The Tesla PowerPack for Time of Use Reduction: Estimating Cost and Greenhouse Gas Emissions at Georgia Tech

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ISyE 4803 Economic and Environmental Analysis
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Abstract

The Tesla PowerPack is a product that is marketed as a solution to the cost and excess pollution that result from trying to match the inherently rigid rate of electricity generation to the cyclical nature of energy demand. We have evaluated this product using the concept of "Time of Use Billing Management", and the Georgia Tech demand profile. We have found this to be a very expensive way to reduce behind the meter charges under Time of Use plans. Peak rates will need to approach $ 0.50 before use of this product in the State of Georgia will come close to reaching a breakeven point. Even more expensive is the price paid for a reduction in emissions. At over $ 1,000 per metric ton of CO_2e, there are many alternatives to reduce emissions that are 2 orders of magnitude lower.

Although we can say that for the Southeastern United States the product won't be a logical investment, it has the ability to get close with a few improvements. It will need to be produced within the region to cut down on costs due to transportation and the cost system integration will need to become better researched. We achieve our conclusion through a detailed but simple modeling that we hope will be refined.

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Problem Statement

The Tesla PowerPack is a new product that will lower the cost of storing electricity. This new cost structure is anticipated to make many applications of energy storage economical. One application in particular, demand reduction, is of interest to nearly every 'campus' style grid. Little data or research exists on the real cost to implement this application with Tesla's product. To properly assess the suitability of the PowerPack for these applications a detailed modeling is required.

Background

Historically, the South Eastern United States has benefited from cheap electricity. While this has incentivized the relocation of industries and eased pressure on households, it has also acted as a barrier to the adoption of new technologies that minimize the environmental impacts of electricity production. Newer or alternative forms of generation such as photovoltaic or wind face a double headwind of low electricity prices and less than optimal environment. This has also affected energy storage systems.

In the state of California, for example, challenges in meeting demand have actually caused government to mandate the integration of energy storage into the grid. The mandate is from the California Public Utilities Commission and directs utilities in California to add 1.3 GW of storage by 2020(mandate target was defined in terms of power, not energy) (Commission 2013). Currently, residential prices in California and Georgia are approximately 18.2 and 12.2 cents per kWh respectively, while prices in Hawaii are about 29.8 cents per kWh (Energy Information Administration 2015).

Demand Reduction

Demand Reduction is composed of many concepts and is implemented for many different reasons. For example, "Demand Charge Reduction" attempts to reduce the costs incurred from demand dependent billing while "Load Shifting" might be implemented to defer the cost of upgrading a generation or distribution system. The graph below shows the effect of using energy storage to shift the load on a system, ensuring better utilization. The common link in these concepts is that the power required is reduced.

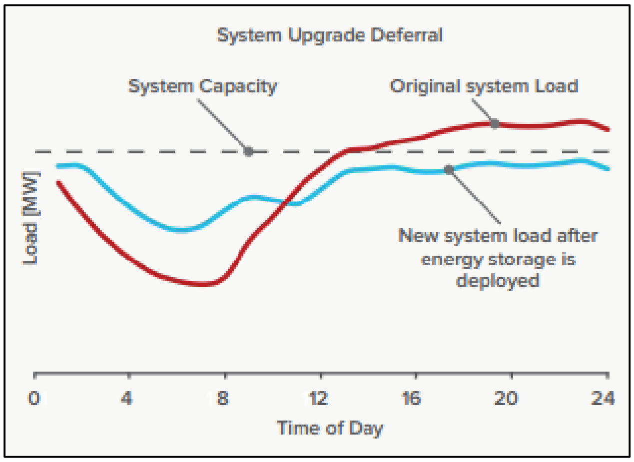


Figure 1 Generic system load profile before and after energy storage is used to defer a traditional distribution system upgrade. (Rocky Mountain Institute 2015)

Demand at Georgia Tech

Electricity flowing into Georgia Tech enters the campus through three primary avenues. Approximately 75% of electricity arrives through a Georgia Power switchyard, 15% of power enters through a separate arrangement that powers Tech Square, the remaining 10% enters through buildings that have been acquired ad hoc (Leasure 2015). The primary utility bill is determined from the reading that is taken for the campus's usage at the switchyard.

With the help of facilities group at Georgia Tech our team was able to obtain the hourly energy usage at the switchyard over the 8 days from 1-8 August 2015. Using this data, we were able to determine the hourly campus demand for each day of that week.

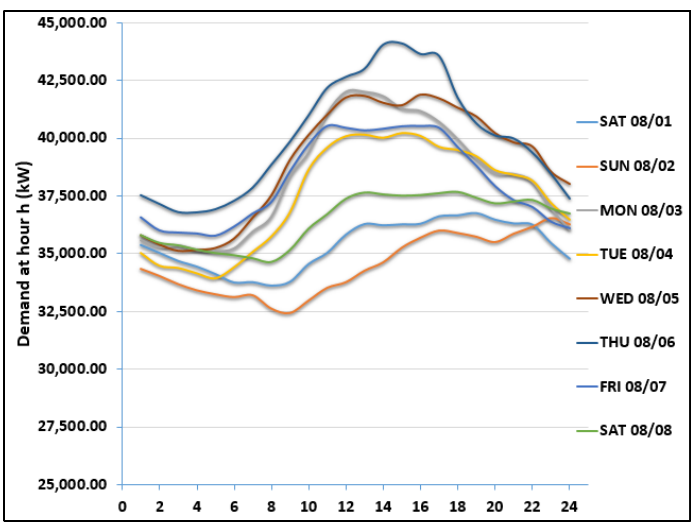


Figure 2 Daily load profile at Georgia Tech (Georgia Power 2015)

Although the load is varying, the actual cost to Georgia Tech is determined by Georgia Power's 'Real –Time Pricing' rate schedule. Under this schedule GT is charged a base charge for the month, plus the sum of hourly charges acquired throughout the month. This rate schedule is generally known as a Time of Use plan(TOU), and incentivizes GT to reduce its demand (load) at any given time, but especially during peak times. Since the actual rate formulation is lengthy it's detailed in a separate appendix.

Reducing the Load on the Grid at GT is a primary concern for the Facilities staff. To minimize costs from the most demanding periods of time the GT Facilities staff will sometimes remotely suspend HVAC systems in large buildings. If we inspect the pricing report for the 1st of August, we can see the hourly cost for additional energy over the GT CBL. As an example, we can look at the time corresponding to 1700. If it was possible to shift the 24,091 kWh required(over the CBL of 12,508 kWh) to meet the demand, it would be possible to reduce the $840.53 charge.

Date	HOUR	ACTUAL LOAD (KWH)	CBL LOAD (KWH)	Hourly Incremental KWH	Interval Price (Cnts/KWH)	Hourly Incremental Cost
SAT 08/01/2015	0100	35,357.00	12,425.00	22,932	0.02924000	670.53
	0200	35,019.00	12,195.00	22,824	0.02090000	477.02
	0300	34,668.00	12,103.00	22,565	0.02048000	462.13
	0400	34,425.00	11,980.00	22,445	0.02017000	452.72
	0500	34,101.00	11,989.00	22,112	0.01975000	436.71
	0600	33,737.00	12,380.00	21,357	0.01970000	420.73
	0700	33,750.00	12,364.00	21,386	0.01969000	421.09
	0800	33,602.00	11,374.00	22,228	0.01953000	434.11
	0900	33,764.00	11,845.00	21,919	0.02044000	448.02
	1000	34,533.00	12,239.00	22,294	0.02880000	642.07
	1100	35,019.00	12,756.00	22,263	0.02925000	651.19
	1200	35,802.00	12,966.00	22,836	0.03093000	706.32
	1300	36,261.00	12,647.00	23,614	0.03419000	807.36
	1400	36,207.00	12,851.00	23,356	0.03447000	805.08
	1500	36,248.00	12,447.00	23,801	0.03509000	835.18
	1600	36,275.00	12,833.00	23,442	0.03419000	801.48
	1700	36,599.00	12,508.00	24,091	0.03489000	840.53

Figure 3 Sample of campus demand highlighting hourly variable costs (Georgia Power 2015)

While this report shows fluctuations from \$ 0.019 to \$ 0.035 (the table header isn't correct, it should be Dollars/kWh, as confirmed by the hourly interval cost), there are many instances where the spread is much larger. We can refer to this range as the Time of Use differential Δ_{TOU}. The 192 different hourly interval prices that Georgia Tech utilized over the observed period range from \$ 0.019 to \$ 0.389. These prices are shown below in a scatter plot.

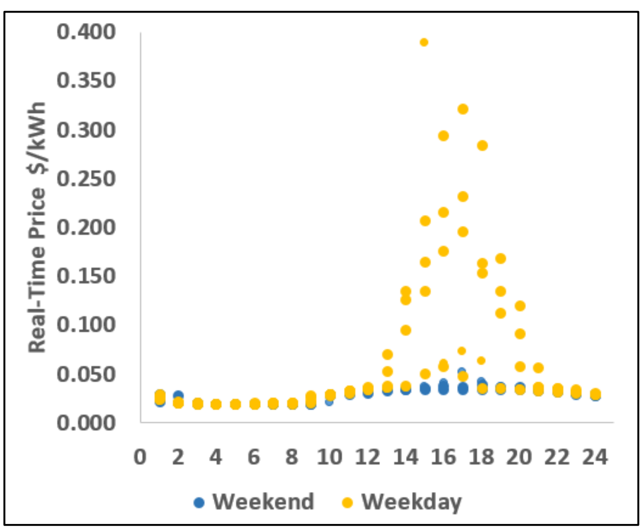


Figure 4 Real-Time Pricing for power entering GT switchyard 1-8 August 2015 (Georgia Power 2015)

The Tesla PowerPack

The PowerPack is a collection of Lithium Ion(Li-Ion) batteries, packed into trays, water cooled, and arranged like shelves inside a metal housing (See Figure 5). It is important to note that the particular battery chemistry for these cells is the same for Tesla's Model S sedan. This fact is being touted by the company as a verification of the PowerPack's quality. We also rely on this fact to make assumptions, in the absence of data, required for our modeling. Assumptions made in this research have been explicitly numbered in superscript and listed in a separate appendix. The publicly available and estimated specifications for the PowerPack are consolidated in Table 1 below.

Figure 5 The Tesla PowerPack, open, with trays and cooling visible (Wood 2015)

Table 1 PowerPack Specifications	
Cycles Available	1000-1500
Cycles per year	60-70
Estimated Weight[1]	1360 kg
Discharge Period	2 or 4 hours
Estimated Cost[2]	$ 25,000
Chemistry	LiNiCoAl
Life at 70 cycles/ year[3]	21.4 yrs

(Tesla Motors 2015)

Introduction

Since the PowerPack is still in its pre-market stage there are few studies on how the packs are actually implemented and their performance. Studies that have been conducted are either very general, or outside of the parameters that allow us to judge it’s cost and impact if it were to be deployed in the southeast.

For these reasons, we’ve focused our research on the benefits of the PowerPack should it be deployed at Georgia Tech for the purposes of demand reduction. We believe this study is useful for informing Georgia Tech and other regional utility customers with a similar disposition (CDC or Atlanta’s International Airport to name a few).

Literature Review

Our literature review concentrated on two primary areas, historical methods used to model the cost of energy storage, and recently developed concepts for integrating ‘cheap’ energy storage on the grid.

Historical methods to model the cost of energy storage- We use many of the definitions and concepts outlined by the NREL guide ‘Deployment of Behind-The- Meter Energy Storage for Demand Charge Reduction’. This guide evaluates how demand reduction can be optimized using lithium-ion batteries. One of the key findings contained in the guide is the fact that operating a Li-Ion system is most cost effective when it “reduce[s] short load spikes on the order of 2.5% of peak demand”. This figure helped guide our selection of 2500 kW for modeling (about 5% of weekday peak). However, this particular study looked at a seasonal rate schedule where there was no hourly spot price, assumed integration of a photovoltaic system, and assumed the cost of storage was $350/kWh (National Renewable Energy Laboratory 2015).

In a paper by the Electric Power Research Institute(EPRI), a non-profit funded by industry, titled “Cost-Effectiveness of Energy Storage in California”, studies were performed of energy storage systems in different usage scenarios. The paper discusses a tool developed by EPRI called ESVT (Energy Storage Valuation tool). Many of the tools calculations and input parameters were adopted for our study. The EPRI also performed a comprehensive sensitivity analysis which we have adopted portions of. One example is the discharge duration sensitivity analysis in which the cost of a two hour and four hour discharge of equivalent capacity systems is compared (Electric Power Research Institute 2013).

Current concepts for integrating ‘cheap’ batteries- A study done by the Rocky Mountain Institute, titled ‘The Economics of Battery Energy Storage’, explored how a distributed model for batteries would allow their maximum utilization. This would in turn minimize the cost from their deployment. In their study RMI defined 13 services that batteries could provide the electrical grid and customers and partitioned where on the grid these services could occur. They then created 4 ‘sets’ of services (called use cases), and estimated the cost for each one. Their “Use Case IV”, for example, explored a deployment where the primary service of the battery was to serve as an energy backup for a solar farm. The secondary services were time of use optimization and select services that benefitted transmission (frequency regulation for example). Of the four use cases, one was found to actually be profitable (demand reduction and backup power), while the other two met or exceeded the cost of implementation. In our research we initially adopted the idea of “stacking services” so as to maximize the opportunity for storage to provide high priority energy services, but time and difficulty getting background on the backup services GT might require has prevented further research. This idea remains potentially valuable and should be considered (Rocky Mountain Institute 2015).

Methodology

In our research we build a model to determine the cost, and effect on greenhouse gas emissions, of using the Tesla PowerPack for “Time of Use Bill Management”. This is essentially shifting energy use from times of peak cost to times of lower cost. While this is similar to demand leveling, it is the cost at time of use that determines how demand is manipulated, not a specifically defined level of demand (Rocky Mountain Institute 2015).

The primary challenge in evaluating the product fairly is making sure every dollar spent on a system will actually be utilized in the reduction of cost. To ensure we have enough energy demand to achieve a fully utilized system, we size a system to supply ~ 5% of Georgia Tech’s peak demand for 4 hours(2500kW).

Since many components of the actual integration are beyond the scope of this research, we have proposed an abstract integration (see Figure 7), from which a more detailed cost estimate can be determined. For a system integration that supports the targeted demand reduction of 2500kW we must first calculate the required storage size.

Determining Storage Size

With a target of supplying 2500 kW for four hours we need to have the ability to *discharge* approximately 10,000 kWh of energy. Although the PowerPack stores 100 kWh, discharging 100% of the battery is stressful enough on the individual cell electrodes to cause premature failure. For this reason, many researchers and manufacturers recommend discharge occur to a depth of 80%. This is known as 80% Depth of Discharge(DOD) (Kandler Smith 2015).

$$Storage\ size = \frac{kWh\ required}{80\%\ DOD} = \frac{10{,}000\ kWh}{\frac{8\ kWh\ discharged}{10\ kWh\ stored}} \approx 12,500\ kWh$$

This leads us to 125 PowerPacks are required to supply 10,000 kWh

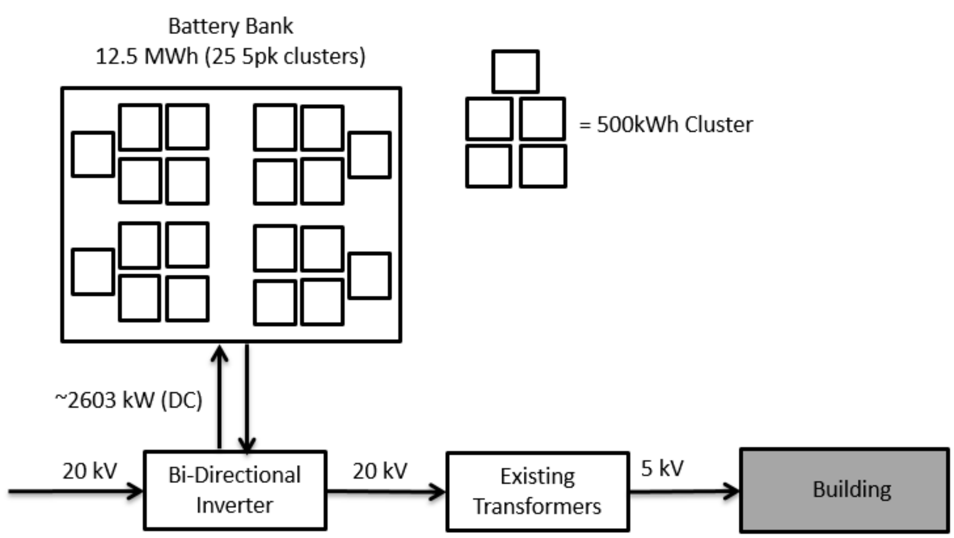


Figure 6 Proposed configuration

Data

Below are the key elements of data that we will use in our calculations of GHG emissions and System Cost. The cost appendix contains the complete details of cost parameters and their assumed or calculated values. In the sensitivity analysis we attempt to quantify how much major assumptions, like the cost of installation and Δ_{TOU}, might vary.

Table 2 Key Initial Cost Data	
PowerPack Cost[2]	$ 25,000
Shipping per PowerPack [4]	$ 2,109
Installation Cost Factor	.33 x System Cost
Δ_{TOU}[5]	$ 0.13
Discount Rate	.03
Cost/Inverter[6]	$ 642,000

Table 3 Transportation Emissions Values	
Number of Power Packs	125
Power Packs Per Truck	10
Number of Inverters	1
Inverters Per Truck	1
Distance From Tesla to Rail Facility by Rail (miles)	2480
Distance from Rail Facility to Georgia Tech by truck (miles)	20
Distance to Inverter Facility (kg CO2e)	100
Using Rail (kg CO2e)	0.16
Using Heavy Truck using Diesel emits	1.40
Power Pack emission (kg CO2e)	50880.03
Inverter emission (kg CO2e)	140.013
Total kg CO2e	51,020

Table 4 Operational Emissions Values	
Operation without batteries (kg CO2e)	425,419
Operation with batteries (kg CO2e)	422,907
Savings Per day (kg CO2e)	2,511
Yearly savings (kg CO2e)	175,801
21 Year Savings (kg CO2e)	3,691,816

Calculation

To determine the cost of the system, and impact in carbon emission, we will use two calculations. This will allow us to compare the result of integrating the PowerPack into the grid with the option of just using the existing infrastructure.

System Cost – the cost to integrate and operate the system. Since our system has a 21 year expected life these costs should be discount in accordance with a discount rate. The itemized calculation can be found in the cost calculation appendix. Since our system will retire so far into the future we have assumed that the salvage price and cost of disposal will cancel out.

$$C_{system} = initial\ capital\ cost + operating\ cost - salvage\ value$$

$$= C_{purchase} + C_{shipping} + C_{installation} + C_{charging} + C_{maintenance} - (P_{salvage} - C_{disposal})$$

Initial Capital Costs			Operating Costs		Salvage Costs	
Purchase Costs	Shipping Costs	Installation Costs	Charging Cost	Maintenance Cost	Salvage Price	Disposal Cost
$ 3,767,000.00	$ 268,625.00	$ 1,243,110.00	$ 214,272.56	$ 55,879.46	0	0

Green House Gas Emissions – the total Scope 1 and Scope 2 emissions CO_2e from sale to salvage. The detailed emissions calculation can be found in the Emissions Calculations appendix.

$$E_{system} = Install\ and\ Transport\ Emission + Operation\ Emission + Salvage\ Emission$$

$$E_{system} = E_{transport} + E_{installation} + E_{operation} + E_{salvage}$$

Uncertainty Assessment

1. The cost for installation itself requires a detailed modeling. The cost may be half as much less (ex. where an inverter exists already(PV)), or more than double (ex. where there is a charge for real-estate)
2. Tesla has limited production capacity until the Gigafactory is able to produce the PowerPacks. Prices may increase or decrease within that time (1-3 years).
3. Demand in August is typically higher than other months. Δ_{TOU} may not keep the form of .15 - .02 for every day of discharge in the year.
4. Real-world, lifetime performance data of the NCA battery is not available. It is possible that the PowerPack life is shorter than the 1500 cycles we've assumed

Data Quality Assessment

1. The CO_2e for each type of plant was calculated using data from the EIA website. The percentage of each type of power used was taken from the Georgia Power website. Because both of these sets of data are rounded it is fair to assume some accuracy has been lost. It is also important to note that the order with which Georgia Power uses their electricity is a high level interpretation. They cannot always use their facilities in this order due to maintenance and other issues.
2. The costs of transporting the system is from Fed-Ex's freight quote system. It is likely the transportation cost's will be much less than the $ 2k per unit. Likely around $ 500 per unit.
3. Emissions for transportation were calculated using the data on EIA website. We made the assumption that Tesla could ship the batteries by rail to Atlanta. This assumption cannot be confirmed because there may be a facility closer to Atlanta in the future. If the product is shipped data for transport emission is likely to be fairly accurate.
4. The near term assumption of the battery performance is likely to be very accurate. Refer to the degradation calculation in the Depth of Discharge Appendix

Gap Analysis

Through our research on this project we have identified several gaps in our analysis.

1. The first gap we will identify is the lack of resources available on the Tesla battery. Since this battery is still being developed and does not have precise specifications that Tesla is willing to release. We have done extensive research to find how this battery will perform based off of its chemical makeup as well the few specifications that have been released.

2. Adoption of load shifting on a large scale will result in a demand curve close to the red line in the graph below. This would likely reduce the magnitude of Δ_{TOU}

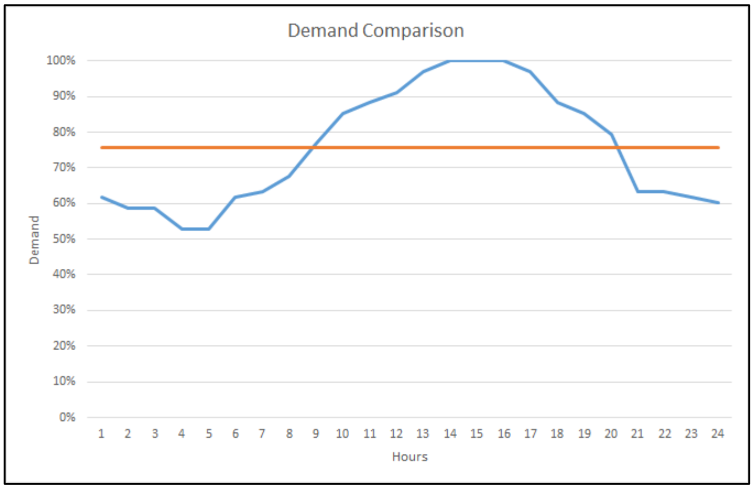


Figure 7 Flat versus Sinusoidal demand

3. Increased adoption of renewable energy at both Georgia Tech and Georgia Power has the potential to dramatically improve cost and emissions profiles. The trending improvements in renewable energy are not accounted for in our CO_2e analysis. This analysis only looks at current emission rates of different power sources and shows them over a twenty-one-year period.

4. Lastly the CO_2e from Nuclear and hydroelectric causes environmental concerns. These two sources of energy do not emit CO_2e as we show in our CO_2e analysis. It is important to note that Nuclear energy does not emit CO_2 but has many other environmental issues. A few of these issues include: very high CO_2 levels emitted from developing uranium, safety issues with core overheating and causing nuclear meltdown and disposal of the reactors when they have reached the end of their useful lifetime. It is also important to note that hydroelectric energy can have negative effects on the ecosystem surrounding dams. Some of these issues include: very high levels of methane found in areas near dams, flooding and altering of fish populations (Ashe, 2010).

Results

Our cost and emissions results from managed vs. unmanaged time of use options are summarized below. The potential cost savings of this project are diluted by the large initial investment to purchase the batteries and have them installed. Below are the summarized costs of implementing the 10,000 kWh system at Georgia Tech.

Total Savings	
Cost at Real-Time Price	$ 1,642,062.70
Less total Cost of System	$ 5,548,887.02
Total Savings	$ (3,906,824.32)

The emissions reduction for this project did result in some GHG reduction. The cost for each tCO_2e saved is $ 1058. This can be considered an extremely expensive way to reduce emissions, even if no emissions from production occur. Below are the results of our emission calculations. For more details, please refer to the appendix.

Savings Per day (kg CO2e)	2,511
Yearly savings (kg CO2e)	175,801
21 Year Savings (kg CO2e)	3,691,816

A Surprising Result

When doing the calculation of charging cost a surprising relationship was found. For at least the situation where charging the Tesla PowerPack occurs from the grid at >96% efficiency, it can be seen that

$$\frac{Lowest\ available\ incremental\ rate\ for\ charging}{Highest\ incremental\ rate\ avoided} \approx \frac{Charging\ Cost\ with\ TOU\ Management}{Energy\ Cost\ without\ TOU\ Management}$$

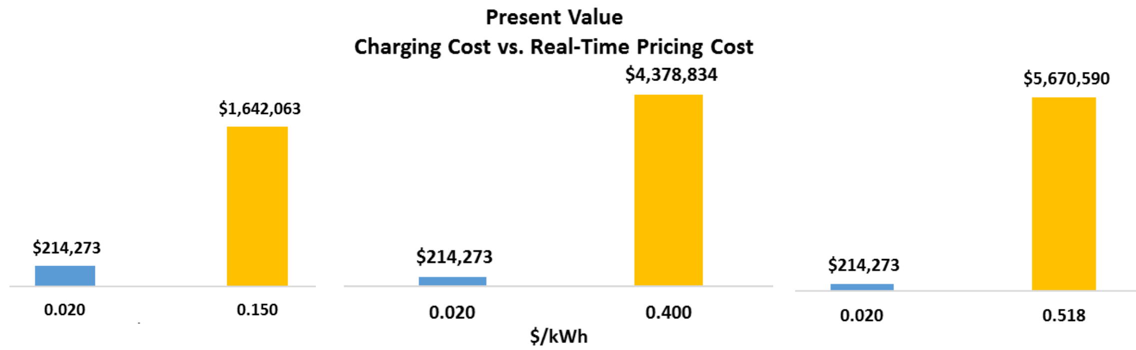
We show the result of these calculation for different charging and discharging ranges below, and leave it to the reader that one need only multiply a current TOU charge by the appropriate ratio to determine the cost of charging.

Charge	$0.02	0.13	$ 214,273.00	Cost with TOU management
Discharge	$0.15		$ 1,642,063.00	Cost without TOU management
Charge	$0.02	0.02	$ 214,273.00	Cost with TOU management
Discharge	$1.00		$ 10,947,084.65	Cost without TOU management
Charge	$0.34	3.4	$ 3,642,633.45	Cost with TOU management
Discharge	$0.10		$ 1,094,708.46	Cost without TOU management

Sensitivity Analysis

One of the major influencers of system price is the DOD factor. For our system if we were able to achieve a 90% DOD (10% more than assumed), we would require roughly 14 less PowerPacks. This translates to a savings of $350,000

The cost that can be deferred as a result of using the system is another parameter we consider. For this role we can use the relation above to see that a ratio of $ 214,273/$ 5,548,887 equal to .0386 must be reached before we cross over the breakeven line. If we assume charging is done at $ 0.02/kWh we see that the time of use price must consistently meet .02/.0386 = $ .518/kWh. We show this situation and other rates for comparison below.



Discussion

Our approach sizes a system to reduce charges from peak daily demand at a frequency of around 70 days a year. We then estimate a $ 0.13 spread between the price of charging and discharging. Although this does have a particularly costly implementation at Georgia Tech, areas where energy costs or demand charges are higher may result in a benefit. The model we have researched can also be used to estimate the result of a large deployment of distributed systems by a utility or industry. It is also important to remember that our analysis focuses solely on managing the incremental charges under the Real-Time Pricing schedule. We have not considered the reduction of demand charges that are built in to the "Standard" component of the Real-Time pricing plan.

Conclusion

Our team has researched how the implementation of the Tesla PowerPack could be used by Georgia Tech to save money and be more environmentally friendly. In our research, we assumed the Tesla PowerPack would be used as an onsite battery to help store energy during hours with cheaper hourly energy rates. By doing this we would normalize Georgia Tech's demand for electricity thus saving money and reducing CO_2 emissions. Given the current parameters, the Tesla PowerPack is not able to achieve adequate savings or emissions reductions. We cannot recommend implementing the Tesla PowerPack at Georgia Tech solely for managing time of use charges. However, the PowerPack might still be a beneficial investment when providing multiple different services with high value, or, when a large system of intermittent renewable generation already exists.

Appendices

Assumptions

1	We have averaged the kg/kWh weight of the Tesla PowerWall and existing Tesla Staionary Storage Prototypes that are deployed to determine the PowerPack weight. This comes from the 70 kWh(900kg) system deployed at La Crema winery and the data sheet for the 7kWh(100kg) PowerWall
2	Cost information is assumed from statement of Tesla CEO using $250/ kWh. "$250/kWh for utility scale is the real kicker", Elon Musk on Twitter, https://twitter.com/elonmusk/status/594186544174366720
3	For determining the useful life of the product we assume that 80% of installed capacity corresponds to "useful life". Based on NREL data, an NCA battery that is cycled using the 80% DOD policy will degrade to the 80% storage capacity at approximately 2300 Cycles. Since 2300 cycles is greater than the stated cycle life of 1500 we assume 1500/70 = 21.4
4	The shipping cost per unit is based off of using the Fed-Ex freight quote tool. The rate was quoted from the Fed-Ex Freight Service center in Sparks Nevada to the Freight Service Center in Smyrna Georgia. Since there is a rail line spur in the industrial park servicing the Tesla Factory, it is assumed rail transport will be utilized for this shipment

5 Data from GT facilities produces us an average of $0.15/kWh for weekdays from 2-6. We subtract .02 from this to get Δ_{TOU} = $ 0.13/kWh

6 For the inverter cost we assume a cost compare able to the inverters for inverting large photovoltaic deployments. (referenced product is the SMA SC800CP Grid Tied Inverter 3-Ph 880kW, cost = $214,354) 880kW * 3 = 2640kW, so assume $214,000*3 = $642,000

Georgia Power's Real-Time Pricing Calculation

BILL DETERMINATION:

An RTP bill is rendered after each monthly billing period and consists of a Standard Bill amount and a charge (or credit) for incremental energy usage based on the difference between a customer's actual usage and its CBL in each hour and the hourly energy prices provided during the billing period. The monthly bill is calculated using the following formula:

$$\text{RTP-DA Bill}_{\text{Mo.}} = \text{Standard Bill}_{\text{Mo.}} + \Sigma\, \text{Price}_{\text{Hr.}} \times [\text{Load}_{\text{Hr.}} - \text{CBL}_{\text{Hr.}}]$$

Where:

$\text{RTP-DA Bill}_{\text{Mo.}}$	=	Customer's bill for service under this tariff in a specific month
$\text{Standard Bill}_{\text{Mo.}}$	=	Customer's bill for a specific month based on usage as defined by the CBL and billed under the standard firm tariff
Σ	=	Sum over all hours of the monthly billing period
$\text{Price}_{\text{Hr.}}$	=	Hourly RTP-DA price based on marginal costs
$\text{Load}_{\text{Hr.}}$	=	Customer's actual load in an hour
$\text{CBL}_{\text{Hr.}}$	=	Customer Baseline Load shape on an hourly basis

Cost Calculations

Table n Cost Parameters for Cost Calculations		
definition	symbol	value used/assumed
Depth of Discharge policy	α	.80
AC-DC conversion efficiency	β	.96
number of PowerPacks	η_p	125
number of inverters	η_i	1
number of kWh needed to charge the system at cycle t	$\eta_{kWh,t}$	$100(\eta_{p^*} D_t)/\beta$
cost of one PowerPack	c_p	$ 25,000
cost of one inverter	c_i	$ 642,000
cost of one kWh at cycle t	$c_{kWh,t}$	$ 0.02
Factor for cost of system installation	c_f	.33
yearly cost of maintenance for one pack	c_{mp}	$ 25
yearly cost of maintenance for one inverter	c_{mi}	$ 500
salvage cost of a pack	c_{sp}	0
salvage cost of an inverter	c_{si}	0
price of salvaged PowerPack	p_{sp}	0
price of salvaged inverter	p_{si}	0
transportation cost of one pack	T_p	$ 2,104
transportation cost of inverter	T_i	$ 5,000
Percent of system capacity remaining at cycle t	D_t	$-(9\text{x}10^{-5})t + 1$

$$C_{purchase} = (c_p n_p + c_i n_i)$$

$$C_{shipping} = n_p T_p + n_i T_i$$

$$C_{installation} = c_f (c_p n_p + c_i n_i)$$

$$C_{charging} = \sum_{t=1}^{1500} \left[c_{kWh,t} * n_{kWh,t} (1+i)^{-\left\lceil \frac{t}{70} \right\rceil} \right]$$

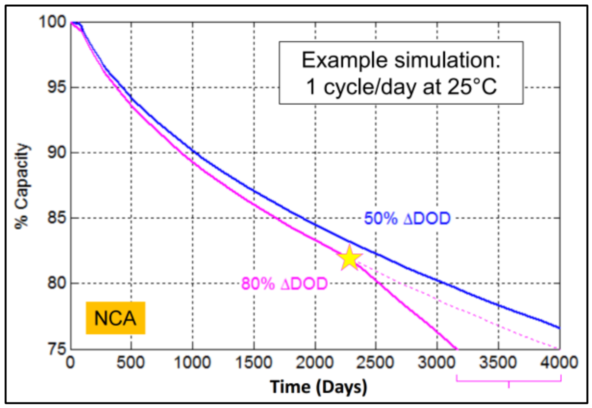
$$C_{maintenance} = \sum_{y=1}^{21} (c_{mp} n_p * c_{mi} n_i)(1+i)^{-y}$$

$$C_{disposal} = (c_{sp} n_p * c_{si} n_i)(1+i)^{-21}$$

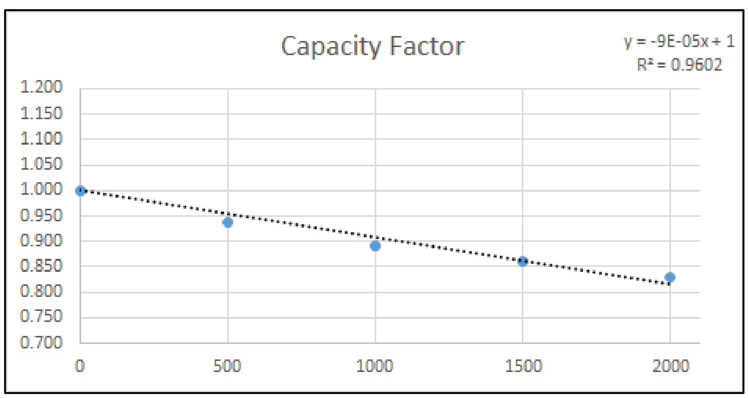
$$P_{salvage} = (p_{sp} n_p * p_{si} n_i)(1+i)^{-21}$$

Depth of Discharge

The Depth of Discharge is the amount of capacity that is discharged from a battery. For example, if a battery holds 100 kWh and 80 kWh are discharged, then the depth of discharge is 80%. This is an important consideration when determining system size **and** life. The more completely a battery cell is discharged, the more stress in incurred on the battery and degradation occurs. Modeling and simulation at NREL has led to estimates of the effect of different DOD policies. We use their research, shown below, to develop our own degradation function.



Here we interpolate several points from the NREL Graph to determine D_t, the percent of battery capacity remaining at cycle t.



This allows us to find the kWh needed to charge the system at cycle t as

$$\eta_{kWh,t} = 100(\eta_{p*} D_t)/ \beta$$

Emissions Generated

Savings Per day (kg CO2e)	2,511
Yearly savings (kg CO2e)	175,801
21 Year Savings (kg CO2e)	3,691,816

Hour	Georgia Tech Demand (KW)	Atlanta Percent Utilization	Power Types Used	kg CO2e	New Demand	New kg CO2e
Demand for one Day=		897,663	1815%			
Without Batteries					With Battery	
Hour	Georgia Tech Demand (KW)	Atlanta Percent Utilization	Power Types Used	kg CO2e	New Demand	New kg CO2e
1	35,753	62%	Nuclear, Hydro, Natural Gas	13,100	36,563	13,397
2	35,355	59%	Nuclear, Hydro, Natural Gas	12,531	36,165	12,818
3	35,163	59%	Nuclear, Hydro, Natural Gas	12,463	35,972	12,750
4	35,019	53%	Nuclear, Hydro, Natural Gas	11,435	35,829	11,699
5	34,920	53%	Nuclear, Hydro, Natural Gas	11,402	35,729	11,667
6	35,067	62%	Nuclear, Hydro, Natural Gas	12,849	35,876	13,145
7	35,490	63%	Nuclear, Hydro, Natural Gas	13,201	36,300	13,502
8	35,848	68%	Nuclear, Hydro, Natural Gas, Coal Fired	14,683	36,657	15,015
9	36,741	76%	Nuclear, Hydro, Natural Gas, Coal Fired	17,921	36,741	17,921
10	37,805	85%	Nuclear, Hydro, Natural Gas, Coal Fired	20,784	37,805	20,784
11	38,705	88%	Nuclear, Hydro, Natural Gas, Coal Fired	21,971	38,705	21,971
12	39,238	91%	Nuclear, Hydro, Natural Gas, Coal Fired	22,932	39,238	22,932
13	39,439	97%	Nuclear, Hydro, Natural Gas, Coal Fired	24,250	39,439	24,250
14	39,528	100%	Nuclear, Hydro, Natural Gas, Coal Fired, Other	24,619	37,100	23,106
15	39,571	100%	Nuclear, Hydro, Natural Gas, Coal Fired, Other	24,645	37,142	23,133
16	39,604	100%	Nuclear, Hydro, Natural Gas, Coal Fired, Other	24,666	37,176	23,154
17	39,535	97%	Nuclear, Hydro, Natural Gas, Coal Fired	24,309	37,107	22,816
18	39,040	88%	Nuclear, Hydro, Natural Gas, Coal Fired	22,162	39,040	22,162
19	38,571	85%	Nuclear, Hydro, Natural Gas, Coal Fired	21,205	38,571	21,205
20	38,060	79%	Nuclear, Hydro, Natural Gas, Coal Fired	19,409	38,060	19,409
21	37,925	63%	Nuclear, Hydro, Natural Gas	14,107	38,734	14,408
22	37,755	63%	Nuclear, Hydro, Natural Gas	14,044	38,564	14,345
23	37,058	62%	Nuclear, Hydro, Natural Gas	13,578	37,867	13,875
24	36,474	60%	Nuclear, Hydro, Natural Gas	13,151	37,283	13,443
				425,419		422,907

Net Electricity Generation for Georgia	
Natural Gas-Fired	40.1%
Coal-Fired	33.2%
Nuclear	22.4%
Hydroelectric	2.0%
Other Renewables	2.9%
	100%

Emissions Information		
Gas Type	Kilograms CO2 Per Million Btu	kg CO2e / KWh
Hydroelectricity	0	0
Oil/Gas	72.6	0.248430202
Nuclear	0	0
Coal Fired	95.3	0.326107414
Natural Gas	53.1	0.181703081

*Assumed Georgia Power uses power plants in order of
Nuclear, Hydro, Natural Gas, Coal Fired, Other (oil/gas)

<u>Calculation</u>

Calculating Emissions information (example for coal fired)

$$\frac{95.3\ kg\ CO2e}{1 * 10^{6}\ Btu} * \frac{1\ Btu}{1055\ J} * \frac{1\ J}{2.77 * 10^{-7} KWh} = .24843\ \frac{kg\ CO2}{KWh}$$

-If utilization was less than 64.5% only Nuclear, Hydroelectric and Natural Gas are used. Georgia Power prefers these forms of energy.

-If utilization goes higher than 64.5% but less than 97.1% Nuclear, Hydroelectric, Natural Gas and Coal Fired is used.

-If utilization is greater than 97.1% Nuclear, Hydroelectric, Natural Gas, Coal Fired and Other is used. Other is assumed to be Oil/gas

(example of hour one calculation for kg CO2e)

$$kg\ CO2e\ Hour\ 1 = \frac{.02}{.62} * 35753\ KW * 0\ \frac{kg\ CO2e}{KW\text{h}} + \frac{.224}{.62} * 35753\ KW * 0\frac{kg\ CO2e}{KW\text{h}} + \frac{.375}{62} * 35753\ KW\ * .248430202\frac{kg\ CO2e}{KW\text{h}}$$

(example of hour one new demand)

Peak times from hour 8 to 20. We will be using the average discharge rate of the battery over its 21-year lifetime of 9713.1 KWh per discharge. Also, we will be cycling the batteries 70 times per year. Based off of this we then will charge from hour 21 through hour 8 as marked on the chart above in blue. We will then discharge from hour 14 through 17 as shown on the chart above in red. By charging during times of lower demand we will be emitting less CO2 than if we were to consume the power during the peak times that we will be discharging the battery (Georgia 2015).

Truck Transpiration Emissions

Number of Power Packs	125	
Power Packs Per Truck	10	
Number of Inverters	1	
Inverters Per Truck	1	
Distance From Tesla to Rail Facility by Rail	2480	
Distance from Rail Facility to Georgia Tech by truck	20	Miles
Distance to Inverter Facility	100	Miles
Using Rail	0.16	kg CO2e/mile
Using Heavy Truck using Diesel emits	1.40	kg CO2e/mile
Power Pack emission	50880.03	kg CO2e
Inverter Emission	140.01	kg CO2e
Total	51,020	kg CO2e

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