage versus natural gas; 2) determine the cumulative impacts of using battery storage versus natural gas over a 14-year period to meet California's electricity demand. This study found that battery storage has a lower impact than natural gas-electricity in four out of six environmental impact categories assessed. Implementing large-scale battery storage over the next 14 years can reduce the climate change impact of California's energy sector by 8 percent. Overall, this project highlighted the potential for battery storage to increase renewable electricity grid penetration, reduce the climate change impact of the energy sector, improve grid flexibility, and allow California to remain a world leader in greenhouse gas emission reductions.

EXECUTIVE SUMMARY

Introduction

Over the last several decades, the electricity generating sector has been the largest contributing sector to the United States' (U.S.) annual greenhouse gas (GHG) emissions (U.S. Energy Information Administration, 2018). This is largely due to the fact that 80 percent of electricity consumed in the U.S. is met by fossil fuel energy sources, such as coal, petroleum, and natural gas (U.S. Energy Information Administration, 2016). Since 2010, the GHG emissions from the U.S. electricity generating sector have declined due to the closure of many coal-fired power plants and the record-high deployment of renewable electricity projects across the country. Renewable electricity resources, such as solar photovoltaic (PV), can displace fossil fuel electricity resources, reduce the carbon footprint of the electricity generating sector, help local and national governments meet their GHG reduction targets, increase domestic energy security, and support economic growth. The cost of utility-scale solar PV has also decreased dramatically over the last decade, driving the competitiveness of solar electricity with incumbent electricity-generating sources. For much of 2017, the average cost of utility-scale solar electricity ranged between $43 to $53 per megawatt-hour (MWh), making it the second cheapest electricity resource after wind (Lazard, 2017).

Despite the many benefits of solar PV and California's high potential for generating solar electricity, California only uses 10 percent of utility-scale solar to meet the state's electricity demands (California Energy Commission, 2017a). Even more perplexing, while the deployment of solar electricity has increased significantly in California, solar penetration on the grid remains underutilized. In addition, California regulators continue to approve the construction of new natural gas power plants across the state, to maintain a reliable source of electricity generation for the grid.

There are two major constraints that prevent greater utilization of solar electricity on California's grid. The first constraint is that solar PV is an intermittent electricity-generating resource. This means that solar electricity production is not continuous and is not always available for meeting electricity demand on the grid. Solar electricity generation varies geographically and temporally (by hour, day, and season) with changes in solar irradiance and cloud cover. Not only is solar generation variable, but it is also consistently unavailable in the evenings after the sun has set. This daily decline in solar electricity production happens to coincide with the daily increase in electricity demand every evening as thousands of electricity customers return home and use their electrical appliances (peak demand). To meet this daily peak demand, California relies on natural gas peaker plants, which can quickly dispatch electricity to the grid.

The second constraint on solar electricity is the potential for solar power plants to produce more electricity during the day than is needed by customers, causing potential damage to the grid. This issue is particularly a problem in California, where many parts of the state receive high levels of solar irradiance during the day. Because California has invested so heavily in utility-scale solar development, the state now generates more solar electricity than is needed during the day (overgeneration) to meet electricity demand. Given the inflexibility of the grid system in dealing with excess power, overgeneration requires grid operators to curtail or export excess solar electricity in an effort to maintain electricity load balance on the grid. Grid operators must always maintain an exact balance between electricity generation and electricity demand on the grid. Thus, challenges with solar intermittency and overgeneration are causing serious issues in maintaining the integrity and reliability of the grid. These constraints of solar electricity have caused grid operators in California to reduce utilization of solar the to meet electricity demand and instead continue rely heavily on fossil fuels to meet peak electricity demand in the evenings. As more solar projects are deployed in California, this issue will continue to get worse, further accentuating the need for fossil fuels to meet electricity demand.

Energy storage is an emerging technology that can be used to store surplus electricity and bridge intermittency gaps by discharging stored electricity onto the grid when electricity demand is high. The recent increase in solar and wind generating capacity has led to a strong push for the development of energy storage technologies. If implemented on a large scale, electricity storage could help resolve the intermittency and overgeneration issues of solar electricity and allow greater penetration of solar electricity on the grid. Energy storage systems cannot store electricity itself, but can convert electricity into other forms of energy, which can be stored for later use and be converted back to electricity when demand is high (World Nuclear Association, 2017). Energy storage systems are constrained by how much electricity they can store, which is expressed in megawatt-hours (MWh), and the maximum power output in a given time (expressed in megawatts, MW). There are various types of energy storage systems, such as battery, flywheel, compressed air, pumped hydro storage, and more (World Nuclear Association, 2017). While there are many energy storage technologies, electrochemical (battery) energy storage is considered one of the most promising and well-suited options for dealing with intermittent renewables at the utility-scale level. This is due to its rapidly declining costs, high energy density, long lifetime, and high round-trip efficiency compared to other energy storage options (World Nuclear Association, 2017).

To support electricity storage deployment, California passed legislation in 2010 requiring the state's three largest investor-owned utilities (PG&E, SCE, and SDG&E) to procure 1,325 MW of electricity storage (not including large-scale pumped hydro storage) by 2020. As of 2017, California has more than 475 MW of electricity storage, the majority of which is battery storage (California Energy Commission, 2017b).

As battery storage emerges as a potential solution for addressing the constraints caused by the high deployment of renewables, efforts are underway to identify key environmental impacts of large-scale battery energy storage systems (BESS). A comprehensive understanding of the environmental impacts of battery storage can help the energy storage industry to develop environmentally friendly energy storage solutions and help decision makers craft sustainable energy storage policies.

The project's client, First Solar Inc. (First Solar) is a major American solar panel manufacturer and provider of utility-scale PV power plants. Like other solar energy providers at the forefront of their industry, First Solar is interested in implementing utility-scale battery storage at their PV power plants to increase utilization of solar electricity on the grid and reduce the carbon footprint of the electricity generating sector.

Objectives

The overall objective of this project was to quantify the environmental impacts of a utility-scale BESS compared to a natural gas power plant to deliver one MWh of electricity to California's grid.

Then the per MWh environmental impacts of the utility-scale BESS and the natural gas-generated electricity were applied over a 14-year period to determine the cumulative environmental impacts of using utility-scale battery storage versus natural gas-electricity to meet California's increasing electricity demand.

Methods

To fulfill the project's first objective, a life-cycle assessment (LCA) was conducted to quantify the environmental impacts of using a utility-scale BESS and a natural gas power plant to deliver 1 MWh of electricity to the grid to meet California's electricity demand. This project assessed environmental impacts based on six environmental indicators (climate change, terrestrial acidification, photochemical ozone formation, particulate matter formation, human toxicity, and freshwater eutrophication) selected from ReCiPe 2016. These six environmental indicators were selected because they are commonly used environmental impact indicators in LCA literature and they represent a robust range of environmental impacts to the climate, air, water, ecosystems, and human health. The environmental impacts of the BESS and electricity from the natural gas power plant were calculated for each of the six environmental impact categories using GaBi ThinkStep (ts) software.

To fulfill the second objective of understanding the long term environmental consequences of using utility-scale battery storage, this project compared two scenarios for meeting California's future energy demand over a 14-year time frame, from 2016 to 2030. The two electricity dispatching scenarios are outlined below:

Business As Usual (BAU) - No Battery Storage Scenario
Today's current scenario with little to no utility-scale battery storage. This scenario assumes a particular evolution of California's energy generation mix over the 14-year time frame, with increasing renewable deployment to meet the California's RPS mandate in 2030. Solar electricity generated during the day is dispatched to the grid to meet electricity demand. Any excess solar production is curtailed to prevent damage to the grid. As solar generation declines in the evening, natural gas electricity is deployed to meet peak electricity demand.

Battery Storage Scenario
A potential scenario that factors in utility-scale battery storage. Like the BAU scenario, this scenario assumes the same evolution of California's energy generation mix over the 14-year time frame. Also similar, solar electricity generated during the day is used to meet electricity demand. However, in contrast to the BAU scenario, excess solar energy is captured and stored in a BESS instead of being curtailed. In the evening, when solar generation declines as peak electricity demand occurs, energy stored in the BESS is discharged to the grid to meet demand. If there is any additional electricity demand after the BESS has been depleted, the

remaining demand is met by natural gas electricity. This scenario assumes that all the excess energy stored in the BESS is dispatched to the grid the same day it was cycled into the battery. This scenario also assumes that energy dispatched from the BESS will only displace the need for natural gas electricity (rather than other energy generating sources) to meet California's electricity demand.

Overall Findings

Normalized per one MWh of electricity discharged to the grid, the BESS showed a lower environmental impact in four out of six environmental impact categories. In one impact category (freshwater eutrophication), the BESS showed a significant increase in impact compared to the natural gas power plant. In addition, the human toxicity impact category showed no significant tradeoff between the BESS and the natural gas power plant.

This study found that implementing utility-scale battery storage from now until 2030 could displace the use of natural gas to meet electricity demand and reduce the climate change, fine particulate matter, photochemical ozone formation, and terrestrial acidification impacts of California's electricity generating sector. Most notably, using the BESS from now until 2030 could reduce the climate change impact of the electricity generating sector by 8 percent.

Conclusion and Recommendations

This project compared the environmental impacts of a BESS versus natural gas electricity to meet California's electricity demand. The project also determined the tradeoffs of displacing natural gas electricity with battery storage energy to meet electricity demand over the next 14 years in California. The findings from this study demonstrated that implementing battery storage could decrease the impacts of climate change, terrestrial acidification, ozone formation, and particulate matter formation. While the BESS resulted in a significant increase in freshwater eutrophication, this impact is a result of the project's assumption in the LCA model that the batteries were disposed in a landfill at the end of their life-cycle. This significant eutrophication impact from the batteries can be dramatically reduced if the batteries are instead recycled rather than landfilled at their end of life.

A main takeaway from this project is that there will always be tradeoffs in any scenario comparison. Because the client for this study is a major solar PV manufacturer, their main priority is to increase solar electricity penetration on the grid as well as maintain the integrity of solar energy as an energy resource with a lower environmental impact. This study found that using utility scale battery storage can increase grid penetration of solar while reducing the environmental impact in four of six assessed environmental impact categories (with no increase or decrease in the fifth impact category). Given the results of this study, it would make sense for First Solar to install battery storage at their utility-scale PV power plants. Considering the large increase in freshwater eutrophication resulting from increase BESS use, it is recommended that battery storage facilities recycle the batteries at the end of life phase.

Overall, this project highlighted the potential for battery storage to reduce the climate change impact of the electricity generating sector, improve grid flexibility, increase grid penetration of renewables, and help government entities around the world to meet their GHG reduction targets.

BACKGROUND

A Leader in Environmental Policy

Over the last twenty years, California has passed various pieces of legislation that have brought the state to emerge as a key global player in climate change policy (Choate & Kay, 2017). In 2006, California elevated its dedication to climate change leadership with the California Global Warming Solutions Act (Assembly Bill 32, AB 32), which was signed by Governor Arnold Schwarzenegger to reduce statewide greenhouse gas (GHG) emissions. AB 32 established a string of GHG mitigation measures, such as the state carbon cap-and-trade program, low carbon transportation fuel standards, electric vehicles promotional programs, standards to increase renewable energy generation, and energy efficiency programs (Choate and Kay, 2017). In 2015, California Governor Jerry Brown extended the state's carbon cap-and-trade program to 2030, requiring California's GHG emissions to be 40 percent below 1990 levels by 2030 (Office of Governor Edmund G. Brown Jr., 2015). This GHG emission reduction benchmark is no small feat, considering the size of California's economy; if it were a country, California would be the fifth largest economy in the world (Choate and Kay, 2017).

One of the most instrumental programs for meeting California's aggressive GHG reduction target has been the state Renewable Portfolio Standard (RPS). The RPS requires California's 16 largest publicly owned utilities to meet 50 percent of their generated electricity sales with eligible renewable energy sources by 2030.[1] This 50 percent RPS target is an increase from the previous goal of 33 percent by 2020, which was revised from the original 20 percent renewable energy target set by the first RPS (Choate and Kay, 2017). California is on track to meet its 50 percent renewable energy requirements, as 30 percent of the state's retail electricity sales in 2017 were met by renewable energy sources (California Energy Commission, 2017). Because of California's rapidly growing renewable energy capacity, state legislators have recently introduced a bill to increase the RPS target to 100 percent renewable energy by 2045 (California State Senate Majority Caucus, 2018).

California's Changing Energy Generation Mix

Since 2011, California has added over 10,000 MW of large-scale renewable energy capacity, over 50 percent of which is from utility-scale solar PV plants (California Energy Commission, 2017). As of 2017, the total installed energy capacity within the California Independent System Operator (CAISO) territory was 70,976.2 MW (CAISO, 2017a). CAISO is the largest of 38 balancing authorities in the Western Interconnection, one of the largest of five electrical grid regions that power mainland North America. CAISO is responsible for managing the flow of electricity for 80 percent of California and a small portion of Nevada (*Figure 1*).

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[1] Eligible renewable energy sources include solar PV, solar thermal, wind, certain biomass, geothermal, certain hydroelectric, ocean wave, thermal and tidal energy, fuel cells using renewable fuels, landfill gas, and municipal solid waste conversion (DSIRE, 2017).

Figure 1. CAISO's operational territory covers 80 percent of California and a small portion of Nevada, including the service territories of California investor owned utilities and the service territories of some municipal utilities. There are a few small areas within CAISO where the local power companies manage their own transmission systems.

The greatest source of electricity for the CAISO region is natural gas, followed by solar, and large hydro (CAISO, 2017a).[2]

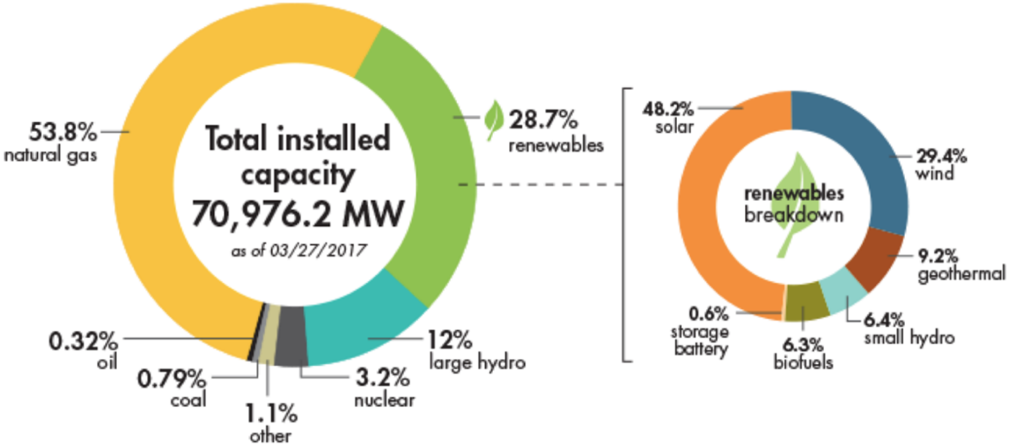

Figure 2. California energy mix as of March 2017. Installed capacity refers to the total amount of generation capacity but does not reflect the total electricity generation available for grid dispatch at any given time. Graph taken from CEC, n.d.

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[2] "Large Hydro" refers to hydropower facilities with over 30 MW of generation capacity (California Energy Commission, n.d.)

The fastest growing renewable energy resource in California is solar PV, due to California's high solar irradiance profile (*Figure 3*) and the dramatically declining cost of solar electricity.

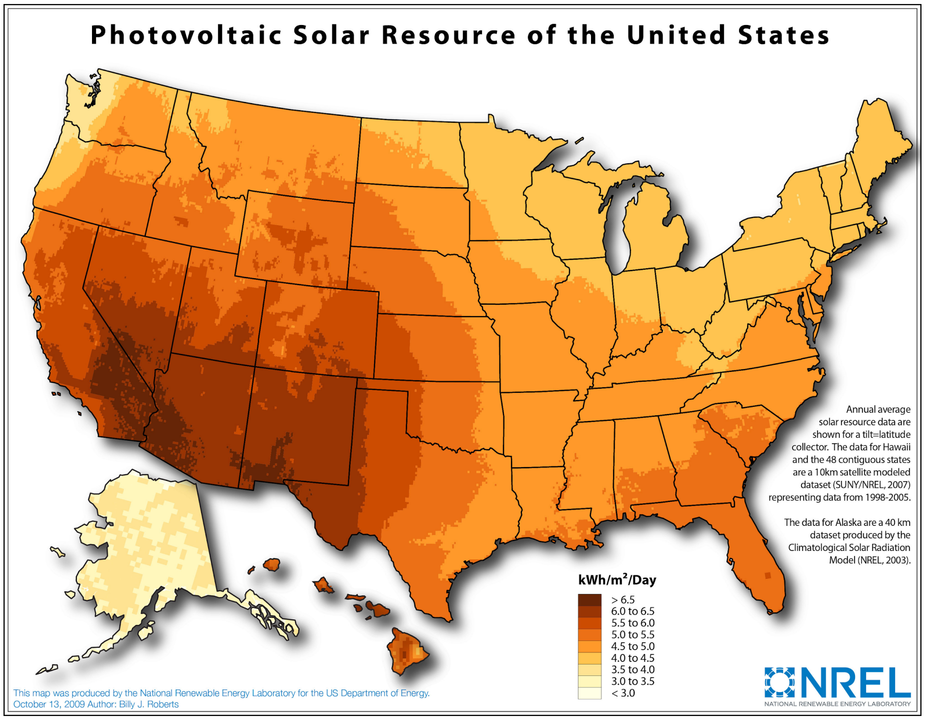

Figure 3. Potential solar electricity generation in the United States (2005). Map taken from NREL, 2009.

Constraints on Solar Generation

Despite California's growing solar PV deployment, solar penetration on the grid remains relatively small compared to natural gas. This is due to two major constraints for solar electricity generation. The first constraint is that solar generation is intermittent, meaning that solar electricity production can vary by hour, day, and season due to changes in cloud cover and seasonal changes in solar irradiance. In addition, solar electricity production declines every day as the sun sets. This daily decline in solar generation coincides with a daily spike in consumer electricity demand (called peak demand) in the evening as energy customers return to their homes and use lights and electrical appliances.

The second constraint on solar electricity is the potential for solar power plants to produce more electricity during the day than is needed to meet electricity demand. This issue is particularly problematic in California because the state has increased its solar electricity production capacity, there is a greater risk of overgeneration on days when there is high solar irradiance. Overgeneration occurs when electrical production exceeds demand, and without intervention from grid operators, the excess electrical output can cause power outages and damage to the grid (Denholm et al., 2015). Thus grid operators must always maintain a careful balance between electricity supply and demand, constantly increasing or decreasing power output from the state's portfolio of electricity generating power plants. However, overgeneration can occur when conventional electricity generating plants cannot be reduced any further than their minimum generation level to accommodate the excess supply of electricity on the grid from renewables. Grid operators can prevent overgeneration through curtailment, which involves decreasing the power output from a solar plant or by disconnecting the PV power plant altogether. Curtailment is generally done to PV or wind power plants, which can power on or off more quickly than conventional, fossil fuel energy sources.

GRID BASICS

Grid Balancing

Electric grids are complex, interconnected networks used to transmit electricity from various generating facilities to residential and commercial energy customers, often across long distance transmission lines. To provide a continuous and reliable flow of electricity to customers, grid operators must exactly match electricity generation with electricity demand on a real-time basis in a balancing act called grid balancing. Electric grids are not designed to store energy, so electricity dispatched to the grid needs to balance electricity demand. Maintaining grid balance is possible because the daily electricity demand can be forecasted in advance since it follows a typical daily trend **and** since fossil fuel power plants can be programmed to change their power output to meet predictable changes in demand. However, grid balancing becomes harder to maintain with unpredictable electricity sources, such as wind and solar, since their electricity production fluctuates.

Least-Cost Dispatching

Another important component of the electric grid system is least-cost dispatching. Least-cost dispatch is the operational procedure used to dictate which power plants should dispatch power first. This procedure works primarily on a least-cost basis, meaning the first increment of power dispatched to the grid to meet demand is the increment of power with the lowest marginal cost to produce (Bosselman, 2008). Once all units of the cheapest energy source are dispatched to the grid, the next cheapest energy source is dispatched, and so on until all energy demand has been met. This rule is followed unless it causes security issues for the grid (i.e. congestion or operational reliability problems) (Bosselman, 2008). Because the cost of wind and solar is lower than fossil fuel generated electricity, wind and solar generators tend to be the first power sources dispatched to the grid. However, this can result in challenges for grid operators to meet energy demand when wind and solar generators fluctuate and are unable to produce power to meet energy demand.

Net Load

The effects of renewable integration on California's grid system can be illustrated by California's net load curve (*Figure 4*), also known as "the duck curve" due to its shape (CAISO, 2016). Power from renewable sources is automatically dispatched to the grid upon generation due to its low marginal cost. The load, shown by the blue curve in *Figure 4*, depicts the customer electricity demand. The net load, shown by the red curve, is electricity demand minus the electricity production of solar and wind (CAISO, 2016). The area between the two curves is the electricity generation from wind and solar resources. Thus, the increased supply of solar-generated electricity during the day causes the net load curve to deepen significantly during the day. The deepening of the net load curve during the day is problematic because of the steep increase in electricity demand in evening as solar production declines. This steep ramp in electricity demand demonstrates the need for a modern electric grid system that can quickly adjust to the abrupt changes in electricity demand. Because of its relatively high ramping flexibility and low cost compared to incumbent energy resources, natural gas is the most common energy resource for generating electricity during the hours of peak energy demand.

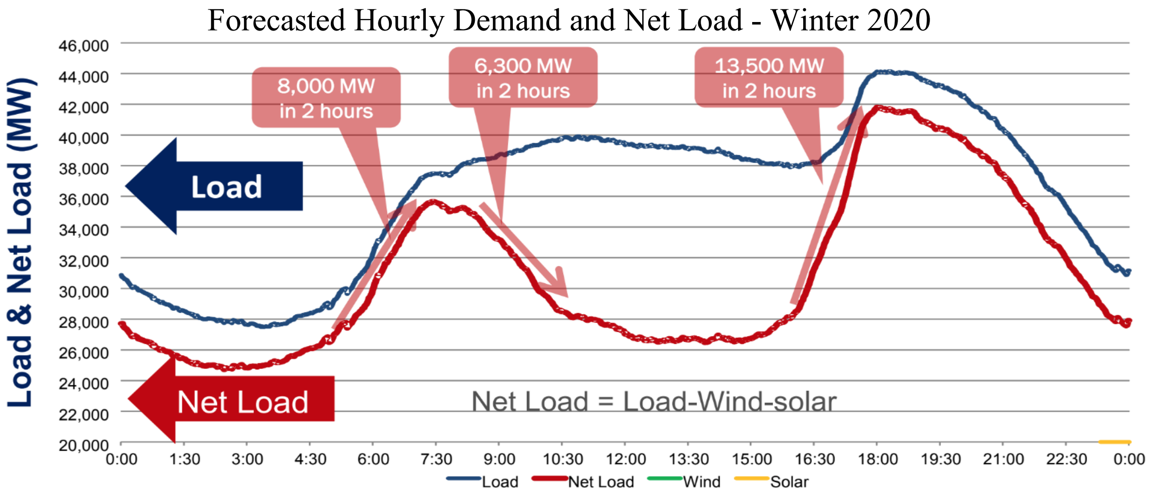

Figure 4. Forecasted hourly electricity demand and net load during a 24-hour day in winter 2020 (CAISO, 2013). During a 24-hour period, the fluctuation in electricity demand is characterized by three steep rates of change, two increasing and one decreasing. These steep ramps in electricity demand demonstrate the need for a modern energy system that can quickly adjust to the abrupt changes in electricity demand.

Curtailment

Grid operators must always maintain a balance between electricity generation and electricity supply on the grid. When solar generators produce more electricity than can be used, grid operators must find ways to reduce the excess generation. The most common method for avoiding overgeneration is curtailment, which is a reduction in the output of a generation source from what it could potentially produce (Bird, 2014). Curtailment, however, is a growing concern in California. In 2015, 187,000 MWh of renewable electricity were curtailed in the CAISO region, and this amount grew to 308,000 MWh in 2016 (CAISO, 2017a). Several studies on solar integration in California have shown that scenarios with solar penetration greater than 25 percent are accompanied by substantial increases in curtailment. This is due to a misalignment of electricity supply and demand, as well as limited grid flexibility (Denholm and Margolis, 2016). The increasing amount of required curtailment due to greater solar penetration can significantly limit the deployment of solar and other renewable energy resources (Denholm and Margolis, 2016).

In addition, the economic impact of curtailment is an increase in the cost of solar electricity. As the frequency of curtailment increases, the cost of solar electricity will also increase because less solar electricity can be sold and dispatched to the grid. This loss of revenue contributes to a smaller return on investment from building solar power plants. As curtailment increases, the benefits of installing solar PV plants may decline to a point where additional utility-scale solar plants are no longer worth the cost, thus creating an economic barrier to solar deployment (Cochran et al., 2015).

Another method for dealing with excess electricity generation is economic curtailment. Economic curtailment is a market-based approach that reduces the price of solar electricity to incentivize neighboring grid networks to purchase excess electricity and alleviate the burden on California's grid. This strategy is the first option for dealing with energy oversupply issues. Economic curtailment can lead to negative pricing, which results in solar generators paying utilities to take their excess electricity (CAISO, 2016). If economic curtailment alone is unable to resolve the oversupply issue, then self-scheduled cuts can be implemented. This is another market-based approach where generators bid on a quantity of electricity rather than price. The market then selects bids based on location and the remaining generators are asked to curtail generation (CAISO, 2016). Exception dispatch is the final curtailment option. In this case, CAISO intervenes to decide which renewable energy plants must reduce their energy output (CAISO, 2016).

Perhaps the greatest concern with the growing solar energy capacity is that the constraints of solar are preventing this resource from reducing GHG emissions to the levels required by AB 32. The full benefit of increased renewable capacity cannot be realized because of the need for fossil fuels, such as natural gas, to step in and meet unmet electricity demand at fast ramping rates when renewable power is unavailable. Every unit of solar electricity that is curtailed is a unit of solar electricity not used and a unit of fossil fuel-electricity not avoided (Denholm et al., 2015).

Therefore, to ensure that California meet its GHG reduction targets, it is essential for the grid to become modernized and flexible to handle the issues presented by renewables. There are many potential strategies that can mitigate the oversupply issues, such as increasing electricity demand response, increasing flexible generation and output levels to the grid, expanding grid operating networks, increasing electric vehicle usage, and increasing energy storage. While these measures can significantly mitigate the risk of overgeneration, even a flexible grid will need additional storage to allow 50 percent penetration of solar energy on the grid (Denholm and Margolis, 2016). As such, this project focused on the impacts of implementing energy storage on a utility-scale and whether the climate change impacts of energy storage will impede California's ability to meet its GHG reduction goals.

ENERGY STORAGE

Utility-scale energy storage (grid energy storage) is a collection of technologies used to store electrical energy on a large scale within an electrical power grid. The recent increase in solar and wind generating capacity has led to a strong push for the development of energy storage technologies. Energy storage involves storing excess electrical energy when electricity production exceeds demand and returning this electricity to the grid at a later time when demand is high. If implemented on a large scale, energy storage could help resolve the intermittency and overgeneration issues of solar energy and allow greater penetration of solar energy on the grid. Energy storage systems cannot store electricity itself, but can convert electricity into other forms of energy, which can be stored for later use and then be converted back to electricity when demand is high (World Nuclear Association, 2017).

Energy storage can also displace or defer the need to build additional energy generation capacity and transmission and distribution lines, creating financial and environmental benefits (Arbabzadeh, Maryam et al., 2015). An energy storage system cannot store electricity itself, but can convert electricity into other forms of energy, which can be stored for later use and be converted back to electricity when demand is high (World Nuclear Association, 2017). Energy storage systems are constrained by how much energy they can store, which is expressed in megawatt-hours (MWh), and the maximum power output (expressed in megawatts, MW). There are various types of energy storage systems, such as battery, flywheel, compressed air, pumped hydro, and more (World Nuclear Association, 2017).

While there are many energy storage technologies, electrochemical (battery) energy storage is considered one of the most promising and well-suited options for dealing with intermittent renewables at the utility-scale level. This is due to its rapidly declining costs, high energy density, long lifetime, and high round-trip efficiency compared to other energy storage options (World Nuclear Association, 2017).

Battery Storage

A battery is an electrochemical device that stores and delivers energy. Battery energy storage systems (BESS) can dispatch renewable energy in a responsive and reliable manner, which is important for grid operators to efficiently manage the power output to the grid. A BESS is comprised of three major components: the battery which is the energy container; the power conversion system (PCS) or inverter, which interfaces the DC battery system to the AC power system; and the power plant controller (PPC) which governs, monitors, and executes the intended functions of the energy storage application.

The battery storage capacity is measured based on the following BESS characteristics:

- Energy Capacity – the maximum usable electrical energy (kWh) stored in a battery.
- Maximum Charge and Discharge Rates – the peak power (usually given as maximum current) the battery can either hold (charge) or discharge without being damaged.
- Depth of Discharge – the percentage of the battery's capacity that be discharged before it needs to be recharged.
- Cycle Life – the number of recharge cycles a battery can undergo before it reaches the end of its life.
- Calendar Life – the duration, in calendrical days, that a battery can be expected to last before it reaches its end of life.
- Energy Density – the amount of energy stored per unit of volume or mass.
- Temperature Limitations – the acceptable operating temperature range of a battery. Some battery chemistries may not operate below freezing temperatures, or at very high temperatures, for example. Some batteries may generate significant heat either while charging or discharging and thus may need an active thermal management system to keep them from overheating.
- Self-Discharge Rates – The rate at which a battery loses charge while not being charged.
- Round Trip Efficiency – The ratio of energy-in to energy-out for one complete battery cycle (i.e., for a complete charge and discharge cycle).

Li-ion Battery Storage

There are several types of batteries available for large-scale stationary storage. Redox flow batteries have the potential to deliver long-duration energy storage applications at lower costs, while advanced lead-acid batteries have proven to be excellent performers in power-intensive applications. While there are various battery storage technologies available, this project focused entirely on utility-scale Lithium-ion (Li-ion) battery energy storage in California. Li-ion batteries have emerged as the leading technology in utility-scale energy storage applications because it offers the best mix of performance specifications, such as high charge and discharge efficiency, low self-discharge, high energy density, and long cycle life (Divya KC et al., 2009). In addition, increased production of electric vehicles with Li-ion batteries is expected to support greater Li-ion production capacity and drive down the cost of Li-ion batteries, continuing to reduce barriers for this technology in stationary energy storage applications (Curry, 2017).

The most likely time frame for battery storage use is during peak energy demand in the evening, since this would add another source of electricity to meet electricity demand and would reduce the need for natural gas-generated electricity, therefore decreasing fossil fuel emissions from the electricity generating sector.

To support energy storage deployment, California passed legislation in 2010 requiring the state's three largest investor-owned utilities (PG&E, SCE, and SDG&E) to procure 1,325 MW of electricity storage (not including large-scale pumped hydro storage) by 2020. As of 2017, California has more than 475 MW of energy storage, the majority of which is battery storage (California Energy Commission, 2017b).

As battery storage emerges as a potential solution for addressing the constraints caused by the high deployment of renewables, efforts are underway to identify key environmental impacts of large-scale BESS. A comprehensive understanding of the environmental impacts of battery storage can help the energy storage industry to develop environmentally friendly energy storage solutions and help decision makers craft sustainable energy storage policies.

This project's client, First Solar Inc. (First Solar) is a major American solar panel manufacturer and provider of utility-scale PV power plants. Like other solar energy providers at the forefront of their industry, First Solar is interested in implementing utility-scale battery storage at their PV power plants to increase utilization of solar electricity on the grid and reduce the carbon footprint of the electricity generating sector. This project came from First Solar's need to understand the long-term impacts of battery storage in California and to determine whether the climate change impacts of battery storage are minimal enough to allow California to meet its GHG emission target by utilizing battery storage.

Given the assumption that utilizing battery storage could displace electricity generation from natural gas power plants during hours of peak electricity demand, this project compared the environmental impacts of using a BESS to the impacts of generating electricity from a natural gas power plant. This project also determined the cumulative impacts of both using and not using BESS over a 14-year period (2016-2030). The time period of this project evaluation begins in 2016, when the most recent electricity demand data was available from the California Energy Commission (CEC), and ends in 2030, when California's investor-owned utilities must meet the state's RPS goal of 50 percent renewable energy sales.

PROJECT OBJECTIVES

The two primary objectives of this project were to:

1. Quantify the life-cycle environmental impacts of using a BESS and a natural gas power plant to deliver one MWh of electricity to California's energy grid.
2. Determine the cumulative environmental impacts and tradeoffs of two scenarios for meeting California's electricity demand over a 14-year time frame, from 2016 to 2030. The two scenarios compared were:

Business As Usual (BAU) - No Battery Storage Scenario
Today's current scenario with little to no utility-scale battery storage. This scenario assumes a particular evolution of California's energy generation mix over the 14-year time frame, with increasing renewable deployment to meet the California's RPS mandate in 2030. Solar electricity generated during the day is dispatched to the grid to meet electricity demand. Any excess solar production is curtailed to prevent damage to the grid. As solar generation declines in the evening, natural gas electricity is deployed to meet peak electricity demand.

Battery Storage Scenario
A potential scenario that factors in utility-scale battery storage. Like the BAU scenario, this scenario assumes the same evolution of California's energy generation mix over the 14-year time frame. Similarly, solar electricity generated during the day is used to meet electricity demand. However, in contrast to the BAU scenario, excess solar energy is captured and stored in a BESS instead of being curtailed. In the evening, when solar generation declines as peak electricity demand occurs, energy stored in the BESS is discharged to the grid to meet demand. If there is any additional electricity demand after the BESS has been depleted, the remaining demand is met by natural gas electricity. This scenario assumes that all the excess energy stored in the BESS is dispatched to the grid the same day it was cycled into the battery. This scenario also assumes that energy dispatched from the BESS will only displace the need for natural gas electricity (rather than other energy generating sources) to meet California's electricity demand.

PROJECT SIGNIFICANCE

One of the most promising options for increasing renewable energy utilization is battery electricity storage. Not only can battery storage store excess renewable electricity and dispatch it onto the grid when renewable energy is unavailable, but it can also be used to smooth out peak energy demand, reduce power fluctuations, and make the electricity grid more reliable (Amrouche et al., 2016).

As California procures more electricity storage capacity to address growing electricity demands and increasing renewable penetration, understanding the spectrum of potential environmental issues from large-scale battery storage becomes a critical step. Batteries require large quantities of metal and mineral inputs, which are mined, produced, and transported at great expenditures of money and energy, leaving behind a significant environmental footprint. Use and consumption of batteries also produce waste, contributing further to the increased environmental impact. This project identified and evaluated key environmental impacts associated with utility-scale battery storage. The research builds upon existing life-cycle assessment (LCA) battery research and publications, with modifications to address the proper sizing of storage needed to capture California's overgeneration. In addition, this project evaluated and quantified the tradeoffs associated with using electricity output from battery storage compared to electricity generated from natural gas power plants. In summary, the research of this project provides a comparison between the environmental impacts of utility-scale battery storage and natural gas-generated electricity. The project also provides assessments of the cumulative impacts of battery storage utilization from now until 2030, the impacts of battery storage utilization in the year 2030 (the year of California's 50 percent RPS mandate), and the consequential impacts of increasing utility-scale battery storage over time on the displacement of natural gas-electricity generation.

Due to its potential benefits and impacts, utility-scale storage has become a major focus for public research and investments in development around the world. The findings of this study will help the project's client, First Solar, understand the environmental impacts and potential benefits associated with combining utility-scale battery storage with their utility-scale PV projects. In addition, the battery storage LCA of this project will help the battery industry identify which battery system components and which processes of the battery life-cycle have the greatest environmental impact. Finally, this study will provide relevant information to California and other state and national policymakers with the goal to increase renewable utilization and develop strategies to transition to a more sustainable energy system.

METHODOLOGY

LIFE-CYCLE METHODOLOGY

This project aimed to quantify the environmental impacts of a Li-ion BESS versus the electricity generated from a natural gas power plant (Objective 1). This project also aimed to quantify the cumulative environmental impacts of using a Li-ion BESS versus generating electricity from a natural gas power plant over a 14-year time frame (Objective 2). To meet these objectives, this project conducted a life-cycle assessment of a Li-ion BESS and the electricity generated from an average natural gas power plant in the United States.

LCA is a systematic analysis for quantifying the environmental impacts of a product during each phase of its life-cycle, from resource extraction to its end of life (Rebitzer et al., 2004). The International Organization for Standardization (ISO) standard 14040:2006 specifies the definitions, principles, and framework for conducting LCAs (ISO, 2010). This project conducted its LCA in accordance with ISO standards; however, every LCA is different and requires careful understanding of the methodology used.

There are two main types of LCA: attributional LCA (ALCA) and consequential LCA (CLCA). ALCA is used to determine or attribute the environmental burdens associated with the production and use of a product at a given point in time. A CLCA is used to quantify the environmental impacts of a product as a result of a change in a system. To meet the first objective of this project, an ALCA was conducted to determine the environmental impacts of using a utility-scale Li-ion BESS versus a natural gas power plant to discharge 1 MWh of electricity to California's grid. Subsequently, a CLCA was performed to meet the second objective of this project - to determine the cumulative environmental impacts of using a Li-ion BESS over a 14-year period (2016-2030) to prevent solar curtailment and meet California's future electricity demand by displacing electricity generated from natural gas. To conduct the LCAs of this project, GaBi Thinkstep (ts) software was used along with the Ecoinvent database (version 3.0).

Functional Unit

In LCA, the functional unit is a quantified description of the performance of a product system. When comparing two different products (e.g., BESS electricity and a natural gas produced electricity) the life-cycle stage that contributes to the greatest environmental impact can differ from one product to another. For a BESS, the greatest environmental impact occurs during the upfront raw material extraction and production phase of the storage system and facility, with little to no impact occurring from the use phase of the BESS. For natural gas generated electricity, the majority of the environmental impacts occurs during the use phase of the combustion of natural gas to produce electricity. To accurately compare the impacts of using each energy technology, the environmental impact created by both sources needed to be defined by a single, common unit of impact per amount of utilization. For this project, the common output modeled for both technologies was the electricity distributed from each source to the grid. Thus, the functional unit of all the LCAs was the delivery of 1 MWh of electricity to the California grid from a Li-ion BESS and from an average natural gas power plant in the United States.

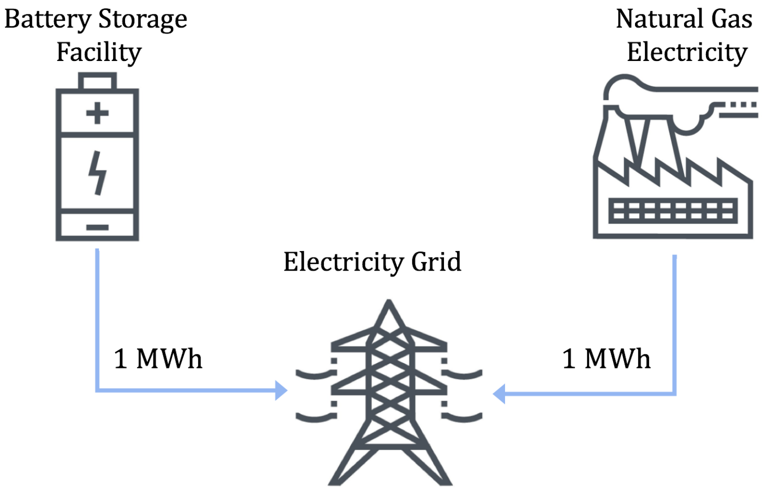

Figure 5. The functional unit allows users to compare different products with distinct stages of environmental burden. To compare the Li-ion BESS and the natural gas power plant, the functional unit of the LCAs was 1 MWh of electricity distributed to California's grid.

LIFE-CYCLE INVENTORIES OF THE BESS

Li-ion Battery

The Li-ion battery model used for the BESS LCA was created by the previous First Solar master's group project using GaBi 6 software (Bilich et al., 2017). This battery model was based on the processes and life-cycle inventories detailed in a detailed ALCA and analysis by Ellingsen and Majeau-Bettez (Ellingsen et al., 2014; Majeau-Bettez et al., 2011). This battery model includes a battery energy density of 112 watt-hours per kilogram (Wh/kg). In addition, the battery model assumes a 20-year lifetime for the BESS. The battery model also assumes that energy stored in the battery is discharged only once daily, during the evening peak demand. This means the utility-scale BESS has the potential for 7,300 cycles (charge and discharge cycles), which equates to one cycle per day over its 20-year lifetime (Hiremath et al., 2015). The following assumptions of different components of the BESS explain the project's assumptions for scaling the utility-sized Li-ion storage capabilities that will be necessary for California to meet the RPS.

Round Trip Efficiency

Li-ion batteries degrade as they are used to charge and discharge energy, reducing their ability to store energy over time and resulting in definable inefficiencies in the energy-storing process. Given this inefficiency, the capacity of the Li-ion battery for this project had to be appropriately sized to yield a required output of electric power. Round trip efficiency is one of the two largest inefficiency factors that contribute to a diminished battery output.

Round trip efficiency describes the fraction of energy that can be retrieved from the battery once it has been stored. While energy is stored in a Li-ion battery, a percentage of that stored energy is lost primarily due to chemical reactions within the battery, internal resistance, and heat released from the battery. This energy loss is increased by external environmental factors such as high temperature and humidity (Wang et al., 2017). Given the assumptions of a daily battery discharge at high voltage in average California weather conditions, an average battery round trip efficiency of 90 percent over the lifespan of the battery is a reasonable estimate for a utility-scale Li-ion BESS coupled with a thermal management system (Erhart, 2018). As such, a 90 percent round trip efficiency was used in the Li-ion battery model.

Depth of Discharge

Depth of discharge (DoD) refers to the fraction of the battery's overall capacity that can be safely discharged without damaging the battery. Similar to the round trip efficiency, DoD limits the amount of energy that can be discharged from the battery without increasing degradation from internal chemical reactions (Wang et al., 2017). DoD is also one of the two largest inefficiency factors that contribute to a diminished battery output. Based on discussions with industry experts, an 80 percent average lifetime DoD was assumed in the battery model (Erhart, 2018). This DoD assumption means that only 80 percent of the energy stored in the fully charged battery can be dispatched to the grid.

Parasitic Loss Factor

While the greatest environmental impact of the battery occurs during the upstream raw material extraction and production phases, the only environmental impact to come from the use phase of the battery is from the stored energy that the BESS consumes to power ancillary components of the facility (e.g., thermal management system). This energy consumption to power ancillary components of the facility is referred to as the parasitic loss factor. For utility-scale storage systems, approximately 1 percent of total energy stored is lost due to parasitic loss (Erhart, 2018). Therefore, a 1 percent parasitic loss factor was applied to the sizing of the Li-ion battery modeled in this project.

Battery Sizing

To fulfill the desired functional unit, the battery was sized to discharge 1 MWh of electricity to the grid. Next, the project had to determine the amount of installed battery capacity needed to achieve the output of 1 MWh of electricity. To determine the installed capacity needed, the required capacity was divided by the battery inefficiencies: round trip efficiency, depth of discharge, and parasitic losses.

$$Installed\ Capacity = Required\ Capacity * (Round\ Trip\ Efficiency * DoD * Parastic\ Loss)^{-1}$$

$$Installed\ Capacity\ = \frac{1\ MWh}{(0.9 * 0.8 * 0.99)} = 1.404\ MWh * \frac{kg}{1.12 * 10^{-4}\ MWh}$$

$$= 12{,}540.13\ kg$$

To discharge 1 MWh of electricity to the grid from the BESS, the Li-ion battery needed a nameplate capacity of 1.404 MWh. With a battery energy density of 112 Wh/kg, the installed capacity needed to fulfill the functional unit was 12,540 kg of Li-ion battery. The assumed power rating of the modeled battery was 1.4 MW.

Storage System Components and Facility Sizing

The following additional components of the storage system and facility (inverter, transformer, thermal management system, cabling, concrete, and steel) were modeled and sized based on the utility-scale BESS installed on Graciosa Island and detailed through literature by Stenzel et al. This literature was the most comprehensive and relevant resource for BESS life-cycle inventory data available (Stenzel et al., 2017). The BESS on Graciosa Island has a 6 MW power rating and 6 MWh capacity of Li-ion battery storage. In addition, in the Graciosa Island BESS, all the BESS components except for the concrete foundation and its internal steel structure, have a lifetime of 20 years.

Inverter

An inverter is a device that converts direct current (DC) electricity to alternating current (AC) electricity. The inverter is needed to convert the stored battery energy from DC to AC electricity that can then be fed to the grid. The inverter must be oversized for protection against damage from power spikes, which can be avoided if the inverter capacity is 20 percent larger than the power rating of the battery (Grana, 2016). Therefore, an inverter loading ratio (ILR) of 1.2 was used to calculate the total inverter requirement for the storage system. Oversizing the inverter based on the 1.4 MWh nameplate capacity rather than the expected electrical output of 1 MWh led to the conservative estimate of how much inverter capacity was required. To model the inverter for the BESS LCA, the Ecoinvent "RER 500 kW inverter" unit process was selected from the Ecoinvent database. To discharge 1 MWh of electricity over a period of one hour or more, the BESS needed the effective capacity of 3.36 - 500 kW inverters.

$$1.4\ MW\ Battery * \ 1.2\ ILR = \ 1.68\ Total\ Power\ Rating * \frac{Inverter\ Piece}{0.5\ MW\ Power\ Rating}$$
$$= 3.36\ Pieces$$

Transformer

A transformer is a device that increases or decreases the alternating voltage in electric power applications. The transformer modeled for the BESS LCA was based on the transformer used by the Graciosa Island BESS. To adjust the voltage of the battery's discharged electricity, the 6 MW Graciosa Island BESS uses eight-800 kilovolt-ampere (kVA) transformers, weighing 2,500 kg each, and two-315 kVA transformers, each weighing 980 kg (Stenzel et al., 2017). The total weight of these required transformers is 21,960 kg. This equates to 3,660 kg of high voltage transformer per MW of power rating. Therefore, the project's 1.4 MW BESS required 5,124 kg of high voltage transformer. The Ecoinvent "GLO high voltage use inverter" unit process was selected for the BESS LCA.

$$\left(8 * \frac{2{,}500\ kg}{Large\ Transformer}\right) + \left(2 * \frac{980\ kg}{Small\ Transformer}\right) = \frac{21{,}960\ kg\ Transformer}{6\ MW\ Capacity}$$

$$= \frac{3{,}660\ kg}{1\ MW}$$

$$\frac{3{,}660\ kg\ Transformer}{1\ MW} * 1.4\ MW = 5{,}124\ kg\ Transformer$$

Thermal Management System

A BESS typically includes a thermal management system to reduce external environmental factors such as high temperature and humidity to maintain battery efficiency. The thermal management system modeled for the BESS LCA was based on the thermal management system in the Graciosa Island BESS. The thermal management system on Graciosa Island includes ventilation systems, pumps, piping, and buffer storage, all of which consisted of 1,000 kg of aluminum, 4,800 kg of low-alloyed steel, 104 kg of copper, 282 kg of mineral wool, 87.5 kg of refrigerant R134a (tetrafluoroethylene), and 792 kg of ethylene glycol. Scaling these processes for the project's 1.4 MW BESS yielded the model requirements of 233.33 kg of aluminum, 1,120 kg of low-alloyed steel, 24.27 kg of copper, 65.8 kg of mineral wool, 20.42 kg of refrigerant R134a, and 184.8 kg of ethylene glycol.

Cabling

Cabling is used to electrically connect the ancillary components of the storage facility with the BESS. The cabling modeled in the BESS LCA was based on the cabling required for the Graciosa Island BESS. The cabling used in the Graciosa Island BESS consists of 2,180 kg of copper, 35 kg of aluminum, and 807 kg of plastic foam insulation. The Ecoinvent unit processes of copper, aluminum, and polyurethane insulation foam were used with respective weights of 508.67 kg, 8.17 kg, and 188.3 kg to satisfy the requirements of a 1.4 MW BESS.

Concrete

Concrete is used for the foundation of the BESS. The concrete modeled in the BESS LCA was based on the concrete used for Graciosa Island BESS. The amount of concrete used for the Graciosa Island facility was 158,000 kg per MW capacity. Scaling linearly for a 1.4 MW system correlates to 221,200 kg of concrete for the BESS model used in this project. The Ecoinvent "CH: concrete, normal, at plant process" unit process was used in this model. Unlike the rest of the components in this storage system, concrete has a longer lifetime, ranging between 60 to 100 years, compared to the 20-year lifetime of the Li-ion batteries and other BESS components. The concrete foundation was conservatively estimated to last 40 years, twice as long as the rest of the BESS. Therefore the 221,200 kg concrete requirement was divided by two to determine how much concrete was needed for the 20-year lifetime of the entire BESS. This resulted in 110,600 kg of concrete to fulfill the functional unit.

Steel for Concrete Foundation

The steel requirement for the concrete foundation was based on the steel requirement for the Graciosa Island BESS, which used steel rebar to reinforce its concrete foundation. In the Graciosa Island BESS, 7,800 kg of steel metalworking was used for every MW of storage capacity. Ecoinvent's "RER: steel product manufacturing, average metalworking" was used to model this process. Scaling linearly for a 1.4 MW system correlated to 10,920 kg requirement of steel product manufacturing for this model. It was assumed that the steel located in the concrete foundation had the same 40-year lifetime as the concrete. Thus, similar to the concrete requirement, the amount of steel manufacturing and metalworking needed for a 1.4 MW system was divided by two to determine how much steel was needed for a BESS with a 20-year lifetime. Dividing 10,920 kg by two yielded a requirement of 5,460 kg of steel product manufacturing and metalworking in this model.

End of Life

All components of the BESS were assumed to be disposed in a landfill at the end of their life, rather than recycled. This end of life modeling scenario was chosen to create the most conservative results for the environmental impacts of the BESS.

Table 1. Li-ion BESS Specifications. Summarizes the electrical and operating characteristics that were included in the Li-ion BESS model.

Category	Quantity	Unit
Battery energy density	112	Wh/kg
Battery lifetime	20	yrs
Discharge rate	1	daily
Cycle life	7,300	cycles
Round trip efficiency	90	%
Depth of discharge	80	%
Parasitic loss factor	1	%
Battery power rating	1.4	MW
Inverter	3.36	500 KW
Transformer	5,124	kg
Concrete	10,600	kg
Concrete lifetime	40	yrs
Steel	5,460	kg
Steel lifetime	40	yrs

Normalizing BESS Impacts to the Functional Unit

The total environmental impacts of the BESS and electricity generated by a natural gas power plant were calculated using GaBi software. The total BESS impacts in each impact category were allocated evenly across every individual anticipated use of the system. The BESS was assumed to have one charge and discharge cycle every day. Given the 20-year lifespan of the BESS, this equated to 7,300 available cycles for the Li-ion battery. Therefore, the total BESS impacts in each of the six impact categories were divided by 7,300 to determine the effective impact the BESS created in every daily use of discharging 1 MWh to the grid.

LIFE-CYCLE INVENTORY FOR ELECTRICITY FROM NATURAL GAS PLANT

The environmental impact of producing 1 MWh of electricity from a natural gas power plant was calculated using Ecoinvent processes with GaBi software. The "RNA: natural gas, at consumer" unit process was selected to model the combustion of natural gas at an average natural gas power plant in the United States, using the "US: natural gas, burned in power plant" unit process. The electricity produced from the natural gas power plant was modeled using the "US: electricity, natural gas, at power plant" unit process. Only the use phase of producing electricity from a natural gas power plant was used to calculate environmental impacts used in this study. The impacts of constructing natural gas plants that already exist in California were not included in the contribution to the environmental impacts from electricity generated from natural gas. The impact of those construction processes allocated over every MWh of electricity produced by the plant throughout its lifetime was considered very small and negligible. Since this project assessed the environmental impacts from the use phase of the natural gas power plant, GaBi software provided the direct natural gas impacts per MWh and no additional normalization was required.

IMPACT ASSESSMENT

LCA uses characterization factors to translate life-cycle inventories into environmental impacts across a range of impact categories. ReCiPe's 2016 hierarchical midpoint indicators were selected because they represent a perspective based on scientific consensus on a medium time frame (100 years for global warming potential) and because they were used by the previous First Solar group project to satisfy the deliverable required by their client. ReCiPe indicators classify the environmental impacts into 18 midpoint and 3 end point indicators. The following 6 midpoint indicator categories were chosen to convey the tradeoffs of using Li-ion battery storage versus using natural gas to dispatch electricity to California's grid (Goedkoop et al., 2009).

Climate Change
Measured in kg of carbon dioxide-equivalent (kg CO_2 eq.). Characterizes the potential of a given substance to impact global warming, or a substance's global warming potential (GWP), over a 100-year period (GWP 100).

Freshwater Eutrophication
Measured in kg of phosphorous-equivalent (kg P eq.). Characterizes the potential of a substance to impact eutrophication in freshwater ecosystems.

Cancer-Causing Human Toxicity
Measured in kg of 1,4-dichlorobenzene-equivalent (kg 1,4-DB eq.). Characterizes the potential carcinogenic toxicity to humans released into the atmosphere from a given substance.

Fine Particulate Matter Formation
Measured in kg of 2.5-micrometer particulate matter-equivalent (kg PM 2.5 eq.). Characterizes how a given substance relates to the formation of particulate matter in the air.

Photochemical Ozone Formation
Measured in kg of nitrogen oxide-equivalent (kg NO_x eq.). Characterizes how a given substance relates to the formation of photochemical oxidants in the air and subsequently damages terrestrial ecosystems.

Terrestrial Acidification
Measured in kg of sulfur dioxide (kg SO_2 eq.). Characterizes the potential of a substance to cause acidification to terrestrial ecosystems.

While there are other impact categories in ReCiPe 2016 and other sets of potential factors, these 6 specific impact categories were chosen because they represent an important mix of environmental impacts to climate, air, water, terrestrial ecosystems, and human health.

CUMULATIVE IMPACT METHODOLOGY

The second objective of this project was to determine the long term environmental impacts of using natural gas versus battery storage to meet California's projected electricity demand over a 14-year time frame, from 2016 to 2030. This objective was met by comparing two scenarios for meeting California's future electricity demand:

Business As Usual (BAU) - No Battery Storage Scenario
Today's current scenario with little to no utility-scale battery storage. This scenario assumes a particular evolution of California's energy generation mix over the 14-year time frame, with increasing renewable deployment to meet the California's RPS mandate in 2030. Solar electricity generated during the day is dispatched to the grid to meet electricity demand. Any excess solar production is curtailed to prevent damage to the grid. As solar generation declines in the evening, natural gas electricity is deployed to meet peak electricity demand.

Battery Storage Scenario
A potential scenario that includes utility-scale battery storage. Like the BAU scenario, this scenario assumes the same evolution of California's energy generation mix over the 14-year time frame. Also similar, solar electricity generated during the day is used to meet electricity demand. However, in contrast to the BAU scenario, excess solar energy is captured and stored in a BESS instead of being curtailed. In the evening, when solar generation declines as peak electricity demand occurs, energy stored in the BESS is discharged to the grid to meet demand. If there is any additional electricity demand after the BESS has been depleted, the remaining demand is met by natural gas electricity. This scenario assumes that all the excess energy stored in the BESS is dispatched to the grid the same day it was cycled into the battery. This scenario also assumes that energy dispatched from the BESS will only displace

the need for natural gas electricity (rather than other energy generating sources) to meet California's electricity demand.

Overgeneration Projection Model

To calculate the long term environmental impacts of battery storage, the project needed to determine how much energy storage would be implemented from 2016 to 2030. This required an understanding of California's future electricity demand and future energy generation mix over the 14-year period Thus, this project created an overgeneration projection model to predict how much excess energy would be produced each year in the 14-year time frame and how much storage would be needed to store this excess energy or overgeneration. The first step in the overgeneration projection model was to determine California's current and future electricity demand and energy generation mix over the 14-year period (*Figure 6*).

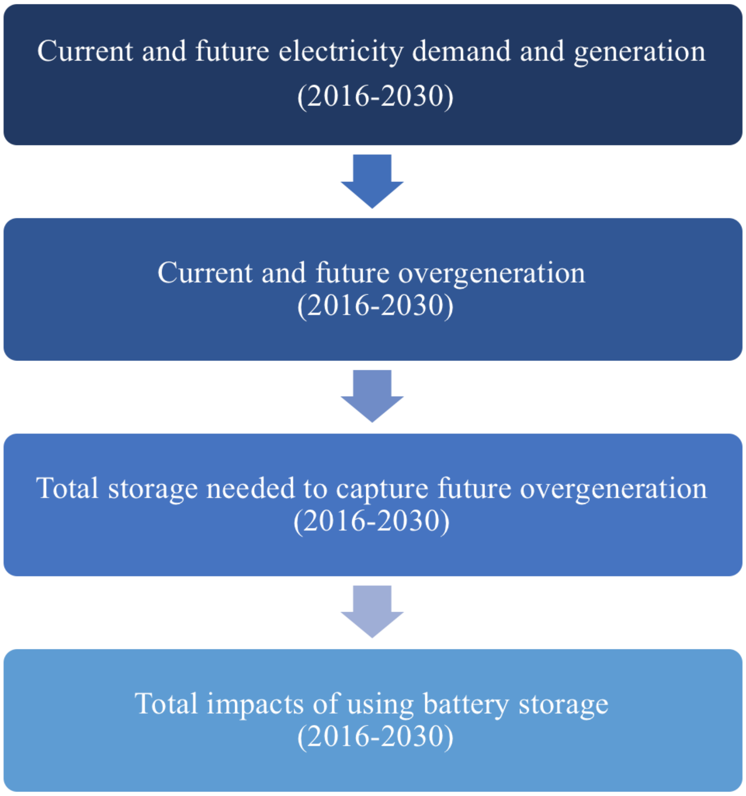

Figure 6. To determine the total impacts of using battery storage from 2016 to 2030, the project first had to determine California's projected electricity demand and generation mix. This would help determine how much excess electricity was projected to occur from 2016 to 2030, and thus dictate how much energy storage would be needed to capture the excess energy to later use.

California's Current Electricity Demand

When this project began, the most recent data on California's electricity demand was for the year 2016 (CAISO, 2017b). Because of this, 2016 became the baseline year of the overgeneration projection model. CAISO's 2016 electricity demand data was given for every hour of every day of every month of the year 2016. An average 24-hour electricity demand profile was developed for each month of the year by averaging the demand data from each hour of the day for all days in a given month. These month-hour averages represented an average 24-hour day for each month of the year 2016 and were used as the baseline (current) electricity demand data. Multiplying the month-hour averages by the days in the month and summing over all months in the year yielded the total electricity demand for the year 2016.

Projected Electricity Demand

California's projected electricity demand from 2016 to 2030 was determined by applying a 1.06 percent annual growth rate to the monthly average electricity demand values of the 2016 base year. Growth in annual electricity demand was assumed to scale linearly. The 1.06 percent annual increase in electricity demand was derived from a CEC report on California's Energy Demand Forecast: 2016-2027, though this project assumed the 1.06 percent annual increase would continue to 2030 (California Energy Commission, 2017c). Once the electricity demand data was scaled annually from 2016 to 2030, the future hourly month averages of electricity demand were summed to find the total electricity demand within an average 24-hour day for each month. These 24-hour totals were then multiplied by the number of days in that month and summed to find the total demand for each year between 2016 and 2030.

California's Current Electricity Generation

Data for California's 2016 electricity generation mix came from CAISO (CAISO, 2017b). This data was given as hourly electricity generation (MW) for each day in California for the entire year of 2016. In addition, hourly generation data was provided for each energy generating resource. Like the 2016 electricity demand data, an average 24-hour energy generation profile was developed for every month of the 2016 year by averaging the generation data from each hour of the day for all days of a given month. These month-hour generation averages represented an average 24-hour day for each month of the year 2016 and were used as the baseline generation data for the overgeneration projection model. By multiplying the month-hour averages with the days in the month and summing over all months, this yielded the total energy generation for 2016.

Projected Electricity Generation

Data on California's projected 2030 energy generation mix was derived from an Energy and Environmental Economics (E3) report. E3 is an energy consulting agency whose prominent research is often cited by the energy industry and government agencies. To determine California's energy generation mix by generation source in the year 2030, the total projected electricity demand for 2030 was multiplied by the 2016 generation mix (*Table 2*). The projected 2030 energy generation mix meets California's RPS goal of 50 percent electricity retail sales from renewable energy sources. After determining California's total generation in the year 2030 by generation source, the project could then calculate the percent change of each generation source from the 2016 yearly total and the 2030 yearly total. The 2016 generation data for each resource was then scaled linearly based on the calculated percent change to determine the annual generation mix for each following year. This was performed for every generation source, except nuclear energy. Nuclear energy is expected to phase out in California with the expected decommissioning of California's Diablo Canyon Nuclear power plant in 2026. Thus the energy generation ratio (*Table 2*) for nuclear generation remained constant from 2016 to 2024, decreased by half in 2025, and became zero for the following years up to 2030. In addition, although projected solar PV generation was also scaled linearly over the 14-year time frame, in reality, the deployment of solar PV will not be a constant, linear increase, but will instead have more upfront installations during the earlier years of the time frame.

Table 2. California's Current (2016) and Project (2030) Energy Generation Ratios by Generation Source. The 2016 generation mix was derived from CAISO data, while the 2030 generation mix was derived from E3.

Year	Biogas + Biomass	Solar PV	Geothermal	Hydro	Natural Gas	Wind	Imports	Nuclear	Solar Thermal
2016	0.02	0.08	0.04	0.11	0.33	0.06	0.28	0.08	0.01
2030	0.03	0.26	0.06	0.12	0.36	0.15	0.01	0.00	0.01

* Energy generation ratios for 2016 and 2030 do not necessarily add up to 1.00 due to rounding assumptions.

Projected Overgeneration Calculation

After determining California's current and future electricity demand and generation mix, the total excess energy production was calculated for every year from 2016 to 2030. For the annual energy generation projections, it was assumed that in each year total generation was equal to total electricity demand. Therefore, the total generation in each day was equal to the total electricity demand in that day. However, the hourly distribution of energy generation did not necessarily equal demand at all hours of the day. This imbalance is due to the large increase in solar generation, which provides its daily share of generation during daylight hours. This hourly discrepancy therefore led to excess energy generation during daylight hours, and less energy generation during evening hours when demand was high.

In the overgeneration projection model, overgeneration occurs when total electricity generation exceeds total electricity demand. One major aspect that the overgeneration projection model had to factor was the minimum generation level of natural gas power plants. In California, the cumulative natural gas electricity generation has a minimum level that it must produce, no matter how great the production of renewable energy. For the overgeneration projection model, the minimum generation capacity of natural gas was set to 2,000 MW; meaning that at minimum, California will always produce at least 2,000 MW of natural gas generated electricity. Due to this minimum generation level, the natural gas generation amount that can be displaced by renewables cannot drop below this minimum generation value.

Total generation is the sum total of energy generation from concentrated solar thermal, solar PV, nuclear, hydropower, wind, biomass, geothermal, nuclear, and electricity imports into California (typically from coal and nuclear resources). Overgeneration is calculated as the difference between total electricity generation and total electricity demand. When this difference is positive, there is overgeneration. In the BAU scenario, overgeneration is curtailed to prevent damage to the grid. In the battery storage scenario, overgeneration is stored in the BESS and discharged to the grid during the hours of the day when the difference between electricity generation and demand is negative. This negative difference between total electricity generation and total electricity demand is referred to as undergeneration in the model.

Projected Undergeneration Calculation

When the difference between total electricity generation and total electricity demand is negative, there is undergeneration. Undergeneration occurs when electricity generation is less than electricity demand. In the past, undergeneration was not usually a problem since grid operators could easily maintain grid balance by forecasting electricity demand and meeting demand with conventional energy resources. However, with the growing deployment of intermittent renewable resources, maintaining a balanced grid has become a challenge due to the unpredictable and fluctuating nature of renewable energy resources. During periods of undergeneration, the overgeneration projection model assumed that electricity demand was met either with natural gas or battery storage since these sources are fairly flexible and can alter their output relatively quickly compared to other energy sources. In the BAU scenario, only natural gas electricity was used to meet electricity demand during times of undergeneration. In the battery storage scenario, the excess electricity stored in the BESS was dispatched to meet electricity demand during undergeneration hours, and any additional electricity demand after the battery was completely discharged was met with natural gas electricity. Total undergeneration was calculated for every year from 2016 to 2030.

After determining the amount of overgeneration and undergeneration occurring in an average day for each month within the years of 2016 to 2030, the overgeneration projection model was able to calculate the total amount of over- and undergeneration in each year from 2016 to 2030. These yearly totals were applied to the per MWh environmental impact values to calculate the cumulative environmental impacts of battery storage and natural gas electricity in the BAU and battery storage scenarios.

DATA QUALITY AND UNCERTAINTIES

LCA Assumptions and Uncertainties

The assumptions with the greatest impact on the BESS LCA results were those regarding the Li-ion battery utilization and lifetime expectancy. In the BESS model, it was assumed that the batteries had a lifespan of 20 years and that each day the batteries would charge to their maximum capacity and then discharged fully onto the grid. This led to the assumption that the batteries underwent 7,300 cycles over their 20-year lifespan. However, in the overgeneration project model, there were days with no excess solar electricity to store and the battery was not utilized at all. This means that the assumed 20 year lifespan of the batteries could be extended, affecting the environmental impact of the BESS. Since battery storage is a relatively new technology, a full 20 year lifespan in utility-scale Li-ion battery storage has yet to be witnessed. While there was uncertainty regarding the actual utilization and lifetime expectancy of a real life Li-ion BESS, the utilization and lifetime expectancy assumptions made for the BESS model in this project were based on industry discussions and a literature review.

To calculate the environmental impacts of a Li-ion BESS per MWh, the total impacts of the BESS were divided by the number of cycles the battery undergoes. Changes to the cycle number assumed would thus change the output of environmental impacts from the BESS on a per MWh basis. In addition, the assumed round trip efficiency (90 percent) and DoD (80 percent) of the batteries also significantly contributed to the BESS use-phase performance and overall environmental impact of the BESS. The round trip efficiency and DoD assumptions were determined through discussions with industry experts and parameters from recent utility-scale BESS applications (Erhart, 2018).

Overgeneration Projection Model Assumptions and Uncertainties

California's 2016 electricity demand and generation data were derived from CAISO. CAISO's operational territory covers 80 percent of California and a small portion of Nevada. Considering CAISO's relatively small service area in Nevada, this project assumed this portion of the 2016 electricity demand and generation data was negligible. This assumption was based on discussions with industry experts. In addition, to ensure that CAISO's electricity demand and generation data represented all of California's demand and generation, the data was scaled up by a factor of 1.25.

Once CAISO's 2016 electricity demand and generation data was scaled to represent the entire state of California, the 2016 electricity demand was multiplied by a factor of 1.06 percent for each year from 2017 and 2030. The 1.06 percent annual increase in electricity demand was derived from a CEC report on California's projected electricity demand from 2016 to 2027, though this project assumed the 1.06 percent annual increase would continue to 2030 (California Energy Commission, 2017c).

California's 2030 energy generation mix was assumed using data from E3 and was scaled linearly every year from 2016 to 2030. Due to the nature of the implementation plans for electricity projects, much of the electricity generated from various sources will not likely increase in a linear fashion over time. Furthermore, the assumed amount of solar electricity generated over the 14-year period affects the amount of overgeneration assumed to occur, the amount of electricity stored in the BESS, and thus the environmental impact of the BESS. This project also assumed that the amount of battery storage required to capture all overgeneration will be available.

With regard to CAISO's 2016 energy generation mix, the energy generation categories did not match up with the energy generation categories in E3's projected 2030 energy generation categories. Because of this data inconsistency, the project needed to re-categorize generation data. Small and large hydro were combined into a singular "hydro" generation category to account for the insignificant small hydro data compared to that of large hydro. Similarly, generation data for biomass and biogas were combined into one generation source called "biomass" to match the "biomass" category in E3's projections.

Nuclear generation data was linearly scaled until 2025, when its generation was halved. From 2026 until 2030, nuclear generation was assumed to be zero to account for the 2026 decommissioning of the Diablo Canyon nuclear power plant. Energy imports were estimated based on E3 projections and were assumed to change linearly. Electricity production from wind was assumed to be generated 90 percent of the time, with minimal fluctuations. Minimum generation of natural gas was determined to be 2,000 MW at all times.

The environmental impacts from natural gas electricity generation are typically higher during periods of ramping. Ramping occurs when the electrical output from natural gas power plants is increased quickly to meet a sudden rise in electricity demand, such as the evening peak demand. During peak demand, solar energy production declines as the sun sets. To maintain grid balance between electricity demand and supply, California relies on natural gas peaker plants to quickly ramp electricity generation to meet demand. The overgeneration projection model in this project assumed that each MWh of electricity produced from natural gas had the same environmental impact as a MWh of electricity produced from natural gas during ramping.

RESULTS

LCA RESULTS

Li-ion BESS Contribution Analysis

The environmental impacts from the Li-ion BESS and from electricity generated from a natural gas power plant were calculated for each of the six environmental impact categories using GaBi ts software. Results were reported using ReCiPe 2016.

A contribution analysis of the Li-ion BESS was conducted to determine how each component of the modeled storage facility contributes to the systems' overall impact in each of the six environmental impact categories. The contributional BESS impacts were reported per daily cycle per MWh discharged to the grid. The BESS component with the largest contribution to all six environmental impact categories was the Li-ion battery itself, likely from the raw material and production phases of the battery. The second and third largest contributors to the environmental impact of the storage system were the inverter and transformer, respectively. This is true for every impact category except freshwater eutrophication and human toxicity.

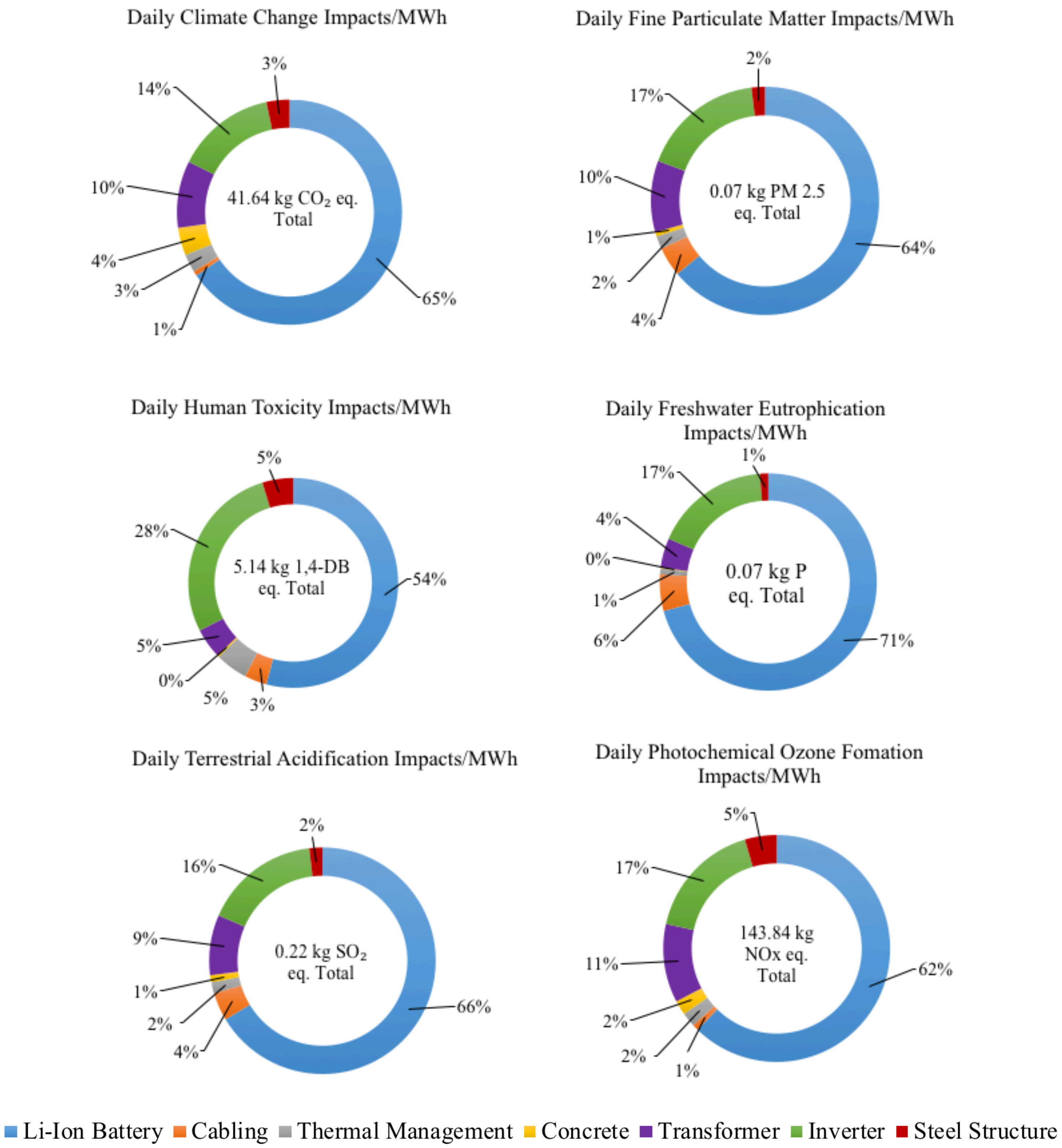

Figure 7. Contribution analysis shows the percent of environmental impact created by each individual component of Li-ion BESS model. The value in the center of each environmental impact pie chart shows the total environmental impact per daily cycle per MWh.

Life-cycle Impact Results

The environmental impacts of the Li-ion BESS were compared to the impacts of electricity generated from a natural gas power plant, using the functional unit of impact per MWh of electricity delivered to the grid. Environmental impact results were reported using ReCiPe 2016 (*Table 3*).

Table 3. The life-cycle impacts of the Li-ion BESS and electricity generated from a natural gas power plant, per 1 MWh of electricity discharged. The table compares the life-cycle climate change (kg CO_2e), fine particulate matter formation (kg $PM_{2.5}$ eq.), freshwater eutrophication (kg P eq.), human toxicity (kg 1,4-DB eq.), photochemical ozone formation (kg NO_X eq.), and terrestrial acidification (kg SO_2 eq.) impacts of the BESS and natural gas generated electricity. Red highlights indicate a large increase in the environmental impact between natural gas generated electricity and the Li-ion BESS. While green highlights indicate a large decrease in the environmental impact between natural gas generated electricity and battery storage. Yellow highlights indicate a small or negligible change in the environmental impact between natural gas electricity and battery storage.

Environmental Impact Category	**Electricity from Natural Gas (per MWh)**	**Electricity from Li-ion BESS (per MWh)**	**Percentage Change from Natural Gas to Storage**
Climate change, GWP100 (kg CO_2 eq.)	721	41.64	-94.22%
Photochemical Ozone Formation, Ecosystems (kg NO_X eq.)	2,350	143.84	-93.88%
Freshwater Eutrophication (kg P eq.)	0.00554	0.07	+1,114.1%
Human Toxicity, Cancer Causing (kg 1,4-DB eq.)	4.63	5.14	+11.02%
Terrestrial Acidification (kg SO_2 eq.)	5.93	0.22	-96.29%
Fine Particulate Matter Formation (kg $PM_{2.5}$ eq.)	1.69	0.07	-95.86%

On a per MWh basis, there was a substantial decrease in the environmental impact of using battery storage compared to natural gas electricity in four out of six impact categories assessed (climate change, fine particulate matter, photochemical ozone formation, and terrestrial acidification). The Li-ion BESS had a much larger impact in the freshwater eutrophication impact category than natural gas electricity. The percent change in impact between natural gas electricity and the BESS is significant for every impact category, except human toxicity (Jolliet et al., 2015). *Figure 8* below compares the percent change in the environmental impact between natural gas electricity and the Li-ion BESS for the six environmental impact categories.

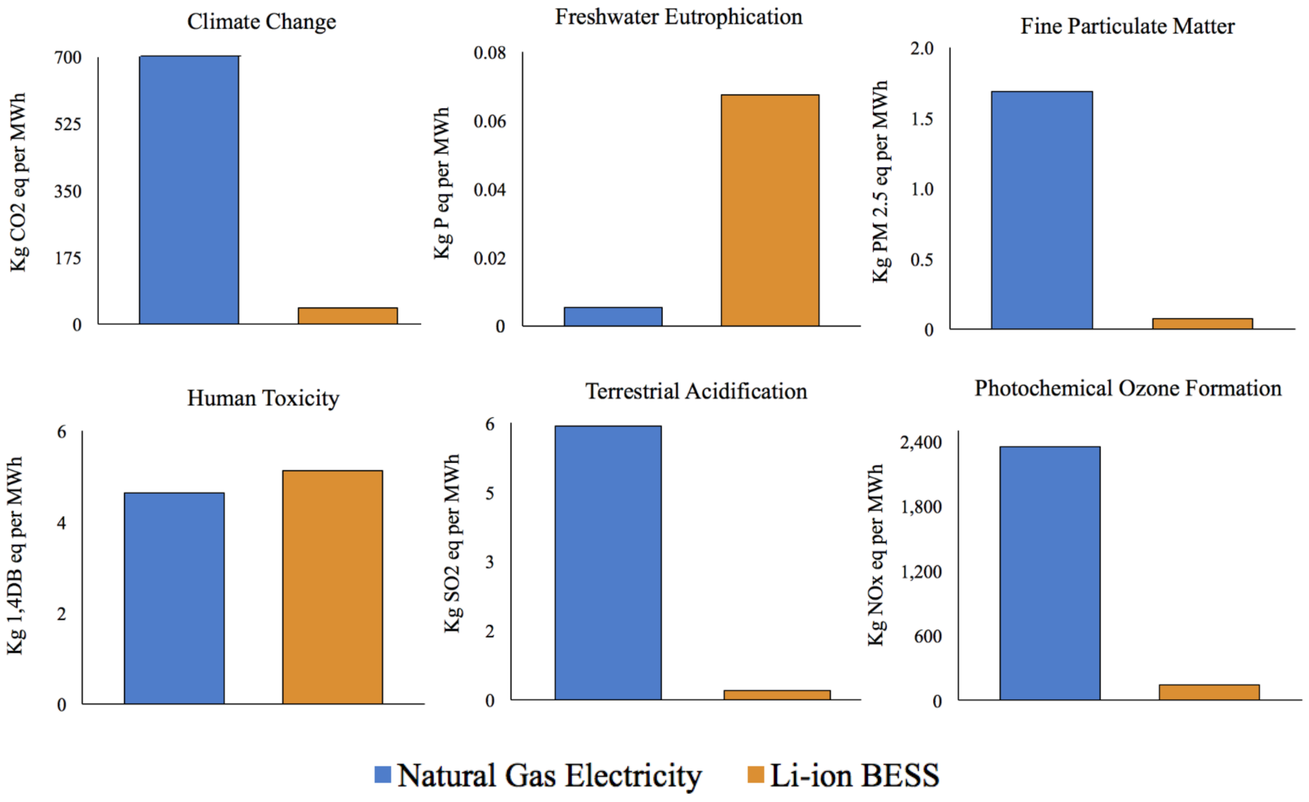

Figure 8. The percent change in environmental impact between natural gas electricity and the Li-ion BESS modeled, per 1 MWh of electricity.

California's 2030 Energy Generation Mix

California's 2030 energy generation mix was modeled for two different grid scenarios: the BAU (no battery storage scenario) and the battery storage scenario. In the BAU scenario, the 2030 energy generation mix was projected to meet California's RPS goal of 50 percent renewable energy without battery storage. In the battery storage scenario, the 2030 energy generation mix was projected to meet the 50 percent RPS goal while implementing battery storage.

BAU Scenario - 2030 Energy Generation Mix

In the BAU scenario, there was an 18 percent increase in solar PV generation from 2016 to 2030 (*Figure 9*). There was also a 9 percent increase in wind generation and 27 percent decrease in energy imports from 2016 to 2030 (*Figure 9*). When overgeneration occurs, grid operators typically curtail generation from solar and wind power plants to maintain grid balance. However, this project assumed that only solar PV generation was curtailed in the case of the BAU scenario or stored in the case of the battery storage scenario. It is important to note that there was a 5 percent increase in natural gas electricity generation from 2016 to 2030 in the BAU scenario. Natural gas generation increased to fill in the generation gaps that occurred between daily peak generation and peak demand hours.

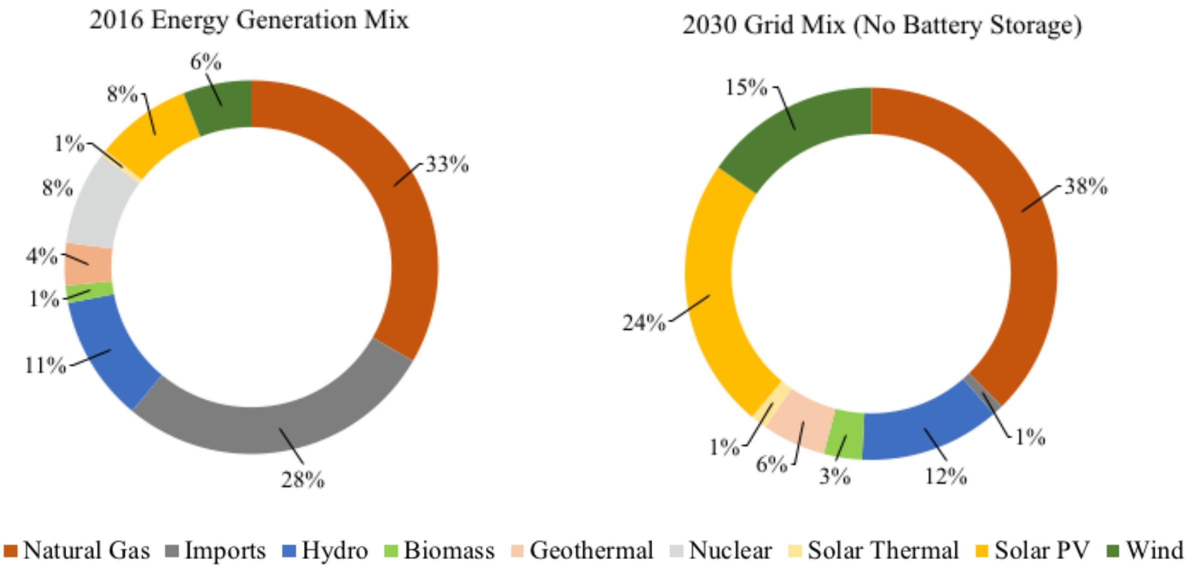

Figure 9. Comparison of California's actual 2016 energy generation mix with the projected 2030 energy generation mix under the BAU scenario.

Battery Storage Scenario - 2030 Energy Generation Mix

In the battery storage scenario, there was also an 18 percent increase in solar PV generation, a 9 percent increase in wind, and a 27 percent decrease in imports from 2016 to 2030 (*Figure 10*). However, in this scenario, natural gas electricity generation increased by 3 percent from 2016 to 2030, compared to a 5 percent increase in the BAU scenario. This difference in natural gas electricity generation between scenarios is due to the implementation of battery storage to capture overgeneration from 2016 to 2030. In this scenario, battery storage displaced natural gas usage by 2 percent. However, natural gas electricity could not be displaced entirely since it was needed to meet the remaining electricity demand after the battery was completely discharged each day. Thus, natural gas electricity generation increased from its 2016 generation, though this increase was less than the BAU scenario.

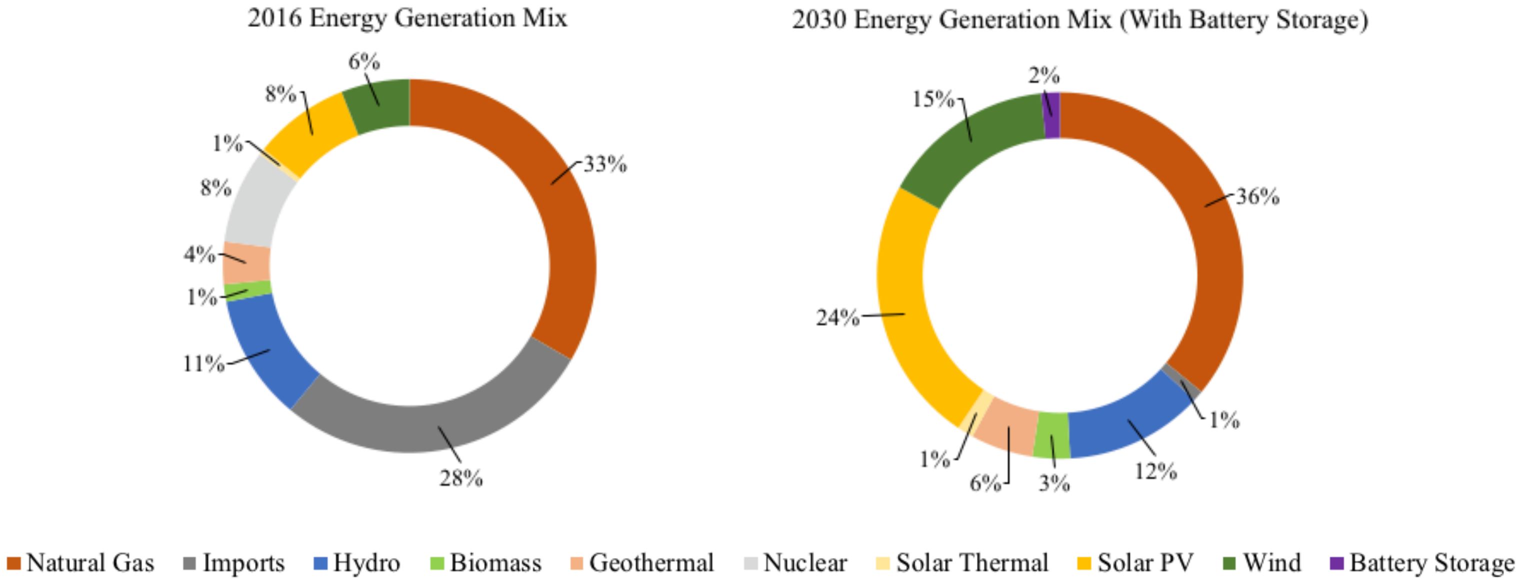

Figure 10. Comparison of California's actual 2016 energy generation mix with the projected 2030 energy generation mix under the BAU scenario.

Natural Gas Displacement

In the battery storage scenario, natural gas electricity generation decreased by 8 percent between 2016 and 2030; equivalent to removing 22,749,355 MWh of natural gas generation. In 2030 alone, natural gas electricity generation decreased by 2 percent, due to the deployment of battery storage. *Figure 11* depicts the reduction in natural gas generation resulting from the implementation of battery storage to deal with the expected overgeneration in California.

Since the battery storage scenario assumed a linear growth of solar PV and battery storage deployment over time, more overgeneration was stored and thus more natural gas was displaced towards the end of the 14-year timescale.

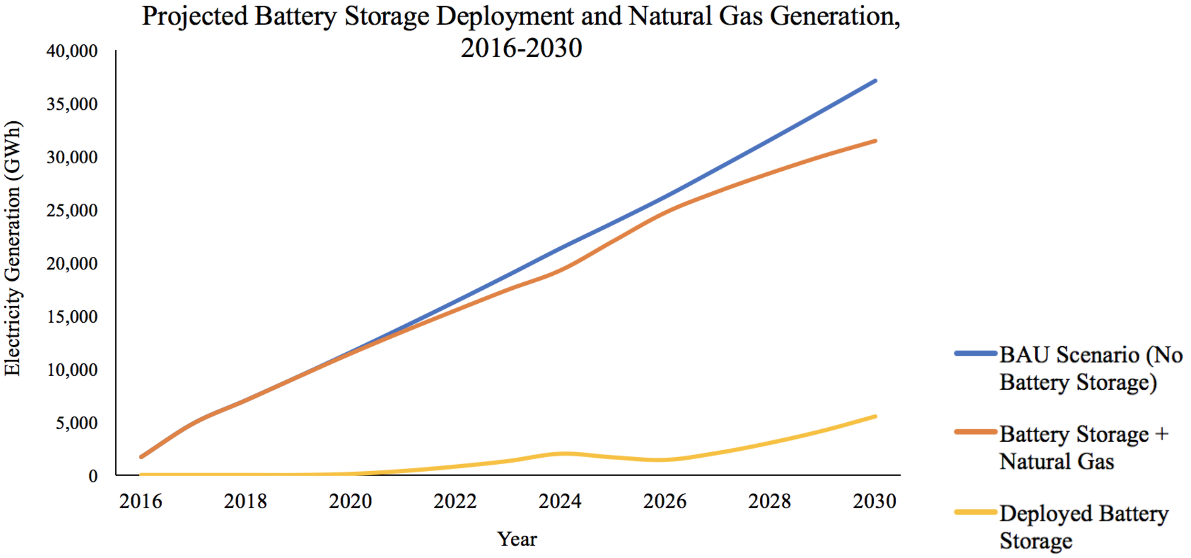

Figure 11. Natural gas electricity generation and battery storage utilization from 2016-2030 in the BAU and battery storage scenario. With the deployment of battery storage from 2016 to 2030, natural gas electricity generation decreased by 8 percent.

Cumulative Impacts of Battery Storage vs Natural Gas Electricity

To determine the cumulative environmental impacts of battery storage and natural gas electricity in the BAU and battery storage scenarios, the LCA results of the BESS and natural gas electricity were applied to the cumulative over- and undergeneration estimates from the overgeneration projection model (*Figure 12*).

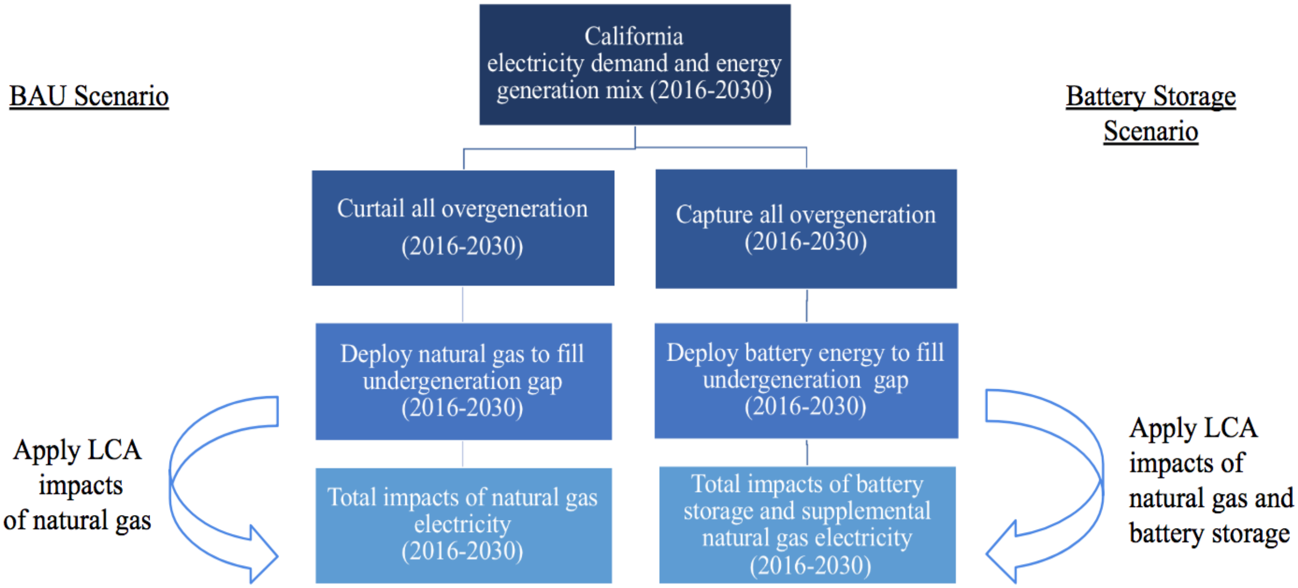

Figure 12. The step-by-step process to determine the environmental impacts associated with natural gas electricity and Li-ion battery storage in the BAU and the battery storage scenarios.

In the BAU scenario, the LCA impacts of natural gas electricity for all six impact categories were multiplied by the total MWh of undergeneration. This means that all undergeneration was met by natural gas electricity.

In the battery storage scenario, the LCA impacts of the Li-ion battery were multiplied by the MWh of battery output, which was calculated from the total MWh of overgeneration and the battery degradation characteristics. Since the battery storage output was not enough to meet electricity demand, supplemental natural gas electricity was required to meet the undergeneration gap. As such, the LCA impacts of natural gas electricity were multiplied by the remaining MWh of undergeneration after the battery deployment. The impacts from natural gas electricity were then added to the impacts of the BESS to determine the cumulative impacts of the battery storage scenario. The cumulative environmental impact results for both scenarios are given in *Figure 13*.

It should be noted that a large percentage of the impacts from the battery storage scenario come from the additional natural gas needed to meet electricity demand. In the battery storage scenario, 264,347,014 MWh of natural gas were needed to meet undergeneration from 2016 to 2030.

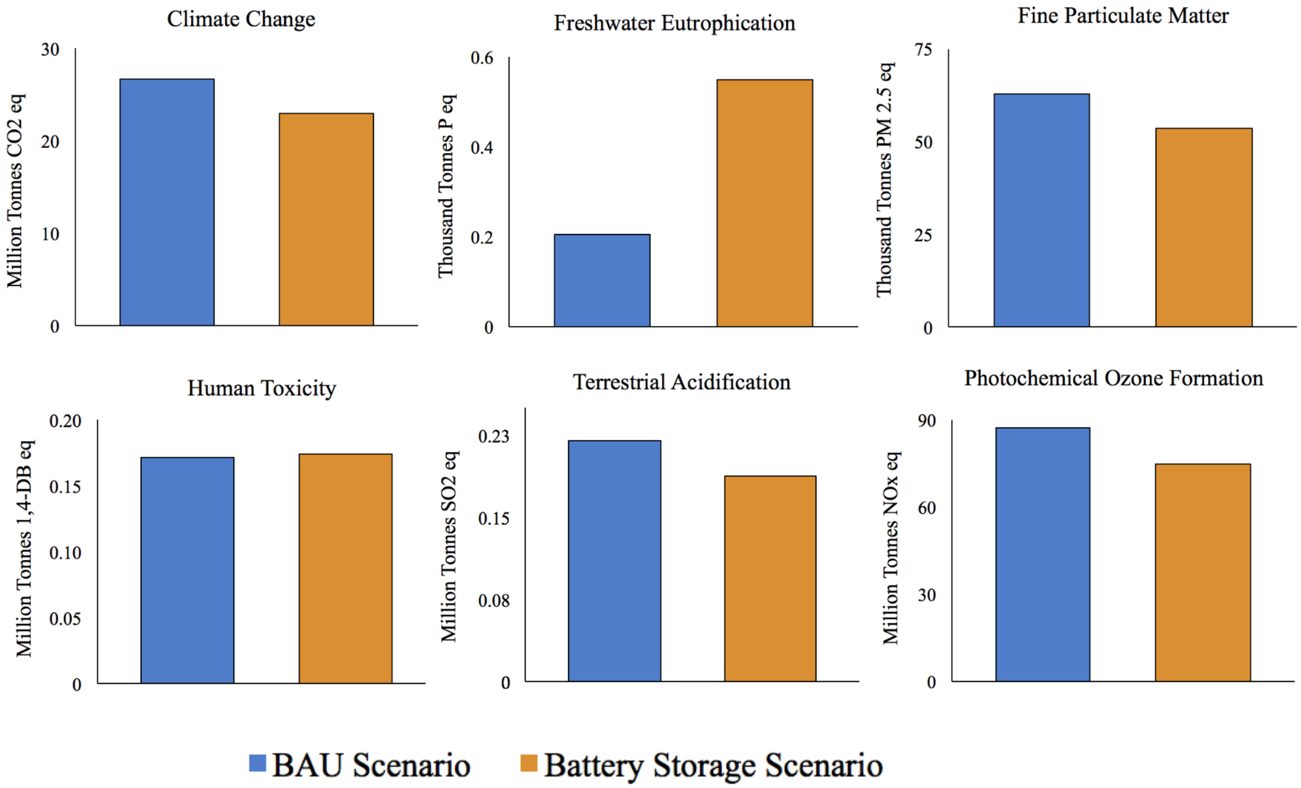

Figure 13. Six LCA impact categories and the associated percent changes of switching from the BAU scenario to the battery storage scenario This graph shows the change in impacts for the year 2030.

Table 4 displays the environmental tradeoffs, given in percent change in impact, between the BAU scenario and the battery storage scenario over the 14-year time frame and in the year 2030 alone.

Table 4. The environmental tradeoffs, given as a percent change in impact, between the BAU scenario and the battery storage scenario. Impact tradeoffs are reported per one MWh of output. Impact tradeoffs are also reported cumulatively over the 14-year time frame, as well as for the year 2030 alone. A positive percent change indicates an increase in the environmental impact between the BAU scenario and the battery storage scenario. A negative percent change indicates a decrease in the environmental impact between the BAU and the battery storage scenario.

	Impact Change per MWh (%)	**Impact Change for 2030 (%)**	**Impact Change for Cumulative 2016-2030 (%)**
Climate Change	-94.2*	-14.2*	-7.5
Fine Particulate Matter	-95.8*	-14.4	-7.6
Eutrophication	+1,114.1*	+167.7*	+88.3*
Photochemical Ozone Formation	-93.9*	-14.1*	-7.4*
Human Toxicity	+11.0*	+1.7	+0.9
Terrestrial Acidificiation	-96.4*	-14.5	-7.6

* Indicates a statistical significance impact change (Jolliet et al., 2015).

Climate Change Impact

Using battery storage with supplemental natural gas from 2016 to 2030 could reduce the climate change impact of the BAU scenario by 7.5 percent. This reduces is equivalent to a reduction in CO_2e emissions of 15.5 million tonnes over the 14-year time frame. The change in the climate change impact were determined to be the most significant result in meeting the goals set out by California to ultimately reduce the state's GHG emissions.

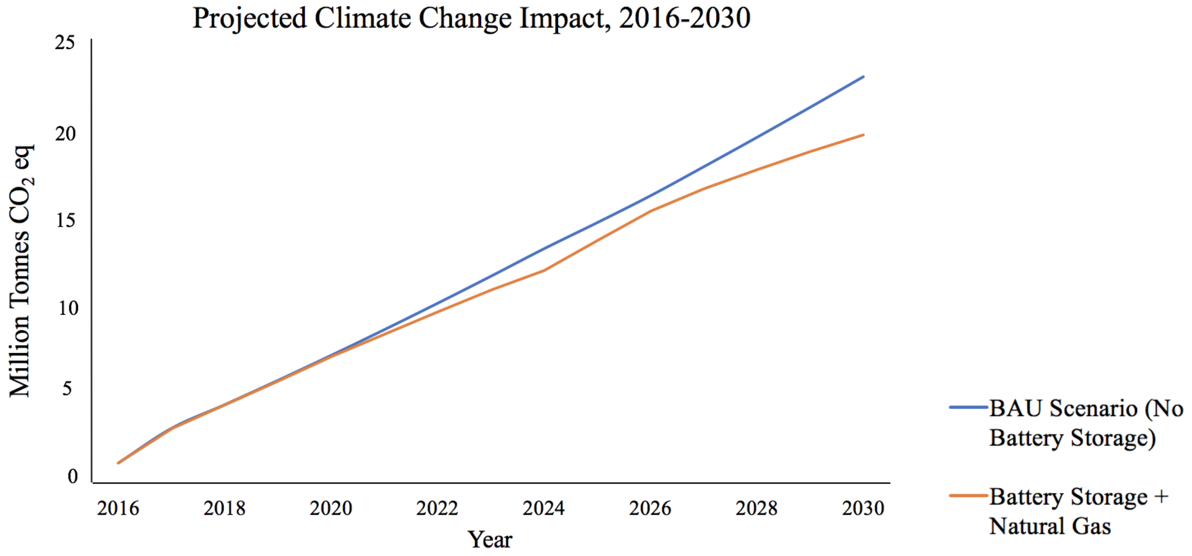

Figure 14. The projected yearly decrease in CO_2e emissions in the BAU scenario compared to the battery storage scenario, over the 14-year time frame.

DISCUSSION

To understand the potential implications of using utility-scale battery storage in California, it is important to consider the tradeoffs of battery storage along with the benefits. This project builds upon existing information on the environmental impacts of battery storage and natural gas to provide a deeper understanding of the long term impacts of battery storage implementation. The project's results on the environmental impacts, long term tradeoffs, and potential displacement of natural gas will provide utility-scale renewable energy developers and energy policy makers with a better understanding of the implications of battery storage in California.

LIFE-CYCLE IMPACTS

The LCA of this project used a cautious approach with assumptions and estimates in order to produce conservative results that present a severe depiction of the potential impacts from implementing battery storage. The use of ReCiPe hierarchist midpoint indicators also contributes to the project's effort to employ a conservative perspective throughout this study. Hierarchist indicators are based on the most common policy principles in regard to time, with the climate change impact using a 100-year outlook for global warming potential. These indicators have a lower value of uncertainty, though they often can be more difficult to interpret than using endpoint indicators.

The contribution analysis of the BESS and the entire facility illustrated how the total environmental impact was proportionally spread across each component. The component that had the largest contribution in all six environmental impact categories was the Li-ion battery itself. The second and third largest contributors to the environmental impact of the storage system were the inverter and transformer, respectively. This is true for every impact category except freshwater eutrophication and human toxicity. For freshwater eutrophication, the concrete unit process had a slightly larger contribution of impact than the transformer. For human toxicity, the thermal management system and the steel supporting the foundation has the same contribution of impact as the transformer.

1 MWH COMPARISON

The same six environmental impact categories assessed in the contribution analysis of the BESS were again evaluated to compare the impacts of 1 MWh of electricity output from the BESS to 1 MWh of electricity generated from a U.S. natural gas-fired plant. The statistical significance of the different impact categories from electricity generated by natural gas and electricity from BESS are compared based on the information from Chapter 5 of "Environmental Life-Cycle Assessment" by Jolliet et al (Jolliet et al., 2015). A category's impact change is considered statistically significant when the change from one source of electricity to the next is large enough that its effect on the environment can be observed. Jolliet et al states that CO_2 and toxicity changes must be greater than 10 percent for significance, while changes in acidification, eutrophication, and particulate matter categories must change more than 30 percent to be significant. According to Jolliet, there was no change threshold that the photochemical ozone formation impact category must increase by to be statistically significant, so the project noted any change in that specific impact category as statistically significant.

The MWh comparison of LCA impacts per 1 MWh of electricity from the BESS and from the natural gas power plant showed that in four of six impact categories that were assessed, the environmental impacts were significantly decreased when the BESS was employed. Below further describes the individual environmental impact categories assessed and the impact contribution of the BESS-generated electricity and natural gas-generated electricity.

Climate Change

Using battery storage over natural gas to delivery 1 MWh of electricity decreased the climate change impact by 94 percent. This climate change impact result was determined to be statistically significant since the decrease in climate change impact is greater than 10 percent (Jolliet et al., 2015). This decrease in climate change is specifically important for the client, First Solar, and for the state of California, given their respective climate change goals. As the CO_2e impact decreases with each additional 1 MWh of battery storage-generated electricity, these LCA results prove that using battery storage can decrease the global warming potential of meeting electricity demand. This decrease in CO_2 emissions could help California work towards its GHG emission target set out in AB 32.

Fine Particulate Matter

Using 1 MWh of BESS-electricity in comparison to natural gas decreased fine particulate matter by 96 percent. Any increase in fine particulate matter could contribute to negative health and environmental impacts. The decrease in PM when switching electricity generation from natural gas to BESS is significant, since the change between the two generation sources is greater than 30 percent (Jolliet et al., 2015).

Photochemical Ozone Formation

Using the BESS instead of natural gas-generated electricity decreased the photochemical ozone formation impact by 94 percent. According to Jolliet et al., there is no threshold for significance when measuring photochemical results. However, presence of a large amount and/or in large concentration of ground level ozone has adverse effects on human health (Jolliet et al., 2015). Because of this, the decrease in the photochemical ozone formation impact is significant, as it will create a noticeable improvement in the environment and human health.

Terrestrial Acidification

Terrestrial acidification describes the atmospheric deposition of sulfates, nitrates, and phosphates into the soil, causing changes to the soil acidity. Such changes to soil acidity can lead to impacts on biodiversity. Using the BESS instead of natural gas-generated electricity decreased the terrestrial acidification formation impact by 96 percent. According to Jolliet, a 30 percent change in terrestrial acidification is necessary for the acidification impacts to be considered significant (Jolliet et al., 2015).

Freshwater Eutrophication

Freshwater eutrophication has significant impacts on freshwater ecosystems, such as lakes, reservoirs, and rivers, and on ecosystem services such as fisheries, recreation, aesthetics, and human health. The largest negative environmental impact of the BESS occurred in the freshwater eutrophication impact category. The Li-ion battery contributed to 71 percent of the overall freshwater eutrophication impact. The majority of this BESS impact stems from the battery management system, which contributes to 40 percent of the battery's impact to eutrophication, and specifically its integrated circuit board, which makes up 33 percent of the battery's impact to eutrophication. Other processes that significantly contribute to the battery's eutrophication impact are the lithium anode, creating 17 percent of battery impact, and the electricity required for battery production, creating 10 percent of the battery's impact. After the Li-ion battery, the largest contributor to the storage system's eutrophication impact comes from the inverter, which creates 17 percent of the system's total eutrophication impact.

Human Toxicity

The 11 percent increase in human toxicity when switching from natural gas electricity to battery-stored electricity is statistically insignificant, meaning that the change between the two sources of electricity would have no measurable impacts on human toxicity levels. Jolliet et al., concludes that a change of one order of magnitude is necessary in order for the impact to be significant (Jolliet et al., 2015). In addition, human toxicity impacts due to long-term landfill emissions are far more uncertain than dominant toxic emissions (Jolliet et al., 2015). This project was run on the premise that for the end of life case, all the Li-ion batteries will be landfilled instead of recycled. Since the majority of the toxicity impacts from the BESS come from the Li-ion battery itself, if these batteries were to be recycled instead of landfilled, the toxicity impacts of the BESS could be significantly reduced.

CUMULATIVE IMPACT COMPARISON (2016-2030)

The comparison of cumulative environmental impact between scenarios from 2016 to 2030 showed that using battery storage only significantly decreases the impact of photochemical ozone formation. The only other statistically significant change was an 88 percent increase in freshwater eutrophication caused by the BESS when compared to natural gas electricity. Below is a discussion of the impacts with significant changes from one electricity source to the next.

Climate Change

Using electricity from the BESS over natural gas electricity during the 14-year time frame decreased the climate change impact by 7.5 percent, which translates to a 15.5 million tonnes CO_2e emissions reduction. However, this reduction in climate change impact is found to be statistically insignificant. The project research and analysis showed minimal amounts of overgeneration occurring in the first 5 years of this time period. Due to the conservative viewpoint of a linearly scaled implementation of solar and storage systems, there was less solar PV installed in the first few years, leading to less need for battery storage. The necessary amounts of overgeneration for battery storage use does not occur until 2020.

Without this increase in battery storage usage, the change in electricity generation from natural gas to a BESS is not significant enough to have a noticeable impact.

Freshwater Eutrophication

Switching from natural gas electricity generation to BESS-electricity resulted in an 88 percent increase in the freshwater eutrophication impact. The BESS LCA conservatively assumed that the batteries would be landfilled at the end of their life. However, the BESS freshwater eutrophication impact could be reduced if the spent batteries were recycled instead of landfilled after their use.

Photochemical Ozone Formation

Over the 14-year time frame, There was a 7.4 percent decrease in the photochemical ozone formation impact when comparing the BESS to natural gas electricity. In the absence of any threshold for significance when measuring photochemical results, any decrease is considered significant and beneficial to human and environmental health (Jolliet et al., 2015).

SUGGESTIONS FOR FUTURE RESEARCH

The limitations of this analysis highlight opportunity for future research. As noted previously, natural gas ramping affects the amount of environmental impacts from 1 MWh of natural gas electricity. In particular, there is a different climate change impact associated with electricity produced during ramping periods. A more accurate climate change impact calculation would include the impacts caused by ramping in the evenings, which would increase the potential for environmental impact benefits of switching to BESS.

The overgeneration projection model should also include various electricity demand projections. Currently, there are various demand-response initiatives and actions being take, which will impact the need for utility-based electricity. These initiatives include time-of-use rates, electric vehicle charging, and rooftop solar. Although the electricity demand rate used in this project's overgeneration projection model considers these factors, it only assumes one scenario for each. The addition of various electricity demand projections in the overgeneration projection model would allow for analysis of how these different demand scenarios impact overgeneration. Therefore leading to a more robust understanding of the magnitude of the different tradeoffs.

In the years to come, grid flexibility will increase. This means the minimum generation levels and purchasing of natural gas and imports should decrease, due to the decommissioning of natural gas and coal-fired power plants. A decrease in minimum generation levels would allow increased PV penetration to the grid at peak hours and may decrease the overall amount of battery storage needed to store overgeneration.

The project's overgeneration projection model should also take into account the non-linear installation of PV in the near future. The overgeneration projection model scaled PV installation linearly, meaning each year has the same MW increase of PV installation from 2016 to 2030. However, it is assumed that the majority of PV systems will be installed long before 2030 and will start generating electricity at the beginning of the project's 14-year timeline. Early installation of PV generation would lead to increased overgeneration sooner using this project's overgeneration projection model, leading to greater overgeneration and storage availability overall.

Lastly, an economic analysis to evaluate the financial feasibility of using BESS and the future comparisons between using BESS-generated electricity and natural gas generated electricity will direct the feasibility of the implementation of these technologies.. Currently, the costs associated with BESS may impede the implementation of this technology, but these costs are expected to decrease over time. The addition of an economic component would provide key stakeholders a more complete overview of the tradeoffs associated with BESS.

IMPACT TO STAKEHOLDERS

In California's changing energy landscape, there is ample opportunity for increased penetration of renewable energy. However, the characteristics of this type of energy present limitations to its diffusion. This research on a prospective solution to solar energy's constraints, provides a more complete understanding for stakeholders involved in shaping California's energy market.

Solar Developers

Solar developers, like this project's client First Solar, include stakeholders and companies involved in the solar industry. As solar developers attempt to deal with the limitations linked to the use of solar energy, they will have to evaluate the potential solution of BESS. With this project analysis, solar developers have a more complete understanding of the environmental impacts caused by BESS and therefore, can make more informed decisions regarding this solution. Depending on the company's mission and goals, solar developers can incorporate this battery storage into their product offerings if they would like to further increase the use of renewable energy-based electricity, while reducing the environmental implications of this electricity production.

State of California

California's electricity market plays a critical role in helping the state realize the ambitious GHG reduction goals laid out in AB 32. With the increased installation of solar energy, BESS can provide a solution to further increase the amount of electricity purchased from these systems, which in turn would assist California in achieving the AB 32 goal.

Through the project analysis, the tradeoffs associated with implementing battery storage are evaluated. When considering the aims of AB 32, BESS not only provides an avenue to increase the amount of electricity sales from incumbent energy resources (i.e., natural gas electricity).

CONCLUSION

California's electricity grid is rapidly changing. Policies like AB 32 convey California's dedication to prioritizing climate change mitigation in the state's plan for electricity generation. A large adoption of renewable energy resources is a key component to California's overall GHG reduction strategy, and economic drivers are supporting this development. Although this approach is well-founded, there are many issues that arise with implementing quick changes to an antiquated electricity network. California's grid infrastructure is challenged in adapting to a large capacity of renewable energy resources. Attempting to build up renewables in California is currently akin to building a house on an imperfect foundation. The inflexibility of California's traditional energy generators combined with the limitations of renewable energy resources is creating an electricity overgeneration and curtailment dilemma. Overgeneration is already a legitimate issue in California and this problem will continue to grow if the state's energy system is not modernized. California has an ambitious target for increasing renewable electricity generation and the state wants to achieve this challenging goal without creating additional problems for development.

Utility-scale battery storage offers a potential solution to the obstacles presented by grid inflexibility and overgeneration. Battery storage can allow California to provide electricity generated from renewable resources at times of the day when it is not normally available. On a per MWh basis, battery storage produces less environmental impacts in four out of six impact categories assessed in this study when compared to electricity produced from natural gas. The two categories where there is no decrease in impact when switching to battery storage are human toxicity and freshwater eutrophication. In the former category, battery storage and natural gas result in an equal impact, and in the latter category, there is an opportunity to reduce the impacts caused by battery storage by changing the end of life assumptions of the batteries to recycling instead of landfilling.

Compared to natural gas, battery storage displays great promise as a low-carbon technology that can reduce the climate change impacts of delivering electricity to the grid. Battery storage can also reduce California's reliance on natural gas plants for flexible electricity delivery. This study shows that if it is used to fully alleviate the electricity overgeneration caused by California's expected growth in renewables, battery storage has the ability to conservatively displace 22,749,355 MWh of electricity produced by natural gas from 2016 to 2030. This result presents an 8 percent reduction in natural gas use compared to a scenario without any utilization of battery storage. This conceivable outcome would also reduce the climate change impact between scenarios by 7.5 percent, further supporting California's climate change goals laid out in AB 32. Although there are many challenges associated with California's climate mitigation strategy, battery storage has the potential to offer many solutions. Battery storage can help California realize its GHG reduction target, further enable the growth of renewables on the grid, and create a more sustainable future by unlocking California's ability to achieve a fully electrified economy.

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