Shaving Peak Electricity Demand:

A Comparative Life Cycle Assessment

ISE 576: Industrial Ecology

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Abstract

With increasing global energy demands and an urgent need to reduce the environmental impacts of electricity production, it is important to weigh the relative impacts of emerging energy smoothing technologies. Namely, it must be determined whether it is preferable to store energy or manage it more efficiently. This study compares two different methods of demand-side energy management: battery storage and energy use optimization with a home energy management system. In order to achieve this, a life cycle assessment was conducted on the Energy Star Smart Home Energy Management System for energy use optimization and the Tesla Powerwall II for battery storage. In conducting an LCA on each technology, we compare the relative environmental impacts and energy shaving potential of both systems and determine which is preferable in terms of environmental and economic cost as well as overall energy shavings. Life cycle assessments were conducted using online softwares to determine the impacts of each technology in terms of energy usage and global warming potential. Energy shaving capacities of each technology were also calculated. The analysis showed that the Tesla Powerwall was more effective at shaving peak demand but produced greater global warming impacts and consumed more energy during all life cycle phases considered. We conclude that the home energy management system is therefore the environmentally preferable energy smoothing technology, but further research is needed to evaluate the impacts in a renewable energy grid, determine impacts on other environmental indicators, and on end-of-life phases.

Keywords:

Demand-side management, Energy optimization, Energy storage, Peak demand shaving, Life-Cycle assessment

Introduction

Problem Statement

Global electricity demand and consumption have significantly increased over the past century. This trend will continue as the global population increases and more people gain access to a higher standard of living. To match this increase in consumption, a sustainable supply of electricity that can meet peak demand becomes necessary. Peak demand is a period of time on a daily, seasonally, or yearly basis where consumer electricity demand is notably higher than average (Susser, 2020). This is a concern for electrical utility companies because peak electricity demand can stress utilities, forcing them to outsource energy to avoid blackouts. The transition to renewable electricity sources further exacerbates these issues due to the disconnect between peak demand and the times in which these sources, like solar energy, are most readily available. In order to counteract this problem, utilities across the country are prioritizing peak demand smoothing by targeting the consumer in an approach called 'demand-side management.' In recent years, demand-side management technologies have emerged, which require evaluation into their environmental impacts to identify those which can sustainably meet rising electricity demands.

Peak Demand & Demand Side Management

Recent developments in domestic energy demand highlight the importance of ensuring that electricity is adequately available to meet demand, especially during peak load times (Kobus et al., 2015). Peak load management techniques that ensure the continued reliability of the electricity grid often result in higher system costs (Eid et al., 2016). This is because during peaks, utilities must start, stop, and alternate between electricity plants to match fluctuations in demand (Amara, 2021). This results in economic and energy losses, prompting a need to shave the peak demand through demand-side management. In some cases, entire plants are constructed for the purpose of meeting occasional spikes in demand to prevent blackouts during a high load. To avoid future construction of these plants and to keep costs low for consumers, developers should aim to reduce peak demand.

Electricity providers and users alike benefit financially from reducing peak demand, and improvements in reliability result from a reduction in overloads and subsequent power failure (US Department of Energy). Amidst pressure to reduce energy consumption and move towards decarbonization to mitigate climate change, electricity demand is expected to continue to increase. Increased demand for electricity in future decades will also be attributable to the emergence of technologies like electric vehicles (Kobus et al., 2015). Therefore, it is crucial to investigate the relative impacts of demand-side energy smoothing technologies to guide the future development of the national electricity infrastructure.

Technologies of Demand Side Management

Rather than focusing on electricity providers, demand-side energy management works by changing the way consumers use the energy once it reaches their home. There are two ways for peak demand reduction to be accomplished: optimizing energy use by running energy-intense appliances and processes during off-peak hours or continuing to use the same amount of energy during peak demand hours but drawing from a source other than a grid, such as with batteries. The first solution, optimization, can be accomplished through behavioral changes or an automated home energy management system that communicates with household appliances and devices, running them when grid energy supply is high and shutting them down when supply is low. By doing this, household electricity consumption is shifted to occur during off-peak hours, rather than peak demand hours, helping the consumer avoid high electricity prices and preventing the utility from getting overwhelmed. The second solution, drawing energy from a source other than the grid when demand is high, can be accomplished through energy storage. The most developed and readily available form of home energy storage is through batteries, typically lithium-ion batteries. Batteries accomplish demand-side management by charging when energy is cheap and plentiful, then discharging when the energy supply is stretched thin. The household can draw electricity from the charged battery rather than from the grid, reducing dependency on the grid during peak hours.

Our analysis will focus on two specific technologies for demand-side energy smoothing: Energy storage via the Tesla Powerwall II and energy use optimization using the Energy Star Smart Home Management System (HEMS). Both of these systems are readily available and use up-to-date technology, making them relevant for our comparison.

Tesla Powerwall II

Batteries work to shave peak demand by storing energy and offering a supply of power to be used during peak hours, avoiding the use of grid electricity during these high-demand periods. Batteries charge at the lowest cost to the consumer, either during off-peak hours during the day or from other renewable sources such as solar panels, then supply power during peak hours so that a user reduces electricity consumption from the grid during peak demand and avoids peak prices (Amara, 2021). Another advantage of using battery energy storage is that an end-user does not have to closely manage their energy use; the battery can be automated to charge during off-peak hours.

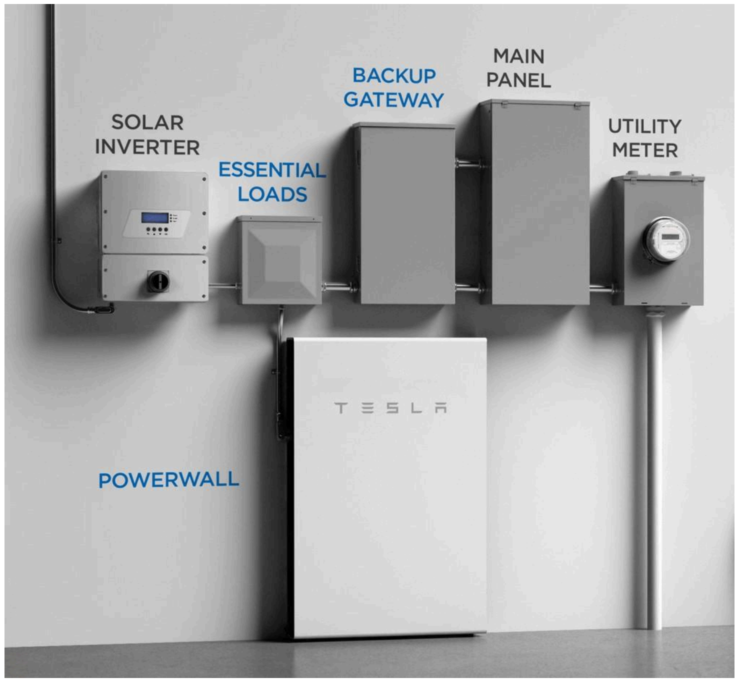

Image 1: Tesla Powerwall II system

The Tesla Powerwall II, a home battery system produced by Tesla, Inc., has been analyzed in this life cycle assessment as an energy storage technology. This system uses a high-quality lithium-ion battery which can store energy from either the grid or solar panels and use it during peak hours or during a power outage. This results in a low-cost storage option that enables us to recharge the system at peak supply when the electricity is less expensive thereby resulting in a reduction of electricity bills. The Tesla powerwall has been one of the critical energy storage systems developed in recent years due to its compact size, state-of-the-art design, and built-in liquid thermal control system (Rodrigues,S et al 2016). This home battery system stores up to 14 kWh of energy with usable energy of 13.5 kWh, a 5kW continuous power output and a peak output of 7 kW. Tesla have declared a 90% round trip efficiency and have also provided a 10-year warranty for the system.

The Tesla Powerwall II system consists of two major components: a rechargeable lithium-ion battery unit and a backup gateway, which controls the battery's activity. Due to a lack of available information about the gateway, likely a result of how new this technology is, it will not be included in this life cycle assessment. Furthermore, the Tesla powerwall system considered for the analysis is only connected to the grid, so charging from solar energy is disregarded. This assumption enables the study to evenly compare both technologies based on the amount of energy shaved from the grid.

Energy Star Smart Home Energy Management System

A home energy management system is a package of energy optimization devices from which a consumer can choose, with certain minimum package requirements. The Energy Star Smart Home Management System consists of a central management device connected to a thermostat, a smart meter, smart plugs, and smart light bulbs. The central management device monitors energy use throughout the household and uses wifi to control connected devices and manage energy consumption. This feature is assumed to be controlled through a smartphone, thus eliminating the need for a physical device, and therefore removing this component from our analysis. Energy optimization achieved through a smart home energy management system offers several avenues for peak demand reductions. Consumers improve the energy efficiency in their homes through automated and behavioral changes prompted by the system. Consumers directly benefit from this increase in efficiency by saving on electricity bills, while utilities experience a reduction in transmission and distribution losses, a smaller peak load, and increases in system stability (do Amaral et al., 2014). Optimizing the use of electricity in a home by, for example, running energy-intensive appliances outside of peak demand hours, therefore tangibly benefits consumers while also shaving peak demand.

The Energy Star Management System is a popular home energy management system already commercially available. The components of the system in the Energy Star Home Energy Management System work together to identify opportunities for users to save energy, limit the standby power of connected devices, automate energy-intensive appliances to operate during off-peak hours and provide feedback to users about their energy savings and opportunities for further savings. This life cycle assessment will consider a total of five devices: smart light bulbs, smart plugs, a smart meter, and a thermostat, all of which are required components of the Energy Star HEMS, as well as a wifi-router. We chose to include a wifi-router in this analysis as it is necessary for communication among devices and between the user and the system.

Life Cycle Issues

The technological advancements and increased commercialisation of energy storage and optimization systems has led to more consumers adopting these technologies for demand-side energy management. While comparing the energy management systems and a battery storage system, consumers have the option of reducing their grid dependency by using renewable energy for recharging the batteries, thereby reducing the overall cost and environmental impacts due to peak demand electricity production. However, storage technologies like the Tesla Powerwall are still extremely expensive, thereby making them unavailable to many potential users. The Powerwall also raises concerns in its material extraction phase, the specifics of which are largely unknown in literature and to the public. The HEMS is a popular option to help consumers manage their own electricity and reduce their monthly energy costs through its interactive interface, but also consumes energy during its use phase. By performing a comparative life cycle analysis, we can arrive at comprehensive results on the overall environmental impacts caused by these technologies throughout their life cycles, from raw material extraction to manufacturing and use phases. This allows a suggestion of which technology is environmentally preferable for energy smoothing.

Current Literature

Technologies for demand side energy management are relatively new and existing research is limited, especially when we consider the comparison of our selected technologies specifically. There are some existing studies for both lithium-ion batteries and home energy management systems that explore the technologies from a life cycle perspective. It is generally agreed upon in the literature that HEMS are a viable tool for reducing energy consumption, shaving peak demand, and moving towards decarbonizing the economy, but can be energy-intensive in their use phase (Louis and Pongrácz, 2017; Kobus et al., 2015). While no literature has been published on the Tesla Powerwall specifically, it is understood that battery chemistry, materials, and efficiency can be major contributors to their greenhouse gas impacts over the product lifetime (Ambrose and Kendall, 2016). These studies provide thorough assessments of what goes into the production and use phases of each technology but information on eventual disposal and recycling is still limited due to the youth of the technologies. These LCA's differ from what our study seeks to achieve in that they explore each technology individually, rather than comparing them as energy management devices.

Objectives of this Study

In a comparative life cycle analysis, we aim to analyze the environmental impacts and economic feasibility of the Energy Star HEMS and the Tesla Powerwall in order to recommend the preferable technology. This life cycle assessment will attempt to answer the following five research questions:

1. What are the cradle-to-gate environmental impacts, from material extraction to the use phase, in terms of global warming potential and energy usage, of each technology?
2. Which life cycle phase of each technology is the most impactful in terms of global warming potential and energy usage?
3. How much electricity is shaved from peak demand using each type of technology?
4. Which technology is environmentally preferable for demand-side management?
5. Which technology is economically preferable?

Methodology

Goal of Life Cycle Analysis

The goal of this life cycle assessment is to assess the relative impacts of the HEMS and the Tesla Powerwall II with respect to their capacities of shaving peak demand. After collecting inventory data on the various life cycle phases of each system, this study will analyze the outputs and produce an impact assessment that indicates which phases of the products' life cycle are most environmentally impactful. The results from the impact assessment and an evaluation of each technology's peak demand shaving power, which in this case is our functional unit, will be used as the foundation for a comparative screening LCA. Once complete, this study will offer valuable insights as to which technology is more effective, less impactful, and more economical.

Scope of Life Cycle Analysis

The impacts and shaving capabilities of each technology in a Los Angeles home will be analyzed on a cradle to gate basis, with the exception of the end-of-life phase. Given the impossibility of physically measuring the inventory, the LCAs are based mostly on secondary data and research conducted by other entities who rely on primary data. Therefore, even though the scale of the study is not constrained to secondary inputs only, it is not a full comprehensive LCA either as no primary data was collected by the members in this study. As a consequence, the LCAs conducted can be defined as *Screening LCAs*.

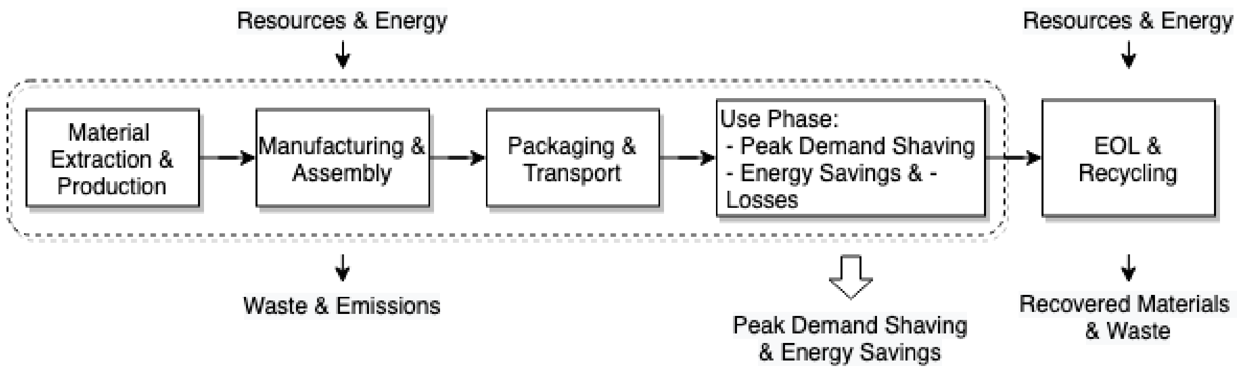

Figure 1: Overview of system scope for both technologies. The system scope is shown in this figure with a dotted line.

Figure 1 above shows that the scope of this study will include inventory and impacts from the material extraction and production phase, as well manufacturing and assembly, packaging and transport, and finally, the use phase, where peak demand shavings and energy savings are also investigated.

Functional Unit

The functional unit (FU) for this life cycle assessment is kiloWatt-hours shaved from peak demand of electricity consumption over an assumed lifetime of 10 years for each technology. Since no Tesla Powerwall II, or modern HEMS system, has yet reached its end of life, a ten year lifetime was assumed based on the Powerwall's 10-year warranty. This limitation is important to recognize because both systems, especially the Powerwall, would have much less environmental impact if the lifetime was extended. For example, a lifetime of 20 years would reduce impacts by 50% compared to a 10 year lifetime. This functional unit was chosen because the analysis aims to identify the technology best suited for shaving peak electricity demand with respect to environmental impacts.

Peak Demand Shaving

To further understand peak demand consumption, data analysis of hourly electricity demand from the grid of California's residents was performed using the hourly electric grid monitor available on the EIA website. The average monthly energy consumption in California was recorded to be 577 kWh by the California Public Utility Commission in 2015. Considering this, the average household energy consumption was assumed to be 18.5kWh per day. Data between June 2015 and July 2016 for California were examined, and these data were utilized to model the graphs below to understand the variations in peak demand requirements across the year. For Southern California specifically, daily peak demand occurs from 4-9 pm, and yearly peak demand occurs during the summer months (Southern California Edison).

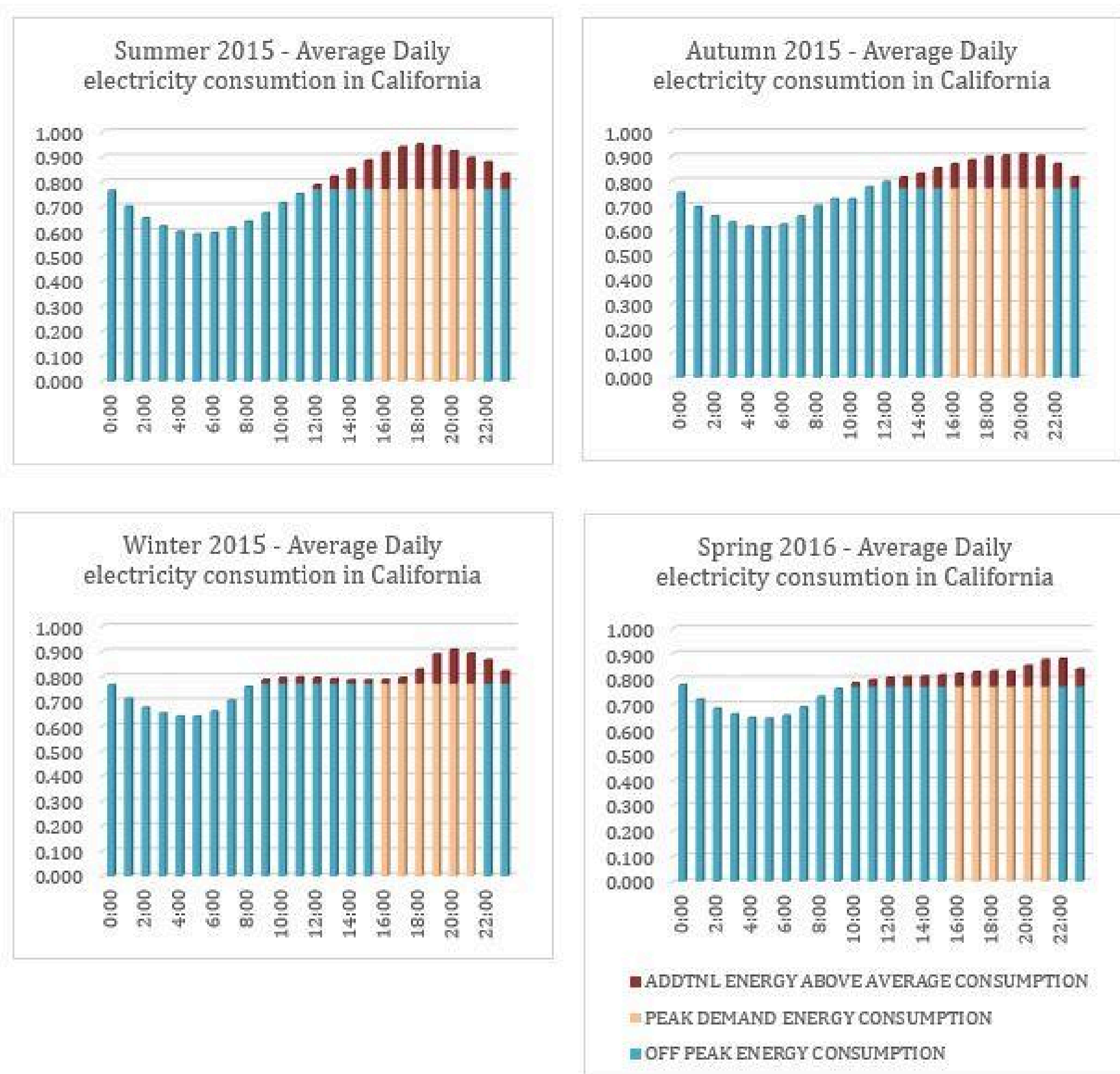

Figure 2: Visual representation of peak energy demand separated by season for California in 2015

Using the Tesla Powerwall for peak energy shaving is an economically viable option due to the large difference in on-peak and super-off-peak hourly tariffs in California (Rodrigues et al., 2016). Based on the hourly energy demand data collected from the U.S. Energy Information Administration website, we can calculate that peak energy demand time periods account for approximately 28% (~5.2kWh) of the daily electricity demand (*U.S. EIA*). This enables us to utilize the stored energy in the powerwall during 4-9 pm when there is peak energy demand on the grid (*Southern*

California Edison). The Powerwall can then be recharged at peak supply when the electricity is less expensive thereby resulting in cost savings. This allows the Powerwall to shave the complete peak demand electricity for the considered household.

Calculating the peak shaving potential of the Energy Star HEMS was done by assuming a set amount of typical household appliances that would be connected to the system and therefore could be directed to run during off-peak hours. It is important to note even with a HEMS, there will likely still be energy used during peak demand hours, for devices such as lighting or a television, so long as the consumer is home during those hours. Therefore for this analysis, it was assumed that peak shaving for a HEMS was achieved by altering the usage times of the following household appliances: one dishwasher, one clothes washer and dryer, the household air conditioning system, and any rechargeable electronics; specifically, two laptops, one tablet, and three smartphones for a four person household. The peak shaving potential was determined by calculating the average daily energy consumption of each appliance, device, or system based on its power output and the duration of use. For appliances that are not used every day, such as the clothes washer and dryer, weekly energy consumption was calculated based on a weekly appliance use assumption, and then divided by seven days to get a daily average. These values were then summed to produce a total average shaving potential, which can be assessed on a daily, yearly, or lifetime basis.

System Boundaries

The system boundaries for this study were determined based on the availability of inventory information at each life cycle stage. For instance, because both technologies are relatively new, it is difficult to find accurate end-of-life (EOL) or recycling data on the technologies and to predict consumer behavior in terms of landfill and recycling habits. Without this information, this phase is excluded from the system scope for both technologies and their LCAs. Scoping boundaries will be kept constant across both life cycle frameworks to avoid the overestimation of impacts from one technology that might have more supporting literature than the other.

Tesla Powerwall II

The system boundary for the Tesla Powerwall II analysis is outlined in Figure 3 below. Because the majority of the system's weight is composed of the lithium-ion battery cells themselves, this LCA will analyze only a few key materials throughout the materials extraction and processing phase that are known to be responsible for the bulk of various lithium-ion battery technologies. Other materials have very low mass or impact per functional unit. One factor that limits the accuracy of our analysis throughout the materials extraction and processing phase is the inconclusivity of each material's origin and the respective spatial implications. It is known that a majority of Tesla's cobalt stock is sourced from the Democratic Republic of the Congo while most Aluminum is imported from China (Maverick, 2019), but to determine a reliable method for evaluating these impacts is beyond the scope of this project.

Battery cell production and battery module assembly are included, but the inventories from these phases are based on secondary data from battery electric vehicle studies and so are more limited. Inventory impacts for packaging, shipping, and use phase are also included in the system boundary while end-of-life and recycling phases are excluded due to lack of information. Our boundaries on this phase are more so limited by the HEMS system, which has more components and little data on the end lives of each system part. Despite this exclusion, it is important to note that all of Tesla's lithium ion battery cells are recycled for further use (*Tesla*, 2021).

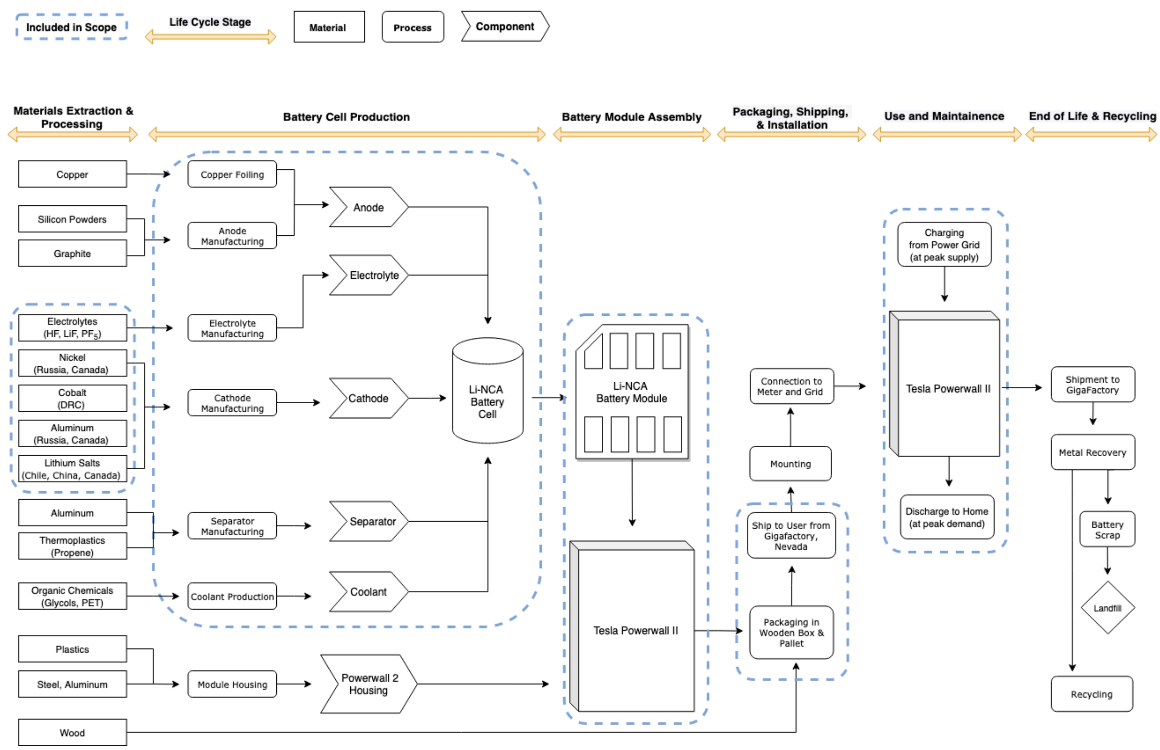

Figure 3: Life cycle framework and system boundaries for the Tesla Powerwall II.

Energy Star Home Energy Management System

The system boundaries for the HEMS analysis are presented in the Figure 4 below. The HEMS involves the use of multiple, relatively small components, resulting in a wide range, but low overall mass of raw materials. Because of this, inventory data for these materials was not readily available, and this study relies largely on secondary data from previous LCA studies of HEM systems. These studies often did not go as far as assessing the impact of the raw materials in each component, and instead assessed the impacts of individual parts like circuit boards, displays, and wiring. As a result, for certain HEMS components, our study was similarly limited to analyzing the impacts of already manufactured parts. Inventory for the manufacturing and product assembly of each component was included, along with inventory for packaging and transportation. Inventory for the use phase was analyzed by collecting available energy consumption data for the HEMS, a typical household, and specific appliances. The inventory impacts that have been excluded from our analysis include installation of the system and end-of-life, as the many components and materials involved in a HEMS lack available recycling and/or disposal data.

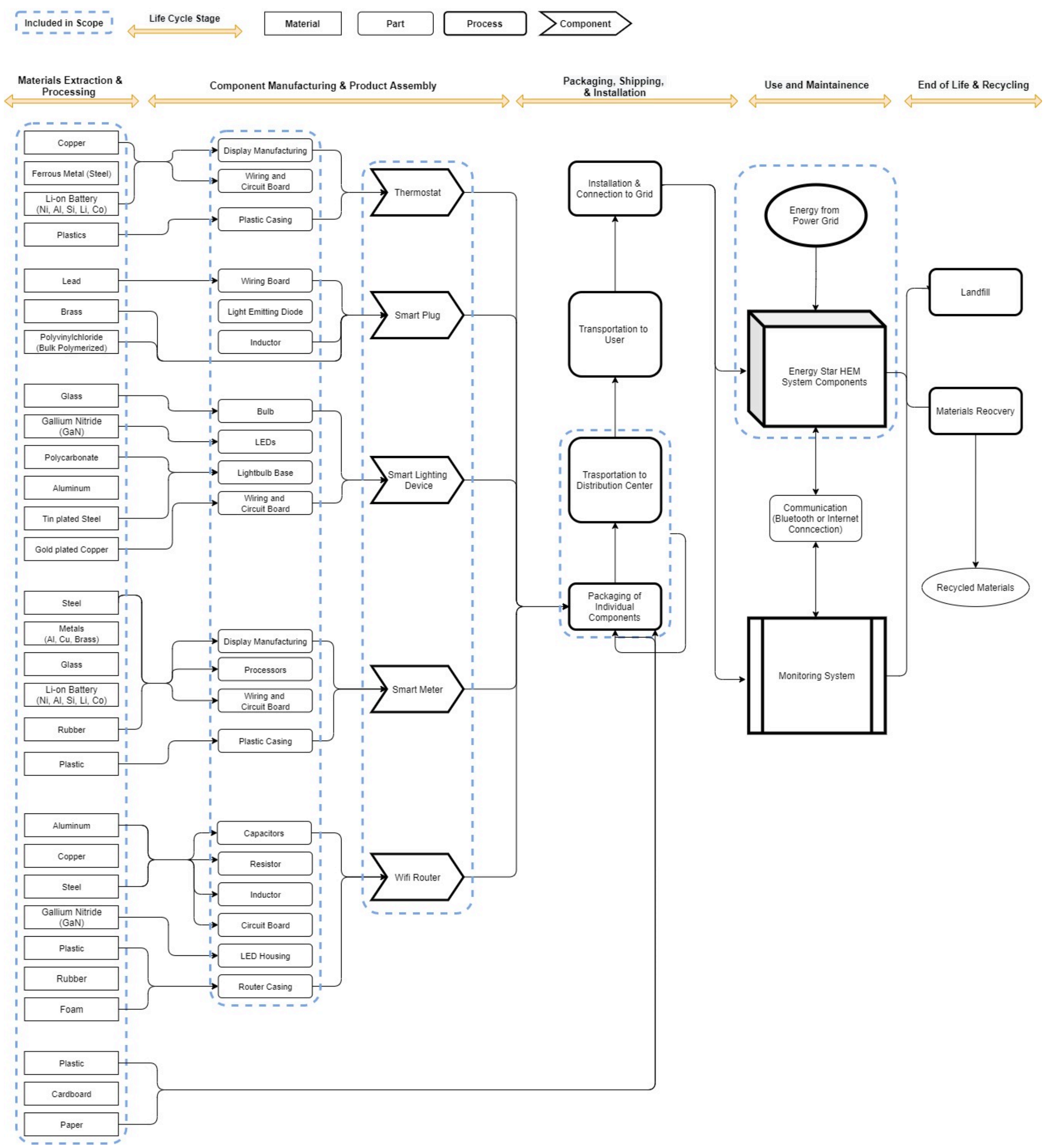

Figure 4: Life cycle framework and system boundaries for the Tesla Powerwall II.

Inventory Data

Inventory data for this study is analyzed from elementary flow information. Materials and energy inputs that are drawn from the environment and enter the systems at each stage are determined using secondary data sources. First, these inputs will be compared on the individual system level so that conclusions can be made about which life cycle phases are most impactful, and so that recommendations for altering these life cycles and reducing environmental footprint can be suggested. Once the analysis at the system level is complete, both technology systems will be compared with respect to the functional unit to see which is a more preferable option for demand-side management.

Tesla Powerwall II

The inventory data for the Tesla Powerwall II system was collected differently for each stage. For the materials production and processing phase, it was determined that a majority of the system's mass is derived from the lithium-ion nickel cobalt aluminum-oxide (NCA) battery cells. The most impactful materials, found in the battery's NCA cathode, are chosen for analysis here. Masses of these materials in each powerwall were calculated using secondary literature on similar NCA battery cells used in battery electric Tesla vehicles (BEVs) and a kWh ratio that provides a quantitative relationship between the larger-capacity BEVs and smaller-capacity Powerwall. Under this framework, the mass of each material in one Powerwall was estimated, along with cost or economic activity, and the corresponding impact categories were calculated using the EIO-LCA. Because many materials were excluded from the materials inventory calculations, the total impact was less than the generalized data provided by a secondary source, therefore the secondary source impacts were chosen for the further stages of LCA comparison.

Table 1: Materials inventory for extraction of key materials in an NCA battery cell.

Materials Inventory for Battery Cell		
Material	**Mass (kg)**	**Price ($)**
Nickel	9.18	$148.81
Cobalt	0.795	$63.21
Aluminum	0.819	$1.90
Polypropylene	10.925	$3.06
Lithium	7.593	$71.30

The table above shows the relative impacts of extracting the primary materials that make up an NCA battery cell. The mass of each material in a Powerwall module was determined using an array of conversion factors from various sources and pricing was determined using a variety of economic resources.

The production phase is dominated by materials production, battery cell production, and battery module assembly. For the Powerwall II, one Powerwall contains one module of about 780 individual NCA cells. 780 is a calculated estimate based on the specific NCA battery used (Panasonic's 2170 NCA Cell), its individual storage capacity, and the Powerwall's total storage capacity (Johnson, 2020). The energy consumption from production and assembly were calculated using parameter distribution factors from a study on battery chemistries and life cycles, while the corresponding GWP was calculated based on an emissions factor from the EPA (Ambrose et al., 2016; Brodrick, 2012). The conversion factors used in the production phase of inventory analysis can be seen in the table below.

Table 2: Conversion factors used for the impact assessment of the production phase for the Tesla Powerwall.

Production Phase	Conversion Factor	Units
Materials Production	42.87	kg CO2eq/kWh Capacity
Battery Cell Production	960	MJ/kWh Capacity
Pack Assembly	0.014	MJ/kWh Capacity

Packaging specifications of material, size, and weight were found online and the route traveled was assumed to be from Tesla's GigaFactory in Sparks, Nevada to Los Angeles, CA. Packaging and shipping inventories were determined from materials mass using PackageSmart LCA software and transport impacts were calculated using conversions for diesel miles traveled. It was assumed that six powerwalls would be shipped at once using a medium heavy duty, class 7 diesel truck.

Table 3: Materials and inputs for packaging and shipping inventory.

Primary Packaging (1 unit)	Total Package Weight	145	kg
	Wooden Box Weight	31	kg
Secondary Packaging (3 units)	Total Weight	453	kg
	Pallet weight	18	kg
In Transport (6 units)	Total Weight	906	kg
	Distance in Transport	471	mi
	Factor, GWP	189	g CO2/ton*mi
	Factor, Energy	137.79	MJ/gal

The inventory in use phase consists of the electrical energy lost via conversion between charging and discharging and impacts were calculated using the same EPA conversion factor from the production phase calculations. Table 4 shows the Tesla Powerwall II specifications and use scenario for this study. As stated previously, inventory from EOL and recycling are not within the scope of this study.

Table 4: Tesla Powerwall II specifications and energy consumption parameters for this study.

Lifetime Warranty	3650.00	days
Usable Capacity	13.30	kWh
Discharge per Day	5.20	kWh
Total Discharge over Lifetime	18980	kWh

Round Trip Efficiency	0.90	
Total Energy Used over Warranty	21088.89	kWh
Total Energy Wasted in Conversion	2108.89	kWh

Energy Star Home Energy Management System

Inventory data for the HEMS system was obtained from a wide variety of sources, including information presented in different publications and data from websites, governmental and non-governmental agencies, among others, along with logical assumptions in order to bridge the gap for the missing figures. Some of the package weights were estimated when data was not available by considering the size of the product and selecting cardboard boxes that correspond to that size. The inventory will be described below.

Internet system (WiFi Router, Power Supply, and Ethernet Switch)

The following table summarizes the inventory for the LAN (Local Access Network) system (Sikdar, B., 2013):

Table 5: Summary of inventory for the HEMS wifi-router.

Wifi-Router, Ethernet Switch, and Power Supply	
Materials	
Component	**Mass of material (g)**
Surface Mounted resistor	1.17
Surface Mounted Capacitor	3.18
Surface Mounted inductor	0.73
Hole Mounted capacitor	18.11
Hole Mounted resistor	0.54
Hole Mounted inductor	39.98
ICs	6.86
Diodes	2.11
Transistors	3.72
PWB	108.83
Fuses	0.2
Connectors	49.87
Screws	4.85

BNC Connectors	81.73
Aluminum cover	1.76
Heat sink	8.83
Clock crystals	1.53
Plastic casing	299.84
Metal casing	115.5
Plug pins	2
Foam	1.6
LED Housing	1.64
Cable	319.57
Grips	0.21
Packaging	
Paper	64
Cardboard	436
Plastic	126
Pins	0.13

No inputs or modifications have been made to this dataset, as it was provided by the study. This research paper considers a system that is manufactured in Asia and it is shipped to the United States. The LCA database was obtained from the Center for Environmental Assessment of Product and Material Systems at the Chalmers University of Technology in Göteborg, Sweden

LED Bulbs

The following table summarizes the inventory for the LED bulbs (Dipert, 2019):

Table 6: Summary of inventory for a single HEMS smart light bulb.

LED Bulb (single)		
Component	**Material**	**mass (g)**
Glass bulb	glass	10.7
LED board connector	gold plated copper	0.5
9 LEDs	multiple	1.5

Heat sink (local, outer, inner)	Aluminum	36.9
Edison base insulator	acrylic, polycarbonate	4.2
Inner insulator + adhesive connections	acrylic, polycarbonate	6.6
Circuit board, capacitors, resistors, transistors, diodes	-	10.1
Edison base and leads	tin plated steel	12.2
Packaging		
Cardboard		~60

Once again, no inputs or modifications were made to this dataset. However, this LCA is pertinent to regular LED Bulbs, which do not fully correspond to the existing light bulb in the HEMS. Due to the unavailability of information, the closest approximation was a 2015 regular LED Bulb. One of the key differences between a regular LED Bulb and a Smart Bulb is the presence of a WiFi module, which was left out of scope. Moreover, the study defines a transportation route that connects China with Washington D.C. through the port of Los Angeles. However, given the negligible impact from transportation described later on, this factor was not adjusted. It is important to note that these are values for a single lightbulb, while the HEMS requires at least two. Thus, the impact values were multiplied by two, assuming linear scaling of impacts.

Smart Meter

The following table summarizes the inventory for the Smart Meter (Aleksic, 2016):

Table 7: Summary of inventory for the HEMS smart meter.

Smart meter	
Materials	
Component	**Specific energy [kJ/kg]**
aluminum plates	341,500
Steel	52,100
Plastic	92,300
Copper	67,000
Iron	51,040
Glass	33,400
Epoxy, Ceramics, Other	20,000

Metals (production)	0.28
Plastic (production)	14.9
PCBs (production) [kJ/m2]	238,400
IC (production) [kJ/IC]	12,500
Processor (production) [kJ/processor]	1,242,000
Packaging	
Cardboard	118

Similarly to earlier tables, no inputs or modifications were made to this dataset. This LCA was the only one available for smart meters that had useful information that was relevant to our analysis. It considers extraction in Shenzhen, China, and utilization in Berlin, Germany. Transportation factors were corrected for a route that connects Shenzhen and Los Angeles. Also, it is important to highlight that the inventory is in terms of energy (kJ/unit).

Nest Thermostat

The following table summarizes the inventory for the thermostat ("Google Nest Learning Thermostat"):

Table 8: Summary of inventory for a HEMS smart thermostat.

Nest Thermostat	
Materials	
Component	**Mass of material (g)**
Copper (PCB)	6.06
Ferrous metal (steel)	108
Li-on battery	12
Plastic	48
Display	31
Electronics	44
Packaging	
Cardboard	73

For the thermostat, some of the inputs or modifications were made to this dataset. The copper content and battery composition were roughly estimated from available information. Nevertheless, it is crucial to highlight that it was not possible to fully estimate the electronics category composition, and therefore the individual components-- such as capacitors, transistors, and ICs-- are unknown and the material these were made from, and thus these were not included in the extraction phase.

Smart Plug

The following table summarizes the inventory for the smart plug (Louis et. al., 2015):

Table 9: Summary of inventory for a single HEMS smart plug.

Smart plug	
Materials	
Component	**Mass of material (g)**
brass	2.55
polyvinylchloride (PVC)	100
Copper	0.9154843918
inductor	1
PCB	-
Packaging	
Cardboard	48

For this last component, there were no available previous LCAs, so it could not be compared to other products as no similar devices exist in literature. Therefore, the material composition was in part obtained from literature, in part estimated. Specifically, the internal components that comprise the smart plug are unknown aside from PCB, which was therefore considered in this analysis.

Impact Assessment

Two impact categories were chosen for this study: global warming potential (GWP) measured in mass (kg) of carbon dioxide equivalents (CO2eq) released and cumulative energy consumption measured in joules (MJ). These categories were chosen based on the availability of relevant primary and secondary data for both systems, and since this study is focused on energy management technologies that help shift demand from nonrenewable to renewable sources, thus reducing emissions, it is suitable to measure how much energy is invested into these systems and quantify the global warming potential these systems add to the atmosphere.

The analyses conducted herein are constrained by a number of limitations. First, time and financial constraints have limited the use of advanced life cycle assessment softwares common in the literature. One previous study on HEMS, for example, used the ReCiPe 2008 Characterisation method from the software SimaPro to yield results based on 18 environmental indicators (Louis and Pongrácz, 2017). So, in addition to extrapolations, conversions, and other manual calculations, this study will rely primarily on the selection of two life cycle assessment tools: Economic Input-Output Life Cycle Assessment (EIO-LCA) and EarthShift Global's PackageSmart LCA Software. The EIO-LCA tool method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy (*Carnegie Mellon University*). With an accurate estimate of economic activity, or money spent on purchasing and producing, the resulting environmental impacts of materials extraction, processing, and manufacturing for each respective technology can be estimated. The PackageSmart tool is intended to help packaging designers evaluate the environmental impacts of certain design decisions and clearly depict where and what changes could be made (*EarthShift Global*). This software will provide our LCA comparison study with accurate impacts on both types of packaging used in each technology's distribution service. Activity data from each technology's use phase was estimated based on each product's technological specifications of efficiency and energy requirements and the corresponding grid mix of electricity generation. Like many other LCA's, this study will combine elements of primary and secondary data to produce more accurate results across our parameters of interest.

Tesla Powerwall II

The outputs for the Tesla Powerwall II impact assessment across the life cycle phases included in this study are summarized in the following table:

Table 10: Impact assessment of Tesla Powerwall II separated by lifecycle phase.

Phase	GWP (kg CO2eq)	Energy (MJ)
Materials Extraction	481.95	5912.3
Materials Production	578.745	6015.1
Battery Production & Assembly	2484.038212	12960.189
Packaging & Shipping	150.99	12777.40233
Use	1025.786672	8132.1984
Total:	4721.509884	45797.18973

The table above illustrates the resulting impact measures from each stage in the Tesla Powerwall II LCA. After the masses of key materials were determined, their corresponding prices were used as an economic activity input into the EIO-LCA tool. The sector chosen here was primarily mining (extraction), and since the EIO-LCA tool only provides a relationship from economic activity within North America, these results from the extraction phase are likely higher in real life as overseas mining operations often work under fewer environmental regulations. During the materials production phase, the EIO-LCA tool was used at first to provide a rough estimate of the impacts derived from materials processing stage for NCA batteries. But after reviewing other secondary sources, an impact conversion factor was discovered and gave higher impact yields (Ambrose, 2016). The conversion factor was chosen to move forward with because it most likely included more metals than those identified in the extraction phase, giving the study more accurate results for this specific stage. Furthermore, an impact conversion factor from the same source was used to gather the battery production and assembly impacts based on the NCA battery's energy capacity. As mentioned earlier, PackageSmart was used to calculate the impacts from packaging and other conversion factors were used to calculate transportation impacts. Since our study could not identify the specific truck used to transport Powerwalls, the transport stage results could differ in reality. Finally, use phase impacts are relatively accurate as they were calculated based on the product spec sheet and no assumptions had to be made.

Energy Star Home Energy Management System

The outputs for the Energy Star HEMS impact assessment across the life cycle phases included in this study are summarized in the following table.

Table 11: Impact assessment results of Energy Star HEMS, separated by lifecycle phase and component.

	Component	kg CO2 (GWP)	MJ
Extraction	**Wifi-Router**	6.1015	295.267932
	Light bulb	13.99	-
	Smart-plug	0.316	3.68
	Thermostat	48.1	776
	Smart-meter	25.875	135
Production		**kg CO2 (GWP)**	**MJ**
	Wifi-Router	10.99827	65.98962
	Light bulb	3.186666667	19.12
	Smart-plug	17.3	103.8
	Thermostat	24.3832	146.2992
	Smart-meter	257.6423333	1545.854
Shipping (Transport + Package)		**kg CO2 (GWP)**	**MJ**
	Wifi-Router	1.54185	58.22928
	Light bulb	0.6673333333	1.966847826
	Smart-plug	0.1234019249	3.473803328
	Thermostat	0.8168	16.40217391

	Smart-meter	1.645106102	25.75213455
Use		**kg CO2 (GWP)**	**MJ**
	Wifi-Router	275.86	1655.16
	Light bulb	227.6	1365.6
	Smart-plug	60.444	362.664
	Thermostat	4.5	27
	Smart-meter	90.67	544.00

The table above illustrates the results from the LCA conducted for the HEMS system. For the internet system, the impacts were directly obtained from literature (Sikdar, 2013), as the information was readily available and it corresponded with the requirements of our HEMS LCA. However, for the other components, a rather analytical approach was employed that required more scrutiny regarding the potential impacts.

Regarding the extraction impacts, the smart meter and the light bulb information was available and no additional inputs were needed. The only additional modification that was required was the conversion of MJ to kg CO2 eq using a series of conversion factors[1] since the information available for the smart meter was in units of energy. Likewise, for all other following stages, this unit balance was utilized for the smart meter. These conversion factors were also employed to account for the energy use (MJ) in the different LCA stages. This corresponds to the emissions produced due to the US grid distribution. For the impacts of the thermostat and the smart plug, *EIOLCA* was utilized with the inventory listed in Table 8 and Table 9. Prices for components such as copper and PCV were obtained from online sources. It is worth noting that, due to the limited information available and the impossibility to physically test these products, the accounted metals are incomplete approximations. As for the thermostat, there are 44 g of electronics that could not be analyzed given that these could not be distinguished in terms of the actual mineral composition. Similarly, the smart plug is also missing certain elements, such as the specific materials breakdown of the inner circuits and overall electronics. Finally, please note that the extraction impacts for the LED lights were not computed. This is because the information is missing, and a full LCA would be required in order to obtain the measures. Therefore, this parameter could not be analyzed.

The production phase for the LED light bulb, the smart meter, and the thermostat were all obtained from available literature (Aleksic, 2016; Dipert, 2019; *Google*). However, for all of these categories, the packaging was included under the "assembly" phase, while in the analysis for this study the packaging is related to shipping. Therefore, in order to avoid double counting, the packaging impacts, obtained from *Package Smart,* were subtracted. For the smart plug, the impacts were obtained from an *EIOLCA* using the inventory listed in Table 9. Energy impacts were estimated using the aforementioned conversion factors.

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[1] 6.9×10^{-4} mt of CO_2/kWh and 1 kWh = 3.6 MJ.

Packaging for the thermostat, the smart meter, and the smart plug were all obtained from *Package Smart.* Packaging for the LED bulbs were obtained from literature (Dipert, 2019). To account for the transportation, trucking to and from the ports were not included given the limitations in marking exactly where the products were produced. Moreover, the transportation of raw materials to factories is not considered because of the challenges in tracking the exact locations of extraction in China, where the devices are manufactured. The only distribution considered is the transportation by ship from China, with Shenzhen assumed to be the point of origin, to the port in Los Angeles. Medium container barges with an average of 21 g CO_2/tonne-km were assumed (ECTA). The addition of packaging and transportation impacts resulted in overall shipping impacts. To convert to energy units, the conversion factors were used for packaging, assuming US grid distribution, and a diesel fuel carbon to energy intensity value of 73.6 g/MJ (University of Helsinki, 2011).

Lastly, use impacts for the smart-meter, the thermostat, and the wifi router were acquired from literature. Out of the five components, two do not correspond to a 10 year lifespan. The LED light bulbs are in terms of hours (25,000) which roughly result in 8 - 10 years of usage. Thus, 10 years were assumed. Similarly, the smart meter is given a lifespan of 15 years. In order to reduce that value to 10 year, the impacts were multiplied by ⅔. The carbon dioxide emissions for the smart plug was calculated from available data online. To convert these impacts to energy consumption, the values were multiplied by the conversion factors.

Analysis

Data Analysis

Tesla Powerwall II

Table 10 in the impact assessment section shows the GWP and energy consumption for each life cycle phase of the Tesla Powerwall II. This impact data is presented in the figures below.

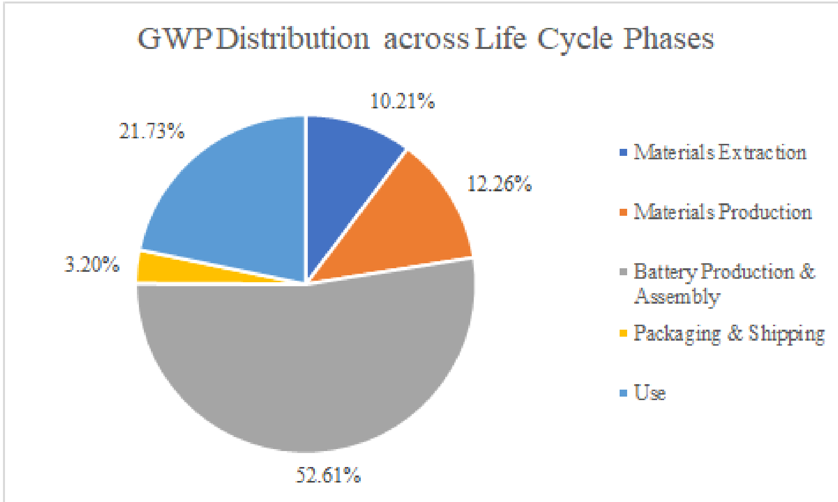

Figure 5: GWP of the Tesla Powerwall across each life cycle phase.

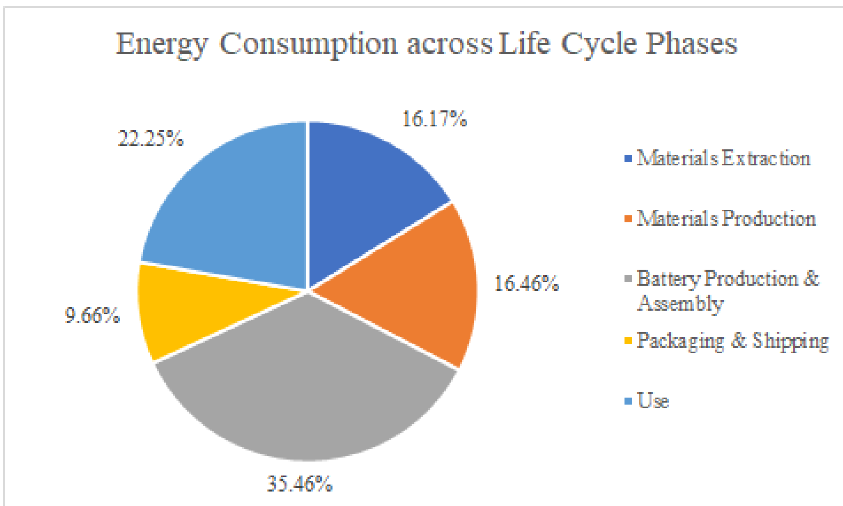

Figure 6: Energy consumption of the Tesla Powerwall across each life cycle phase.

From these figures we can see that the battery production phase is the most impactful in terms of both GWP and energy consumption; making up 52.6% of the total GWP impacts and 35.3% of the total energy consumption impacts. After battery production, the use phase is second most impactful for both categories, closely followed by materials production, materials extraction, and packaging and shipping.

At the materials extraction phase, the impacts per kilogram of mass of each material and per Powerwall are displayed below. By far the most impactful of these materials is cobalt, due to its controversial mining practices in the Democratic Republic of the Congo (Posner, 2020). There is very little cobalt in the Powerwall system but its impact per mass is greater than all others combined. The graphs below show the energy consumption and global warming potential by mass for each material.

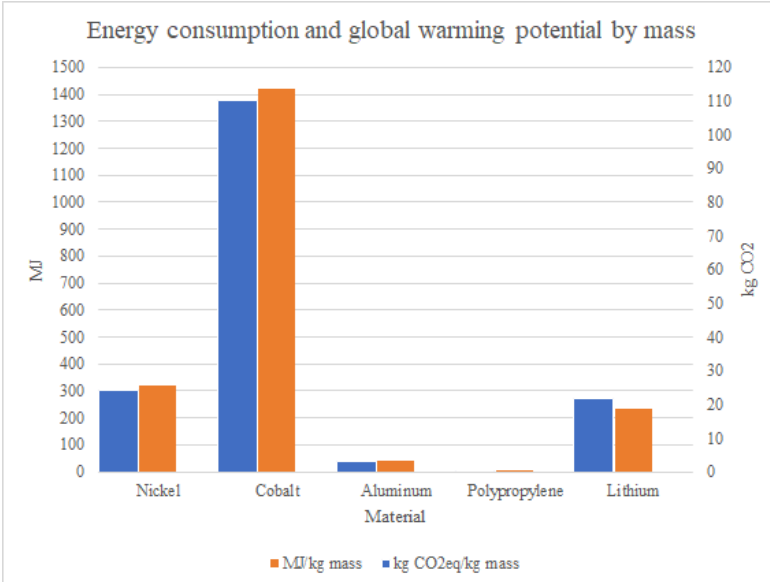

Figure 7: GWP (kg CO2 EQ) and Energy Consumption (MJ) per kilogram mass of each material.

It is important to highlight the relative impacts resulting from the use of each material. As lithium-ion batteries become more and more popular, issues relating to materials extraction will continue to grow. From the bar graph above, it is apparent that a few key materials are responsible for a majority of the impacts in this phase. This is why companies like Tesla are not worried about the levels of plastic in their batteries, but instead are striving to create future batteries with little to no cobalt. Similar to the other metals, it is very difficult to evaluate the impacts resulting from the material's extraction and consumption when those impacts are so broad, ranging from emissions release to habitat destruction to socio-economic issues. For this reason, the study's scope is more limited in this area and our impact analysis is heavily based on the pricing of each material.

Looking across each life cycle stage, it is clear that the production phase for the Tesla Powerwall, including materials and battery production, has the greatest impact. The GWP and energy consumption for this phase is significant, stemming from the intense production process of lithium-ion batteries and their components.

Peak Shaving for Tesla Powerwall II

The Peak shaving capacity for the Tesla powerwall while connected to the Grid is tabulated as shown below. Table 12 shows the total energy shaving for the Powerwall system and Figure 8 shows the Peak demand shaving and recharging model for the Tesla Powerwall.

Table 12: Total Energy shaving for the Powerwall system.

Powerwall System Peak Shaving		
Daily shavings:	5.20	kWh
Yearly shavings:	1925	kWh
10 year lifetime:	19250	kWh

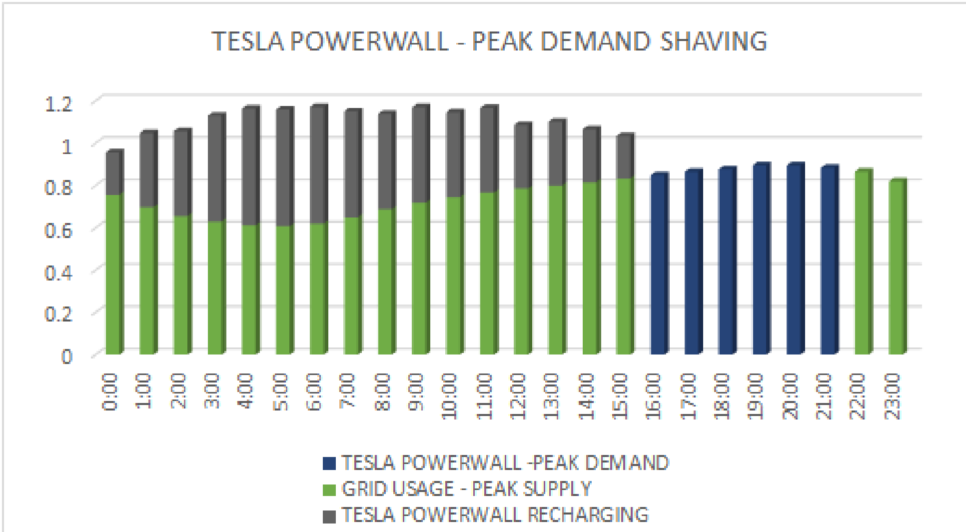

Figure 8: Peak demand shaving and recharging model for the Tesla Powerwall

Energy Star Smart Home Energy Management System

The GWP and energy consumption impact of each HEMS component are tabulated in Table 11 from the Impact Assessment section. The plots below present this data, organized by system component and life cycle phase.

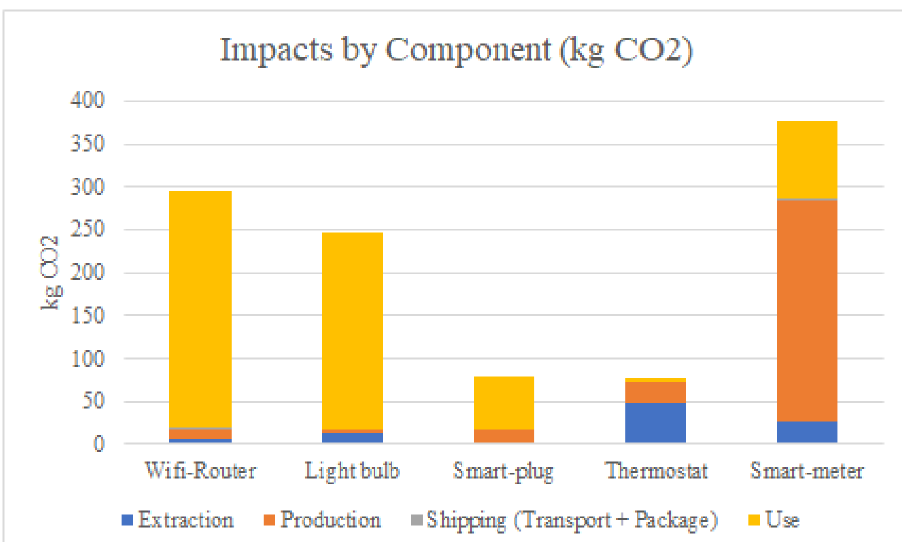

Figure 9: GWP of the Energy Star HEMS separated by life cycle phase and component.

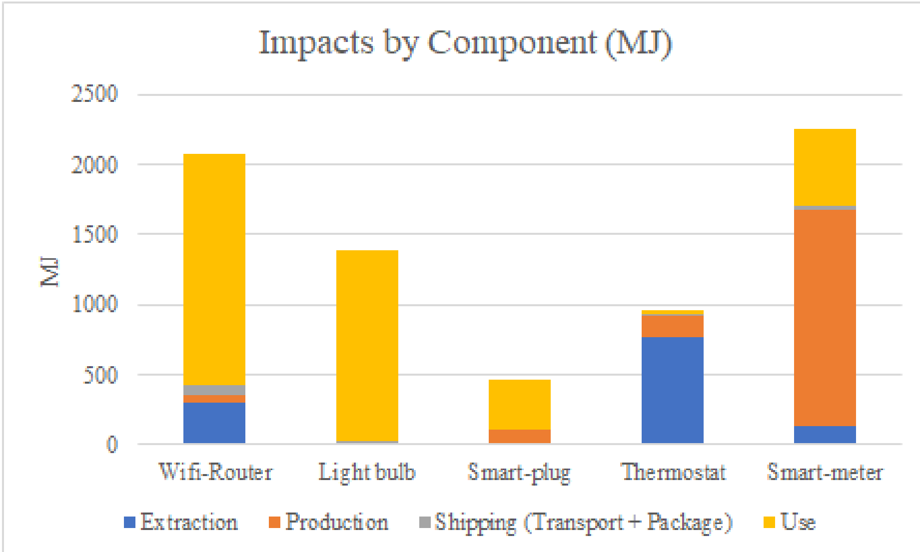

Figure 10: GWP of the Energy Star HEMS separated by life cycle phase and component.

As it is depicted in these figures, the wifi-router, smart light bulbs, and smart-meter account for a majority of GWP and energy consumption impacts of the HEMS. For the wifi router and light bulb, the impacts are dominated by the use phase. Both of these products are physically relatively small but use significant amounts of energy once installed resulting in higher impacts during the use phase. On the other hand, most of the GWP and energy consumption impact for the thermostat stems from the extraction phase and almost none come from the use phase.

This same data is presented again in the pie charts below to better compare the relative impacts of each lifecycle phase for the entire system, not just individual components.

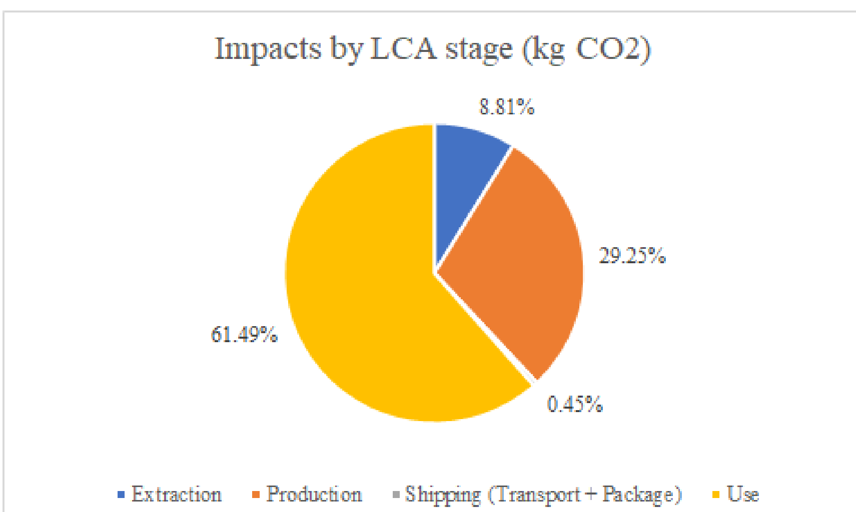

Figure 11: GWP of the HEMS across each life cycle phase.

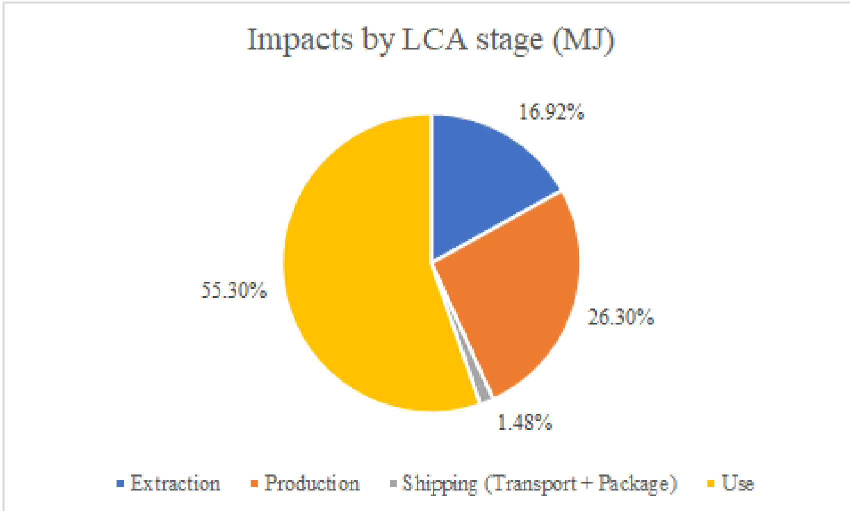

Figure 12: Energy consumption of the HEMS across each life cycle phase.

These figures show us that for the HEMS as a whole, the use phase has the greatest impact, accounting for over 50% of both GWP and energy consumption. This result makes sense considering the small size, and relatively low resource intensity of the physical HEMS components. Most of the impacts associated with a HEMS occur after it has been installed in the home as it uses and directs energy from the electricity grid.

Peak Shaving for Energy Star Smart Home Energy Management System

The calculated peak shaving potential of the Energy Star HEMS is tabulated below. Table 13 contains the calculated energy consumption of each appliance connected to the system and Table 14 presents the total energy shaving potential of the HEMS on a daily, yearly, and lifetime basis.

Table 13: Energy shaving potential of HEMS.

HEMS Peak Shaving	
Appliance	**Energy Consumption (kWh per day)**
Dishwasher	1.8
Clothes Washer	0.143
Clothes Dryer	0.333
Air Conditioning	0.74
Rechargeable Electronics	0.172
Total	3.188

Table 14: Total Energy shaving for the HEMS system.

HEMS System Peak Shaving		
Daily shavings:	3.188	kWh
Yearly shavings:	1,163.62	kWh
10 year lifetime:	11,636.2	kWh

Comparison of Results

In order to properly compare these two technologies in terms of both overall impact and energy shaving ability we normalized the impact over the functional unit (kWh of peak demand energy shaved) across a 10 year lifetime. Our results are presented in Table 15 below.

Table 15: Impact per functional unit for each system.

Technology	GWP per kWh shaved (kg CO2eq / kWh)	Energy consumption per kWh shaved (MJ / kWh)
Tesla Powerwall II	0.25	2.41
Energy Star HEMS	0.096	0.64

After applying the functional unit, it becomes clear that the impact per kWh for GWP and energy consumption is notably lower for the HEMS than for the Tesla Powerwall. These results are normalized and further presented in the figure below. The Tesla Powerwall has significantly higher GWP and energy consumption impacts through the extraction, production, and shipping phases, highlighting the overall intensity of creating a Tesla Powerwall. In the use phase, these two technologies are much more closely matched. The HEMS uses almost as much energy as the Tesla Powerwall, and actually appears to have a slightly higher GWP, during the use phase. This is an important result to notice as it reveals the real difference in impacts between each technology does not stem from when the technologies are actually installed and in use, but rather comes from the earlier, often overlooked, lifecycle phases of extraction and production.

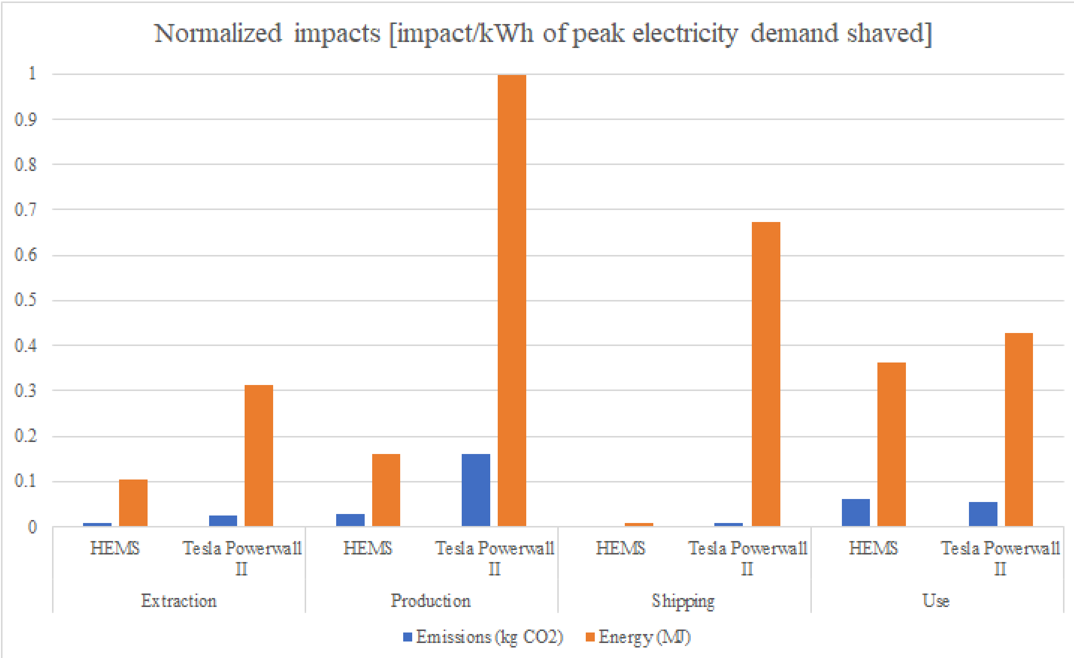

Figure 13: Normalized impact per functional unit of each technology, separated by life cycle phase

Sensitivity Analysis

The results of this analysis could have been impacted by the share of renewable energy in the electricity grid. This analysis assumes standard, fossil fuel sources of energy for the electrical grid, but considering solar energy to charge Powerwall batteries can increase overall Peak shaving capacity of the powerwall thereby reducing the impacts of the technology. Further, end-of-life fates were not considered in this analysis due to constraints of time, costs, and data availability. However, this is likely to change the magnitude of the results rather than the outcome. This is because the Tesla Powerwall is much larger than the components of the HEMS and uses rare metals in its material composition, so its end-of-life impacts are surmised to be significant. Finally, the analysis conducted on HEMS used a set number of devices, plugs, and smart light bulbs. The results are based on that quantity, but a user may have opted for additional devices, which would make the impacts of the HEMS higher.

Limitations

Given that the Tesla Powerwall is a relatively new technology with little publicly available data, much of its material composition and end-of-life fates are unknown. For this reason, the analysis for both technologies was conducted 'cradle-to-gate,' from raw material extraction through the use phase. Data availability limited the accuracy of material composition for the HEMS as well. Where data was available for this technology, no previous study had been conducted on the specific Energy Star brand bundle of devices. The assumption of a 10 year lifespan for both technologies may also impact the data but the recency with which the Powerwall entered the market makes it difficult to determine an accurate lifespan. Both analyses were constrained by the availability of advanced life cycle assessment software like SimaPro. Despite these limitations, this analysis is still a useful approximation for the global warming impacts and energy usage, along with peak shaving capabilities, of both the Powerwall and the HEMS.

Cost-Benefit Analysis

A comparative cost analysis was performed on both the systems to understand which system shaved more energy during the 10 years resulting in economic benefits to the consumer. From the data analyzed from the EIA website, we can assume that the household being considered utilizes 18.5 kWh per day with 5.20 kWh used during the Peak demand.

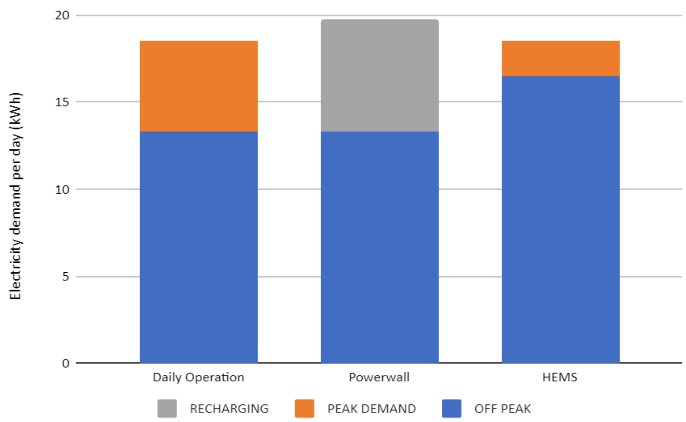

Figure 14: Daily electricity demand of each system.

The cost savings for both the systems were calculated using the T-O-U residential rate plans (*Southern California Edison*). The unit cost of electricity varies based on the seasons and the time of the day which is shown in Table 16 below.

	SUMMER (JUNE - SEPTEMBER)			
	PEAK	MID PEAK	OFF PEAK	SUPEROFF PEAK
(WEEKDAY)	16:00 - 21:00		21:00 - 16:00	
	$0.43		$0.27	
(WEEKEND)		16:00 - 21:00	21:00 - 16:00	
		$0.35	$0.27	

WINTER (OCTOBER - MAY)			
PEAK	MID PEAK	OFF PEAK	SUPEROFF PEAK
	16:00 - 21:00	21:00 - 8:00	8:00 - 16:00
	$ 0.37	$ 0.28	$ 0.26

Table 16: California electricity rates during summer and winter months.

Based on the Energy shaving methodologies considered earlier in the paper, we know that the Tesla Powerwall can be entirely used during the peak demand requirement and recharged when the electricity cost is lesser during peak supply. This enables the powerwall to shave 5.20 kWh of peak demand per day. Due to the 90% round trip efficiency declared by Tesla, we would require 6.42 kWh during the peak supply in order to recharge the Battery. Therefore, though the powerwall shaves the complete peak demand, it requires an additional 1.22 kWh for recharging the battery during the peak supply and thereby incurs some additional cost when compared to the HEMs system.

For the HEMS, cost savings were determined using the California electricity rates specified in Table 15 along with the calculated peak demand energy shaving potential of 3.18 kWh per day. By subtracting peak demand rates from off-peak rates across 3.18 kWh we were able to determine daily cost savings, which were then applied to the lifetime of the project. In order to determine the cost savings from energy saved by the HEMS through energy optimization we assumed an average energy use reduction of 12% per year (Miziolek, 2015).

By comparing the cost savings and the return on investments between both the technologies, as seen in Table 17 below, we can clearly see that the HEMS is the economically preferable option. The very high cost of the Tesla powerwall reflects that it is very difficult to obtain an ROI while connected to the grid. The savings are considerably lower than the HEMS due to the additional energy required for recharging the battery. The HEMS yields a better return on investment with higher financial savings from both peak shaving and energy savings from energy optimization in the system.

COST ANALYSIS:		POWERWALL	HEMS
COST OF TECHNOLOGY	Initial cost of	$9,600	442.5
	Use phase cost + maintenance	$600	$600
	TOTAL	**$10,200**	**$1,043**
COST SAVINGS in 10 Years	Peak Shaving	$1,105	$1,397
	Energy optimization	$0	$2,360
	TOTAL	$1,105	$3,757
	Difference	**$1,105**	**$6,117**

Table 17: Cost analysis comparison between Powerwall and HEMs

Conclusion & Recommendations

Our analysis shows that while the Tesla Powerwall has a higher peak demand shaving potential, the Energy Star Smart Home Energy Management System is environmentally and economically preferable. Across a 10 year lifetime, the Energy Star HEMS has a GWP of 0.096 kg of CO2eq and consumes 0.64 MJ of energy per kWh of energy shaved. In contrast, the Tesla Powerwall has a GWP of 0.25 kg of CO2eq and consumes 2.41 MJ of energy per kWh. Comparing the cost savings, the HEMS has a much better return on investment when compared to the Powerwall. This is essentially due to the higher savings during Peak shaving and energy optimisation of the HEMS and also since the Powerwall is very expensive in comparison to the HEMS. Using a HEMS like the one from Energy Star is an effective way to reduce peak energy demand and smooth consumption without investing in an incredibly expensive, materials intensive technology such as lithium-ion batteries. The devices involved in a HEMS are small from a mass standpoint and relatively basic, resulting in significantly lower environmental impacts for the materials extraction and production phases than we see from the Tesla Powerwall. Based on our results, at this time we would recommend the use of the Energy Star HEMS over the Tesla battery if peak demand shaving is the main goal. However, as both demand side management and energy storage become increasingly important, battery technologies will likely improve. Under current conditions, the materials intensity of batteries has significant environmental consequences that make them hard to justify as an energy smoothing technology. However, as can be seen through this analysis, the relative impacts during the use phase of the Tesla battery is comparable to the use phase of the HEMS. If the materials intensity and production processes for the Tesla battery were to improve, through using less & more common metals for example, the environmental impact may approach that of the HEM S.

Future Research

Directions for Future Research

This life cycle assessment points to several areas in need of further investigation. First, we were unable to compare the impacts of pollutants like SOx and NOx, water depletion, or those on human health due to data limitations. Fortunately, online publications that were utilized for data collection, including tools like *EIO-LCA* and *PackageSmart,* offer estimates on these categories. Future research could use these tools, or other more sophisticated software packages to account for these impacts. Furthermore, the LCAs conducted were limited in scope as the end of use phase was excluded due to data limitations. This last life cycle phase could be incorporated in future assessments. More broadly, it would also be beneficial for future examinations to obtain primary data instead of relying on estimates that add uncertainty to the results, and simultaneously consider the origins of the materials used.

Other questions that can be addressed given the current framework include the compatibility of this study with the possible impacts provided that these systems were to be deployed in other states or countries. Moreover, it would be interesting to extrapolate the results herein to a regional scale; the current study is centered in Los Angeles, California.

Finally, one of the main impacts in energy shaving is the connection to the grid. For the purposes of this research, a continuous grid supply was assumed. However, it has been demonstrated that off-grid systems result in greater economic savings. This would include more comprehensive systems with solar panels and specific electric distribution within the household, along with more advanced components that have been left out of scope such as centralized monitoring systems, or specialized solar panel installations. Regarding the HEMS, it would be beneficial to employ a full-scale system to account for all possible components in quantity and characteristic, and not limit the analysis to the minimum. Last, although information regarding the monetary benefits of these systems is well-documented in literature, the impacts of these have not been previously analyzed. A full-scale life cycle assessment could address these aspects of the system.

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