Evaluating the Profitability of a Supply Chain that Utilizes Electric Trucks for Transportation of Batteries that Store Otherwise Curtailed Renewable Energy

Word Count: 5,218

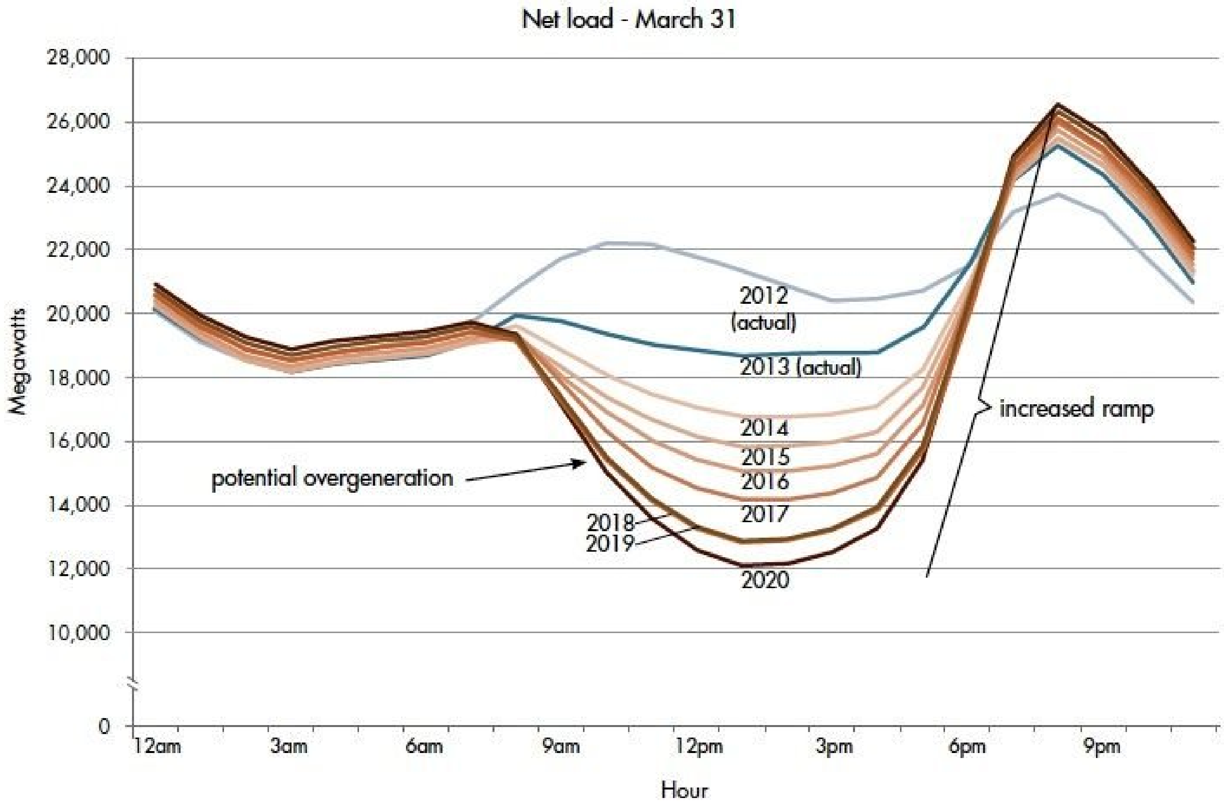
Abstract

California's aggressive push for renewable energy penetration has exacerbated their curtailment problems, where, according to researcher Zhanlong Zhang, the generated energy exceeds local demand and production must be reduced because of limited transmission capacity (Zhang, 2018). In 2020, the California Independent System Operator (CAISO) curtailed 1.5 million megawatt-hours (MWh) of renewable energy, which, at the November 2021 price of 18.96 cents per kilowatt-hour (KWh), costs $284,400,000 (United States Energy Information Administration, 2021). An alternate supply chain, in which electric trucks ship batteries that store otherwise curtailed renewable energy to distribution centers, could alleviate the state's curtailment issues. The profitability and curtailment reduction of this mode were evaluated under 2021, 2024, and 2030 conditions. The data was obtained by simulating the supply chain based on CAISO's 2021 5-minute interval curtailment data. This study calculated the profitability of the supply chain to be $4,274,179.28 in 2021, $20,128,388.76 in 2024, and $29,674,662.37 in 2030. The curtailment reduction was 260,871.03 MWh in 2021, 460,458.92 MWh in 2024, and 531,969.54 MWh in 2030. These results suggest that this mode is a feasible and moderately impactful solution that, combined with other solutions (e.g. CAISO's Energy Imbalance Market), can considerably reduce curtailment in California. Furthermore, this simulated model can be applied to other states or countries if the input data is provided.

Literature Review and Introduction

In recent years, California has taken aggressive measures to increase its renewable energy penetration rate. In 2019, the California Energy Commission reported that "36 percent of the state's retail electricity sales were provided by Renewables Portfolio Standard (RPS)-eligible sources such as solar and wind" (California Energy Commission, 2020), which exceeded their original goal of 33% RPS generation. However, in 2018, the state signed Senate Bill 100, which required 60% RPS generation by 2030 and 100% RPS generation by 2045 (California Energy Commission, 2020).

However, renewable energy has unintended side effects caused by its intermittency (output fluctuates during the day as the sun's intensity changes and wind speeds vary). This intermittency has caused 2 main problems: grid stability and renewable energy curtailment. The electrical grid has to constantly be load-balanced, which means that supply and demand for electricity are always equal to maintain a nominal frequency of 60 Hz (frequency is essential for all equipment operating on the grid). With the advent of renewable energy, the demand curve has shifted drastically. The demand curve used to be shaped like a camel with 2 humps (one in the morning and one at night), but the curve is more like a duck now with a huge valley (sometimes negative) in the middle of the day (California ISO, 2016).



Duck curve phenomenon illustrated by a larger midday drop in net load.

Traditionally, electricity utility companies have controlled all aspects of production, so they can start up spinning reserves to meet demand and lower production when needed. However, suppliers have very little control over the production of renewable energy, so their ability to load balance has been hindered. Utility's decreased control overproduction combined with the steep, variable drops in demand during the middle of the day take a toll on grid stability. According to a study in the journal *Energy Strategy Reviews*, systems with over 20% photovoltaic penetration (over 20% of energy is supplied via solar energy) experienced higher overvoltages in transmission line busbars [metal bars used for conducting high currents] and larger voltage drops after faults (Impram et al., 2020, p. 10). The voltage fluctuations caused by renewable energy have the potential to damage grid equipment and cause unreliability. In addition, the supply of renewable energy often exceeds all demand, which results in curtailment (reduction in the output of an electricity source to meet load balancing requirements). In 2020, California ISO (CAISO) curtailed 1.5 million megawatt-hours (MWh) of utility-scale solar production with nearly negligible wind curtailment (United States Energy Information Administration, 2021), which is up from just 187,000 MWh in 2015 (California ISO, 2017). With California's aggressive policy, curtailment rates have seen a rapid increase in the past five years, which means increased losses for utility companies. Based on the November 2021 electricity price in California of 18.96 cents per kilowatt-hour (KWh) (United States Energy Information Administration, 2021), renewable energy curtailment costs the state of California $284,400,000 annually.

Projected Changes to Curtailment Rates and Battery Costs

With aggressive renewable energy policies, curtailment rates are bound to change rapidly. According to Wesley Cole, a researcher at the National Renewable Energy Laboratory (NREL), found that if the United States achieves the Department of Energy's SunShot targets, curtailment rates will rise to 2.8% in 2030 and 3.7% in 2050 (Cole et al., 2017). As renewable penetration grows, the grid will become more intermittent and likely rely on curtailment more heavily to achieve load balancing. This is counterproductive to the Department of Energy's goals, so an efficient energy storage system is needed to reduce curtailment to further drive down emissions.

Battery costs have dropped precipitously over the past 20 years and are projected to continue falling. BloombergNEF projects average electric vehicle (EV) battery costs to be $94/KWh in 2024 and $62/KWh in 2030 (Goldie-Scot, 2019). These capital costs are far below the $259/KWh line of profitability for a battery energy storage system (BESS) suggested by Maryam Arbabzadeh's paper in *Nature* (Arbabzadeh et al., 2019), which means that lithium-ion batteries will be an increasingly effective energy storage technology moving forward. With these improvements, a battery transportation supply chain could become a valuable tool for reducing curtailment.

Current Methods for Reducing Curtailment

One widely proposed curtailment reduction solution is energy storage technology. By installing a few GWh of energy storage, utility companies can store renewable energy during times of surplus and distribute this energy during times of higher demand. The most commonly researched technologies are lithium-ion batteries and pumped hydroelectric storage (PHES).

In PHES, energy is stored by pumping water from a lower reservoir to an upper reservoir using otherwise curtailed energy. When demand for electricity increases, the water in the upper reservoir can be released to drive turbines and produce electricity. This is the most common type of utility-scale energy storage at the moment. In a study of 2012 curtailment and energy storage technologies, Maryam Arbabzadeh found that PHES could decrease curtailment rates in California from 27.04% to 8.89% (Arbabzadeh et al., 2019). PHES is a very efficient method of storing and releasing energy, but it faces geographic limitations. PHES is only feasible in regions with elevation changes as well as an abundance of land and water to create large reservoirs.

Lithium-ion batteries are the leading utility-scale battery technology. According to the United States Energy Information Administration, lithium-ion batteries make up over 90% of America’s 1,236 MWh utility-scale battery capacity. In Arbabzadeh’s study of 2012 curtailment data in California, she concluded that lithium-ion batteries were not an economically viable method of reducing curtailment based on capital and system costs at the time. However, her economic model found that if the cost of lithium-ion batteries dropped below $259/KWh, they would be profitable (Arbabzadeh et al., 2019). With advances in lithium-ion technology, this price has been eclipsed by battery producers and prices should continue to drop. This makes lithium-ion storage an attractive solution moving forward.

Another solution is to optimize the charging of plug-in electric vehicles (PEVs). By controlling the times of active charging, demand can be raised during times of surplus in a process known as smart charging. According to a 2020 study by Julia Szinai, assuming a 0.95 million total of PEVs in California, smart charging can reduce renewable energy curtailment by 119 GWh or 119,000 MWh and reduce overall grid costs by $119 million. Based on the mid estimate for 2025 PEV totals, smart charging can reduce curtailment by 238 GWh or 238,000 MWh and reduce overall grid costs by $208 million (Szinai et al., 2020). While the reductions in curtailment are small compared to the 1.5 million MWh curtailment total, the reductions in system costs for California make this solution efficient.

These energy storage studies evaluate the profitability of a centralized utility storage facility. The energy in the centralized facility is then distributed on the grid to consumers. However, these studies fail to consider battery transportation, which would eliminate grid costs and could be more profitable.

Finally, there was a study in 2018 by Zhanlong Zhang in the *Journal of Modern Power Systems and Clean Energy* that used trains for battery transportation. This mode of battery transportation would be economically feasible up to a delivery radius of 800 kilometers in the United States (Zhang et al., 2018). This gives supply chains using battery transportation a promising future. This study hopes to use a similar supply chain design as Zhang's but with electric trucks as the shipping vehicle for greener transportation.

Methodology

Proposed Supply Chain

The proposed supply chain worked by storing otherwise curtailed renewable energy in batteries and shipping them on electric trucks to local distribution centers. At these distribution centers, consumers can charge EVs directly by using the DC power from the batteries. The rest of the electricity can be sold to retail consumers after DC/AC power inversion is completed. The batteries were then shipped back to the solar and wind farms using the electric trucks after they were completely discharged. The electricity sold at the distribution centers will be priced at a 0.9 discount (10% off) to incentivize consumers to use the otherwise curtailed energy rather than using electricity that is distributed on the grid and produced in a non-renewable manner.

Data Collection

Because of limited time and resources, all of the data that was input into the simulation program and economic model was secondary.[1] Curtailment rates were gathered from the CAISO's ProductionAndCurtailmentsData_2021 spreadsheet. Battery information was based on the BYD Blade lithium iron phosphate battery. Capital battery cost projections were gathered from BloombergNEF. Electric truck information was based on the Freightliner eCascadia along with the federal rebate. Since the eCascadia is still in early stage testing, estimations had to be made regarding its price. Trucker wages were obtained through the Bureau of Labor Statistics.

Creating a Cost Function

The cost function utilized in this study is based on Zhanlong Zhang's cost function in his 2018 study regarding a supply chain that uses trains to ship batteries that store otherwise curtailed wind energy. Slight modifications were made to adjust for using trucks instead of trains,

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[1] The exact source for each piece of data is provided in the input parameter tables in Appendix B. A brief overview is provided here.

but the main cost variables did not change. Originally, a factor analysis was to be used for identifying the most important variables to include in the cost function. However, this study provided an already validated set of variables, which saves time and improves accuracy.

The annual levelized cost function includes 5 major aspects, which are the capital cost of batteries, the capital cost of trucks, the cost of electricity, the cost of trucker wages for shipping, and the environmental benefit of promoting renewable energy and reducing curtailment.

The levelized annual cost function is given by:

$C_{levelized} = C_{battery} + C_{truck} + C_{electricity} + C_{shipping} - V_{environmental}$

1) The levelized capital costs of batteries is modeled by:

   $C_{battery} = (p_{battery} * KWh_{needed}) / (cycleLife / cyclesPerYear)$, where

   $p_{battery}$ = capital cost of the battery per KWh

   KWh_{needed} = total capacity in KWh of all batteries

   cycleLife = number of cycles before degradation

   cyclesPerYear = number of charge-discharge cycles completed in a year

2) The levelized capital costs of electric trucks is modeled by:

   $C_{truck} = (p_{truck} * trucksNeeded) / (cycleLife / (2 * cyclesPerYear))$, where

   p_{truck} = cost of purchasing an electric truck

   trucksNeeded = number of trucks needed to transport the batteries

   truckLife = years before truck degradation

   cycleLife = number of cycles before degradation

   cyclesPerYear = number of charge-discharge cycles completed in a year (note: this refers to battery charge-discharge cycles not truck charge-discharge cycles, hence it is multiplied by 2)

3) The annual cost of electricity is modeled by:

$C_{electricity} = p_{electricity} * k_{discount} * electricityUsed$, where

$p_{electricity}$ = normal cost $/KWh of electricity

$k_{discount}$ = discount given by producers because energy would have otherwise been curtailed

electricityUsed = total electricity sold and consumed by trucks during shipping in a year in KWh

4) The annual cost of trucker wages for shipping is modeled by:

$C_{shipping} = trucksNeeded * truckerWages$, where

trucksNeeded = number of trucks needed to transport the batteries

truckerWages = annual wages paid to class A truckers

The annual revenue function is much simpler and given by:

$R_{annual} = p_{electricity} * p_{discount} * electricitySold$, where

electricitySold = electricity (KWh) sold to consumers in a year

$p_{electricity}$ = normal cost $/KWh of electricity

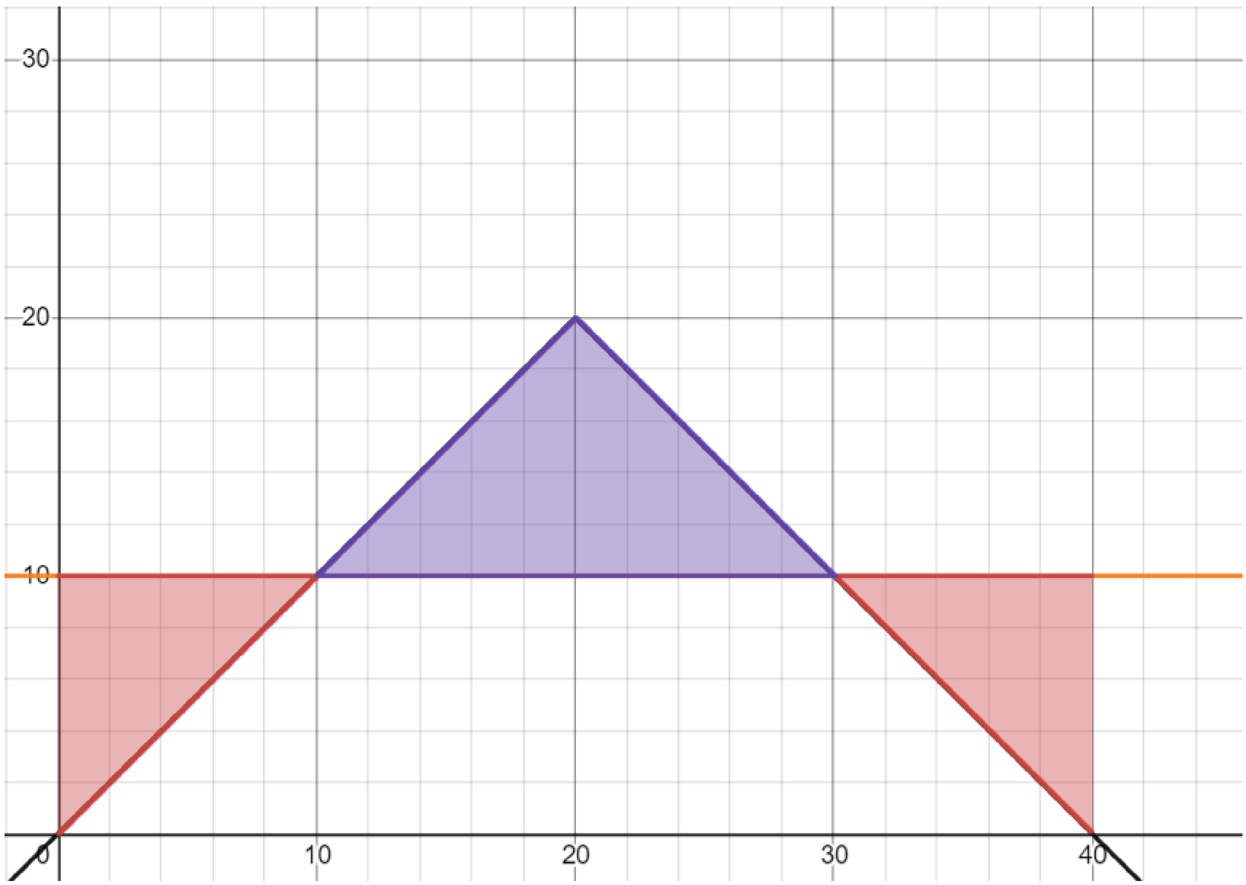
$p_{discount}$ = discount given to consumers to incentivize them to buy my electricity

Thus, the annual profit function is given by:

$P_{annual} = R_{annual} - C_{levelized}$

Simulating the Supply Chain

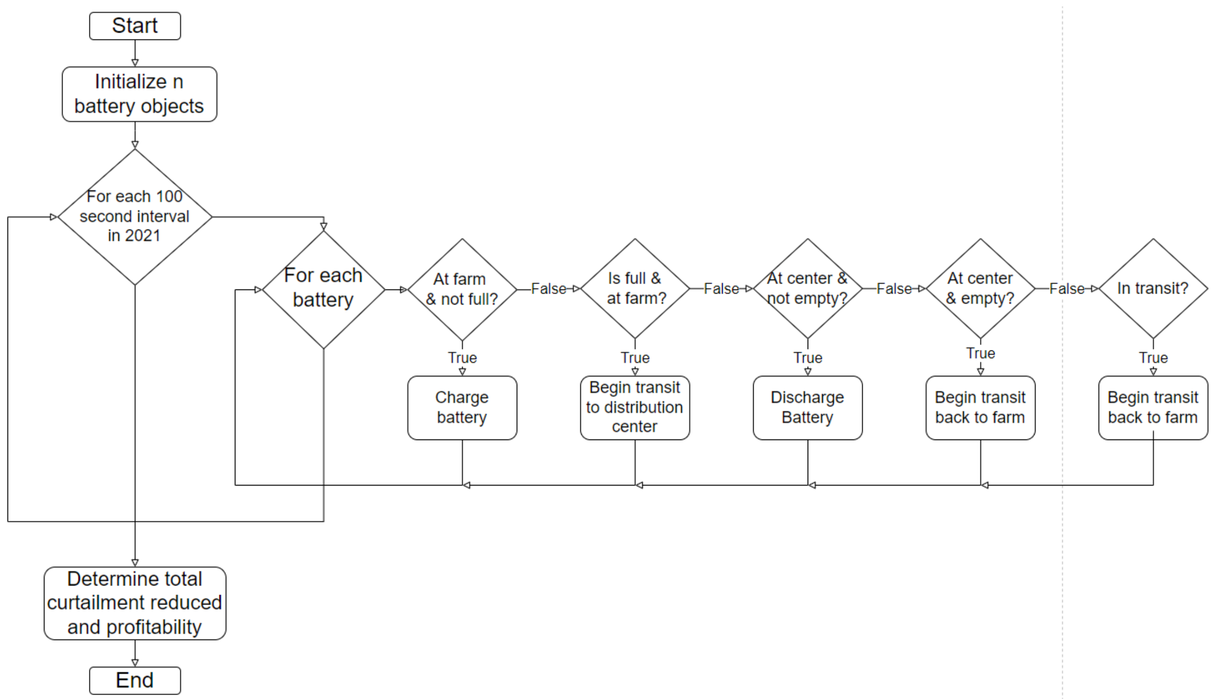
A Java program was used to simulate the supply chain using 5-minute interval curtailment data from CAISO over the year 2021. The advantage of utilizing 5-minute interval data is that it allows for more precise battery quantity optimization. In previous studies, like Zhanlong Zhang's 2018 paper, the average annual curtailment ratio was used. However, this gives an improper account of the effectiveness of the supply chain because renewable energy is intermittent with high peaks and low troughs. The following graph is an illustration of how 5-minute intervals are more precise than averages.



Graph representing 5-minute interval versus average approach to renewable curtailment.

In this example, the absolute value graph represents the curtailed power, in say MWh, at any instant of time, and the orange line represents the average power over the time interval from 0-40 seconds. If only averages were used, it would seem like 10 MW of battery power can fully absorb all of the curtailed energy over this time interval. However, this is not at all the case. The sum of the red (actual power < 10) and purple (actual power > 10 so batteries cannot absorb) areas represent the energy that, according to the average approach, would be absorbed but can't be absorbed in practice. 5-minute interval data won't be continuous like the absolute value graph, but it gives a picture that is much closer to reality than the average approach.

For the program design, a battery object was created to model the state of a real life battery.[2] During each iteration of the simulation the number of battery objects initialized was incremented by 1 to optimize the battery quantity. Once the profitability dropped for the marginal battery, the max profitability was determined at the quantity of batteries directly preceding the drop. A slightly oversimplified flowchart of the program is shown below.



Simulation program logic.

An outer for-loop is used to iterate through each 100 second, and the inner for-loop changes the state of each battery to represent its position in the supply chain. This flowchart does not show the outer loop for incrementing the number of batteries because it would have been too messy visually and is not important to the overall logic. It also glosses over the handling of edge

[2] There were more instance variables that can be found in the Battery.java file in Appendix A

cases when evaluating and changing the state of the batteries. Finally, it does not show the multi-threading that was used when the program was executed, which was used to decrease runtime but does not impact the logic.[3]

Dealing with Uncertainty in the Input Variables

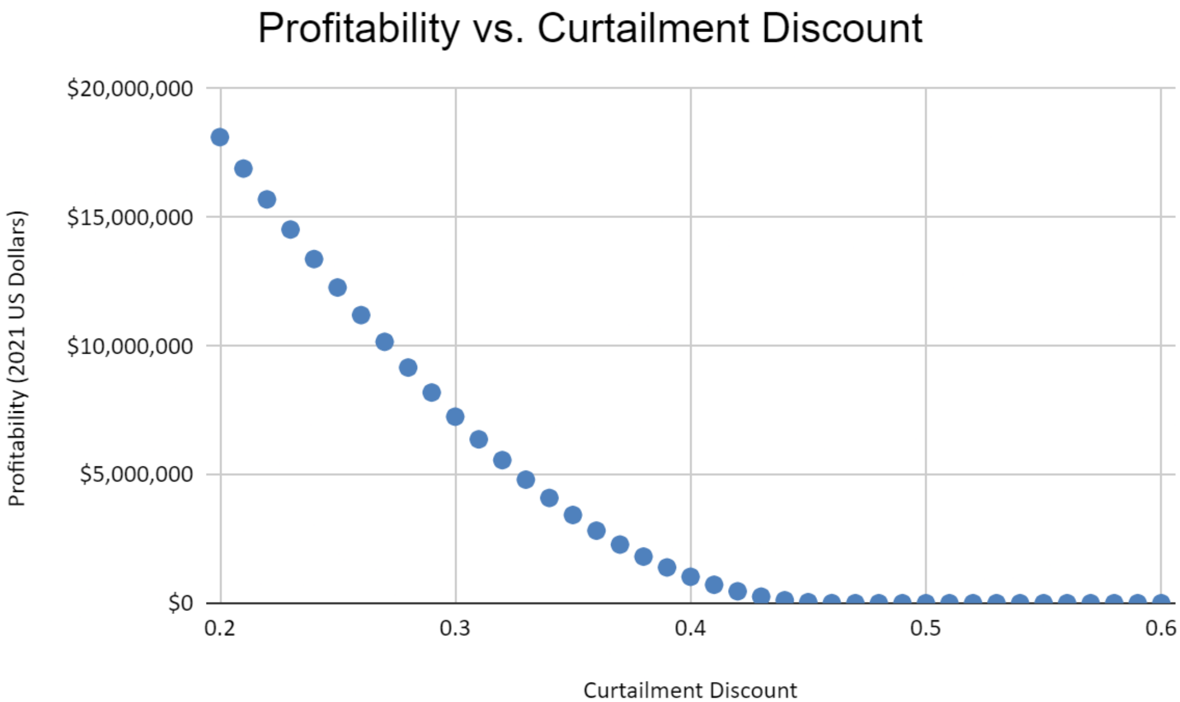
Because the data for all of the input variables were secondary, the researcher could not be certain of their accuracy. For many parameters, there were no peer-reviewed papers for cost projections, so less credible sources had to be used. As a result, it was decided that the model would be run for a gamut of input conditions to reflect the impact these variables had on profitability. This way, the study could show the sensitivity to each variable and become a more effective POC.

Results

Effect of Curtailment Discount on Profitability and Energy Savings

The curtailment discount is the parameter with the greatest uncertainty. Because this supply chain has not yet been implemented, it is difficult to gather data on the discount that solar and wind farms would be willing to give on otherwise curtailed electricity. As a result, the model was run for curtailment discounts[4] ranging from 0.2 (i.e. 80% off) to 0.6 to illustrate the effects of the discount on profitability. In other curtailment studies, like Zhanlong Zhang's paper in the *Journal of Modern Power Systems and Clean Energy*, the discount rate was presumed to be 0.4 (Zhang, 2018). Consequently, 0.2 was decided as the lower bound for the figure because higher discounts deviate greatly from the presumed value and seem unrealistic. A discount of 0.4 is used as the baseline for this study.

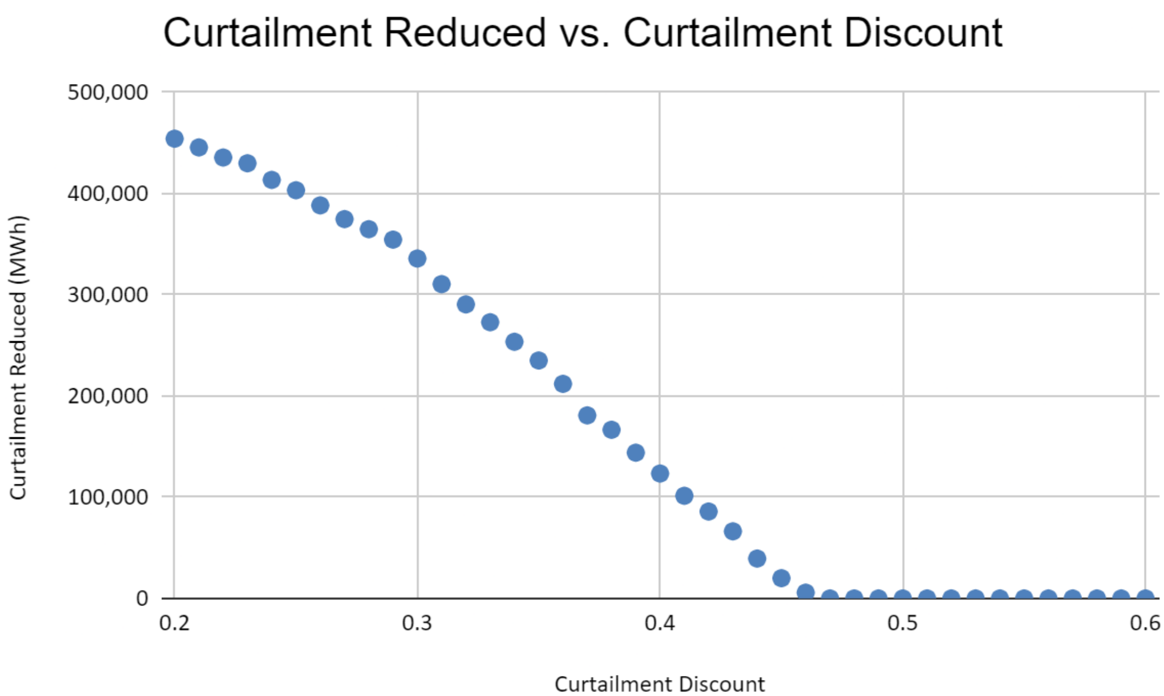
[3] The complete source code without any simplifications can be found in Appendix A
[4] Curtailment discount refers to the proportion of money that still has to be paid



At 0.2, the profitability of the proposed supply chain is $18,119,478.71. The profitability declined to $7,251,103.03 at 0.3, $1,026,751.80 at 0.4 (baseline), and hit $0 at 0.47.[5]

Furthermore, the rate of discount had a strong relationship with the amount of curtailment that was reduced. The model was run with the same range of curtailment discounts as above. The amount of curtailment reduced that is reported in the following chart is the curtailment reduced at maximum profitability for a given rate of discount. For instance, if, say, 284 battery backs are required for max profitability at 0.4, then the curtailment reduction is the energy that those 284 packs delivered plus the energy that the electric trucks consume in delivering those batteries.

[5] Exact values with a step of 0.01 are provided in Appendix C



At 0.2, the proposed supply chain reduced 454,202.36 MWh of curtailment. For context, the data set that was used reported a total annual curtailment of 1,504,802.61 MWh, which means that ⅓ of the curtailment could have been prevented. The curtailment reduction dropped to 335,836.22 MWh at 0.3, 123,414.70 MWh at 0.4 (baseline).

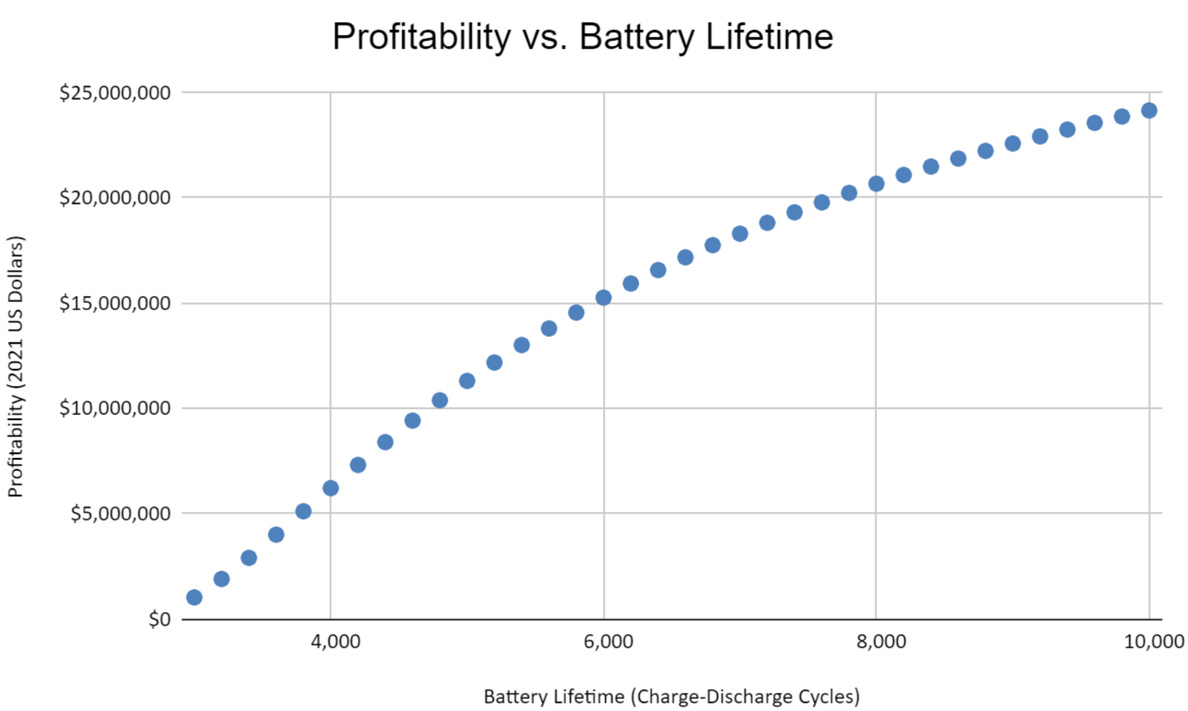
For both charts, all other variables were set to 2021 defaults. The cost inputs are based on the Lithium-Iron-Phosphate (LFP) BYD Blade battery, the Freightliner eCascadia, the Southern California Edison (SCE) and Pacific Gas and Electric Company (PG&E) tier-1 retail electricity rates, and an environmental benefit of $0.036/KWh curtailment reduced.[6]

Effect of Battery Lifetime on Profitability and Energy Savings

For the following calculations, all other parameters, except for battery charge-discharge lifetime, are the same as above (curtailment discount is set back to the baseline of 0.4).[7] The

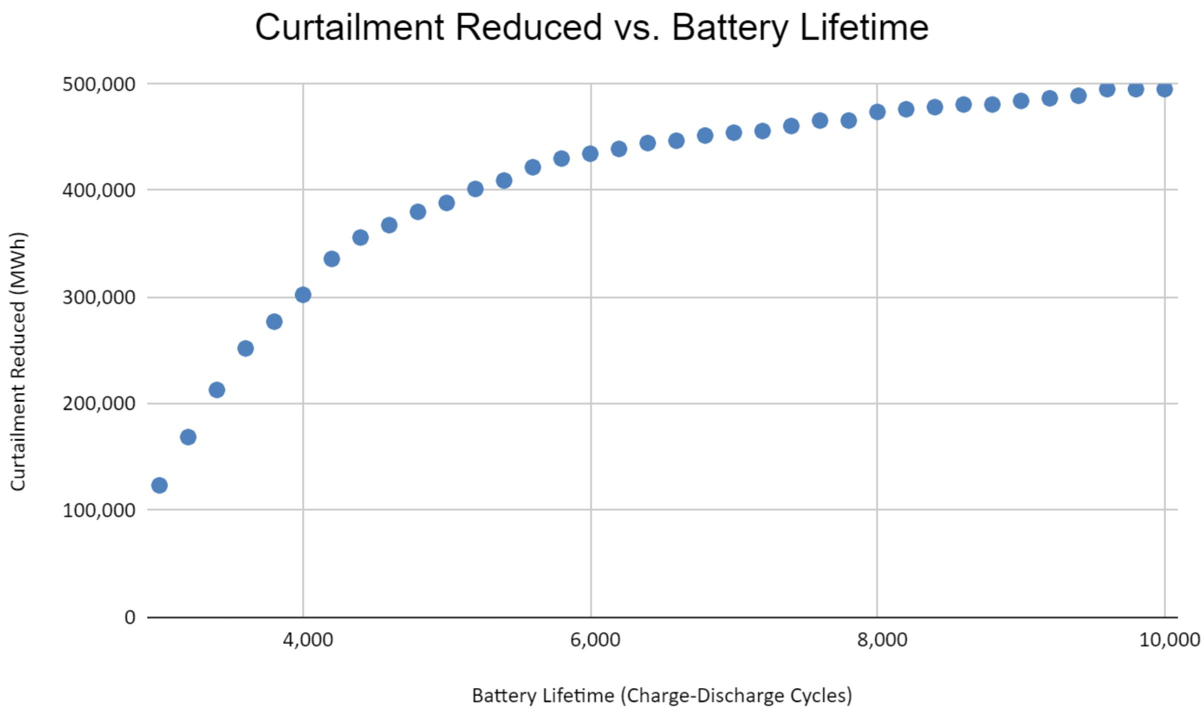
[6] The exact input values can be found in Appendix B
[7] This ceteris paribus approach is also used when calculating the effects of shipping distance and truck prices on profitability and curtailment reduced

battery industry is rapidly evolving with newer technologies quickly pushing the charge-discharge lifetimes up. While projections on battery capital costs into 2030 can be made with relatively high confidence, there is much more uncertainty regarding battery lifetimes. Currently, there are no widely adopted commercially available battery cells with lifetimes longer than ~3,000 charge-discharge cycles. However, there are numerous developments (e.g. Yuliya Preger's 2020 study in the *Journal of the Electrochemical Society*) showing slightly modified chemistries can reach up to almost 9,000 charge-discharge cycles. It is valuable to determine the impact these innovations can have on the profitability of the supply chain. A battery lifetime of 3,000 is used as the baseline for this study.



As battery lifetimes increase, profitability increases in a concave-down pattern. The profitability is $11,305,925.98 at 5000, $18,295,951.89 at 7000, and $22,577,428.32 at 9000.[8]

[8] Exact values with a step of 200 are provided in Appendix D. The profitability at 3000 was not reported, because that is the baseline and was already reported in the curtailment discount section. This applies to the rest of the calculations, as well.

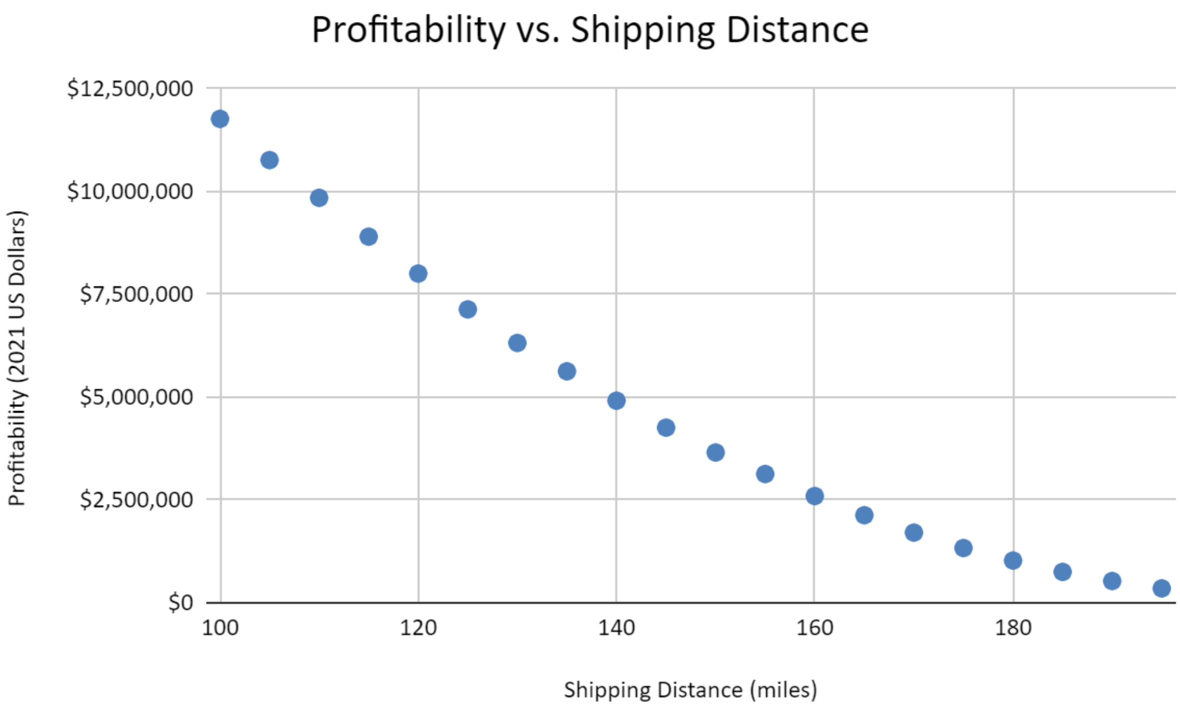


The curtailment reduction was 388,338.03 MWh at 5,000, 454,202.36 MWh at 7,000, and 484,030.95 MWh at 9,000.

Effect of Shipping Distance on Profitability and Energy Savings

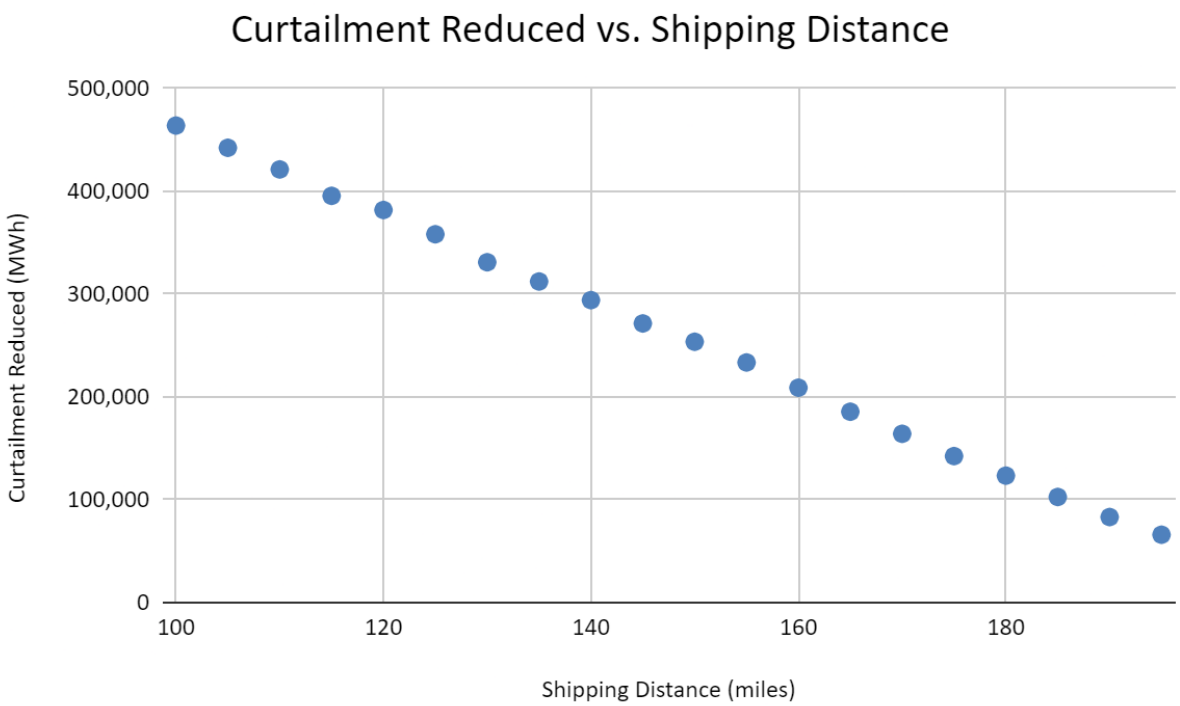
Shipping distance is significantly simplified in this model. Because there was little data regarding curtailment from individual solar farms, it was assumed that all curtailment comes from two solar farms.[9] The baseline shipping distance was set to 180 miles because this splits the distance between San Francisco and Los Angeles (two major destinations). However, there could be a range of actual distances depending on the distribution of solar farms. The model was run for distances between 100 miles and 195 miles (distances over 195 miles are unreasonable as that would require solar farms to be outside of California). It is valuable to determine the effect of various distances on the profitability and curtailment reduced by the supply chain.

[9] See limitations for a more detailed explanation



For non-baseline values, the profitability was $11,766,578.51 at 100 miles, $8,004,692.89 at 120 miles, $4,913,849.57 at 140 miles, $2,595,582.63 at 160 miles, and $350,046.76 at 195 miles.[10]

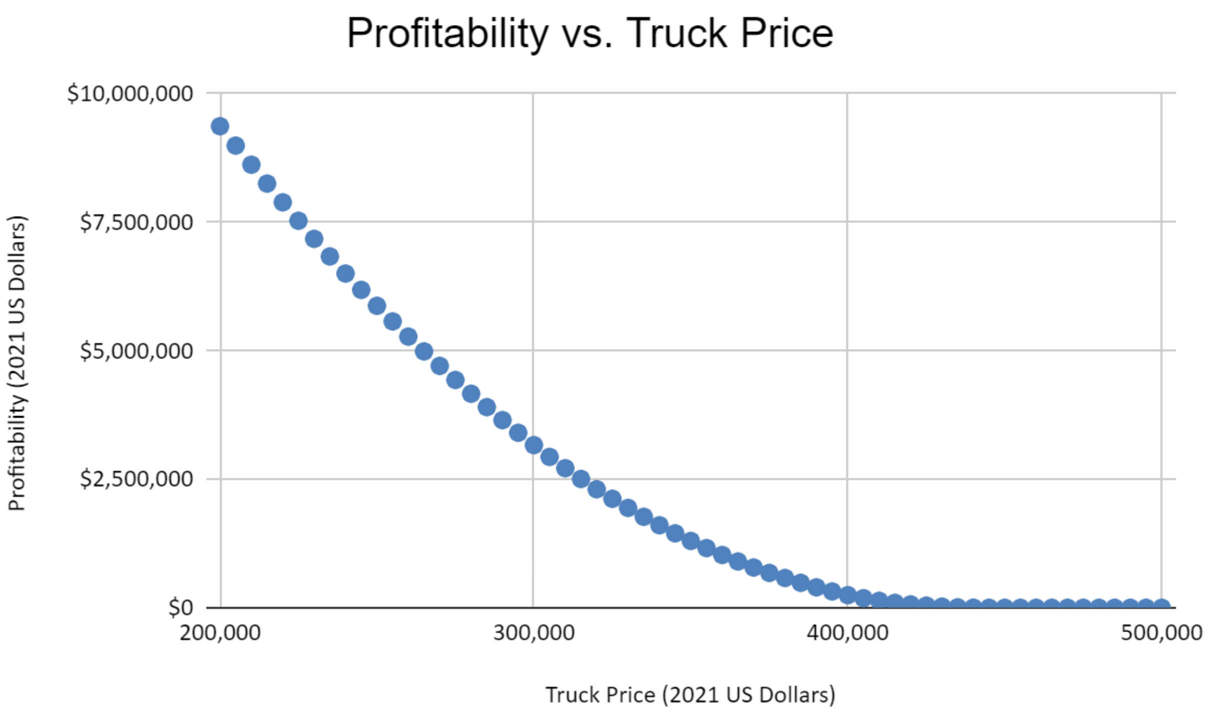
[10] Exact values with step of 5 miles are provided in Appendix E



The curtailment reduction was 463,908.50 MWh at 100 miles, 381,779.40 MWh at 120 miles, 294,120.11 MWh at 140 miles, 208,942.25 MWh at 160 miles, and 65,952.25 MWh at 195 miles.

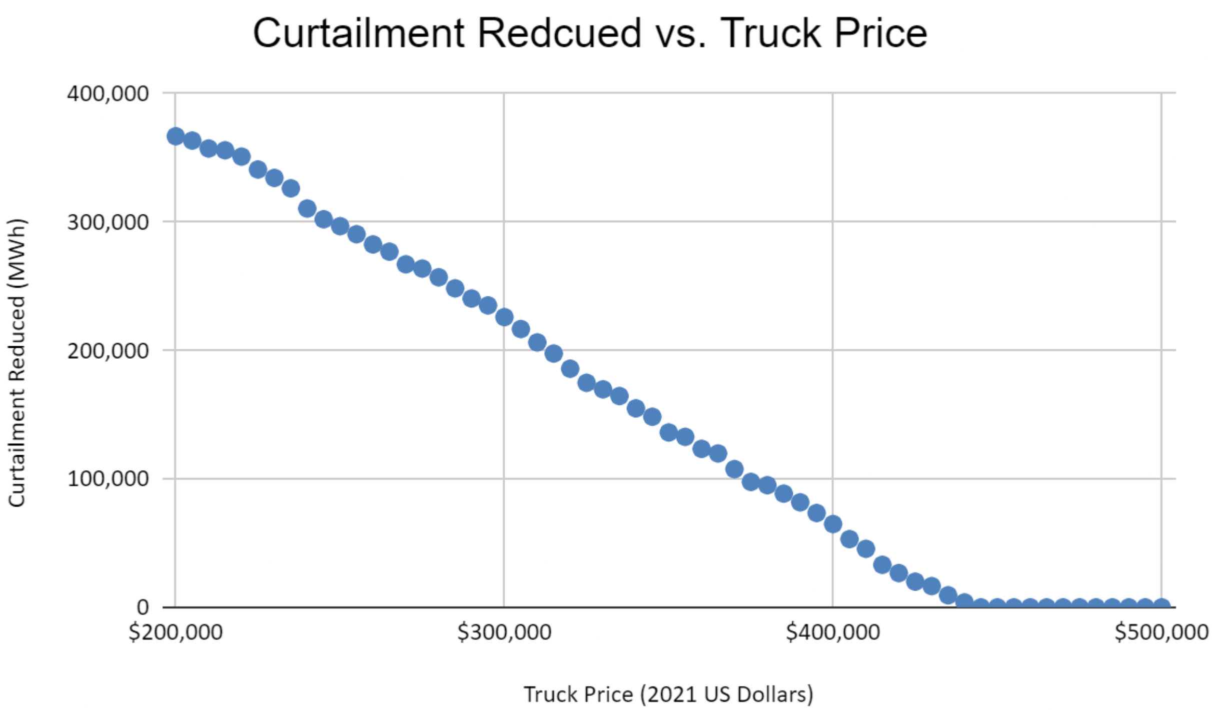
Effect of Truck Prices on Profitability and Energy Savings

Because the electric truck industry is still in its infancy, there is little cost data for a Class-8 electric tractor trailer. However, estimates put the price of an electric tractor trailer at 2-3 times the price of a comparable diesel truck. Since a diesel Freightliner Cascadia costs $160,000, a 48 foot trailer costs ~$20,000, and there is a $120,000 rebate on electric trucks, the price of one truck could range from $200,000 to $500,000 if the rebate goes away. For this study a baseline price of $360,000 was used, which is a conservative estimate given the rebate.



The profitability was $9,367,401.10 at a truck price of $200,000, $3,164,321.33 at $300,000, and $245,535.00 at $400,000. It hit $0 at $445,000.[11]

[11] Exact values with step of $5,000 are provided in Appendix F



The curtailment reduction was 366,826.63 MWh at a truck price of $200,000, 225,984.67 MWh at $300,000, and 64,867.56 MWh at $400,000.

Projections for 2024 and 2030

Since battery technologies and the electric grid are rapidly evolving, the profitability of the supply chain could see significant improvements in the future. Using modified battery capital costs, truck capital costs, battery cycles, and electricity prices, the model can output profitability for the years 2024 and 2030.[12] It was difficult to obtain highly-credible projections for these parameters, so the profitability may not be entirely accurate, but the trends that are revealed are nevertheless valuable. The projected profitability and curtailment reduction in 2024 are $15,277,717.72 and 434,496.78 MWh, respectively. Moving into 2030, the profitability and curtailment rose to $25,306,538.84 and 501,992.18 MWh, respectively.

[12] The exact input parameters can be found in Appendix B (same location as the 2021 input parameters)

Discussion

Findings

The profitability of the proposed supply chain is very sensitive to changes in the price of capital resources and utility discounts. Under favorable conditions, the supply chain can alleviate ⅓ of annual curtailment, while under baseline conditions, the supply chain can reduce only 1/12 of annual curtailment. Furthermore, under unfavorable conditions, the supply chain is no longer profitable.

Out of the four factors tested for, ceteris paribus (i.e. all else equal), battery lifetimes were the most significant factor in determining profitability. At the current experimental best-case scenario of ~9,000 charge-discharge cycles, the profitability jumps to $22,577,428.32, which is a 2,098.92% increase over the current baseline. However, the profitability as a function of battery lifetime exhibits concave-down growth, so further increases in battery charge-discharge cycles will have a smaller impact on profitability. Another point to note is that unlike the curtailment discount or truck prices, battery lifetimes will only increase ceteris paribus, which will, in turn, necessarily increase the profitability of the supply chain. Thus, it can't drive the profitability to $0 like the other parameters.

The curtailment discount was the second biggest factor in determining the profitability of the supply chain. In the best-case scenario of a 0.2 discount, the profitability rose to $18,119,478.71, which is a 1,664.74% increase over the current baseline. Furthermore, a 17.5% increase (0.4 to 0.47) in curtailment discount from the baseline was enough to cause profitability to hit $0.

The other two variables, shipping distance and truck price, had smaller but still considerable impacts on the profitability of the supply chain.

Under the best-case scenario shipping distance (100 miles, which is quite unlikely), the profitability was $11,766,578.51, which is a 1,046.00% increase over the baseline. A more realistic condition would be a shipping distance of 160 miles, where the profitability was $2,595,582.63, a 152.80% increase over the baseline. Under the worst-case scenario of 195 miles, the profitability was $350,046.76, which is a 65.91% decrease from the baseline. One thing to note regarding shipping distance is that once it is set, it is highly unlikely to change in the future because solar farms cannot be moved around and new farms will probably be built in similar areas as existing ones. The reason that shipping distance was included as a variable was due to a lack of data, causing uncertainty in the parameter.

Under the best-case scenario of truck price ($200,000), the profitability was $9,367,401.10, which is a 812.33% increase over the baseline. A more probable scenario would be a 208.19% increase in profitability to $3,164,321.33 at a truck price of $300,000, and a 76.09% decrease in profitability to $245,535.00 at a truck price of $400,000. Finally, a 23.61% increase in truck price ($360,000 to $445,000) was enough to cause profitability to hit $0. Similar to shipping distance, truck prices are unlikely to experience big changes due to the costs of raw materials. A decrease in battery capital costs will have a small impact, but many of the other materials will prevent the cost from being driven down substantially.

Finally, the supply chain gets significantly more profitable in 2024 and 2030 due to innovations and cost reductions. There is a projected 1,387.97% increase in profitability to $15,277,717.72 by 2024, and a projected 2,364.71% increase to $25,306,538.84 by 2030. In these scenarios, nearly ⅓ of total curtailment is reduced, which is a considerable proportion.

Implications

The results indicate a possibility that the proposed supply chain can be used to slightly alleviate the curtailment problems in California as they scale up their solar production to meet state requirements. In the near term, this solution can be combined with CAISO's Energy Imbalance Market, which reduced 16% of total possible curtailments in 2020 (Aniti, 2021), and electric grid improvements to reduce a more substantial proportion of curtailment. Furthermore, policymakers can monitor changes in the input variables and adjust the supply chain quite quickly, as there is a 1,387.97% projected increase in profitability by 2024 due to rapid technological developments. In the long term, the supply chain can play a more important role in addressing California's curtailment issues.

Fulfillment of Gaps in Research

This study addresses a gap in research on using electric trucks to mobilize batteries and bypass the electric grid. In pre-existing studies, utility-scale battery storage centers are the most common, however, these facilities still rely on the grid and need to adhere to contingency protocols. By operating independently of the electric grid, mobilized batteries can add reliability to the network. There are existing studies that mobilize these batteries. However, in those studies, trains are used to ship the batteries. Meanwhile, when electric trucks are used, shipping will also be emission-free, and this can act as another source of curtailed energy consumption. Additionally, the use of electric trucks allows for more individualized transportation of batteries. These gaps served as the motivation for this study.

Model Limitations

In the process of creating the model, assumptions were made to simplify the algorithm in the interest of time.

The model iterates in 100-second intervals and doesn't take into account the power after a battery is done charging (e.g. a battery completes charging in 1 minute, but the power for the last 40 seconds was unutilized). The expected energy loss from the model is 50 seconds per charge-discharge cycle. However, the charge-discharge cycle takes just over 9 hours (1 hour for charging, 3.5 hours in transit to the distribution center, 1 hour to discharge, 3.5 hours in transit back to the farm). Even though the 1-minute energy leakage is not ideal, the effects on profitability are relatively small. This problem could have been avoided by running the model in 1-second intervals. However, the runtime of the model under these conditions would be over 48 hours, which was not feasible for this study.

The model also doesn't take into account land costs and DC/AC power inversion. It is assumed that SCE and PG&E downtown substations can be utilized to house the batteries and perform power inversion. Land and power inversion costs are definitely not negligible, so a partnership would have to be made with SCE and PG&E to secure these resources. However, it is unknown what royalty would be paid to these utility companies, so the total profitability was reported instead.

As mentioned in the results section, the model assumes that there are 2 large solar farms, each 180 miles from a population center. With the presently available data, there would have been no way to treat each solar farm as a separate node because there is no solar farm level curtailment data. However, a more accurate shipping estimate could have been created using a Google Maps API (or something similar) to perform a weighted average (based on curtailment amounts) of the distance of each farm to a population center. However, due to time constraints, this was not executed. In addition, when setting the price of retail electricity, the SCE and PG&E prices were averaged, because without individual solar farm data, it is impossible to optimize which city to ship to. This simplification could have reduced the profitability of the supply chain because energy was shipped 50/50 instead of shipping a larger proportion to the more expensive PG&E-controlled areas.

It was also assumed that the batteries could discharge at their maximum discharge rate once they arrived at a distribution center. This was done to avoid the need to incorporate demand-side data, which would have significantly increased the runtime of the model. As a result, a 10% discount was placed on the electricity sold to somewhat counteract this assumption. The discount would increase the demand for electricity from this source and make the assumption slightly more valid.

For the 2024 and 2030 scenarios, it was assumed that the curtailment amount was the same as in 2021. The projections by Cole et al. were for the United States as a whole, and there were no California specific projections. As a result, it was difficult to assess how California's curtailment would progress, especially considering their rapid policy changes for both scaling up renewables and combatting curtailment.

Finally, it was assumed that the weather in 2021 was representative of the weather in a typical year. Because curtailment amounts have been changing steadily every year, the curtailment amounts couldn't be averaged over multiple years to produce a more representative weather year. If the weather in 2021 was abnormally conducive to renewables, then the profitability of the supply chain would be overestimated, and vice versa if 2021 was abnormally adverse to renewables.

Parameter limitations

In the interest of time, the researcher did not synthesize any of the costs or cost projections that were entered into the model as parameters. Because there were not many peer-reviewed journals that conducted cost projections on the various parameters that were used, less credible sources had to be utilized to at least obtain some data. As a result, the profitability numbers may not be highly accurate. This was addressed by showing how four of the most important and uncertain variables can affect profitability, so the study can reflect a range of possible profitabilities given different inputs. There is even more uncertainty regarding the accuracy of the projections into 2024 and 2030, Nevertheless, the model still demonstrates big-picture trends.

Future Directions

With a promising POC, more precise models can be developed to obtain more accurate profitability estimates, which would aid the implementation of the proposed supply chain. The limitations in interval time, land and power inversion costs, and charging/discharging and shipping configurations can be addressed in a future model. Moreover, the economic model is generalizable, so it can be applied to other states or countries if the needed parameters are gathered and can therefore be used to conduct the same profitability analysis in these areas. Finally, a slightly different model can be developed to determine the profitability of using Bitcoin miners as a source of curtailment reduction and generation smoothing. Bitcoin miners would also offer a source of demand response for more grid robustness.

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Appendix A

The following is a link to the GitHub repository containing the source code for the project:

https://github.com/86f7e437faa5a7fce15d/curtailment-supply-chain-simulator

(Note: the username is part of a SHA-1 hash to prevent the researcher from being identified)

Appendix B

2021 Inputs

Name	Input	Comments
BatteryPrice	64	Directly from Ref. 21
BatteryCycles	3000	Directly from Ref. 21
SaleDiscount	0.9	Assigned by researcher
TruckerWages	51400	Directly from Ref. 38
ElectricityPrices	0.27	From base-tier (lowest price) of Ref. 28 & Ref. 33
EnvironmentalBenefit	0.036	Directly from Ref. 41
TripDistance	180	Assigned by researcher
BatteryDensity	0.185	Calculated from "blade-type battery" data in Ref. 42 and voltage data in Ref. 25
BatteryWeight	38000	Calculated based on 80,000 federal max weight; truck weight from Ref. 11; trailer weight from Ref. 12
CRating	1.273148148	Calculated from battery capacity and charging rate in Ref. 26
TruckBatteryCapacity	475	Directly from Ref. 9
ProducerDiscount	0.4	Based on estimate in Ref. 43
TruckPrice	360000	Assigned by researcher; based on estimates in Ref. 40 and Ref. 35

2024 Inputs

Name	Input	Comments
BatteryPrice	50.98305085	Calculated from current cost data in Ref. 21 combined with cost projection data in Ref. 14
BatteryCycles	5000	Assigned by researcher based on Ref. 31
SaleDiscount	0.9	Assigned by researcher
TruckerWages	51400	Directly from Ref. 38
ElectricityPrices	0.27986	Calculated from current retail electricity rates in Ref. 28 & Ref. 33 combined with rate increase% projections in Ref. 23 (Note: the rate projection are for 2025 not 2024 but the difference is miniscule)
EnvironmentalBenefit	0.036	Directly from Ref. 41
TripDistance	180	Assigned by researcher
BatteryDensity	0.185	Calculated from "blade-type battery" data in Ref. 42 and voltage data in Ref. 25

BatteryWeight	38000	Calculated based on 80,000 federal max weight; truck weight from Ref. 11; trailer weight from Ref. 12
CRating	1.273148148	Calculated from battery capacity and charging rate in Ref. 26
TruckBatteryCapacity	475	Directly from Ref. 9
ProducerDiscount	0.4	Based on estimate in Ref. 43
TruckPrice	333803.3898	Determined by calculating how battery price reductions will reduce truck prices from the assigned baseline via Ref. 19

2030 Inputs

Name	Input	Comments
BatteryPrice	33.62711864	Calculated from current cost data in Ref. 21 combined with cost projection data in Ref. 14
BatteryCycles	7000	Assigned by researcher based on Ref. 31
SaleDiscount	0.9	Assigned by researcher
TruckerWages	51400	Directly from Ref. 38
ElectricityPrices	0.28281974	Calculated from current retail electricity rates in Ref. 28 & Ref. 33 combined with rate increase% projections in Ref. 23 (Note: the rate projection are for 2025 not 2024 but the difference is miniscule)
EnvironmentalBenefit	0.036	Directly from Ref. 41
TripDistance	180	Assigned by researcher
BatteryDensity	0.185	Calculated from "blade-type battery" data in Ref. 42 and voltage data in Ref. 25
BatteryWeight	38000	Calculated based on 80,000 federal max weight; truck weight from Ref. 11; trailer weight from Ref. 12
CRating	1.273148148	Calculated from battery capacity and charging rate in Ref. 26
TruckBatteryCapacity	475	Directly from Ref. 9
ProducerDiscount	0.4	Based on estimate in Ref. 43
TruckPrice	298874.5763	Determined by calculating how battery price reductions will reduce truck prices from the assigned baseline via Ref. 19

Appendix C

Curtailment Discount	Profitability (2021 USD)	Curtailment Reduced (MWh)
0.2	$18,119,478.71	454,202.36
0.21	$16,896,938.46	445,587.44
0.22	$15,699,130.46	435,623.00
0.23	$14,527,936.84	429,943.37
0.24	$13,378,706.68	413,519.36
0.25	$12,273,899.48	403,283.07
0.26	$11,200,308.13	388,338.03
0.27	$10,161,885.56	374,771.64
0.28	$9,161,765.09	364,797.49
0.29	$8,190,793.83	354,486.77
0.3	$7,251,103.03	335,836.22
0.31	$6,371,394.50	310,541.62
0.32	$5,562,071.74	290,528.60
0.33	$4,803,563.55	272,884.52
0.34	$4,091,671.60	253,570.54
0.35	$3,429,792.43	235,104.45
0.36	$2,820,388.19	212,000.80
0.37	$2,279,133.39	180,861.52
0.38	$1,811,431.15	166,631.70
0.39	$1,390,826.95	144,010.25
0.4	$1,026,751.80	123,414.70
0.41	$716,941.60	101,430.80
0.42	$463,738.28	85,874.11
0.43	$254,628.04	66,310.93
0.44	$115,128.03	39,407.92
0.45	$39,892.36	20,029.20
0.46	$3,442.26	5,728.18
0.47	$0.00	0.00
0.48	$0.00	0.00
0.49	$0.00	0.00
0.5	$0.00	0.00
0.51	$0.00	0.00
0.52	$0.00	0.00
0.53	$0.00	0.00
0.54	$0.00	0.00
0.55	$0.00	0.00

0.56	$0.00	0.00
0.57	$0.00	0.00
0.58	$0.00	0.00
0.59	$0.00	0.00
0.6	$0.00	0.00

Appendix D

Battery Lifetime (Cycles)	Profitability (2021 USD)	Curtailment Reduced (MWh)
10,000	$24,146,140.07	495,043.94
9,800	$23,857,660.99	495,043.94
9,600	$23,557,161.95	495,043.94
9,400	$23,240,559.89	488,856.21
9,200	$22,915,725.66	486,454.91
9,000	$22,577,428.32	484,030.95
8,800	$22,225,445.46	480,623.17
8,600	$21,862,768.28	480,623.17
8,400	$21,481,794.63	478,163.61
8,200	$21,084,478.62	476,179.79
8,000	$20,669,087.31	473,681.40
7,800	$20,231,025.68	465,597.22
7,600	$19,782,488.09	465,597.22
7,400	$19,309,147.82	460,467.76
7,200	$18,812,817.38	455,778.42
7,000	$18,295,951.89	454,202.36
6,800	$17,749,911.84	451,538.92
6,600	$17,173,379.40	446,681.30
6,400	$16,569,108.98	444,496.82
6,200	$15,931,078.06	438,979.00
6,000	$15,259,101.60	434,496.78
5,800	$14,548,975.75	429,943.37
5,600	$13,796,533.09	421,797.71
5,400	$13,008,121.05	409,344.59
5,200	$12,179,509.42	401,435.17
5,000	$11,305,925.98	388,338.03
4,800	$10,387,271.02	379,991.72
4,600	$9,421,093.49	367,496.53
4,400	$8,398,903.34	355,888.07
4,200	$7,316,344.97	335,836.22
4,000	$6,215,368.35	302,179.13
3,800	$5,117,060.26	276,962.21
3,600	$4,006,515.29	251,848.85
3,400	$2,904,829.55	212,939.31
3,200	$1,903,105.54	168,706.14
3,000	$1,026,751.80	123,414.70

Appendix E

Shipping Distance (miles)	Profitability (2021 USD)	Curtailment Reduced (MWh)
100	$11,766,578.51	463,908.50
105	$10,763,992.67	442,278.71
110	$9,846,826.62	421,237.31
115	$8,902,414.38	395,558.04
120	$8,004,692.89	381,779.40
125	$7,133,658.10	358,192.60
130	$6,317,939.05	330,974.91
135	$5,628,083.60	312,238.61
140	$4,913,849.57	294,120.11
145	$4,258,970.78	271,445.88
150	$3,654,296.09	253,629.65
155	$3,130,672.85	233,489.02
160	$2,595,582.63	208,942.25
165	$2,128,976.20	185,591.03
170	$1,706,463.78	164,105.55
175	$1,331,202.89	142,427.39
180	$1,026,751.80	123,414.70
185	$750,806.94	102,670.81
190	$529,180.21	83,146.14
195	$350,046.76	65,952.25

Appendix F

Truck Price (2021 USD)	Profitability (2021 USD)	Curtailment Reduced (MWh)
$200,000	$9,367,401.10	366,826.63
$205,000	$8,990,729.88	363,444.74
$210,000	$8,618,701.74	357,276.43
$215,000	$8,251,338.85	355,888.07
$220,000	$7,887,173.18	350,962.49
$225,000	$7,527,893.18	340,933.32
$230,000	$7,176,629.83	334,370.19
$235,000	$6,834,445.37	326,263.37
$240,000	$6,501,793.04	310,541.62
$245,000	$6,183,617.47	302,179.13
$250,000	$5,874,491.95	296,790.76
$255,000	$5,570,763.91	290,528.60
$260,000	$5,274,702.15	282,586.83
$265,000	$4,987,454.46	276,962.21
$270,000	$4,705,243.48	267,104.57
$275,000	$4,431,822.77	263,774.46
$280,000	$4,163,569.19	257,000.97
$285,000	$3,903,110.67	248,386.05
$290,000	$3,649,828.99	240,473.40
$295,000	$3,403,919.08	235,104.45
$300,000	$3,164,321.33	225,984.67
$305,000	$2,934,424.21	216,699.85
$310,000	$2,714,914.26	206,301.75
$315,000	$2,505,600.40	197,631.81
$320,000	$2,305,570.10	185,829.18
$325,000	$2,119,824.00	174,838.85
$330,000	$1,942,231.16	169,738.50
$335,000	$1,769,925.79	164,531.36
$340,000	$1,605,398.97	154,964.99
$345,000	$1,447,871.24	148,421.27
$350,000	$1,299,770.03	136,175.27
$355,000	$1,160,920.57	132,761.02
$360,000	$1,026,751.80	123,414.70
$365,000	$900,756.65	119,828.93
$370,000	$783,315.97	107,634.71

$375,000	$678,135.00	97,654.09
$380,000	$579,491.74	95,107.15
$385,000	$485,638.04	88,550.50
$390,000	$397,637.08	81,789.95
$395,000	$317,538.26	73,456.59
$400,000	$245,535.00	64,867.56
$405,000	$185,879.00	53,139.36
$410,000	$135,814.28	45,589.17
$415,000	$96,170.22	33,119.87
$420,000	$65,893.17	26,686.18
$425,000	$42,096.58	20,029.20
$430,000	$22,899.58	16,569.64
$435,000	$9,055.26	9,411.04
$440,000	$2,019.23	3,847.91
$445,000	$0.00	0.00
$450,000	$0.00	0.00
$455,000	$0.00	0.00
$460,000	$0.00	0.00
$465,000	$0.00	0.00
$470,000	$0.00	0.00
$475,000	$0.00	0.00
$480,000	$0.00	0.00
$485,000	$0.00	0.00
$490,000	$0.00	0.00
$495,000	$0.00	0.00
$500,000	$0.00	0.00