EVALUATION OF THE IMPACT OF REPURPOSING USED ELECTRIC VEHICLE BATTERIES FOR RESIDENTIAL ENERGY STORAGE SYSTEMS

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EVALUATION OF THE IMPACT OF REPURPOSING USED ELECTRIC VEHICLE BATTERIES FOR RESIDENTIAL ENERGY STORAGE SYSTEMS

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LIST OF ABBREVIATIONS

BEV	Battery Electric Vehicle
DCDC	DC voltage to DC voltage
DOD	Depth of Discharge
EOL	End Of Life
EV	Electric Vehicle
EVB	Electric Vehicle Battery
FCEV	Fuel cell Electric Vehicle
HES	Home Energy Storage
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LMO	Lithium-Manganese-Oxide
MPPT	Maximum Power Point Tracker
PHEV	Plug-in hybrid Electric Vehicle
PV	Photovoltaic
SEI	Solid Electrolyte Interface
SOC	State of Charge
TOU	Time of Use
UPS	Uninterruptible Power Source
V2G	Vehicle to Grid

SUMMARY

Electric vehicles could provide a solution to several major challenges caused by the transportation sector. However, the cost of electric vehicles is a substantial barrier to overcome. As batteries make up a significant part of this cost, one solution is to create a resale value for the used battery. At the end of its life in the electric vehicle, it is expected that the battery will retain 80 % of its originally manufactured capacity. This reduced capacity renders the battery unfit for automobile applications but still provides value for stationary applications such as home energy storage.

Previous studies have suggested the economic benefit of home energy storage is small, but these studies also lack diversity in experimental scenarios. Therefore, this thesis proposes a varied boundary condition approach to model the environmental and economic effects of home energy storage battery reuse from electric vehicles and the additive effects of different control schemes. Some of the variations of boundary conditions in this study involve scenarios such as including solar power or the presence of an electric vehicle.

To offer an additional benefit of installing a home energy storage system, it could be used to provide a possibility to fast charge an electric vehicle at home. As only very few researchers have investigated this new field of application, this thesis investigates in more detail how using the home energy storage system for fast charging influences the economic and ecological benefits, and the availability for fast charging that could be achieved.

Varying control schemes are analyzed in combination with the different scenarios. The control schemes focus on different objectives such as generating profit, increasing energy self-sufficiency, lowering the CO_2 footprint of the household, and increasing the availability of the system for fast charging.

Furthermore, it is investigated, how the performance of a home energy storage system based on reused electric vehicle batteries compares to a system based on newly manufactured cells.

The results from this analysis suggest the battery reuse benefits are heavily dependent on the varying scenarios and control schemes, but overall the results agree with past studies in regard to the economic benefits of home energy storage not outweighing the associated costs. In the best-case scenario through employing a home energy storage system based on a reused battery from a 2013 Ford Focus Electric, a profit of $ 480 per year could be generated.

However, the results also demonstrate that it is possible to significantly increase the households' self-sufficiency as with the reused battery home energy storage system it is possible to reduce the grid energy reliance from 76 % to 62 % of total household energy consumption. Additionally, 15 additional miles may be added from the home energy storage system to an electric vehicle range through fast charging. Overall, the results show that from an economic and environmental perspective, it is far better to reuse electric vehicle batteries in lieu of new batteries for home energy storage solutions. As home energy systems based on newly manufactured batteries are already sold commercially, this underlines the economic and ecological potential that reuse of electric vehicle batteries could offer. Further analysis is needed to determine the effects that degradation has on the battery cells and the user's preferences in the profitability of home energy storage solutions.

CHAPTER 1

INTRODUCTION

1.1 Electric Vehicles as a solution to upcoming Problems

It is estimated that currently there are around a billion vehicles used worldwide [1]. The traditional passenger transport vehicle is commonly equipped with an internal combustion engine, relying on fossil oil for energy input. This has led to various problems:

- The transport sector is responsible for 23 % of globally emitted energy-related greenhouse gases which further global warming [2]
- High air pollution in cities due to the vehicles, which causes health issues that can lead to death. Ambient air pollution kills about 3 million people annually and is affecting all regions of the world [3]
- Oil depletion [4] resulting from over 70 % of the petroleum consumption in the US is used for transportation; petroleum itself accounts for over a third of the energy used in the US [5]
- Energy security is not guaranteed, as many of the resources lie in politically unstable regions and its dependency could become problematic [4]

On top of the already prevalent issues, these problems will be further amplified in the future as the market for vehicles is still steadily growing. In 2017 almost 100 million vehicles were sold globally. [6]

To counter these problems, alternative approaches for designing future passenger transport vehicle are explored with the most dominant concepts being electric vehicles and vehicles using biofuel [7] [8]. In recent years, electric vehicles in particular have gained more and more popularity. The market for electric vehicles is rapidly increasing; the global electric car stock has reached over 2 million vehicles in 2016, and experts estimate a further rapid increase of this number in the future [2].

Although the number of electric vehicles (EV) is rising worldwide, there are still significant challenges that need to be overcome to enable electric vehicles to fully replace vehicles with combustion engines. One of the current major barriers of the EV adoption is the high cost of an electric vehicle compared to a common internal combustion engine (ICE) vehicle [9].

1.2 Reuse of Electric Vehicle Batteries to mitigate high costs

One of the big contributing factors to the high price of EVs, is the expensive battery [10]. The cost of a battery in an electric vehicle can account for more than a third of the total cost [11]. This high battery cost is even more problematic, as the batteries have a shorter lifespan than the vehicles, which makes replacements during the usage of the EV necessary [11].

To overcome the cost barrier of EV vehicles and to further offset the ecological costs of manufacturing the battery, one approach is to find profitable reuse possibilities of the EV battery after the end of its life in the electric vehicle. This could reduce the high initial cost by creating resale value while other advantages would be a reduction in the consumption of resources and a reduced burden of recycling [12].

Because aging mechanisms result in a decrease of the battery's capacity and efficiency, the battery of an EV must be replaced periodically [13], [14]. It is assumed that the batteries will still retain 70 % to 80 % of their capacity at this point, which is considered unfit for electric vehicles [15], [12], [16]. However, as the remaining capacity is still relatively high, there is an opportunity to extend the life of the battery through remanufacturing and reuse. Different reuse possibilities are stationary or semi-stationary storage as well as usage in less demanding mobile applications (for example wheelchairs) [14].

Stationary storage applications are seen as an especially profitable possibility for EVB reuse. As an example of a stationary application, the used EVBs could be remanufactured for home energy storage for residential users [17], [18], [10]. These storage systems could provide different benefits for the users such as:

- Reduced electricity bills through peak shaving and load shifting [17] (more explanation in section 2.3.1)
- Increased self-sufficiency of the home in combination with PV [19], [20]
- Back-up power during power outages [17]

Especially the first two benefits are of higher interest to the average home owner, as power outages are usually quite rare in the US and normally do not last long. For example, in 2015 the average electric utility customer in the US experienced only roughly one outage lasting about 3 hours [21]. Depending on the electrical tariff structure, through load shifting (shifting loads from high utility price times to low utility price times) or peak shaving (reducing peaks to avoid financial penalties) the electricity bill could be reduced by using a home energy storage system.

Additionally, there is a trend towards self-sustainability. Being able to increase the self-sufficiency and reducing the reliance on the grid is one of the major factors motivating people that have solar panels to also buy home energy storage systems [20]. Increasing the self-sufficiency could furthermore result in financial benefits, as there are utility companies that do not offer a feed-in tariff or only at a much reduced rate [22]. In this case, feeding excess solar power into the grid might only be compensated with a fraction of the current electricity rate or not be financially compensated at all. Using home energy storage systems, excess solar power could be stored instead and used later, resulting in a higher self-sufficiency and reducing the energy that needs to be bought from the grid.

However, it is not proven yet if the economic benefits of these systems will be able to pay back the initial costs. One of the major challenges in determining the economic feasibility is that currently not many EVBs have reached their end of life and could be used for experimental testing. Therefore, theoretical models are currently used for exploring the financial and economic impacts of battery reuse. Overall, a majority of studies came to the conclusion, that the financial benefit that could be generated through utilizing home energy storage systems is currently relatively small and usually not high enough to offset initial costs associated with purchasing and installing the system. [23], [18], [24], [25], [26], [27], [28], [19]

As the economics of utilizing these systems to generate an overall profit seem to be challenging at the least, Spence proposed in [29] to include an additional benefit to the user: to offer a possibility to fast charge an electric vehicle through the home energy storage system. Charging time is another major barrier hindering the widespread deployment of EVs, as charging can take several hours which makes the usage of EVs more inflexible than the usage of vehicles with internal combustion engines. Through fast charging, it is possible to charge the vehicle in a fraction of this time, thus having a fast charging system installed at home would be a great convenience to the user. Fast charging systems are usually very expensive so implementing this application into the home energy storage system will give more incentive to customers to install them.

1.3 Research Questions and Methods

This study will explore the financial and ecological impact of adding a home energy storage system based on reused electric vehicle batteries. For this, a household will be modeled which includes a home energy system, an electric vehicle, and solar panels. A whole year will be simulated to cover seasonal differences in solar power generation, outside temperature, and daily load profiles. To evaluate the economic impact, the energy cost for the whole year will be evaluated, while to evaluate the ecological impact, the equivalent CO_2 emissions of the consumed energy within the household will be evaluated. Additionally, the percentage of the EV charging that could be fast charged with the help of the home energy storage system will be evaluated as well. The inclusion of fast charging as a possible application of a home energy storage system based on reused batteries, has not been studied in detail yet.

The model used in this work is based on Spence's battery model [29] which puts a heavier focus on the thermal behavior and management of such a system, as the heat generation inside the battery cells due to fast charging cannot be neglected.

Although in general the economic (and in fewer cases also the ecological) impact of reusing EV batteries for home energy storage systems has been studied before through setting up numerical models, most researchers model one scenario only. As the results seem to be quite sensitive to some of the boundary conditions such as the electric tariff [30] or the inclusion of solar power, it raises the questions if it is possible generalize these results and transfer them to other scenarios. Therefore, the work conducted in this study aims to explore a high number of different scenarios with varying boundary conditions instead of focusing solely on one single scenario. Through this, the results might still not be quantitatively transferable on new use cases; however, they will shed light on the influence of different boundary conditions on their overall impact of the system. Through this, it will be easier to identify possible scenarios that will benefit most from including residential home energy storage systems, and it will indicate the types of cases in which it might not be financially or ecologically beneficial.

The following boundary conditions will be varied for the different scenarios:

- Inclusion of EV in the household
- Inclusion of solar panels
- Electric tariff structure either ‘Flat’ or ‘Time of use rate’
- Inclusion of feed in tariff

Another topic that will be investigated, is the control of the system. Different control schemes are used in the model, and how these control schemes change the economic and ecological benefits of the system for different boundary conditions will be analyzed. Furthermore, if the scenario includes an electric vehicle, how well the system can serve demand for fast charging will also be evaluated.

The following control schemes will be evaluated:

- Maximize self-sufficiency
- Maximize self-sufficiency and keep a reserve for fast charging
- Load shifting and increase self-sufficiency
- Load shifting, increase self-sufficiency and keep a reserve for fast charging
- Load shifting, increase self-sufficiency and keep a reserve for both load shifting and fast charging

Finally, although the financial benefits of utilizing a home energy storage system might still be questionable, the positive response following the introduction of the Powerwall, a home energy storage system manufactured and sold by the company Tesla, has shown that, regardless of the actual profitability, there is demand for such technology [31].

Currently, multiple companies (eg. Tesla, Redflow, LG Chem) offer such products. However, all of these home energy storage systems offered are based on new batteries, purposely manufactured for this application. This study will investigate the inclusion of home energy storage systems in the scenarios for both home energy systems based on new battery cells, and home energy systems based on reused ones. If home energy storage systems based on reused batteries can offer similar benefits to ones based on new battery cells but at a reduced cost, it might be profitable to reuse the EV batteries, as the demand for this technology is there, even though the overall financial benefit of such a system has not been proven yet. In this study all the scenarios that include a home energy storage system will therefore be evaluated for both a new battery and a reused one.

The household that is modeled to investigate these questions will be based on the ReNEWW House, a project between the company Whirlpool, Purdue University, and other industry partners to retrofit a house to make it most energy and water efficient. The ReNEWW House is located in West Lafayette, Indiana. The load profile containing all the consumed electricity as well as the generated solar power for the year 2017 will be used as a base for the model of the household. Additionally, as the ReNEWW House is equipped with an electric vehicle, the data containing the charging times and amount of charge delivered, will also be used as an input to the model.

CHAPTER 2

TECHNICAL BACKGROUND

2.1 Electric Vehicles

2.1.1 Overview

The term "Electric Vehicles" commonly includes all types of vehicles that fully or partially use electricity to create movement such as Hybrid Electric vehicle (PHEV), Battery Electric Vehicles (BEV), and Fuel Cell electric vehicles (FCEV). However, as this thesis is examining the reuse of EV batteries, the focus in this study will therefore only be on electric vehicles which are dominantly using a battery based-technology. These battery-based EV types are mainly Battery Electric Vehicles and Plug in Hybrid Electric Vehicles but, based on the configuration, could also include Hybrid Electric Vehicles. As this study focuses on EV batteries, in the further parts of this study, the term "Electric Vehicle" (EV) will therefore only refer to battery based EV types and will not take other EV types such as FCEVs into account.

In general, the battery based electric vehicles can be classified in the following categories:

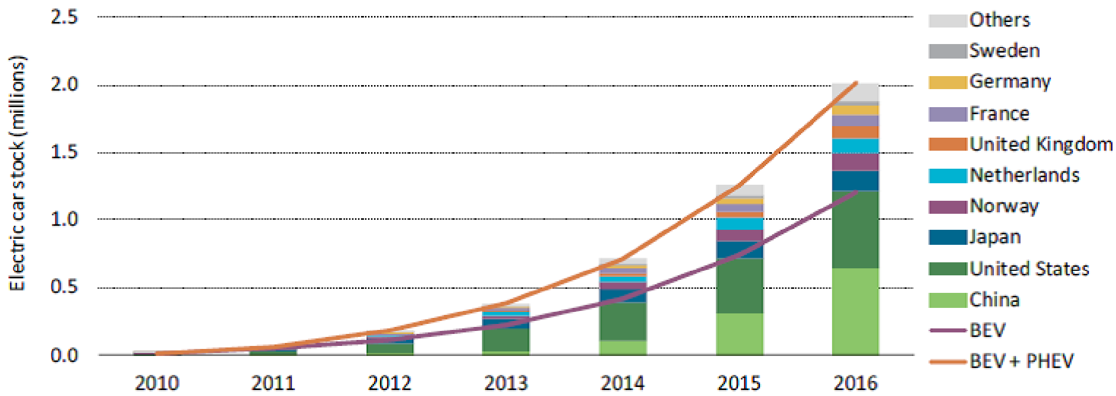
- *Battery electric vehicles (BEV):* These vehicles use an electric motor only which is powered by an electric battery. Batteries for these types of vehicles usually have a high specific energy. [1]
- *Hybrid electric vehicle (HEV):* These vehicles use multiple power sources for their drivetrains such as combinations of batteries and diesel/petrol but also batteries and

fuel cells. It is not uncommon for HEVs to feature both an electric motor as well as an ICE. Batteries for these types of vehicles usually have a high specific power. Typically, the electricity for operating the electric motor is generated through transforming the chemical energy of petrol/diesel into electricity. [1]

- *Plug-in hybrid electric vehicle (PHEV):* This is a form of hybrid vehicle in which the grid-provided electricity is the main source of energy. The battery can be charged from the grid and is mainly used to provide the driving force. The PHEV is therefore closer to the BEV, as it mostly relies on its battery; However, it does have the possibility to extend the range of the vehicle through using an ICE and stored petrol/diesel. [32]

Other types of electric vehicles with a battery-based technology are, for example, Low Speed Electric Vehicles (current global stock approx. 3-4 million), 2 or 3 Wheelers (200-230 million), and Electric Busses (approx. 350,000) [2]. This study will not take these into account; however, results regarding the battery reuse might be also applied to these vehicles as well as they provide an additional source of second hand batteries.

The number of global PHEVs and BEVS is rapidly increasing, reaching a total number for the global stock of 2 million electrical vehicles in 2016. The development of the global electric vehicle stock can be seen in the figure below:



[2]

Figure 2.1: Development of the global number of electric vehicles.

As can be seen in figure 2.1, over the years, the global stock of electric vehicles has rapidly increased, with BEVs (battery electric vehicles) being the dominant portion compared to PHEVs (Plug in hybrid electric vehicles).

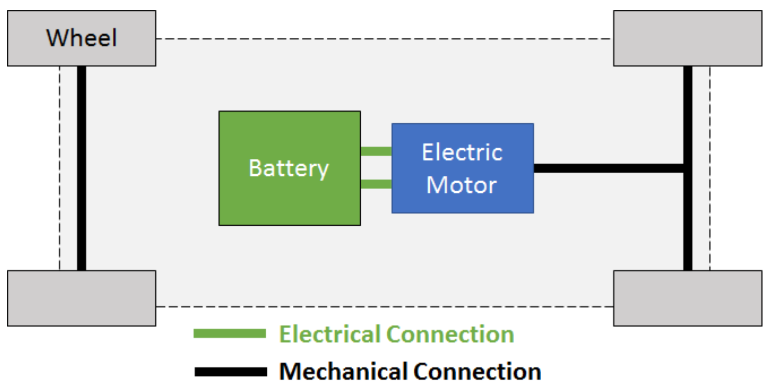
Currently still only 0.2% of the global number of passenger vehicles are electric vehicles. However, this percentage is most likely to increase in the future. In 2016 the annual growth rate of the global electric vehicle stock was roughly 60%. Predictions regarding the future development of the global EV stock see the figures rise to a total amount between 9 million and 20 million by 2020 and between 40 million and 70 million by 2025 [2]. This shows that electric vehicles will likely play a dominant role in the passenger transport sector in the future. In the next chapter, the structure of Electric Vehicles will be explained in detail.

2.1.2 General structure of Electric Vehicles

In this section the general structure of an electric vehicle's drivetrain will be presented. Here the focus will be on BEVs and the HEVs (including PHEVs), as these types of vehicle use primarily an electric battery for energy storage.

Battery Electric Vehicles

The drivetrain of a BEV consists of the following main components: electric motor, controller, battery, and auxiliary system [1], [33]. For BEVs the two most common battery types are nickel metal hydride (NiMH) and lithium-ion (Li-ion) batteries [4]. A schematic layout of the drivetrain's main components can be seen in the next figure:



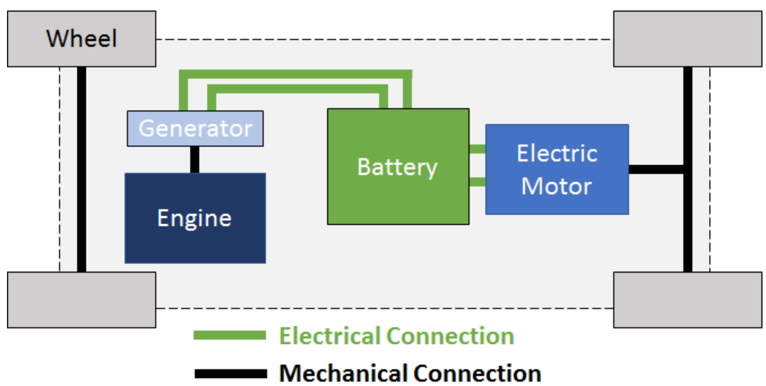
based on [33]

Figure 2.2: General structure of battery electric vehicles.

Hybrid Vehicles

There are many different variations of hybrid electric vehicles which use different combinations of power sources, and the balance between these power sources is varied greatly between different models. The most common combinations are hybrid vehicles featuring electric motors and internal combustion engines. In these hybrid vehicles, the internal combustion engine can be used to generate electricity for charging the battery, so the range of the vehicle does not solely depend on the charge held in the battery. Therefore, the batteries in these vehicles are generally smaller compared to the batteries in BEVs [33]. Most current HEVs use a NiMH battery [1]. The drivetrain of an electric/ICE HEV consists of similar components to the BEV, with the addition of a combustion engine and a generator in the drivetrain. For electric/ICE HEVs two basic configurations are the most common: the series hybrid vehicle and the parallel hybrid vehicle [33]. These two configurations are explained below in more detail.

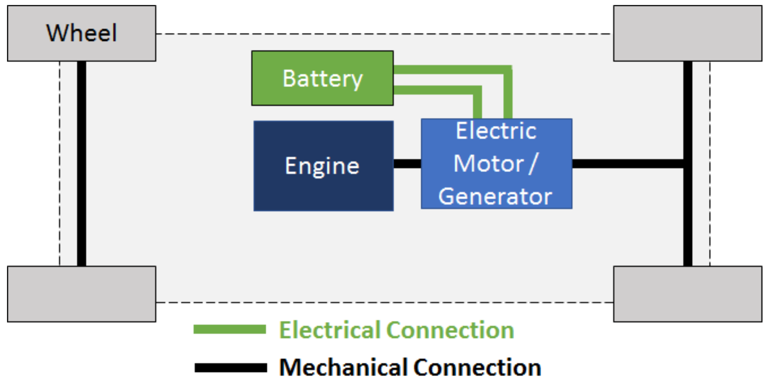
Series Hybrid: In the series hybrid vehicle, the driving force of the vehicle comes from the electric motor only; the ICE is only used in combination with a generator, transforming the chemical energy of the diesel/petrol into electricity, which is then stored in the battery. One of the biggest disadvantages of this configuration is that the energy for providing the driving force must pass through both the generator and through the electric motor, which increases losses [33].



based on [34]

Figure 2.3: General structure of series hybrid vehicles.

Parallel Hybrid: In the parallel hybrid, both the ICE and the electric motor are directly connected to the wheels through a transmission. Through this, the ICE can fully or partially generate the driving force for the vehicle to support the electric motor. [33]



based on [34]

Figure 2.4: General structure of parallel hybrid vehicles.

Plug in hybrid vehicles are a subcategory of hybrid vehicles referring to vehicles whose battery can be directly charged by the grid. Similar to hybrid vehicles, plug-in hybrid vehicles can also be found in both of the configurations parallel and series. Therefore, the schematic outlay follows the ones shown above. Another difference between traditional hybrid and plug-in hybrid vehicles is that usually plug-in hybrid vehicles have a battery energy storage system with a higher capacity. Plug in hybrid vehicles also include a connector which enables the user to charge the battery from the grid. Currently many PHEVs use Lithium-Ion batteries.

2.1.3 Charging of Electric Vehicles

The charging of EVs is classified into three different categories, level 1, level 2, and level 3 depending on the power that can be used to transfer energy from the grid to the battery. These different levels will be explained in more detail:

Level 1: For level 1 charging, a normal standard power outlet is used with 120V and 15 A. This has the advantage that charging on level 1 is possible almost everywhere that a grid connection exists. The charging, however, is quite slow. With an expected power of

1.9 kW it can take 11 to 36 hours to charge a typical EV [35].

Level 2: For level 2 charging, a special 240V outlet is needed. This is the charging level most dominantly used for electric vehicles, as it requires relatively few extra components but provides a significantly higher power than level 1 charging [35]. Currently, level 2 charging provides power of roughly 7 kW [36]. Through level 2 charging, it is possible to charge an EV in 2 to 6 hours [35]. Purchasing a level 2 charger for a residential home currently costs between $ 500 to $ 2,000 before installation [37].

Level 3 / Fast charging: Fast charging or level 3 charging is the fastest charging method but requires expensive electrical equipment. The provided power can be up to 50 kW, which enables a user to fully charge an electric vehicle within 0.4 to 1 hour [35]. Prices for these systems can be quite high, e.g. the Delta EV 25 kW DC fast charger costs over $ 7,000 [38].

Considering a typical EV battery energy, with an in miles conversion rate of 3 Miles/kWh [39] and disregarding potential efficiency losses, the range in miles added per hour of charging can be seen in the figure below:

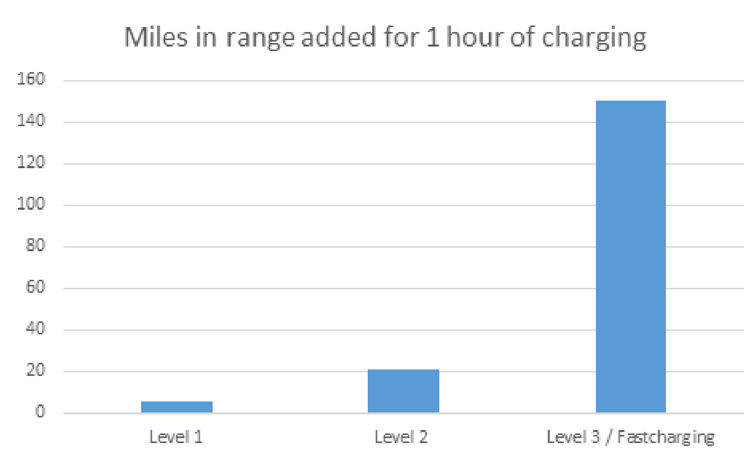


Figure 2.5: Differences in electric vehicle charging levels.

2.1.4 Current Barriers in Electric Vehicle Development

Although the deployment of EVs is rapidly increasing, there are still several issues and concerns that need to be addressed before they can fully replace ICE vehicles. Warner pointed out common barriers in the adoption of electric vehicles [40]:

- *Cost:* Although the price is rapidly declining for Lithium-Ion batteries which are used in BEVs and PHEVs, there is still a lot of room for progress, as EVs are still more expensive than conventional vehicles due to their high initial cost.
- *Availability:* The number of different models is still very limited compared to conventional vehicles.
- *Charging Time:* EV charging takes significantly longer than refueling conventional vehicles.
- *Education:* Electric vehicles are still seen as exotic and unusual. Customers are not yet familiar with the new technology.
- *Range Anxiety:* As EV vehicles usually have a smaller range than vehicles with ICEs and as charging stations are limited, customers are still concerned regarding the electric vehicle's range, and they fear to become stranded.
- *Charging Infrastructure:* As the number and distribution of charging stations still leaves a lot of room for improvement, customers are concerned regarding the availability and convenience of charging possibilities.

2.1.5 Electric Vehicles Battery Packs

One of the main components of a BEV or PHEV drivetrain is the battery. It is especially important, as its performance is directly linked to the vehicle's performance. For a long time, battery technology has not been at an adequate level to support electric vehicles, which was a major hindrance in their deployment. [41]

In BEVs and PHEVs it is currently most common to use Lithium-Ion batteries [42] due to their high energy density compared to other battery technologies. Therefore, this study will mostly focus on this battery technology. Apart from Lithium-Ion batteries, NiMH batteries are also used in electric vehicles. NiMH batteries are mostly used in HEVs as they are cheaper, have an easier availability of materials, a lower environmental impact, and are, generally speaking, safer and more robust towards temperature ranges. [1]

The batteries inside electric vehicles deteriorate over time, which mainly depends on the usage but also on the current lifetime of the battery [43]. Two of the most dominant effects the degradation has on the battery's performance are the decrease in capacity and efficiency [44]. The degradation of batteries will be explained in further detail in section 2.2.4. Due to the degradation, batteries in electric vehicles are supposed to be replaced with a new battery pack once the capacity decreases by 20 %, as a corresponding 20 % decrease of range is seen as unsuitable for users [45]. As most deployed electric vehicle batteries have not reached their end of life yet, predictions regarding their lifetimes are difficult especially as the lifetimes of batteries depend heavily on the vehicle user behavior. An estimate based on the warranties of the batteries that are given by the manufacturers is that the lifespan of a new electric vehicle battery is roughly 8 years [44].

According to EU laws, car manufacturers are responsible for their products at the end of lives (financially or physically). The intention of these laws is to increase the recycling, reuse, and remanufacturing of products. This also includes the EV battery [46]. This regulation affects car manufacturers in the US as they manufacture and sell their products globally. It is also possible for US laws to adopt these regulations in the future.

Due to the mentioned responsibility of the manufacturers to either remanufacture, recycle, or dispose of the product, and considering that recycling and disposal can be costly, remanufacturing would be the economically best choice. Additionally, it would be advantageous to create resale value for the used batteries, especially as the cost of a battery in an electric vehicle accounts for more than a third of the total cost, and the battery needs to be replaced in the EV periodically [11]. This could help to decrease the cost of new batteries by either retaining value through recycling or through remanufacturing and reusing.

Recycling of Electric Vehicle Batteries

Zeng et al. reported in 2013 that, although a lot of progress had been made in research regarding recycling of used EVBs, no recycling process has matured yet. All processes have either been in pilot or laboratory scale. [47]

Usually a large amount of valuable metal is needed for producing Lithium-Ion batteries. The metals inside a Lithium-Ion battery include aluminum, iron, copper, lithium, cobalt, nickel and manganese. Recycling efforts for Lithium-Ion batteries focus mostly on the recycling of the valuable metals [48]. Cobalt is the rarest and most expensive of the metals inside, and consequently current recycling efforts have been mostly driven by the recovery of this metal. One of the problems regarding the recycling of Lithium-Ion batteries is the high temperature that is needed for the recycling process, which can make the extraction of individual elements very difficult. At the moment the costs for recycling certain elements such as Lithium are higher than their current market price, which makes recycling economically infeasible [46]. However, this might change in the future if shortages lead to increasing prices [4].

Although recycling of batteries has increased over the last years, the Guardian reported in 2017 that, in the EU, only 5 % of Lithium-Ion batteries are recycled. It should be noted, however, that this number accounts for all Lithium-Ion batteries, and not just the ones used in electric vehicles. Many of these Lithium-Ion batteries are parts of consumer electronics which users could have simply forgotten to recycle. Due to the size and weight of EV batteries, however, it can be assumed that this will not happen for these and that the recycling rate of the EV batteries will be higher. As the manufacturer is responsible for collection and recycling of the EV batteries in many countries, this has already led to manufacturers investing in facilities for Lithium-Ion battery recycling. [49]

Remanufacturing of Electric Vehicle Batteries

As was explained above, recycling of the battery is currently an economically infeasible option. Apart from disposal, a different path for the EV battery at its EOL would be remanufacturing for reuse. For a product's end of life, this is generally seen as the most environmentally friendly possibility. Possible benefits of this are the reduced resource use and reduced emissions connected with the production of an equivalent new product. According to Gutowski et al. there are three main requirements for successful remanufacturing. The first one is that at the end of life, the product must have significant residual value. The second one is that the collection of the retired product is possible for the remanufacturing firm within reasonable effort and cost. The third is that it is possible to restore the product to a usable condition with an economically feasible effort. [50]

Batteries are one of the most expensive parts of electric vehicles. Although they deteriorate over time they still retain around 80 % of their capacity at their end of life. This makes them not suitable for usage in electric vehicles but still opens possibilities for usage in less demanding applications, such as for stationary or semi-stationary energy storage [14]. Therefore, the first requirement that the product needs to still have significant value at its end of life is very certain.

The second requirement regarding the possibility of recollection is also very likely to be fulfilled. Due to the size and weight of these batteries, it is very unlikely that any owner of an electric vehicle will be able to dispose of the battery without any commercial facility to assist. Adding the fact that the recycling of the battery is currently economically expensive and (at least according to EU law [46]) the manufacturer is responsible for it, this will create an incentive for the vehicle owners to return the batteries to the manufacturer (or a similar facility offering to take the used battery) so that the current owners of the batteries do not have to take care of the battery disposal themselves.

The third requirement regarding the possibility to restore the product to a usable condition is more difficult to evaluate. Due to the mentioned aging of the battery (which will be explained in more detail in chapter 2.2.4), it will not be easy to bring the battery to an equal-to-new state. However, as mentioned above, it would be possible to reuse the batteries in less demanding applications, such as stationary and semi-stationary applications.

Possible reuse applications for Electric vehicle batteries that have been identified by different researchers include:

- *Home Energy Storage:* Retired EVB could be used in home energy storage systems to provide benefits such as: Back-up power in case of power outages, peak shaving, load shifting, and decreasing the grid dependency by increasing the self-sufficiency in combination with solar power. [45], [17], [13], [30]

- *Community Energy storage:* Similar to home energy storage systems, centralized located reused EVBs could provide benefits to communities. This could help to distribute the cost and increase the utilization of the storage systems. [45]

- *Electric Supply Applications:* Applications regarding the regulation of electric supply such as shifting the energy from off-peak hours to on peak hours and offering capacity to balance sharp increases in demand. [45]

- *Helping Integration of Renewable Energy:* As renewable energies tend to be unpredictable in behavior, and their peak generation time might not overlap with the time of peak demand, implementing energy storage systems could help to increase the consumption of renewable energy. [51]

- *Grid System Applications:* Benefits for reuse of Lithium-Ion batteries in grid system applications could be: supporting transmission through back up power and increased capacity, transmission congestion relief, transmission and distribution upgrade deferral, and back-up power for substation and control devices. [45]

- *Creation of Offgrid - Systems:* Reused EVB could be used in combination with, for example, solar panels to create off-grid systems such as off-grid charging stations for EVs. This could help the deployment of EVs as with such a system, users could access a charging station even at remote locations. [52]

It should be kept in mind that most of these reuse applications have not been studied in detail regarding their economic and technical feasibility. Since the deployment of EVs is just beginning, there are few mass manufactured EV batteries that have reached their end of life and could be used for testing. Therefore, experimental studies of battery reuse are rare, and most of these applications are just developed in theory and need to be explored in practice before there can be any judgment regarding their feasibility. Overall, researchers studying reuse applications concluded that it is very likely that economically feasible applications exist [14], [53], [30], [24], [13]. However, these conclusions vary a lot depending on the individual settings and assumptions. A detailed literature review will be presented in chapter 3.

Furthermore, different researchers also pointed out the various barriers that must be overcome before a systematic reuse of EVBs can take off on a larger scale. These barriers include:

- Uncertainty regarding economic feasibility of different reuse applications.

- There are complex and adverse regulatory structures regarding Lithium-Ion batteries that restrict the possible reuse cases and complicate business models. [54]

- There are liability concerns regarding who will be responsible for the second-life battery as the original manufacturer warranty usually only covers the first life and the manufacturer will not give any warranties for second use applications that were not foreseen during the battery's design. [54]

- There is a lack of data about the battery's performance, both for its first life and for its second life [54]

- Non-standardized battery modules and different loads depending on the electric vehicle usage, which leads to varying State of Health (SOH) can make it difficult to match modules with similar capacity for second use. [17]

- Used batteries might have a lower perceived value in the eyes of the consumers even if the performance is similar to new ones. [17]

- There will be uncertainty for the customer regarding the quality of the remanufactured battery [9]. Especially as the quality heavily depends on the use patterns during the first life, and as assessment of the current battery quality would be very difficult for users without special knowledge regarding lithium ion batteries, this might deter potential customers to invest in these.

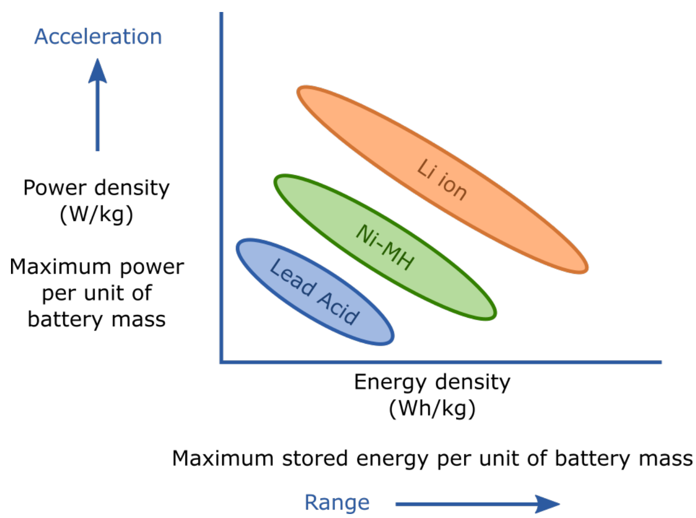
However according to Cready et al. although it might take time until a widespread reuse of EV-batteries is achieved, there do not seem to be any issues that could not be resolved. [17]

Several car manufacturing companies such as GM, Toyota, BMW, and Renault are already researching EVB reuse possibilities for applications such as power supply or renewable integration [55]. The car manufacturing company Nissan is also doing research in this area, specifically on home energy storage systems based on reused EV batteries [49]. This application of reused EVBs will also be explored in this study. As car manufacturers are already interested in the remanufacturing of the EV batteries, it can be assumed that reuse will play a role in their future life cycle.

2.2 Lithium-Ion Batteries

2.2.1 Overview

Lithium-Ion batteries are the currently dominating battery type for BEVs and PHEVs [56], [41]. This is mainly due to their ability to output high energy and power per unit of battery mass [57]. As can be seen in figure 2.6 Lithium-Ion batteries have the highest power density of all currently relevant battery technologies.

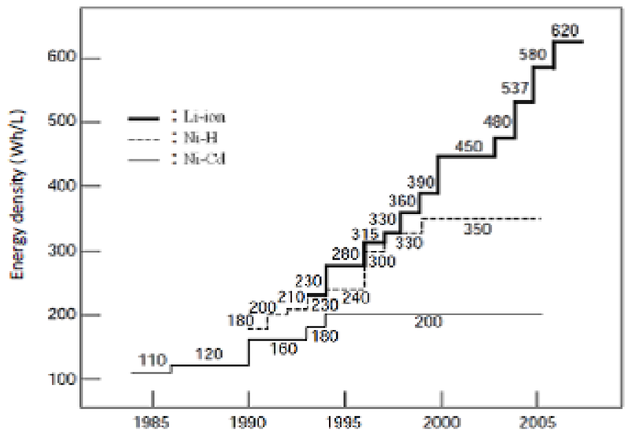


[57]

Figure 2.6: Comparison of different battery technology.

Not only do Lithium-Ion batteries achieve a very high energy density compared to other battery technologies, advancements in the technology of Lithium-Ion batteries have led to a rapid increase in this parameter over the years, as can be seen in figure 2.7. This is not the case for other more mature battery technologies such as the ones based on nickel cadmium

(Ni-Cd) and nickel metal hydride (Ni-MH). For these batteries, the energy density has stayed mostly the same since 1995 and 2000 respectively. Thus, it can be assumed that Lithium-Ion batteries still show potential for further advancement which could strengthen their dominance even more. [57]



[57]

Figure 2.7: Development of the energy density in Lithium-Ion battery technology.

Compared to other battery technologies used in EVs, such as lead acid and nickel metal hydride batteries, Lithium-Ion batteries also display high energy efficiency, no memory effects, and a relatively long cycle life, which contributes further to their popularity in BEVs and PHEVs [57]. Apart from their dominant usage for BEVs and PHEVs, Lithium-Ion batteries are also dominating the battery market for high end electronics and power tools [41].

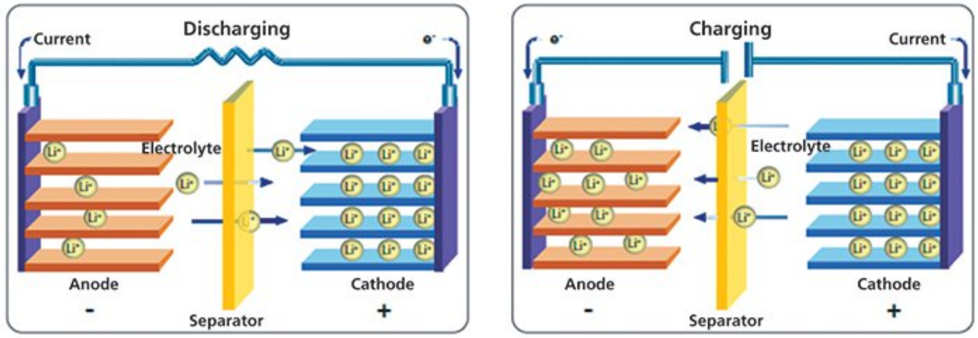
One of the issues of Lithium-Ion batteries is the availability of Lithium. However, studies show that the current known global reserve of Lithium would be more than enough to replace all the world's current vehicles with EVs that include Lithium-Ion batteries. Furthermore, adding that there was also found a seemingly unlimited amount of Lithium in sea water, and that there is the possibility to recycle Lithium from used batteries, material scarcity of Lithium should not be a limiting factor for EV deployment. [41]

Another issue of the Lithium-Ion battery technology is the high cost of the battery, which adds a significant amount to the total cost of the EV, especially as the battery also has to be replaced approximately every 8 years [44]. However, the cost for this battery type is rapidly decreasing, with prices higher than $ 1,000/kWh in 2007, falling to around $ 300/kWh in 2015 [56]. Therefore, it can be assumed that with further development and production scaling, the cost will decline even further. Additionally, this work will examine the possibilities of reusing the batteries, which will add some resale value to the battery price to further decrease the overall cost.

Furthermore, the safety of Lithium-Ion batteries is also a concern. This topic will be explored further in section 2.2.5.

2.2.2 General Structure and Properties

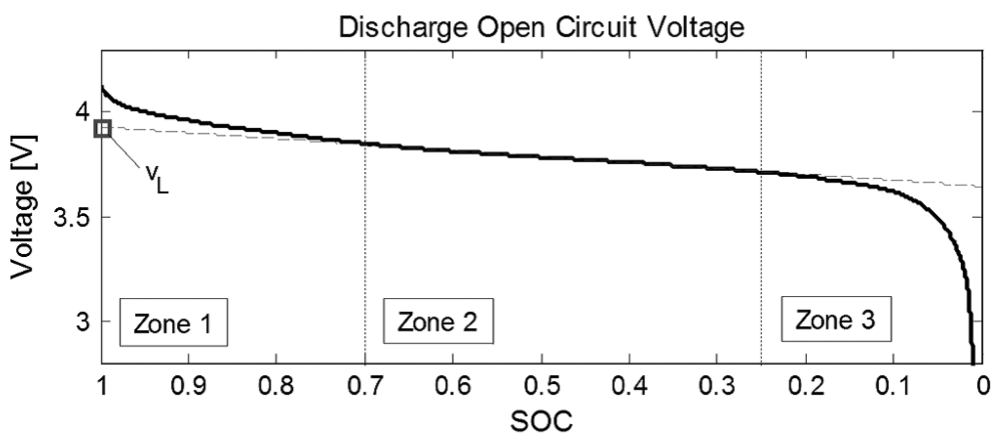
Lithium-Ion batteries are able to store and release charges by moving lithium ions between the anode and cathode, which creates a flow of electricity. During the discharge, Lithium is ionized at the anode, which liberates an electron. The lithium ions are emitted into the electrolyte, cross a porous separator and attach to the cathode, which consists of lithium metal oxide. During this process, the electrons that are released at the anode create an electric current and can be transmitted to outside electric circuits. As this process is reversible, the battery can be charged in a similar process but in a reversed order. In the charging cycle, lithium ions are emitted from the cathode to the anode [57]. A figure depicting the basic components and the discharging process can be found in figure 2.8.



[58]

Figure 2.8: Charging and discharging in Lithium-Ion batteries.

The delivered voltage of the cells depends on the battery's current charge stored within the battery. With a decreasing state of charge, the open circuit voltage of the battery decreases as well as can be seen in figure 2.9:



[59]

Figure 2.9: Open circuit voltage over SOC.

The discharge curve can be split into three zones, as can be seen in the previous figure. In zone 1, the voltage curve starts with a steep decrease in voltage over state of charge, which slowly flattens until the voltage curve reaches an approximately linear dependency on the charge in zone 2. In zone 3, the voltage drastically decreases again with a decreasing charge.

As can also be seen in figure 2.8, there are four main components in the battery cell, the anode, the cathode, the electrolyte, and the separator [57]. In the following paragraph, these components will be explained in more detail.

- The anode's function is to emit lithium ions during discharging and receive and store lithium ions during charging. A common material for the anode is graphite powder. [57]

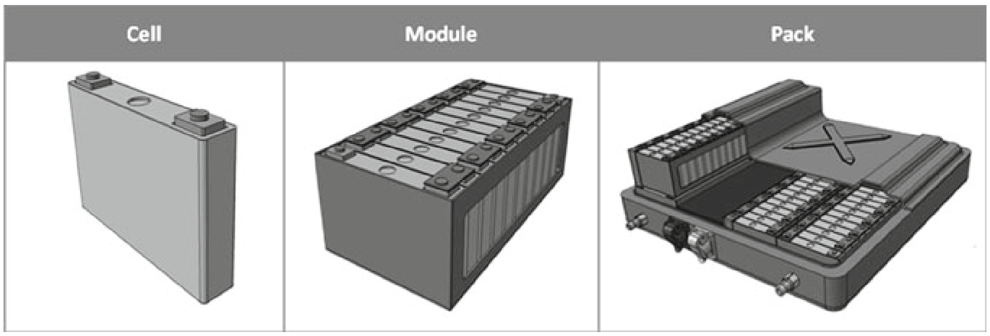
- The cathode's function, opposite of the anode's: to receive lithium ions during discharging and emit lithium ions during the charging process. A common material for the cathode is lithium metal oxide powder. [57]

- The electrolyte enables the lithium ions to move between the anode and the cathode. The electrolyte is usually made out of lithium salts and organic solvents. [57]

- The separator's function is to separate anode and cathode to prevent a short circuit. The lithium ions can pass through ores in the separator. The separator is made out of a micro-porous membrane. [57]

According to Thaler and Watzenig, individual cells usually have a voltage between 2.5 V and 4.2 V. To reach the voltage necessary to power the electric motor in EVs and PHEVs, several hundred cells are connected in series. To increase modularity and to support the assembly, the cells are first assembled into modules containing multiple cells. The modules still have a relatively low voltage, size, and weight that can be handled by individual workers. [60]

These modules are then assembled into battery packs containing multiple modules, as can be seen in figure 2.10. Apart from the modules, the battery packs also include battery management systems and other support structures such as safety disconnects or cooling systems [57]. There can also be an additional modularization step in which modules are grouped into several arrays before inserting them into the battery pack.



[60]

Figure 2.10: Modularization levels of electric vehicle batteries.

The cell chemistry can vary for different Lithium-Ion batteries. There are multiple common materials that can be used for the electrodes. Especially for the cathode, there are multiple different material choices, and the name of the cell chemistry usually refers to the cathode material.

Typical materials for the cathode can be found in the following list (taken from [61]):

- Nickel-manganese-cobalt (NMC)
- Nickel-cobalt-aluminum (NCA)
- Lithium-iron-phosphate (LFP)
- Lithium-titanate (LTO)
- Lithium-manganese-oxide (LMO)
- Lithium-cobalt-oxide (LCO)

2.2.3 Common Battery Parameters and Abbreviations

Some of the typical parameters and important abbreviations regarding EV batteries will be explained in this section:

End of Life (EOL): The EOL of the EV battery is usually reached once the maximum capacity has decreased to 80% of its original amount. As the capacity and the power of the battery is decreased, the acceleration (defined by the battery's power during discharge) and range (defined by the battery's capacity) is deemed as unsatisfactory for the user and the battery is replaced. [34]

Depth of Discharge (DOD): Depth of discharge measures how much of the battery pack's nominal capacity will be used for the application. Usually only charges and discharges bounded by thresholds at 20% and 90% of the battery's total capacity will be made. The upper limit is to prevent overcharging, which can lead to degradation of the battery while the lower limit is set to ensure that the voltage, which decreases during the discharging process, will remain at a certain level that is feasible to run the application with [34]. An alternative to this definition is by Young et al. [62] defining the DOD as the percentage of the rated battery capacity that is currently discharged. However, this second definition will not be used in this study.

State of Charge (SOC): The state of charge measures how much effective energy is left in the battery at a specific point of time. It can be measured as a percentage ranging from 0% to 100% against the DOD [34] or as a percentage against the total rated capacity of the battery [62]. In this study the definition by Young et al. will be used, namely that the SOC gives the current state of charge as a percentage of the rated capacity, regardless of the DOD.

State of Health (SOH): This measurement denotes the current state of health of the battery. However, there is no standard definition for this, as different researchers and companies define this value differently. Generally speaking, SOH indicates how much time is left until the battery reaches its end of life. [34]

2.2.4 Degradation Mechanism

Aging of Lithium Ion batteries results in general in capacity decrease and power fading, which can be caused by various mechanisms and interactions inside the cell [63]. Additionally, the aging also leads to an efficiency fade [44]. In general, battery aging is a very complex mechanism that depends on the individual composition and cell chemistry. In this section, the most dominant degradation mechanisms will be presented following the work of Vetter et al. [63].

A battery cell's aging processes depend on the cell's current lifetime, which will affect the battery's calendar life. The aging processes also depend on the battery usage, which can additionally limit the cycle life. Aging at the anode differs significantly from aging at the cathode [63]. It will therefore be explained in different sections. Also, the electrolyte ages and, as this happens mainly at the electrodes, it will be explained in connection to the degradation at the electrodes.

Aging at a Graphite Anode

As mentioned before, the aging mechanisms are very complex and depend a lot on the individual cell's chemistry and components [63]. As graphite anodes are very common in Lithium-Ion batteries, the aging mechanisms will be explained for this type of anode.

In general, the most dominant aging process at the carbon anode takes place at the electrode/electrolyte interface during cycling. The anode operates at voltages at which the electrochemical stability of the electrolyte is not given anymore. This leads to reductive electrolyte decomposition and irreversible consumption of lithium ions at the interface of the electrolyte and electrode during charging. The products of this decomposition build up on the electrode's surface and form a protective layer which then stabilizes the interface. Thus, this layer build-up occurs for new batteries most dominantly at the start of the charging process during the first cycle. This layer at the interface, where lithium ions transport into or from the graphite structure, is called the solid electrolyte interphase (SEI). [63]

The build-up of the SEI leads to an impedance rise which is related to the power and efficiency fade and can change the charge/discharge curves. The formation of the layer is also linked to capacity fade and self-discharge. Further growth of the SEI increases the fade even more. Furthermore, as some diffusion through the SEI of electrolyte components is still possible, it can lead to further corrosion of the anode and capacity loss, decomposition of the electrolyte, and growth of the SEI during cycling and storage. Therefore, this process will continue during the entire battery life but only at a very reduced rate after the first formation of the SEI. During high temperatures, however, the SEI layer can break down, which removes the protection and again leads to increased aging. The properties of the SEI depend on the cell chemistry. [63], [44]

There are also further aging mechanisms at the anode, such as changes in porosity, contact loss of active material particles, decomposition of binder, that can change the active material and composite material and thus can contribute to cell ageing. During low temperatures, metallic lithium plating and the growth of lithium spikes, so called lithium dendrites, can occur [63]. This accelerates the aging processes and can decrease the safety of the cell [64]. Processes during storage, such as the formation of metastable electron-ion-electrolyte complexes, can lead to additional capacity fade [65].

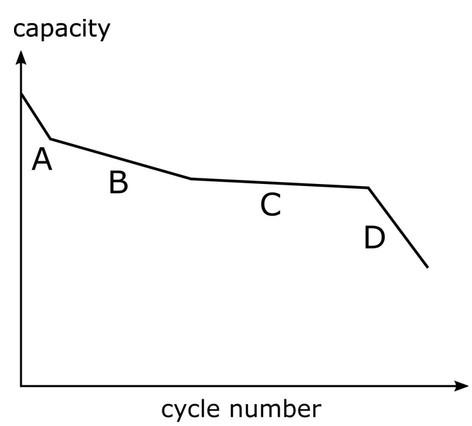
Thus, in general, the most noticeable effects of aging at the anode are capacity fade, power fade, and efficiency fade [63], [44]. The aging processes are enhanced by high temperatures, low temperatures, overcharge and over discharge, high cycling rate, poor cell balance, and high DODs [63].

Aging at the Cathode

The aging mechanisms highly depend on the individual electrode composition, cell chemistry, cycling, and storage conditions which can vary quite a lot depending on the manufacturer. In general, the following aging mechanisms can occur here: Aging of active material, degradation of electrode components and oxidation of electrolyte components. The most dominant effect aging at the cathode has on the batteries performance is capacity and power fading. [63]

Effects of aging on the Batteries Performance

As was explained before, the main effects of aging on a battery's performance are capacity fade, power fade, and efficiency fade. The typical curve of the capacity fade over cycling can be seen in the next figure:

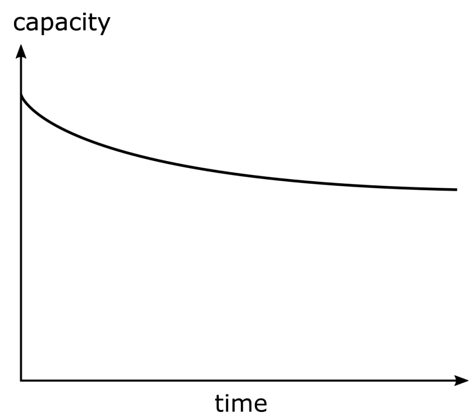


[66]

Figure 2.11: Capacity fade over cycling.

As can be seen in figure 2.11 at first the capacity decreases at a high rate with the number of cycles in section A, afterwards the decrease continues but at a lower rate in section B. In section C the rate of the decrease is even lower than in B, reaching a “knee” at the end, after which, in section D, the capacity decreases again at a very high rate.

The typical curve for capacity fade over calendar life can be seen in figure 2.12. At the beginning, the capacity decreases at a higher rate over time; however, the curve quickly flattens out.



[66]

Figure 2.12: Capacity fade over time.

Both capacity fade mechanisms can be active at the same time. The capacity fade due to cycling is usually the more dominant effect; however, this depends on the individual conditions of use.

2.2.5 Safety of Lithium-Ion Batteries

One of the major concerns of implementation and management of Lithium-Ion batteries is the safety aspect [67]. There have been some prominent cases in media of malfunctioning Lithium-Ion batteries where one example ultimately lead to the recall of 2.5 million Samsung Galaxy smartphones [68]. Considering however, the high number of globally used Lithium-Ion batteries, there have been very few incidents, relatively speaking, where harm was caused in terms of damage or personal injury [67]. One of the issues of Lithium-Ion batteries is that if they do fail it can create very serious and dangerous situations. In the worst-case scenario, malfunctioning Lithium-Ion batteries can combust into flames and explode. This scenario is often called a thermal runaway.

The thermal runaway is an exothermal reaction between the electrolyte, anode, and cathode [69] that can occur under certain abusive conditions [42]. One of these conditions is if the cell temperature increases over a certain limit. This accelerates the chemical reactions which themselves will increase the temperature even further and can lead to an emission of smokes and flames [67] or lead to an explosion of the battery cell [18].

However, as Armand and Tarascon pointed out, accidents regarding thermal runaways have generally not been a failure of the technology as such but mainly a result of fierce cost-cutting and decreasing safety margins, which lead to internal short-circuits [41]. Currently, cases of unprovoked malfunctioning of Lithium Ion batteries are extremely rare, and due to efforts from manufacturers, equipment designers, and regulatory agencies, the safety of this battery technology is even further increasing [70].

In a battery pack there are usually several levels of safety systems in place. The first is, on the cellular level, where the appropriate materials have to be chosen, cell safety mechanisms (such as internal vents, current interrupt devices,. . .) have to be implemented, and strict Quality Control measures have to be applied. On the pack level, safety circuits are implemented for protection against overcharge or over discharge, and additional secondary safety components are included that monitor the pack's temperature, voltage, and current. Furthermore, charge control mechanisms are implemented on the system level to ensure a stable and safe charging process. The final level is the environment and interaction with the end-user, which includes identifying the environmental conditions and influences and also the mitigation of foreseeable misuse of the product. [67]

2.3 Home Energy Storage Systems

2.3.1 Overview

Energy storage systems can be used to decouple energy supply from demand, which creates flexibility in the choice of primary energy sources [71]. This is becoming increasingly important as energy production is shifting from traditional power plants using coal and oil to renewable energy sources [5]. In this chapter the focus will be on one of the more prominent renewable energy generation technologies, which is harnessing solar power, and, in a lesser degree, the focus will also be on harnessing wind power. Other technologies for renewable energy generation such as biofuel or hydroturbines will be excluded in this section, as they can show a very different behavior in many of the addressed aspects.

One of the characteristics of wind and solar power is their high volatility in electricity generation and their unpredictable behavior short-term to medium-term [27]. There are different strategies to counter these problems. One is to install additional power plants, so called peaking power plants, with electricity generation rates that can be quickly adjusted [72]. However, this means that the supplemental power plant will be rarely used for its full potential, which lowers the efficiency of the electricity generation, especially when the economic and environmental costs of building the plant are also considered. Another strategy is demand management, which refers to the change of the electricity demand to match the current supply [72]. However, this means the users have to change their behaviors and use patterns which can be difficult to achieve. A third possibility that could be used to overcome these challenges is to save energy in energy storage systems [72]. With these, energy can be stored during times where the energy supply is larger than the energy demand and discharged when the energy supply is lower than the energy demand. This might not fully replace supplemental energy generation facilities to balance longer periods of mismatch between supply and demand but would certainly help to balance the short-term volatility of the energy production from renewable sources.

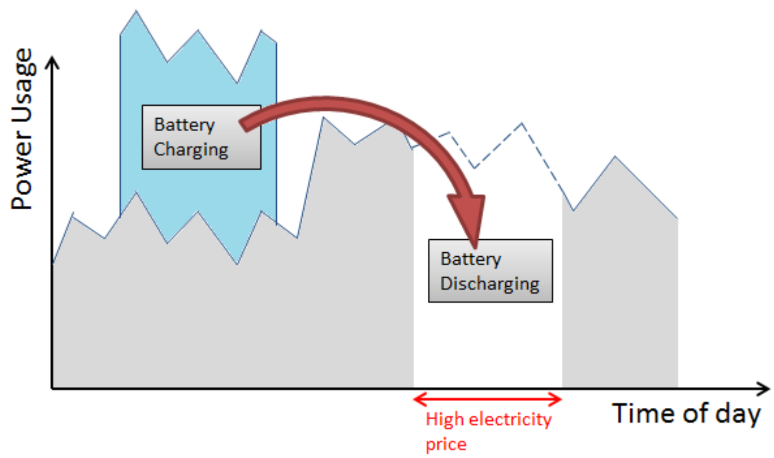
The importance of smaller scale energy storage systems is rapidly growing. Electricity generation is increasingly done on a more local level, where it is not uncommon that the producer self-consumes most if not all the electricity generated. During the last years the sale and installation of residential rooftop solar panels in the US has rapidly increased, reaching numbers of over 2 000 MW solar capacity being newly installed during each year since 2015 [73]. Reasons to install solar panels are the rising costs of electricity and the desire for self-sufficiency [74].

However, to reach 100% self-sufficiency, the solar panels or the wind turbine must be massively oversized. And even then, it is very difficult for individual households to reach full self-sufficiency, as there will always be downtimes (e.g. during the night for solar panels, during windless times for wind turbines). For example, it has been estimated that by just relying on solar power panels, the self-sufficiency of an individual household can only be 40% [19]. This leads to an increasing demand for home energy storage systems which would allow the user to store excess energy during peak production times for later self-consumption. Studies have shown that by utilizing both solar panels and home energy storage systems, it is possible to increase self-sufficiency up to 80% while maintaining a reasonable system cost and size [19]. However, it was also shown that it is not advantageous to increase the self-sufficiency even further, as this could only be done by massively oversizing the system: The battery connected PV system fails during time periods with extreme conditions, such as during the winter when a lot of energy for heating is needed but, due to unfavorable weather, the energy generation is not sufficiently high. During these times energy still needs to be imported by the grid or needs to be generated by using generators that rely on fuel [75]. Even though 100% self-sufficiency is not feasible even with including batteries to the residential PV system, home energy storage systems still play an important role in increasing the self-sufficiency of households and will also facilitate the deployment of renewable energy generation systems.

Apart from increasing the self-sufficiency of the household (and thereby reducing the dependence on the grid, which could be particularly beneficial for very remote locations without any grid access) further benefits of home energy storage systems are supplying back-up power in case of power outages and using the storage system to optimize the electricity imported from the grid in regards of economic and ecological benefits. [17]

There are several ways to optimize the household load for economic benefits utilizing a home storage energy system, and the profitability depends heavily on the specific electrical tariff. Two of the more common methods are peak shaving and load shifting [17]. Peak shaving can be economically feasible when the electricity bill depends on the largest load peak during a specified period of time. An energy storage system could be used by supplying the household with energy during this peak and thus lowering the electricity bill significantly. In this scenario the energy storage system has to be charged during off peak times. The other strategy, load shifting, could be utilized if there are different rates for electricity during different times of the day. The energy storage system could be charged during low-price times and could then supply energy to the household during high-price times. If the electrical tariff offers net metering, which means feeding energy into the grid is fully reimbursed with the current electricity rate, the battery could even discharge into the grid during high-price times thus creating a profit.

In figure 2.13 and figure 2.14 the two different strategies can be seen. These application strategies do not depend on having an energy generation technology, such as solar panels, installed. Installing an energy storage system by itself might already provide economic benefits.



based on [76]

Figure 2.13: Load shifting.

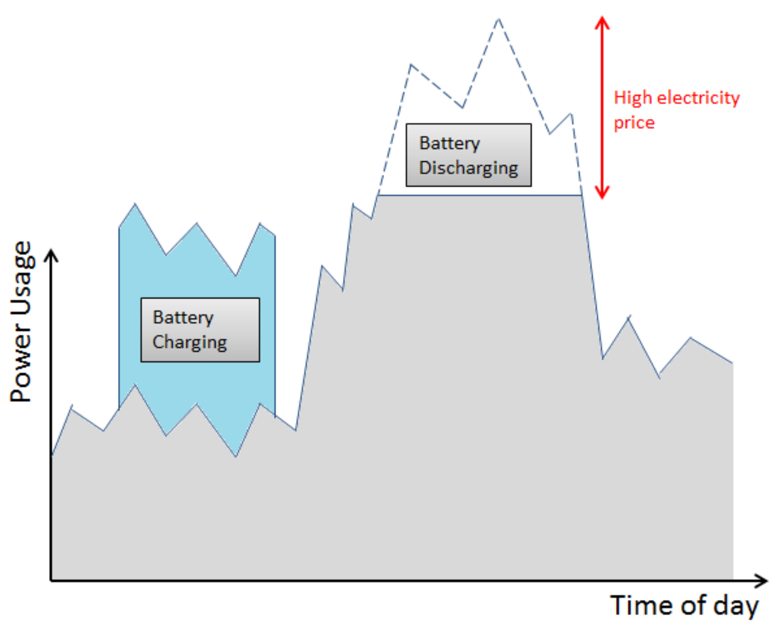


Figure 2.14: Peak shaving.

In combination with solar panels, these strategies could increase the economic feasibility even more, as the produced energy could be stored first and discharged in a pattern optimized to the load profile and tariff structure. Also, financial benefits can be obtained with adding a home energy storage system to installed solar panels if no feed in tariff applies to the household. This means that any excess power generated through the solar panels would be fed in to the grid with no financial compensation. Through utilizing a home energy storage system, the excess energy could be stored instead and used during times where the household energy demand is higher than the solar power generation.

Although the market for home energy storage systems (HES systems) is quite new, an increase in the number of households implementing an HES system can be expected [30]. Currently there are already several companies offering home energy storage solutions including the Powerwall 2 from Tesla [77], the ZCell from Redflow [78], or the RESU battery from LG Chem [79]. Tesla's introduction of the Powerwall in particular, has lead to a rise in the popularity of these systems, and it can be safe to assume that the market will strongly increase in the future.

CHAPTER 3

LITERATURE REVIEW

This section will give a brief overlook on the current research on the topic of home energy storage systems and on reusing EV batteries for stationary storage. First studies regarding the EV battery reuse in home energy storage applications will be summarized, afterwards studies evaluating the profitability of HES systems in general are presented.

3.1 Electric Vehicle Battery Reuse for Home Energy Storage

Spence investigates the reuse of EV batteries in a stationary application in residential households. He proposes to offer not only the conventional benefits of an HES system but to additionally provide a possibility to fast charge an EV with such a system. Spence creates a model of a household using an HES system based on a reused EV battery. The focus of his study is on thermal management, including the heat generation and the cooling system. The HES system's performance was evaluated or different battery types, cooling systems, load profiles, and city of residence. The main conclusions are that the application of a reused battery HES system is possible under the evaluated conditions while maintaining a safe operating temperature inside the battery. During fast charging, an active cooling system is necessary to prevent overheating; during normal load shifting, passive cooling would be sufficient. An optimistic outlook regarding the future use of such a system was given, as implementing the vehicle fast charging functionality seems possible from a thermal management perspective, and such an additional application would increase the system's attractiveness to consumers and thus increase the demand for reused EV batteries. The model created by Spence will be further used in this study with some adaptations to allow an investigation of this study's research questions. [29]

Tong et al. created a study of a single family household in California, with solar panels and a battery storage system based on reused EV batteries. Through setting up a battery management system and experimental testing, it was shown that an increase in self-sufficiency and solar penetration was possible. It was further shown that a home energy storage system could be used in a demand response application with dynamic pricing. Economic or Environmental savings through implementing this system were not further investigated upon. [80]

Saez-de-Ibarra et al. conducted a numerical study of a residential household in Spain with solar panels and an energy storage system based on a reused EV battery. The home energy storage system is used for demand response management. The study gives a suggestion of an election process for an optimal battery size. In the study there is no degradation accounted for in the model and a simplistic lifetime calculation model was chosen. The results of this study show that there are economic benefits for installing PV and battery storage systems in the Spanish electricity market; however there is no information on how much these benefits can be credited to the energy storage system alone. [53]

The study by Beverungen et al. analyzes the requirements and parameters that need to be assessed to decide for what kind of application a used EV battery can be repurposed. This included a Delphi study of experts and analysis of a currently installed proof of concept project of a home energy storage system based on used EV batteries in a residential household. [14]

Cready et al. wrote one of the first more extensive and detailed analyses of potential applications of HES systems based on used EV batterys (EVBs). This includes estimates of economic feasibility in different use scenarios. However, as this work was performed very early in the advancements of EVs, the focus of this study is on Nickel/Metal Hydride batteries, which was the most dominant battery technology for EVs when the study was conducted. [17]

The study by Fischhaber et al. lists potentials and barriers in EV battery reuse and incudes numerical studies considering the reuse of EVB for providing primary balancing power for electricity grids and for home energy storage systems. The case study assumed the HES system to be based on either new or used batteries and considers a household in Germany that is connected to PV. It concluded that using the energy storage for providing primary balancing power to utility companies is economically feasible and the reuse of EVB gives an economic advantage compared to new batteries. However the results for using the batteries for home energy storage are less promising. Although it results in increased self-sufficiency and reduced emission production, it is economically infeasible for both reused and new batteries. [23]

Heymans et al. studied reuse of EV batteries in an HES system application focusing on load shifting. A model of a household in Ontario with an HES system was created, but no solar power was considered in this study. The modeled application results in only marginal economic benefits, which would not justify installing this system. However comparing an HES system based on used batteries to ones based on new batteries, it shows that HES systems with used batteries costs significantly less. Government incentives and favorable electricity tariffs could assist to make it economically feasible. [18]

Kirmas and Madlener created a model of a residential household in Stuttgart Germany with an integrated PV system and HES system. The HES system focused on peak shaving and load shifting. The study showed promising results regarding potential economic feasibility. However it concludes that the profitability heavily depends on the tariff and the price of the used battery, so no general conclusion regarding the economic feasibility or infeasibility could be made. [30]

A study was conducted by Menn regarding implementation of a PV system and an HES system based on reused EV batteries into single and multi-family residential households in

Switzerland. Overall the study concludes that such a system can be economically feasible for multi-family residential households but not for single family households, as the optimal size for the system is too small in these households. The HES systems alone however are not viable in either scenario. The HES system based on reused EV batteries can be more profitable than new systems, depending on its remaining lifespan. [24]

Assunção et al. created a model of a residential household in Portugal with PV and HES systems; different sizes of reused batteries were considered. A baseline model with a system that does not include an HES system was created and compared to scenarios with reused battery HES systems. Results showed that for used battery packs, the payback time was significantly less than its remaining life time. Also new battery HES systems were considered; however for these the payback time was longer than the estimated life time. The self-sufficiency increased significantly with the implementation of the HES system; the economic benefits depend on the selling price of the used batteries. The study concluded that reused batteries can still provide benefits; even after their degradation during first use, their use is economically feasible and it provides better benefits than HES systems based on new batteries. [13]

Walker et al. modeled an HES system based on used EV batteries. The HES system is implemented in a typical household in Ontario and focuses on load shifting. The influence of different parameters such as battery price, electricity tariff and efficiency were evaluated. Overall the study concludes that installing a reused battery HES system does not provide any financial benefits to the household under current conditions. This might change if tariff structures give more incentives, as the installation provides significant benefits for the utilities and electrical operators through load shifting, backup power supply and transmission services. [25]

The study by Aziz et al. concluded both numerically and experimentally that it is possible to use EV batteries in load levelling applications for peak shaving and load shifting to support a building energy management system. Both the reuse of EV batteries and the use of the battery currently used in an electric vehicle, in combination with solar panels, was investigated and both concepts showed promising results from the technical viewpoint. However the economical or ecological feasibility of such a system was not further analyzed. [81]

Casals et al. investigated the reuse of EV batteries in different applications while focusing on their ecological impact. Different reuse scenarios were evaluated such as a standalone HES system for load shifting, connecting HES systems to a renewable energy source to create an island installation and connecting HES systems to both renewable energy sources and to the grid, using the HES system in case the renewable energy source does not generate enough energy. The study concluded that ecologically speaking the reuse of batteries is only profitable in combination with a renewable energy source, as otherwise the decreased efficiency of the batteries will always lead to a worse performance than found in new ones. Furthermore, it was shown that reused Lithium-Ion batteries, in combination with a renewable energy source, are more profitable than new lead-acid batteries. However, the results depend a lot on the chemistries of the reused battery cells, as they have great influence on the degradation and the batteries' performance during possible reuse. [82]

Faria et al. conducted a Life Cycle Assessment of the EV battery. Different first use scenarios were considered; for second use two HES systems strategies were considered: peak shaving and load shifting. It was found that the ecological impact of the reused EV battery depends heavily on the grid electricity mix and the battery's efficiency. The economic analysis showed that the reused battery HES system is only profitable when additional reimbursed grid service applications are implemented. The potential profit depends heavily on the price the grid operator is willing to pay for these as well as the battery capacity that the owner is willing to appoint for this. Comparing peak shaving to load shifting, peak shaving is more profitable, as the capacity required for this is usually smaller than that required for load shifting. [83]

Martinez-Laserna et al. studied the degradation of second use batteries in two different scenarios. The first scenario is in a residential energy storage system used for demand management for a Spanish household connected to PV. The second one is energy storage for power smoothing to integrate renewable energy. The study concluded that depending on the previous use and the respective degradation, EV battery reuse might be challenging for highly demanding applications. It was observed that at a certain point during the cycling, the performance dropped significantly, indicating a change in the dominant aging mechanism. Reuse after this point results in very fast degradation and might not be feasible. Reuse prior to the battery reaching this point however seems to be possible, as the battery still shows very good performance. It was noted that these results were only evaluated for certain battery type and cell chemistry and might not be directly transferable on other ones. [84]

3.2 Economic Profitability of Home Energy Storage Systems

Kono studied the effect of V2G, demand response and community battery storage on micro-grids through evaluating both individual households and small communities containing 10 households over different scenarios. The scenarios included different tariff structures, user behavior, power outages, the presence of EV Vehicles and others. It concluded that V2G, demand response and community batteries can save electricity cost by reducing the peak load and by demand shifting and helping to bridge short power outages. Overall however, the economic benefit for the household is fairly small. [85]

Dodds evaluated an HES system in a household in San Francisco or the UK combined with either a wind turbine or PV. Different battery types were considered and compared with each other. Lithium-Ion batteries had the best performance but due to the high price of this battery type, lead acid batteries were more economically profitable. In general, the study concluded that installing batteries in a household will always be less profitable as selling the surplus energy back to the grid. In island grid systems however, battery energy storage will cost less than running generators to produce necessary energy during the downtimes of the RES. However, no final economic assessment could be made for the implementation of an HES system in both scenarios as the economic feasibility depends on many unknowns. [27]

In the report by DiOrio et al. an HES system for peak shaving coupled with PV is modeled for households in Tenessee and California with different battery sizes. Economic profit through such a system could be achieved in California but not in Tennessee. However, an HES system without PV generates revenue for both locations. In general Lithium-Ion batteries were more economically feasible, but the economic results were heavily influenced by the tariff and other location specific parameters. [86]

Van der Stelt et al. studied the effects of implementing HES systems and community energy storage systems on households in the Netherlands through setting up models. The households were connected to PV and different capacity sizes were considered. While it was possible to increase self-consumption through implementing the storage system, the model showed that none of the systems were economically profitable. To make the systems economically feasible for all scenarios, battery cost of less than 100 €/kWh are needed. If costs are less than 200 €/kWh the systems can be profitable depending on the other parameters. [28]

Uddin et al. conducted an experimental and numerical study of a household in the UK which included PV and a battery storage system. The battery was used to maximize self-consumption. Aging tests of Lithium ion battery cells were conducted and a degradation model was created and verified. The result showed that adding an HES system provided no economic profit compared to selling surplus energy to the grid but rather results in additional costs. The economic loss becomes significant when the cost and degradation of the battery is considered. However, the self-sufficiency was increased and as the solar panels generate clean energy, there were CO_2 savings when an HES system was added. This does, however, not factor in the environmental burden to manufacture the battery, so the overall savings in CO_2 remain unclear. One of the major factors that were identified to lead to economic infeasibility were the degradation of the battery. In the considered model a replacement of the battery would be necessary every 5 years. This high degradation most likely stems from the intensive cycling with a SOC swing of 80%. A battery with a higher capacity might lead to less degradation. [26]

De Oliveira e Silva and Hendrick, studied how Lithium-Ion batteries, used for an HES system and in connection to PV, increases self-sufficiency in Belgian households. A model was created; for the batteries no degradation was considered. With this system a self-sufficiency of up to 80% could be reached. However, such a system would not be economically feasible compared to a grid connected system. To make this setup profitable, not only does the battery cost need to decrease but also all the other components of the HES system. Trends show that the price for these is already declining, so the author is optimistic regarding the future feasibility of HES systems. The author additionally suggest that economies of scale could be used through installing community energy storage systems instead of HES systems. [19]

Reniers et al. created different models for Lithium-Ion batteries, and the predicted degradation of the batteries is compared to experimental data. These models are then evaluated during a load shifting scenario. The results show that the economic feasibility is strongly connected to the degradation of the battery. With a higher accuracy in the model it is possible to decrease safety factors, which increase the predicted profitability. However, in these models no long-term degradation was considered. The evaluation of the degradation was stopped after a simulated time of 3 years, or 4,000 cycles. The simulations predicted an economic feasibility, but the projected revenue was small. [87]

Apart from simulation or experimental studies, also a survey study was carried out on this topic. Agnew and Dargusch studied the consumer preferences regarding HES systems through conducting a survey in Queensland/Australia, measuring the preferences regarding parameters and functionality of residential battery storage. It showed that the main functionality for the customer was to decrease the electricity bill. Furthermore, self-sufficiency, grid independence and creating ecological benefits were also key factors influencing the consumer's decision to invest in an HES system. Most of the survey takers preferred larger batteries that increased self-sufficiency significantly, even if it also meant an increase in cost and payback time. It should be noted however, that the scope of the conducted survey was relatively small; in total 268 people were interviewed for this study. [20]

3.3 Discussion of the Literature

Overall most studies agree that EV batteries offers great potential for reuse and especially the use in home energy storage systems seems to be a possible choice for second life application. The economics of such systems however seem challenging and depend heavily on the individual circumstances. Most studies are made on a theoretical basis, analyzing only one scenario. This study will give a greater scope instead. Through varying the boundary conditions of the scenarios, a full picture of the benefits in different situations can be given. Through this it can be identified which scenarios are particularly interesting to implement such a home energy storage system in. Furthermore, as the profit generated with home energy storage systems might not return the cost of investment, adding a fast charging functionality would give further incentive to invest, which will also be studied in this work.

CHAPTER 4

METHODS

In this section the methods to investigate the economic and ecological impact of adding an HES system to the household will be described. It starts with section 4.1, in which an overview of the proposed HES system and the assumptions regarding its physical structure will be given. In section 4.2 the modeled component and the main assumptions made for the setup of the model will be presented. The battery model including the electrical model and the thermal model will be explained in section 4.3. Next, in section 4.4, the modeled household will be presented which includes solar panels and an EV. In section 4.5, the economic model will be presented. This includes the electrical tariff structure, calculations to estimate the cost of purchasing and installing an HES system both based on reused or new batteries and also it contains information concerning how the economic benefits will be evaluated. Similarly in section 4.6 the ecological model will be presented, and all assumptions and methods to evaluate the ecological impact of the HES system will be stated. Section 4.7 presents the evaluated scenarios and control schemes of the HES system. In section 4.8 the parameters to evaluate the performance of the HES system will be presented, and in section 4.9 the model setup will be shown. Finally, section 4.10 covers a summary of the parameters used in the model.

4.1 Investigated Home Energy Storage System

4.1.1 Overview

The model evaluated in this thesis will continue to use the assumption from Spence's work that the HES system is based on a single and complete battery pack. Keeping the pack together has the advantage of making remanufacturing easier, as all the critical components for controls and thermal management are already included in the pack. A similar assumption has also been made in other studies on this topic. [29]

As shown in the literature review, evaluations regarding the economic feasibility of HES systems based on reused EVBs give a wide variety of results. However, as the popularity of Tesla's Powerwall has shown, even if HES systems might not be economically feasible, there will be a demand for these systems. This might be due to fact that many owners of PV panels strive for self-sufficiency. A study by Agnew has shown that self-sufficiency and grid defection is one of the main reasons people consider buying an HES system [20]. To give further incentive to install an HES system based on reused electric vehicle batteries, Spence proposes to implement an additional feature into the HES system, an opportunity for fast charging EVs [29].

This fast charging feature could be very beneficial for the user, as the high charging time and range-anxiety is one of the major problems in the deployment of EVs. Having the possibility to fast charge the EV at home if necessary will significantly improve the user's confidence in this new technology.

EV batteries are designed to discharge high energy in a short time to provide the power for accelerating the vehicle. As this fast discharge is also necessary during fast charging, reused EV batteries would be ideal for this application. These fast charging systems usually come at a high cost; implementing this as an additional feature might make an HES system based on reused batteries very attractive, even if they don't provide enough financial benefits through peak shaving and load shifting to justify an investment.

The home energy storage system that is also further evaluated in this study was designed to fulfill the following applications [29]:

- Fast charging of EVs

- Storage of generated solar power to increase self sufficiency
- Load shifting for economic benefits
- Providing back up power during power outages

This system will be implemented in a residential household that can also include PV and an EV. In figure 4.1 a general overview of the system actors can be seen:

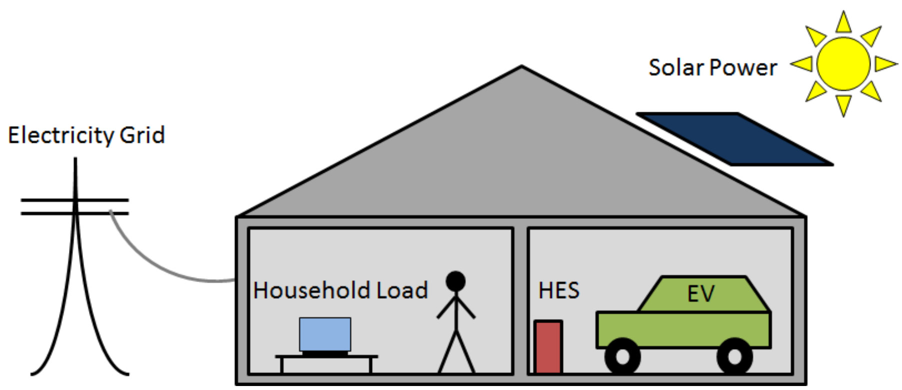


Figure 4.1: Actors in the modeled system.

In the following sections first the physical structure of the investigated HES system will be explained in more detail, then the models for the relevant components (electrical mode, thermal model, degradation model) will be presented.

4.1.2 Physical Structure of the proposed Home Energy Storage System

To create a home energy storage system, other components beside the battery pack are needed. These include structural, electrical, thermal and safety components. This section will focus on the components that have an impact on the model structure and performance, which are mainly the battery cells, the electrical components and the components for thermal management.

Spence analyzed the critical system electrical components that are needed apart from the battery cells to realize the desired applications with the home energy storage system [29]:

- Maximum power point tracking (MPPT) system to connect the battery system to the solar panels. This component converts the voltages generated by the PV to the optimal level to ensure that the highest amount of power that is possible is transferred to the battery.

- Bidirectional ACDC inverter to transform the DC current provided by the battery and the solar panels into AC current to cover the household load and to be fed into the grid. It is bidirectional to ensure that the battery can also be charged by the grid.

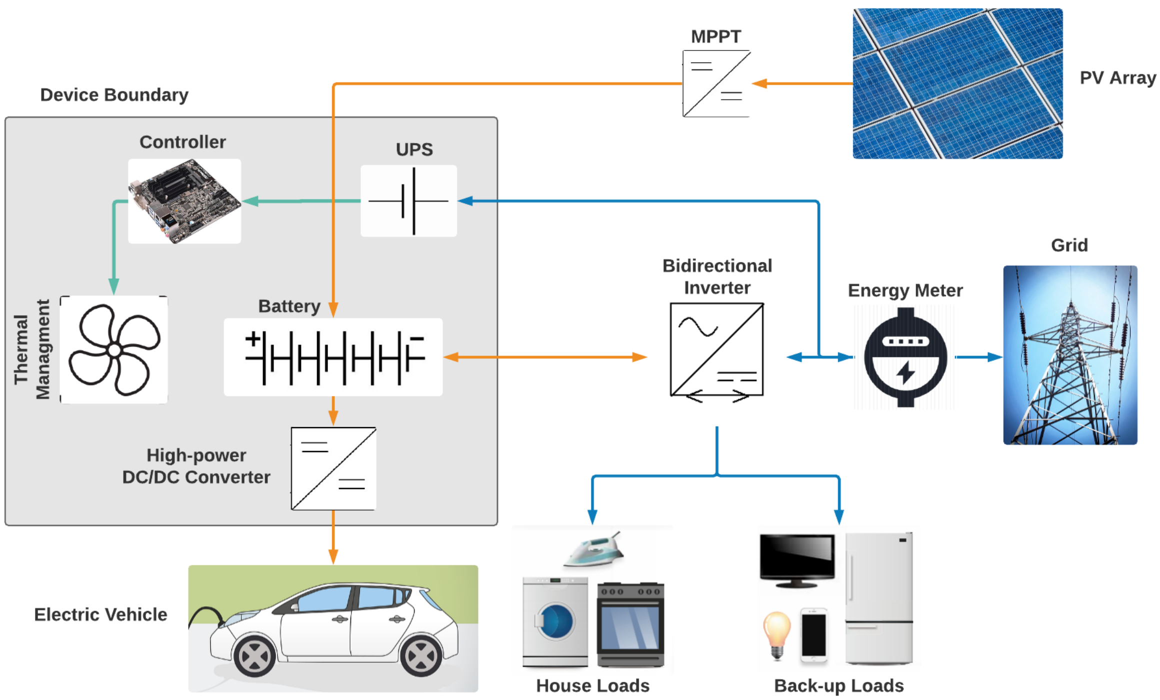
- Back-up load panel to power only critical appliances in case of a power-outage.

- Uninterruptible power source for back-up scenarios to ensure that a cold start is possible with no power from the grid

- High voltage DCDC converter to provide the optimal voltage to the EV during fast charging.

- Low voltage DCDC converter to power the low voltage components inside the HES system such as the coolant pump or for charging the UPS. This component is included with the uninterruptible power source (UPS) in figure 4.2.

In figure 4.2 the device containing the mentioned electrical components can be seen:



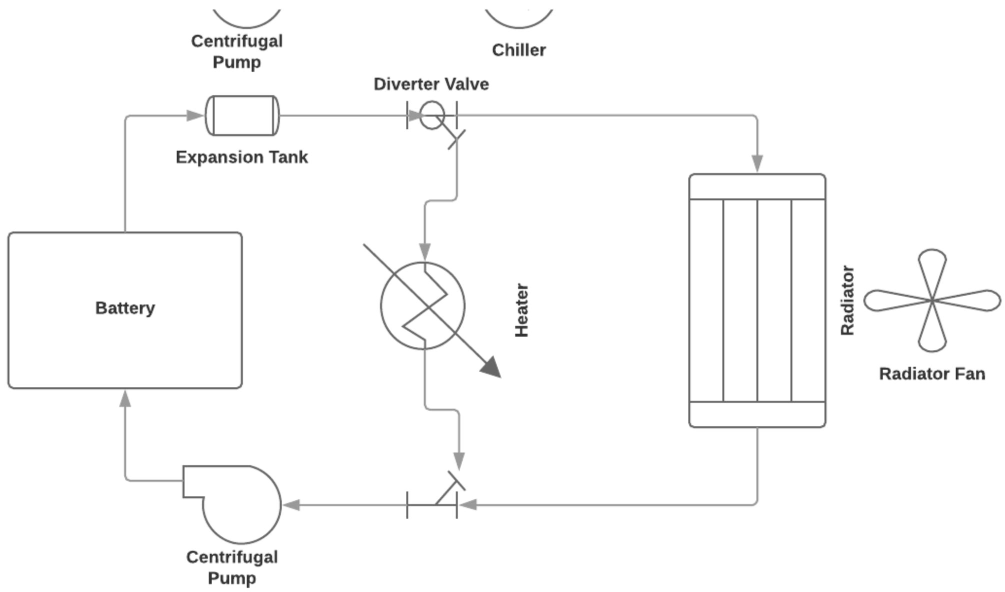
[29]

Figure 4.2: Electrical components.

For ensuring a safe thermal environment for the battery cells, a cooling system needs to be installed in the HES system. The following thermal components are critical for active liquid cooling which will be included in the system evaluated in this study [29]:

- Coolant pump
- Liquid to air heat exchanger
- Liquid chiller (if cooling under ambient temperature is necessary)
- Miscellaneous: Coolant hoses, diverter valves, expansion tank

A general circuit diagram of the cooling system (in this case without a chiller) can be seen in figure 4.3:



[29]

Figure 4.3: Cooling circuit diagram.

Other components that need to be included in an HES system are:

- Structural components (casing, fixtures, connectors, . . .)
- Safety components (sensors, emergency safety switches, insulation, . . .)
- Control components (control unit, user interface, . . .)
- Miscellaneous (sensors, connectors, . . .)

4.2 Modeled Components and main Assumptions

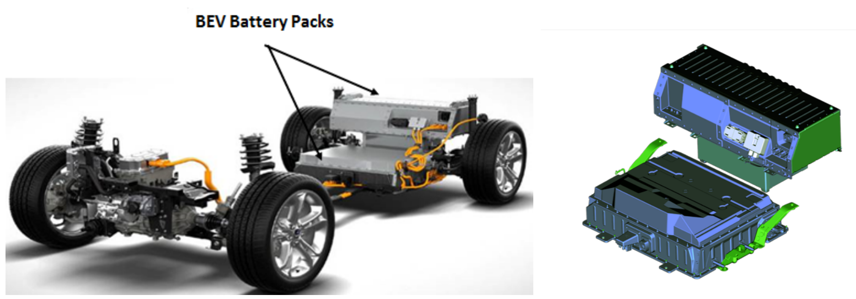
In the following list different parameters of electric vehicle models from around the year 2013 can be seen:

- *Nissan Leaf (2013):* Capacity 24 kWh, Weight 290 kg, System Voltage 365 V [88]

- *Ford Focus Electric (2013):* Capacity 23 kWh, Weight 303 kg, System Voltage 318 V [89]

- *BMW i3 (2014):* Capacity 18.8 kWh, Weight 235 kg, System Voltage 355 V [90]

The home energy storage system analyzed in the model will be assumed to be based on the battery packs of a 2013 Ford Focus Electric as this battery pack represents typical values for electric vehicle batteries. The battery of the Ford Focus Electric have a LMO chemistry [89], their outer appearance is similar to the ones seen in figure 4.4:



[91]

Figure 4.4: Battery packs of the 2013 Ford Focus electric.

The battery packs of the Ford Focus Electric have a combined energy capacity of 23kWh [89]. Further specifications of the battery pack can be found in section 4.10 and in Appendix A. As it can be seen in the previous list, the parameters for batteries of other electric vehicle models are very similar thus the results of this study can be transferred to these models as well.

In this study the electrical component of the system will be modeled. However, some of the electrical components mentioned in the previous chapter will not be included. The uninterruptible power source and the backup load panel, will not be modeled, as no power blackout scenario will be investigated. The MPPT system will also not be modeled in detail;

it will be assumed that the transformation of voltage to charge the battery from the PV runs at 100% efficiency. The same assumption will be also made for the low voltage DCDC converter, as the power required by the components connected to this converter are only based on estimates; it will be assumed that the power loss due to the voltage transformation is included in the power draw.

The efficiencies of the bidirectional ACDC inverter and the high voltage DCDC converter will be included in the model, but the components will not be modeled in more detail.

For this study, it will be assumed that it is not necessary to cool the battery lower than ambient temperature. Therefore similar to figure 4.3, no chiller is included in the model. For the cooling system a number of assumptions will be made [29]:

- The thermal management system will only be activated if the battery cell temperature reaches a temperature under a lower or over an upper threshold. If the battery cell temperature is in between these thresholds of safe operational temperatures, the thermal management system will be in idle. If the thermal management system is started, it will always run at least for 30 minutes to avoid a constant back and forth pattern at threshold temperatures. After 30 minutes the system will check the new battery cell temperature again.

- There is an upper shut down temperature. Should this temperature be reached, further safe operation of the battery cannot be guaranteed and the battery will shut down. The HES system will not restart in that case, even if safe temperatures are reached again.

- The thermal model will be based on energy balances. Heat is generated by the battery and also by the heater if activated, heat loss is only possible at the heat exchanger or through natural convection on the cell sides.

- A constant power draw of the pump is assumed for circulating the coolant fluid. The fluid and its movement will not be modeled.

- The heater will have a constant power and a constant efficiency.

The additional parts such as structural components, safety components, control components, etc. will not be included in the model, as they don't have any significant influence on the analyzed overall electrical behavior.

To model the home energy storage system, some further assumptions are made to simplify the system:

- During a simulation timestep (5min) the power for the household loads or solar generation is assumed to be constant by taking the average load during that timestep. A similar assumption applies also to the power delivered to or from the battery. However the maximum and minimum limits of the battery and car capacity are taken into account to ensure that these limits are not accidently broken due to the assumption of constant power during a timestep. If a limit is reached the model will readjust the power draw for that timestep to a power level that can be constantly inserted/withdrawn from the battery during the whole timestep.

- The temperature is assumed to be constant over the whole battery. Furthermore it is assumed that the ambient temperature is the same as the outside temperature, as the home energy storage system is assumed to be stored in a garage.

- The power for the battery thermal control system will be added to the household load; thus the battery does not provide its own energy. This assumption was made to avoid loops inside the differential equations and to make sure that the thermal control still operates even if the battery is fully discharged.

- All years are similar, and only one year is computed. The following years are assumed to give a similar result.

- For simplicity it is assumed that the power needed for running the controls of the battery is negligible and therefore will not be taken into account in the model.
- It is assumed that the HES system always starts from an empty state at the beginning of the computed year, which corresponds to a SOC of 20%.

4.3 Battery model

4.3.1 Electrical model of the Battery

The electric model of the cell manages the charge and discharge behavior of the battery. For this, the new battery's SOC, the energy inserted or drawn from the battery, the internal resistance and the current draw from the battery are calculated for each timestep. The internal resistance depends on the battery temperature, which is determined in the thermal model. The current draw can be calculated based on an equivalent circuit. It depends on the delivered or consumed power and the open circuit voltage, which itself depends on the current SOC of the battery. The change in SOC is calculated by using the current draw. The energy delivered to or from the battery is calculated by multiplying the timespan with the average power delivered to or from the battery during the timespan.

As mentioned before, the model evaluated in this work is based on Spence's model [29]. He assumed the coulombic efficiencies of the battery to be 100 %, as Lithium-Ion batteries have very high coulombic efficiencies [92].

Then the model uses the following equations to determine the SOC of the battery [Spence18]:

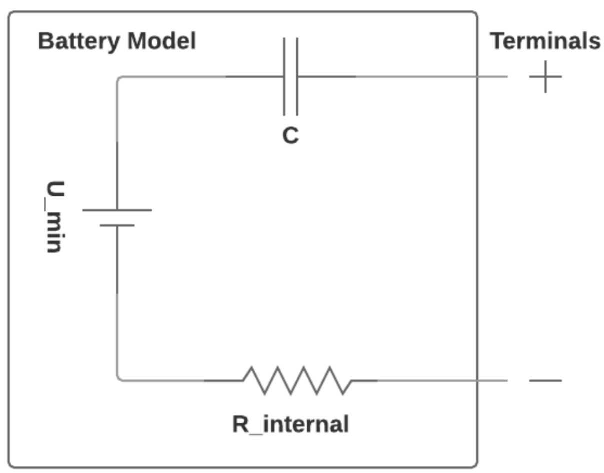
$$\frac{dSOC}{dt} = I/Q_{Ah} \tag{4.1}$$

Where I stands for the current draw from the battery in amps, and Q_{Ah} is the capacity of the battery in amp-hours.

Next, it is assumed in that the voltage drop inside of the battery is due to only the internal resistance, which allows us to set up the following equation for the closed circuit voltage [29]:

$$U = U_{ocv} - Ir \tag{4.2}$$

The equivalent circuit model that can be used based on this assumption can be seen in the next figure:



[29]

Figure 4.5: Equivalent circuit for the electrical model.

Using this equivalent circuit model, the following equation to calculate the current draw from the battery based on the power delivered to the load can be determined [29]:

$$Power = IU_{ocv} - I^2 r \tag{4.3}$$

Here U_{ocv} is the open circuit voltage and r is the internal resistance of the battery in ohms. In general, the open circuit voltage of EV batteries is not linearly dependent on the SOC, especially at very low and very high SOCs. However, to calculate the open circuit voltage in the battery model, it was assumed that the voltage of the battery is linear. This assumption was made as only SOC states between 20% and 100% are considered in the model for which the voltage over SOC curve is mostly linear [29]. To calculate the open circuit voltage, the following equation is used [29]:

$$U_{ocv} = \alpha \cdot (SOC - SOC_{nom}) + U_{nom} \tag{4.4}$$

Battery data from Idaho National Labs [93] was used to find the parameters for equation 4.4 [29]. The battery packs evaluated in this study will be assumed to stem from a 2013 Ford Focus Electric as this model represents typical EV parameters from models made in 2013. This is also one of the models that were evaluated in Spence's work. The electric parameters used for calculating the open circuit voltage of this battery pack, are the following: $\alpha = 62.7$, $U_{nom} = 358V$, $SOC_{nom} = 1$ [29].

4.3.2 Thermal model of the Battery

In general, the thermal model solves a differential equation to calculate the battery temperature for the current timestep. This temperature is used as an input in the thermal control function, which controls the heating and cooling of the battery to ensure a safe operation. Also the internal resistance of the battery is dependent on the temperature in the model.

The current battery temperature, calculated in the thermal model, depends on the ambient temperature as well as the heat generated through effects associated with charging and discharging and the heat that is generated or dissipated through the thermal control system.

To model the thermal behavior of the battery system, some basic assumptions were made [29]:

- The cooling system is set in parallel for the cells
- A single cell is modeled, and results are extrapolated to the rest of the battery pack
- The temperature is uniform over the battery

First the heat generation $\dot{Q}$ inside the cells is calculated. Here the main heat generation mechanisms, Joule heating and heat generation due to chemical reactions, are taken into account. For this an equation based on the Current I, the resistance r, the Temperature T and the entropic heat coefficient $\frac{dU}{dt}$ is used [29]:

$$\dot{Q} = I^2 r - IT \frac{dU_{ocv}}{dT} \tag{4.5}$$

To determine the entropic heat coefficient $\frac{dU}{dt}$ Spence's model uses a polynomial fit of experimental data taken from [94]. Lui et al. measured the entropic heat coefficient in dependence on the SOC for an aged lithium-manganese-oxide cell, which is the same cell chemistry as the cells considered in this model. Spence assumes that due to the same cell chemistry, the entropic heat coefficients will be similar [29].

The internal resistance of the battery was modeled as a function of temperature using the following equation [95]:

$$r = r_{ref} \cdot \left[\exp\left(-\frac{E_\alpha}{R_{ug}} \cdot \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right) \right] \tag{4.6}$$

E_α is a constant that can be derived experimentally, R_{ug} is the universal gas constant, T_{ref} is the reference temperature and r_{ref} is the reference resistance of the cell; here the internal resistance of the cell was chosen for this parameter (for values of the parameters, see Appendix A).

The heat generation model was validated by Spence through recreating experimental tests done by Liu et al. It showed that the model predicted experimental data well [29].

Furthermore a model of a liquid cooling system is implemented. For this, the thermal energy that is stored inside the battery is balanced with the heat that is generated and the heat that is removed through the cooling system [29]:

$$C_p\, m \frac{dT_{batt,avg}}{dt} = \dot{Q}_{gen} - C_{p,f}\, \dot{m}_f (T_{f,out} - T_{f,in}) \tag{4.7}$$

C_p is the heat capacity of a cell, a value of 1,100 W/mK is chosen, which is the average of experimentally determined values for this cell chemistry [29]. The variable m denotes the cell's mass. $C_{p,f}$ is the heat capacity of the fluid, $\dot{m}_f$ the mass flow rate of the fluid and $T_{f,out}$ and $T_{f,in}$ are the temperatures of the fluid at the outlet and inlet respectively. $\dot{Q}_{gen}$ refers to the cell heat generation.

Some further assumptions are made to simplify this equation [29]:

- The temperature of the fluid at the outlet is set equal to the maximum battery surface temperature.
- The change of the maximum temperature of the cell is seen as equal to the change of the average temperature.
- No heat transfer is considered inside the fluid hoses. The temperature of the fluid at the battery outlet is seen as equal to the temperature of the fluid at the heat exchanger inlet.

These assumptions result in the following simplified equation [29]:

$$C_p m \frac{dT_{batt,max}}{dt} = \dot{Q}_{gen} - H(T_{batt,max} - T_{amb}) \tag{4.8}$$

Here, H denotes the heat transfer capacity of the heat exchanger (see Appendix A for values).

This equation is solved for $T_{batt,max}$ as the maximum internal battery temperature. According to the assumptions stated earlier, this temperature is seen as uniform over the whole battery and will be exported as the battery's current temperature.

A fluid model was created to calculate the power draw of the pump (and fan) for active air cooling. This power draw was then used in the full model. Spence's studies showed that in general the power draw of the heat exchanger fan dominates the power draw of the coolant systems [29]. In the model the constant power draws of these components are included as an additional load for the battery coolant system.

Running the thermal system for cooling will draw a power of roughly 100W, including the power draw of both the pump and the heat exchanger. During battery heating, the heater needs to be supplied with a power of roughly 560 W and will provide 500 W of heat to the battery cells. [29]

As with the assumptions made by Spence [29], it will be assumed that natural heat convection is possible only at the cell sides and that there will be no heat convection between the cells, as the natural heat convection between the front faces is assumed to be negligible compared to the liquid cooling. The coefficient used for natural heat convection on the cell sides is 3 W/m^{2}K [29].

4.3.3 Degradation

As was done in [29], it will be assumed that the remaining capacity of the Ford Focus battery will be 70 % after the first life, and the growth in internal resistance will be by 30 %. These values were based on estimations made by Neubauer et al. as well as testing by the Idaho National Laboratory and battery warranty information. Neubauer et al. measured a capacity decrease of roughly 28.5 % and a resistance increase of 27.5 % for a vehicle in Minneapolis, which is close to the household evaluated in this study (West Lafayette Indiana) [96].

The degradation mechanisms inside Lithium-Ion batteries are very complex and hard to predict, especially as there is not much experimental data currently available. Degradation of the battery cells and its modeling is still being researched and requires further experimental testing. According to Martinez-Laserna et al. , the second life degradation in capacity will depend heavily on whether the degradation already reached the ‘knee’ in the capacity fade curve (see figure 2.11). If the degradation has already started to accelerate, Martinez-Laserna et al. states that the battery will probably not be reusable anymore. If the degradation curve has not reached the knee, the further degradation during second use will be rather moderate [84].

For this model it is assumed that the battery has not reached the ‘knee’ in the curve yet and thus still displays a good performance. Thus after the degradation during its first life, there will be no further degradation taken into account in the model. This assumption has also been made by other researchers such as Heymans et al [18].

4.4 Model of the Household

The modeled household is based on the ReNEWW House, a project of Whirlpool Corporation in cooperation with Purdue University and other partners. The aim of the project is to retrofit an existing house to make it most energy and water efficient. For this, different steps were taken including incorporating a geothermal pump for heating and solar panels for electricity generation. Up to three Whirlpool engineers live in that household, studying at Purdue university and doing research work in sustainability. The house is located in West Lafayette Indiana (see figure 4.4). [97]

[98]

Figure 4.6: Location of the ReNEWW House.

Inside the house multiple sensors to measure the electric energy consumed or generated, the temperature, the humidity etc. are installed. This data will be used in the study conducted in this thesis.

4.4.1 Load Profile and Solar Power Generation

A full year is modeled to include seasonal differences. For this, the measured load profiles and the solar generation profiles of 2017 were used as input parameters into the household model. The data is measured in one minute increments, in the figure 4.4.1 and figure 4.4.1, examples for a weekly profile during winter and one during summer can be seen:

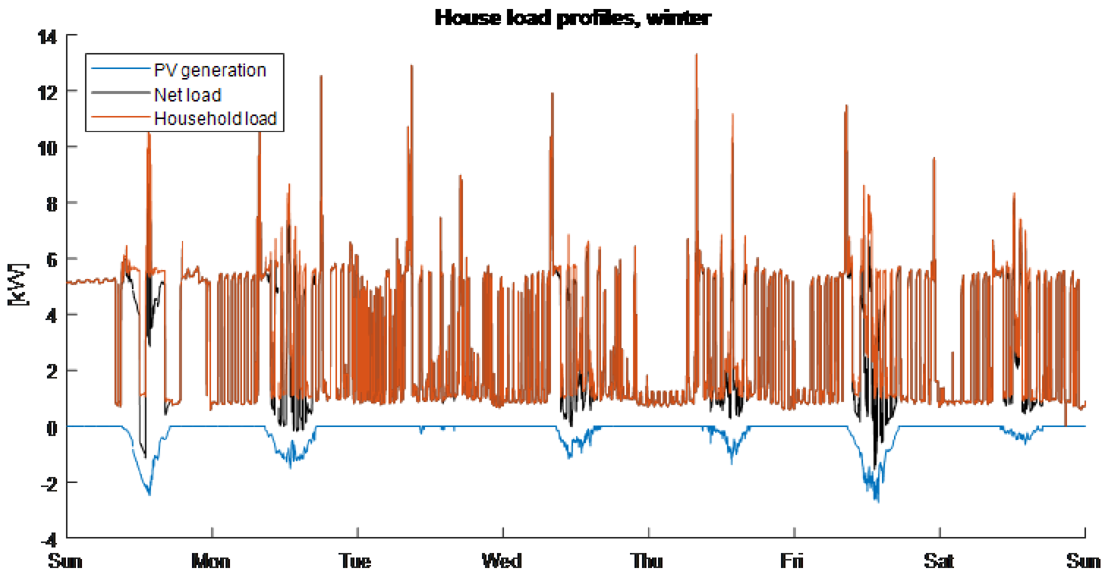


Figure 4.7: Household load and solar generation profile during winter (beginning on the 8^{th} of January 2017).

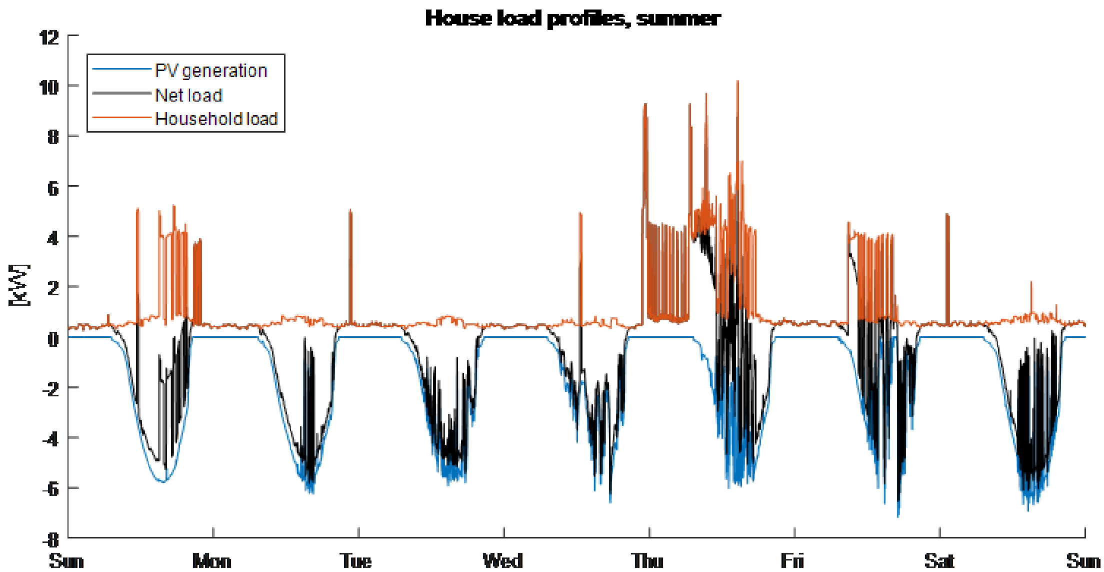


Figure 4.8: Household load and solar generation profile during summer (beginning on the 2^{nd} of July 2017).

The step like behavior that can be seen in the profile during winter is due to the geothermal pump which is used for heating. Additionally it can be seen that the solar generation during winter is fairly low; there is almost no excess solar energy. This changes significantly during summer, during which there is a large amount of excess solar energy.

Furthermore it is assumed in the model that the HES system will be placed inside the garage, which is assumed to have a temperature similar to the outside temperature. The outside temperature is measured in an hourly interval. Similarly to the load profile, data for the whole year of 2017 was used in the model. Example profiles for a week during winter and a week during summer can be seen in the figure 4.4.1 and figure 4.4.1.

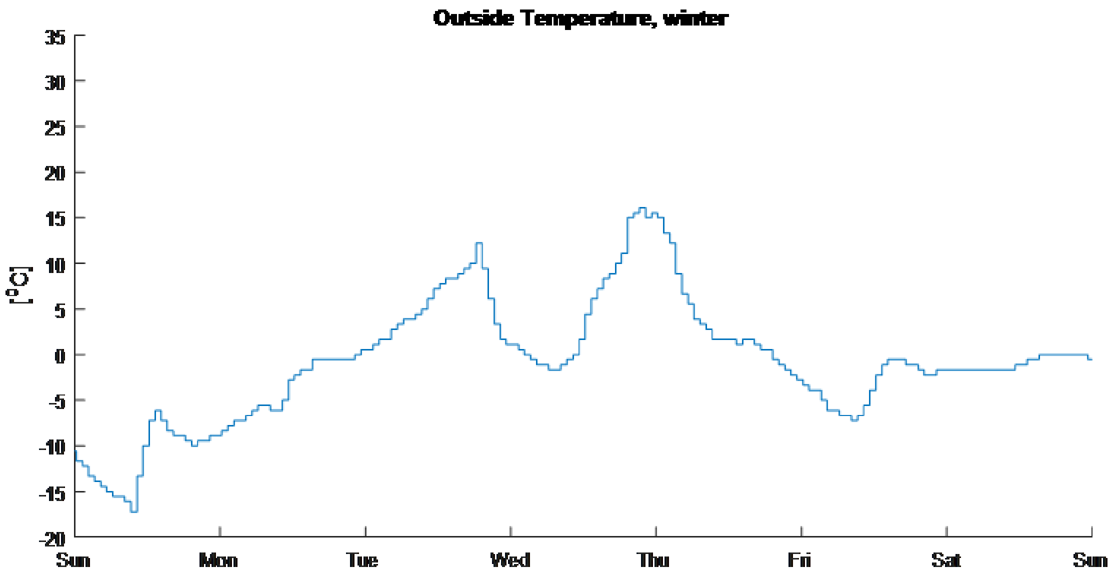


Figure 4.9: Temperature profile during winter (beginning on the 8^{th} of January 2017).

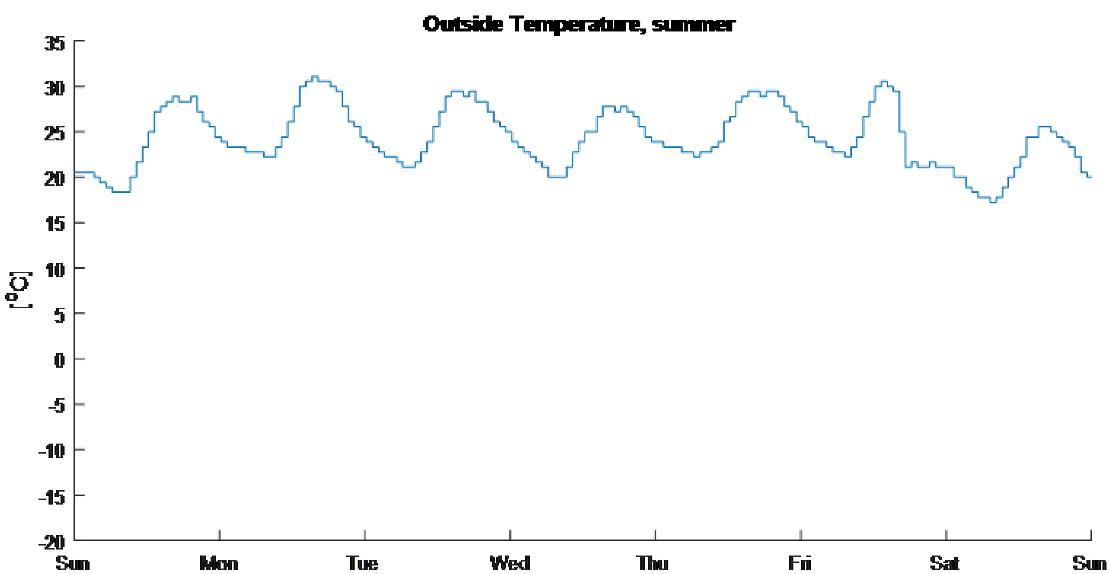


Figure 4.10: Temperature profile during summer (beginning on the 2^{nd} of July 2017).

The measured outside temperature reaches from -20°C during winter to 34°C during summer.

As the model solves a differential equation for each timestep during the year and nearly

100 different combinations of scenarios and control schemes were evaluated (see chapter 4.7), calculating the full year in one minute timesteps would take approximately 75 minutes per scenario. It was therefore necessary to reduce the amount of timesteps to be calculated to reach a feasible calculating time. A timestep of 5 minutes was chosen for the model, which resulted in a total computational time of roughly 12 minutes per scenario. For this the 5 minute average was taken for the load profile and the solar power generation, and it was assumed that the power consumption stays constant during this timestep. Similarly it was assumed that the hourly measured temperature is constant for the whole hour.

In the next figure, the adjusted load profile consisting of 5 minute averages can be seen for the summer week as an example:

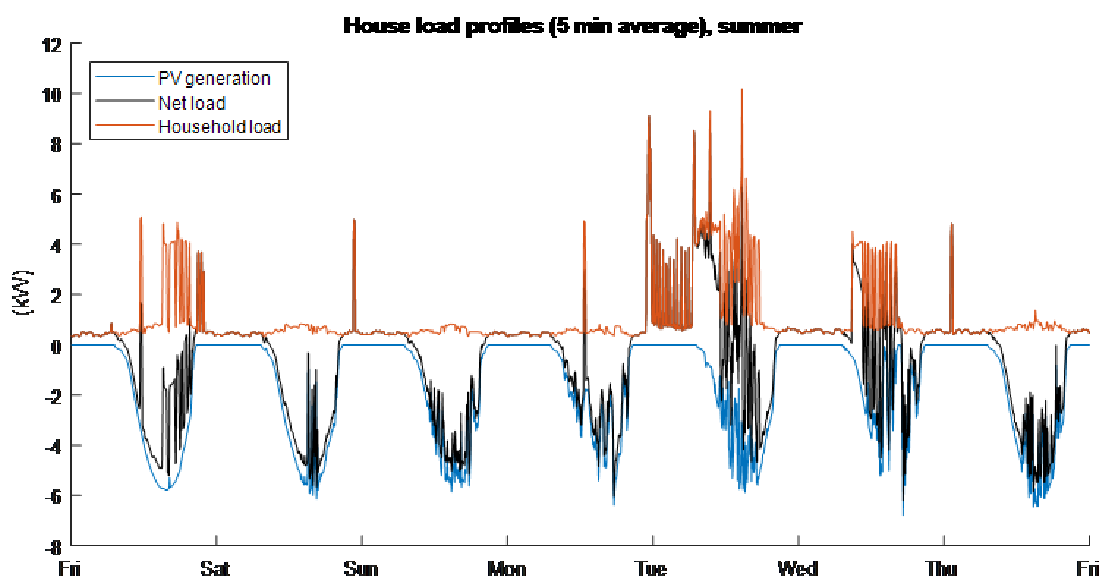


Figure 4.11: Average (5 min) household load and solar generation profile during summer (beginning on the 2^{nd} of July 2017).

There were some gaps in the data, as for some points in time during the year the load profile or temperature was not measured. These gaps usually consist of a timespan less than 5 minutes with a few exceptions. The biggest gaps in the data were for 37 minutes, 1 hour, 3 hours and 4 days. To bridge the gaps, different steps were taken based on the gap size. If the timespan of the gap was less than 30 minutes, the missing data in between will be linearly approximated. An example for bridging the smaller gaps can be seen in the next figure:

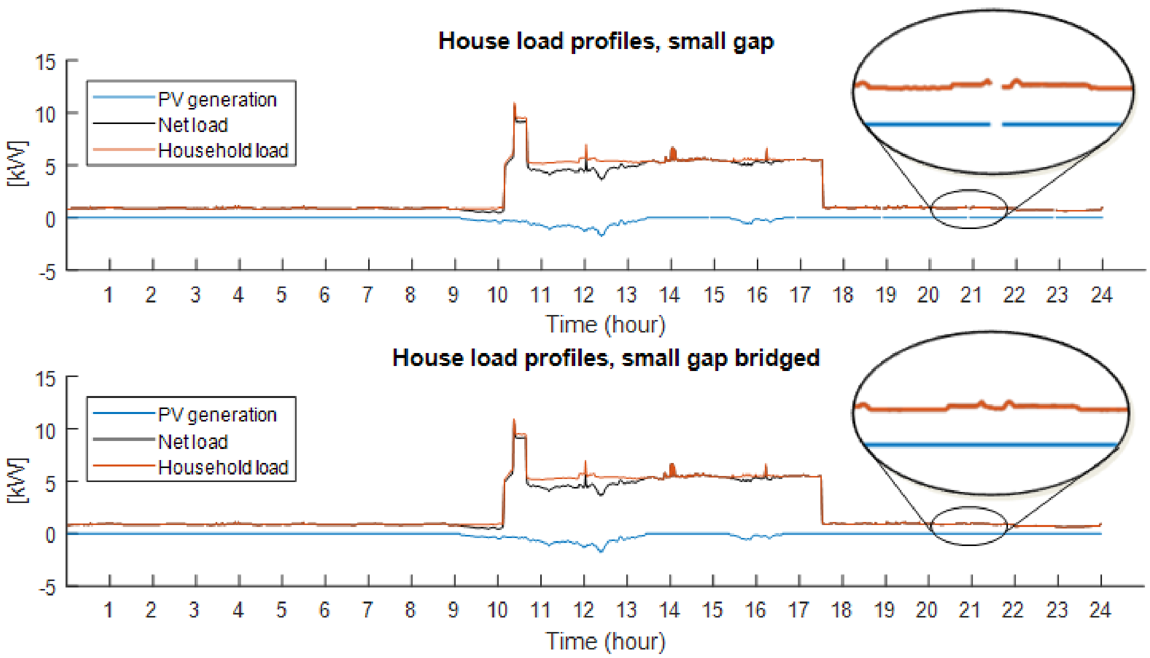


Figure 4.12: Bridging small gaps (data for the 3^{rd} of January 2017).

For the four gaps bigger than 30 minutes, a different approach was chosen. Here data from the same weekday in the previous week was copied inside the gap. As an example the bridging of the biggest gap of 4 days can be seen in figure 4.4.1:

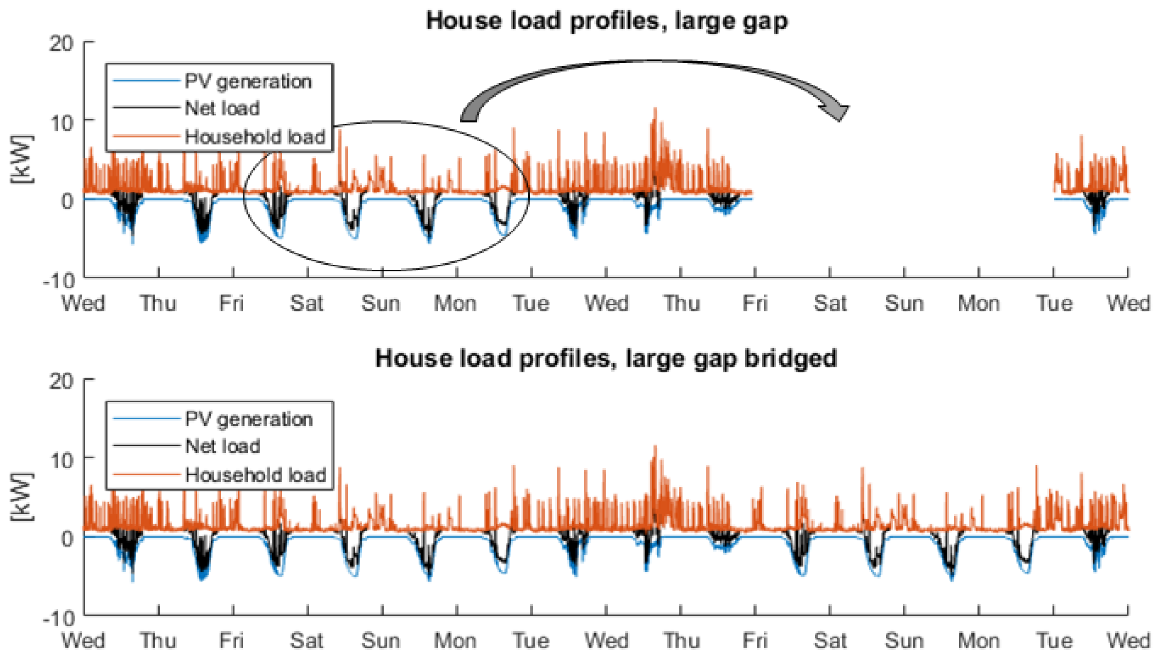


Figure 4.13: Bridging larger gaps (data beginning on the 27^{th} of September 2017).

4.4.2 Electric Vehicle Inclusion

In the ReNEWW House an electric vehicle is present which will also be included in the model to analyze its influence and to analyze the fast charging opportunities with the HES system. For the model it is assumed that the EV will only be charged in the household and always fast charged if possible. If it is not possible to fast charge the EV all the required amount of energy, it will charge the remainder through level 2 charging. There will be various "Charging Events" distributed over the timespan of the year based on data collected at the ReNEWW House.

The data collected at the ReNEWW House stems from a 2017 Ford Focus Electric. All the charging events of the electric vehicle are collected, be it at ReNEWW House or at some outside charging station. In this model however, it will be assumed that all the recorded charging events take place within the household. In the collected data the EV was not always charged up to 100 %; sometimes the charging was stopped earlier. However, as the difference in SOCs before and after charging was recorded for all events, only this difference is used in the model. Here the EV is assumed to charge up to 100% by this difference in SOC. Furthermore as the EV was only included at the end of 2017 and, until the beginning of 2018 only rarely used, the charging event data for the model will only be based on the collected data from the timespan: 01/01/2018 until 05/18/2018. In figure 4.4.2 the collected data can be seen:

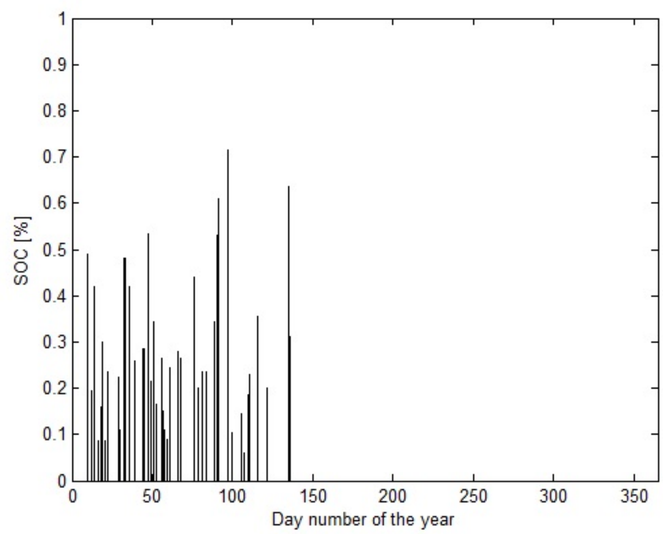


Figure 4.14: Collected electric vehicle charging data (beginning of 2018).

To obtain data for a full year the collected charging data for the timespan was copied two times and shortened at the end to not exceed the timespan of one year. For this it was ensured that the charging times of day and weekdays stayed the same to not influence the data further. This new dataset can be seen in the next figure:

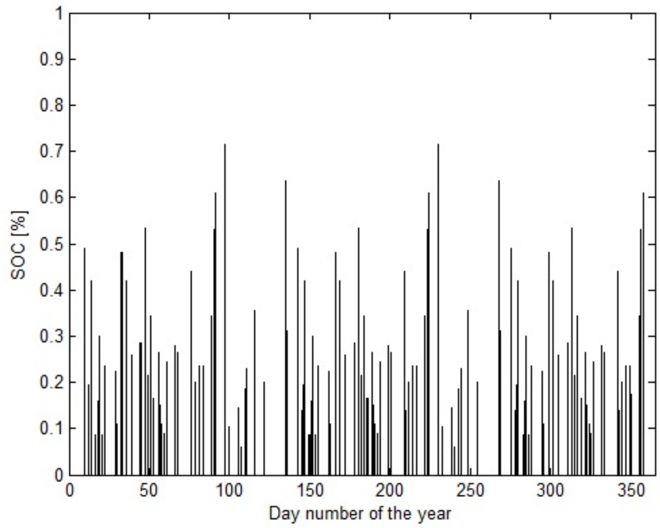


Figure 4.15: Created electric vehicle charging dataset for a whole year.

The electric vehicle battery of the 2017 Ford Focus Electric has a capacity of 33.5 kWh [99]. In the model it is assumed that the efficiency of the vehicle is similar to the 2013 model which has a miles per kWh ratio of 3.23 miles/kWh (based on 0.31 kWh/miles [89]). For the evaluation of the scenarios and control schemes, the fast charging that was possible will be grouped into several classes depending on how many miles could be added to the EV's range through fast charging. This parameter can be calculated using the capacity of the vehicle, the miles per kWh ratio and the difference in SOC through charging. In figure 4.16, the charging events, grouped into these classes according to how many miles were added through each charging event, can be seen:

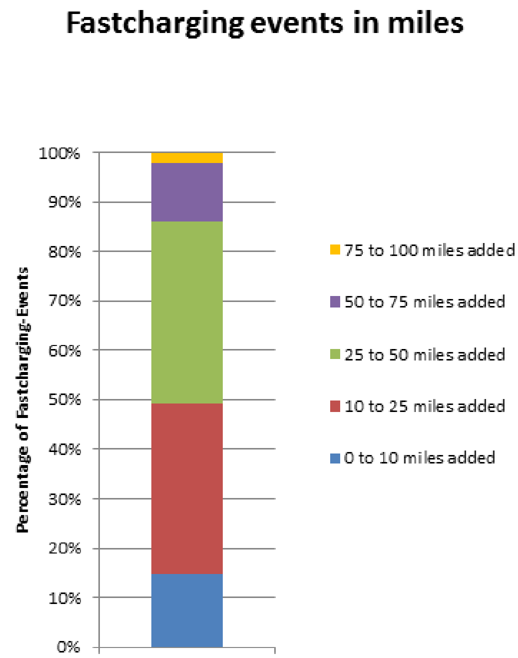


Figure 4.16: Classifications of fast charging events.

As can be seen in figure 4.16, most of the charging events add 10 to 50 miles to the electric vehicles range, amounting to 71 % of the total number of charging events. During 15 % of the charging events, less than 10 miles were added to the EV's range through charging. In roughly 12 % of the charging events, 50 to 76 miles were added, and in 2 % of the cases in between 75 to 100 miles were added through charging.

Overall it should be noticed that the vehicle is used less than the average car in the US. According to the dataset described above, the vehicle will be driven for a total of roughly 3,900 miles during the whole year. An average vehicle in the US is driven roughly 1,5000 miles per year for users that are in between 20 and 54 years old. [100]

The efficiency for fast charging is based on the efficiency for high voltage DCDC converters which is 0.97 % [101] (as the power is already converted to DC and never passes through the charger, the efficiency of the Ford Focus Electric charger will not be taken into account). The efficiency for level 2 charging is based on the overall efficiency of charging, which is 0.79 % [89]. For level 2 charging it is assumed that a power of 7 kW [36] is fed into the battery (thus the power provided by the household is slightly higher due to inefficiencies). For fast charging, the battery pack will provide a power of 50 kW which is common for fast charging [35]; the power received at the EV battery will be slightly reduced due to the EV battery's inefficiencies.

4.5 Economic Model

To evaluate the economic feasibility, different areas need to be taken into account. First the electrical tariff structure used in the model will be presented. Then an estimate of the purchasing and installment cost of a new battery HES system and a reused battery HES system will be made, finally the methods for calculating the economic benefits will be presented.

4.5.1 Electrical Tariff Structure

The electrical tariff price structure used in the model is based on Tipmont REMC, one of the electric utility companies operating in West Lafayette, where the household is located. Two tariff structures will be evaluated: a flat price tariff, and a time-of-use (TOU) tariff. Charges for power cost adjustment which take, among others, varying fuel cost into account, will be excluded for simplicity. Also the monthly flat service charge of $ 32.50/month will not be taken into account for simplicity, as this charge would be the same in all scenarios evaluated. The sales tax for electricity in Indiana of 7 % will be added on top of the costs defined below. [102]

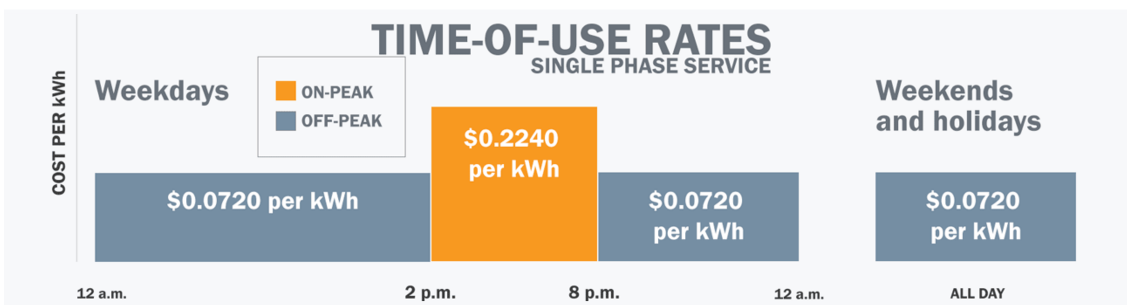
The flat tariff remains constant over the whole year. The time-of-use tariff defines certain peakhours during the day during which the electricity price is considerably higher; however, during off-peak time, the electricity price will also be lower than the one in the flat tariff. The electricity rates taken from Tipmont REMC can be seen below:

Flat Tariff: Energy Charges: $ 0.1026/kWh [102]

Time-of-Use Tariff: On-peak energy charge: $ 0.2240/kWh, off-peak energy charge: $ 0.0720/kWh [103]

For the time-of-use rates, peak time is between 2pm to 8pm on weekdays, and there are no peak hours on the weekend or on holidays (New Year's Day, Memorial Day, Independence Day, Labor Day, Thanksgiving Day, Christmas Day). [103]

The tariff structure for the time-of-use rates can also be seen in figure 4.17:



[103]

Figure 4.17: Time-of-use tariff structure.

Apart from the tariff structures, the model will also evaluate scenarios with or without net metering. If net metering is active, the household will only be charged for the net energy, which essentially means that the household will be reimbursed for electricity generated and fed into the grid by the current electricity sales price. If no net metering is included, it will be assumed that the household will not be reimbursed at all for any electricity fed into the grid.

4.5.2 Cost Estimation of Home Energy Storage Systems

The estimation for the price of a new battery HES system will be estimated based on Tesla's Powerwall 2, which is a currently offered HES system (including an inverter) at a very competitive price at around $ 7,600 [77]. In this price the installation cost of roughly $ 1,000 (using the lowest estimate from [77] are already included. As the Powerwall 2, has a capacity of 13.5 kWh the price per kW for this hES system is $ 560/kWh.

To estimate the price for a reused battery HES system, first the price for new battery cells alone will be estimated. For this it is assumed that the cost for the inverter and other electrical and structural components will be roughly $ 3,000, with the cost for the inverter taking the main portion, as it has a current commercial standalone price of roughly $ 2,500 [104]. Taking the price for Tesla's Powerwall 2 into account, and excluding the cost for installation, the price of the new battery cells alone could be determined to be $ 270/kWh. This is in line with Nykvist and Nilsson, who determined the cost for new Li-Ion cells to be roughly $ 300/kWh in 2015 [56]. Additionally, $ 290/kWh are needed to cover the cost for the additional electrical components and installation.

Assumptions from Gur et al. are used to find a possible price for the reused battery HES system. His price estimations are based on [10] who assumed that customers will pay for a reused product maximal 75 % of the price of a new product. This led to the assumption that the price of used battery cells will be within the range of 30 % to 75 % of new ones [55]. Using the previously calculated value of $ 270/kWh the price for reused battery cells can be estimated to be $ 80/kWh to $ 200/kWh. It is further assumed, that the cost for the other electrical components and installation will remain the same as for a new system and thus stay at $ 290/kWh for the system based on reused batteries. This assumption for the fixed cost of electrical components and installation should be valid, as the home energy storage systems evaluated within this study will have a higher capacity than the Powerwall 2 which means that the ratios of fixed cost due to electrical components and installation per kWh might be lower than $ 290/kWh. Using this estimate and the estimated cost for reused battery cells, the total cost for a reused battery HES system including electrical components and installation could be estimated to range in between $ 370/kWh and $ 490/kWh.

4.5.3 Calculation of Economic Benefits

The first step to analyze the economic benefits is to evaluate the change in the yearly electricity bill from including a home energy storage system. For this the electricity costs are calculated based on the electrical tariff first for a base case scenario that does not include an HES system, and then for a scenario in which the home energy storage system is included. The difference of these bills is the yearly profit (or loss) that was made through including the HES system.

Similarly, the economic benefit of including an electric vehicle instead of a conventional vehicle with an internal combustion engine is evaluated. For this the cost for the energy necessary for charging the vehicle is computed and the miles that could be driven with this charge (including losses through charging inefficiencies). Then the cost of the energy is compared to the cost of the amount of gas needed to drive the same amount of miles with a conventional car. For adding the electric vehicle to the household charging data from a Ford Focus Electric model year 2017 was taken. The energy per mile coefficient for this model is 0.31 kWh/mi [[105]]. To calculate how much gas is used for a conventional car to drive the same amount of miles, a typical miles per gallon rate of 23.41 is used [106]. For the gas prices a value of of 2.8$/gallon is used which is similar to current prices [107]. The cost of the EV will not be taken into account in this study.

To investigate the economic benefit in more detail, the payback time is also computed. Here several assumptions will be made. First, it will be assumed that the performance of the HES system will stay constant every year. This assumption represents the best case scenario, as in reality the battery will deteriorate over time due to aging mechanisms that are not included in this model, as this topic is still part of the current research and more experimental studies will have to be made to create a valid model for the EV battery's degradation. To further simplify the estimation and keep the estimate at a best case scenario, no inflation or discount rate will be taken into account either.

4.6 Ecological Model

First the environmental impact of the electricity used in the household will be analyzed. As the household is based in Indiana, it will be assumed that the grid electricity used by the household resembles the mix of energy sources used in Indiana to produce electricity. The sources for electricity production in Indiana can be seen in figure 4.18; the data is based on the year 2014 [108].

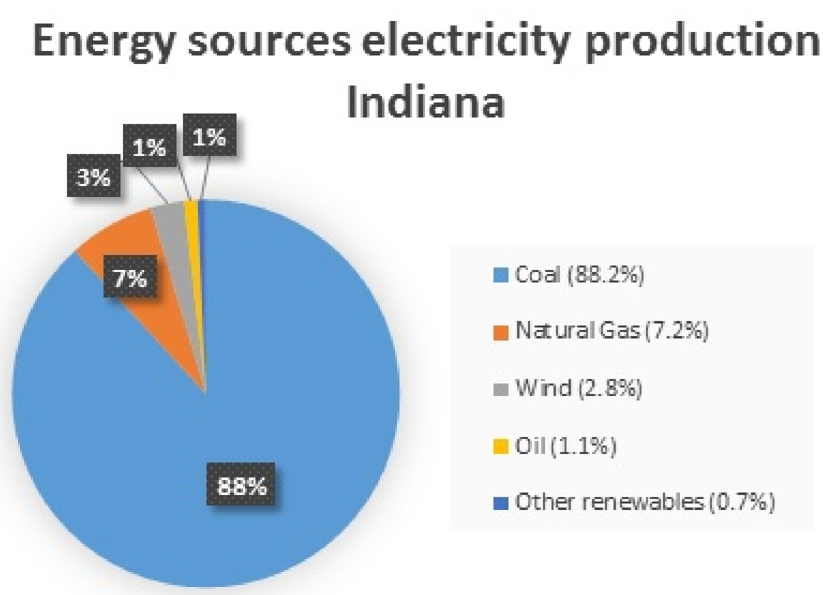
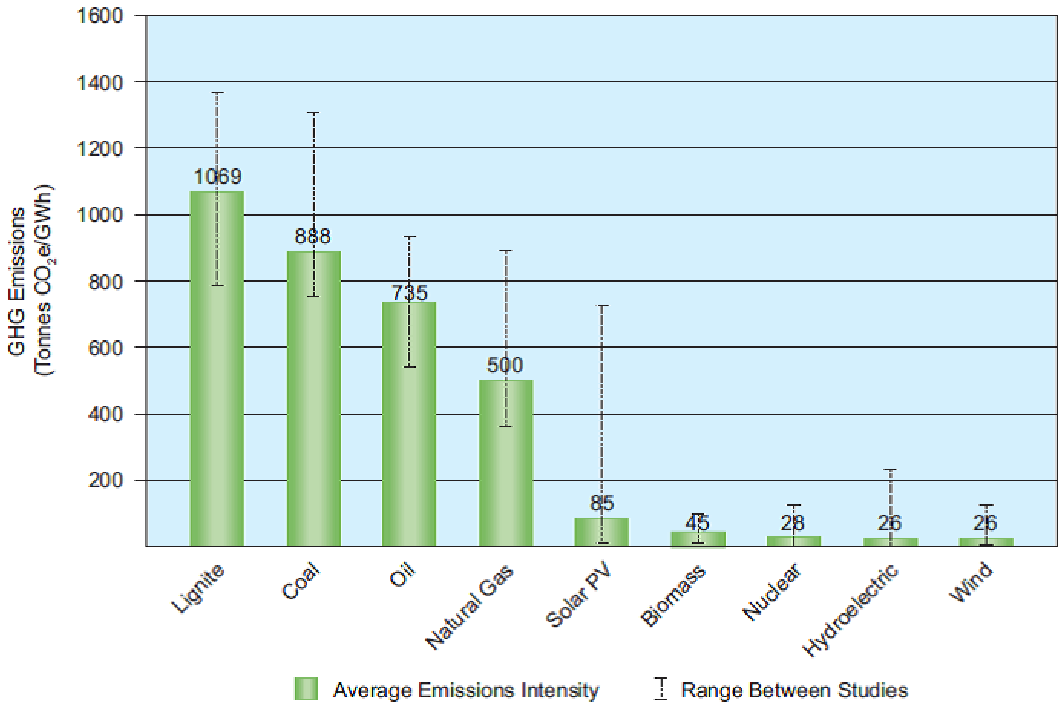


Figure 4.18: Energy production in Indiana.

To figure out the environmental impact of producing the electricity, the CO_2 equivalent over the whole life cycle for each power generation source will be used. The CO_2 equivalent emissions for different electricity production sources can be seen in figure 4.19:



[109]

Figure 4.19: Environmental impact of electricity production sources.

The contribution of each individual energy source in Indiana's electricity mix towards the overall CO_2 equivalents per kWh can be calculated. Using the average numbers for CO_2 equivalents per GWh presented in figure 4.19 and using the percentages of different energy sources from figure 4.18, the total CO_2 equivalent per generated kWh for Indiana's electricity mix could be calculated as: 0.8282 kgCO_2e/kWh.

For taking the environmental impact of the solar power generated in the household into account, the CO_2 equivalent for solar power presented in figure 4.19, namely 0.085 kgCO_2e/kWh, is used which, among others, takes the manufacturing of the panels into account [109].

In some scenarios, electricity from both the grid and the solar panels is stored within the battery. This energy inside the battery is then used to either support the household load profile or it is inserted into the grid for load shifting. To calculate the solar energy used within the household, the percentage of solar power stored inside the battery is calculated at all times. If energy is discharged from the battery it will be assumed that the discharged energy contains the same percentage of solar energy.

The next factor that will be taken into account when calculating the ecological impact of including a home energy storage system based on new or reused EV batteries, is the CO_2 equivalent associated with the manufacturing of these systems. As all the parts for both systems are the same except the battery packs, which are either new or reused, only the difference in the ecological impacts of these packs will be taken into account here. For the reused battery packs the CO_2 equivalent associated with manufacturing is set to zero, as the current alternative of reuse is disposal. Environmental burden due to collection and transportation of the used battery cells will be neglected. Therefore the reuse of the battery packs can be seen as without any environmental cost as these packs are not especially produced for this application and would still be manufactured (and discarded) if they were not reused in a home energy storage system.

For the economic impact of creating a new battery pack, an analysis of multiple LCAs of EV batteries, conducted by Peters and Weil, will be used. According to Peters and Weil, the CO_2 equivalent per kg battery manufactured is roughly 13.5 $kgCO_2e$ for the cell chemistry used within this study (LMO) [110]. Using the mass of the Ford Focus Electric 2013 Battery pack of 302.5 kg [89], the CO_2 equivalent of the total battery pack can be calculated as 4,083.8 $kgCO_2e$. As the new battery HES systems will have higher efficiencies and capacity, it is likely that it leads to higher savings in CO_2 equivalent emissions. For comparing the new and the reused battery HES system, an ‘ecological payback time’ will be calculated, which is the time it takes for the new battery HES system to recover its initial environmental burden through the difference in CO_2 equivalent emissions saved

Finally the environmental impact of including the electric vehicle will be evaluated. For this the emissions associated with the energy for charging the EV will be compared to the emissions generated through running a vehicle with a conventional ICE. In both cases the CO_2 equivalent associated with manufacturing or disposal of the vehicles will not be taken into account. This could shift the overall results regarding the environmental impact of the electric vehicle so further studies should investigate this in more detail. The energy that is transferred to the EV will be translated into miles that can be driven with this charge and additionally the emissions associated with generating this charge will be calculated. Now these emissions can be compared with the emissions that a vehicle with an ICE generates driving the same amount of miles.

For these calculations the following parameters are needed, some of which were already mentioned in the section regarding the economic model:

- EV battery energy in miles conversion rate: 310 Wh/miles [89]
- Typical ICE miles per gallon rate: 23.41 [106]
- CO_2 equivalent emissions from burning a gallon of gasoline: 8.9 kgCO_2e/gallon [111]

4.7 Evaluated Scenarios and Control Schemes

In the following sections, the scenarios and the control schemes that will be applied to the model will be explained in detail. First the possible scenarios are presented, then the control schemes are desctribed.

4.7.1 Scenarios

In this section, the considered scenarios that will be evaluated in combination with different control schemes will be presented. As some scenarios are not fit for certain control schemes (such as keeping a certain percentage of the battery for fast charging only makes sense, if there is a vehicle in the household that could be fast charged) some scenarios will be excluded for specific control schemes. The individual control scheme and for which of the scenarios it will be evaluated in, will be explained more in section 4.7.2.

The different parameters that will be varied in the scenarios are:

- Tariff structure (Flat Tariff, TOU Tariff)
- Presence of net metering
- Presence of an electric vehicle
- Presence of Solar Panels
- Battery control scheme
- Inclusion of an HES system (No HES system, Reused battery HES system, New battery HES system

The different scenarios will be presented in more detail in the following sections:

No Solar Power and Flat Tariff

These scenarios represent some of the base cases that other scenarios can be compared to. In these scenarios there are no solar panels included in the household and the electric tariff structure is flat. As there are no solar panels, increasing the self-sufficiency with a battery is not possible; neither is load shifting, as there are no different electricity prices during the day. Therefore no HES system will be included in these scenarios.

In table 4.1, the scenarios are presented:

Table 4.1: Scenarios no solar power and flat tariff.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 1	Flat				
Scenario 2	Flat			✓	

No Solar Power and Time-of-Use Tariff

Similar to the previous scenarios, in these scenarios there will be no solar power connected to the household. However, in this case, the tariff structure is the time-of-use (TOU) tariff, which means that a home energy storage system could be used for load shifting. Therefore, cases in which a home energy storage system is present (either based on a reused EV battery or a new one) will be evaluated additionally to including an EV to the household. As load shifting can be affected by the presence of net metering, this parameter will be varied in these scenarios as well. The scenarios for evaluation can be seen in table 4.2:

Table 4.2: Scenarios no solar power and TOU tariff.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 3	TOU				
Scenario 3.1	TOU				2^{nd} Use
Scenario 3.2	TOU				New
Scenario 4	TOU			✓	
Scenario 4.1	TOU			✓	2^{nd} Use
Scenario 4.2	TOU			✓	New
Scenario 5	TOU		✓		
Scenario 5.1	TOU		✓		2^{nd} Use
Scenario 5.2	TOU		✓		New
Scenario 6	TOU		✓	✓	
Scenario 6.1	TOU		✓	✓	2^{nd} Use
Scenario 6.2	TOU		✓	✓	New

Solar Power and Flat Tariff

In these scenarios solar power will be added to the household, and the electric tariff structure will be flat. Different configurations of adding an EV, net metering and a home energy storage system based on a reused EV battery or a new battery will be explored. The full list of scenarios can be seen in the following table (table 4.3):

Table 4.3: Scenarios solar power and flat tariff.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 7	Flat	✓			
Scenario 7.1	Flat	✓			2^{nd} Use
Scenario 7.2	Flat	✓			New
Scenario 8	Flat	✓		✓	
Scenario 8.1	Flat	✓		✓	2^{nd} Use
Scenario 8.2	Flat	✓		✓	New
Scenario 9	Flat	✓	✓		
Scenario 9.1	Flat	✓	✓		2^{nd} Use
Scenario 9.2	Flat	✓	✓		New
Scenario 10	Flat	✓	✓	✓	
Scenario 10.1	Flat	✓	✓	✓	2^{nd} Use
Scenario 10.2	Flat	✓	✓	✓	New

Solar Power and Time-of-Use Tariff

The following scenarios are similar to the previous ones with the only difference that the electrical tariff is changed from a flat structure to a TOU electrical tariff. Again, all combinations in regard of adding net metering, an EV or home energy storage systems are explored:

Table 4.4: Scenarios solar power and TOU tariff.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 11	TOU	✓			
Scenario 11.1	TOU	✓			2^{nd} Use
Scenario 11.2	TOU	✓			New
Scenario 12	TOU	✓		✓	
Scenario 12.1	TOU	✓		✓	2^{nd} Use
Scenario 12.2	TOU	✓		✓	New
Scenario 13	TOU	✓	✓		
Scenario 13.1	TOU	✓	✓		2^{nd} Use
Scenario 13.2	TOU	✓	✓		New
Scenario 14	TOU	✓	✓	✓	
Scenario 14.1	TOU	✓	✓	✓	2^{nd} Use
Scenario 14.2	TOU	✓	✓	✓	New

4.7.2 Control Schemes

In this section the different control schemes that are applied to the home energy storage systems will be presented. Furthermore, as the battery controls depend on the parameters of the previously discussed scenarios, it might not make sense to evaluate certain scenarios for a particular control scheme. Thus a table specifying which of the scenarios will be used in combination with the control scheme, will be given.

The control schemes have some parameters in common. It is assumed that the DOD is 80 % which was also used in [18], [25] and [29]. For this the maximum SOC is assumed to be 100 %, the minimum SOC is assumed to be 20 %. Additionally, in some of the control schemes a reserve will be kept for fast charging; here a battery SOC of 60 % is kept as a reserve and the battery will be only discharged lower during fast charge events. In some of the control schemes it is further assumed that the battery can be charged from the grid. Here, as the battery is based on an EV battery, a charge rate of 7kW will be used, which is similar to level 2 charging of an EV [36].

Base Cases without an HES System (no Control Scheme)

First, all the base scenarios where no HES system is included are evaluated. As no HES system is included in these scenarios, there are no controls necessary. The list of scenarios evaluated as base cases can be seen in table 4.5:

Table 4.5: Scenarios evaluated as base cases, no HES system.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 1	Flat				
Scenario 2	Flat			✓	
Scenario 3	TOU				
Scenario 4	TOU			✓	
Scenario 5	TOU		✓		
Scenario 6	TOU		✓	✓	
Scenario 7	Flat	✓			
Scenario 8	Flat	✓		✓	
Scenario 9	Flat	✓	✓		
Scenario 10	Flat	✓	✓	✓	
Scenario 11	TOU	✓			
Scenario 12	TOU	✓		✓	
Scenario 13	TOU	✓	✓		
Scenario 14	TOU	✓	✓	✓	

As an example in the next figures there are two weeks displayed for scenario 14, one during winter and one during summer:

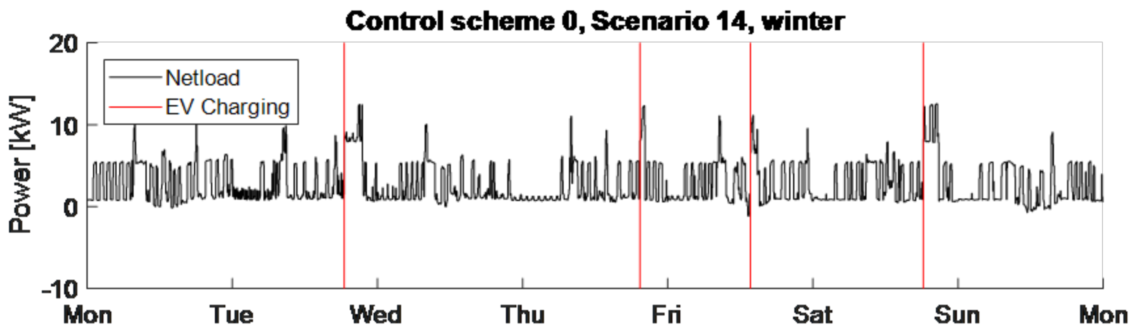


Figure 4.20: Example for no control scheme during winter (beginning 9^{th} of January 2017).

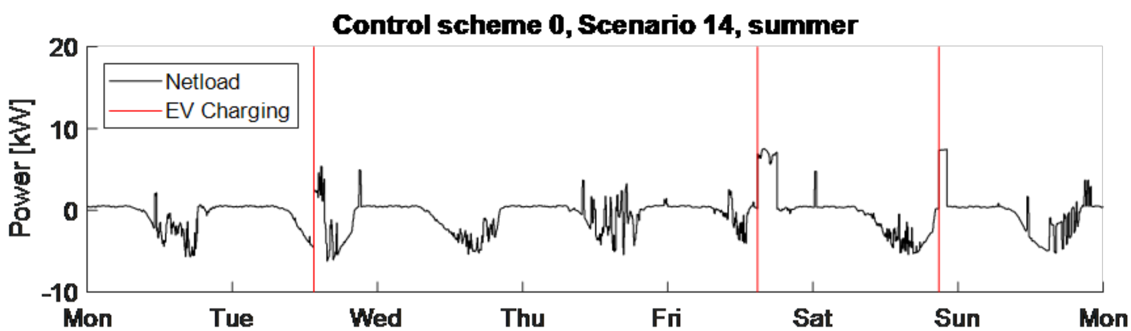


Figure 4.21: Example for no control scheme during summer (beginning 26^{th} of June 2017).

As can be seen in figure 4.7.2 and figure 4.7.2, the load profiles are very different in the different seasons. During winter the power consumption is a lot higher than during summer, the spikes in the winter load profile are caused by the geothermal pump which is used for heating. These spikes are not present during the summer. In the summer the solar power generation is a lot higher than during winter. While during winter only rarely was excess solar power generated (the net load stays almost always above zero); this changes drastically during summer. During summer, there is usually a high surplus of solar energy at the middle of the day, which is then fed into the grid. As no HES system is added in the load profiles seen above, only level 2 charging for the EV is possible. This charging causes the temporarily higher net load after each charging event (the time of the charging events are marked by the red line).

Control Scheme 1: Maximize Self-Sufficiency

The aim of this control scheme is to maximize self-sufficiency through setting up a control scheme that retains a maximum of the generated solar power for usage in the household. This also minimizes the amount of grid energy that needs to be imported. Although for this control scheme TOU electrical tariff scenarios are evaluated as well, the on-peak or off-peak time does not influence the controls. The control scheme for this case can be seen in figure 4.22:

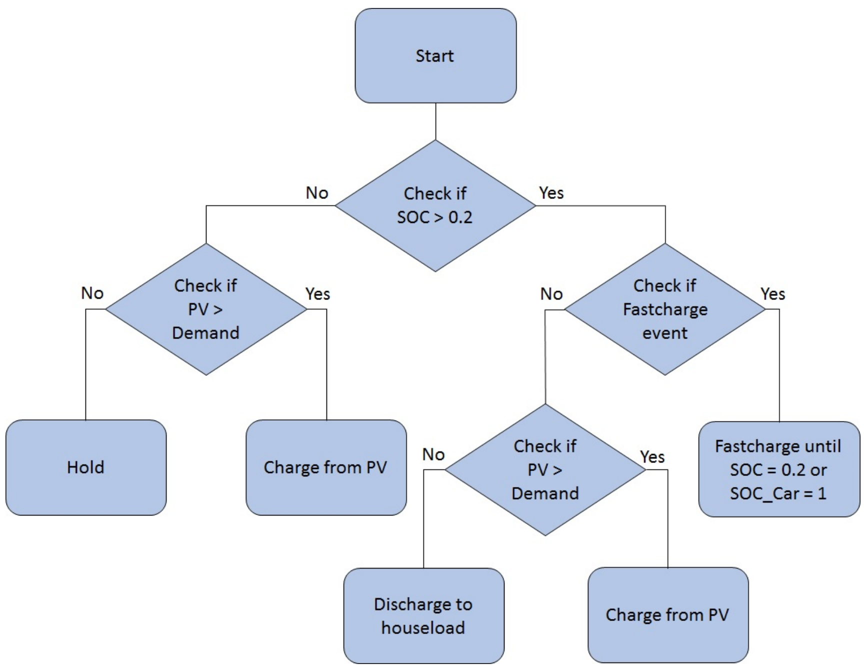


Figure 4.22: Control scheme 1 state diagram.

As can be seen in the figure, the control scheme basically checks at each point in time if the solar power generation is higher than the demand. If it is the case, the surplus will be stored in the home energy storage system. If, the demand is higher than the generation, the stored charge will be used first to serve the demand before grid electricity is used. In case of a fast charging event, if necessary all the remaining charge in the home energy storage system will be used for charging the EV.

The scenarios that will be evaluated for this control scheme are listed in tables 4.6 and 4.7. Note that some of the relevant base Scenarios which do not include a battery are still included in this list. These scenarios have already been computed earlier and will be used for comparison. As the goal of this control scheme is to maximize self-sufficiency, only scenarios that include solar power are evaluated. Thus scenarios that do not include solar power, where the home energy storage system could be only used for load shifting, will not be included in the evaluation of this control scheme.

Table 4.6: Scenarios evaluated for control scheme 1, Part 1.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 7	Flat	✓			
Scenario 7.1	Flat	✓			2^{nd} Use
Scenario 7.2	Flat	✓			New
Scenario 8	Flat	✓		✓	
Scenario 8.1	Flat	✓		✓	2^{nd} Use
Scenario 8.2	Flat	✓		✓	New
Scenario 9	Flat	✓	✓		
Scenario 9.1	Flat	✓	✓		2^{nd} Use
Scenario 9.2	Flat	✓	✓		New
Scenario 10	Flat	✓	✓	✓	
Scenario 10.1	Flat	✓	✓	✓	2^{nd} Use
Scenario 10.2	Flat	✓	✓	✓	New

Table 4.7: Scenarios evaluated for control scheme 1, Part 2.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 11	TOU	✓			
Scenario 11.1	TOU	✓			2^{nd} Use
Scenario 11.2	TOU	✓			New
Scenario 12	TOU	✓		✓	
Scenario 12.1	TOU	✓		✓	2^{nd} Use
Scenario 12.2	TOU	✓		✓	New
Scenario 13	TOU	✓	✓		
Scenario 13.1	TOU	✓	✓		2^{nd} Use
Scenario 13.2	TOU	✓	✓		New
Scenario 14	TOU	✓	✓	✓	
Scenario 14.1	TOU	✓	✓	✓	2^{nd} Use
Scenario 14.2	TOU	✓	✓	✓	New

To explain the control scheme in more detail, in the next figure the net load profile is presented along with the SOC profile of the battery for an example week during winter, and later also for an example week during summer:

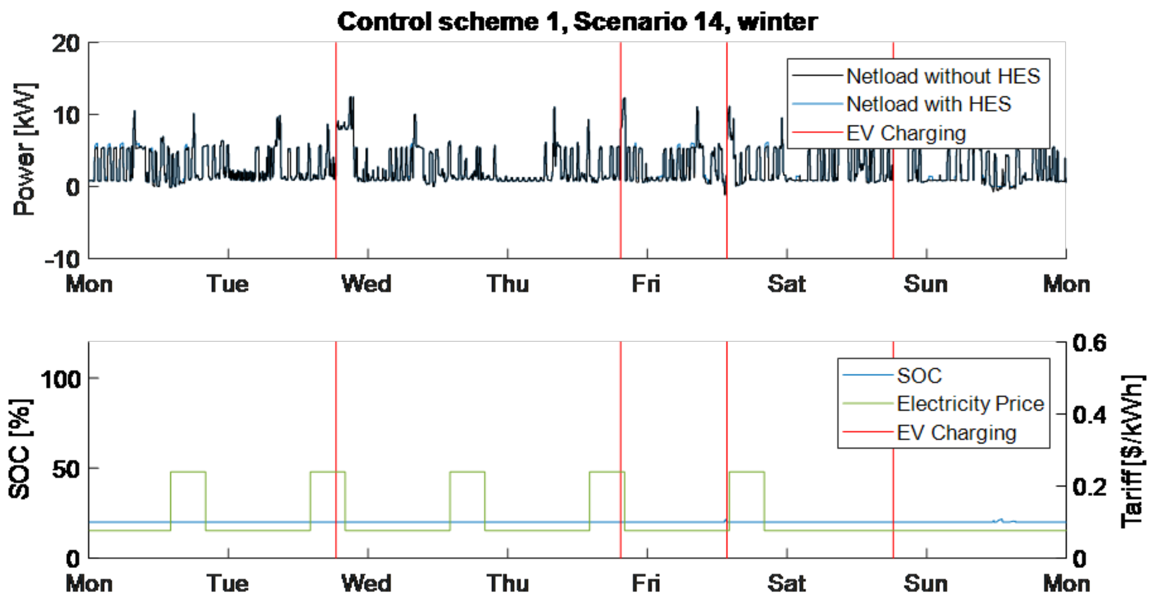


Figure 4.23: Example for control scheme 1 during winter (beginning 9^{th} of January 2017).

As in this control scheme the battery is only charged by excess solar energy, and during winter almost no excess solar energy is generated, the HES system is not used much during this week. As can be seen in the figure depicting the net loads, the profiles with HES system and without HES system are almost identical. The main difference is only the slightly higher profile for the case with HES system due to the energy needed to keep the battery at a temperature above zero. As can be seen in the figure depicting the SOC, the SOC stays mostly at 20 % which is the minimum capacity. If there is a small excess in solar energy it is used immediately afterwards. As almost no energy is stored inside the HES system during the winter, no fast charging is possible. The electricity price can also be seen in this figure. As explained in section 4.5.1, the peak price is present during weekdays between 2 pm and 8 pm; there is no peakprice time during weekends. This electricity price was added to the figure as it has a high influence on other control schemes such as load shifting. However, for the current load profile there is no such influence.

In figure 4.24, the HES system's response and household load during a week in summer can be seen:

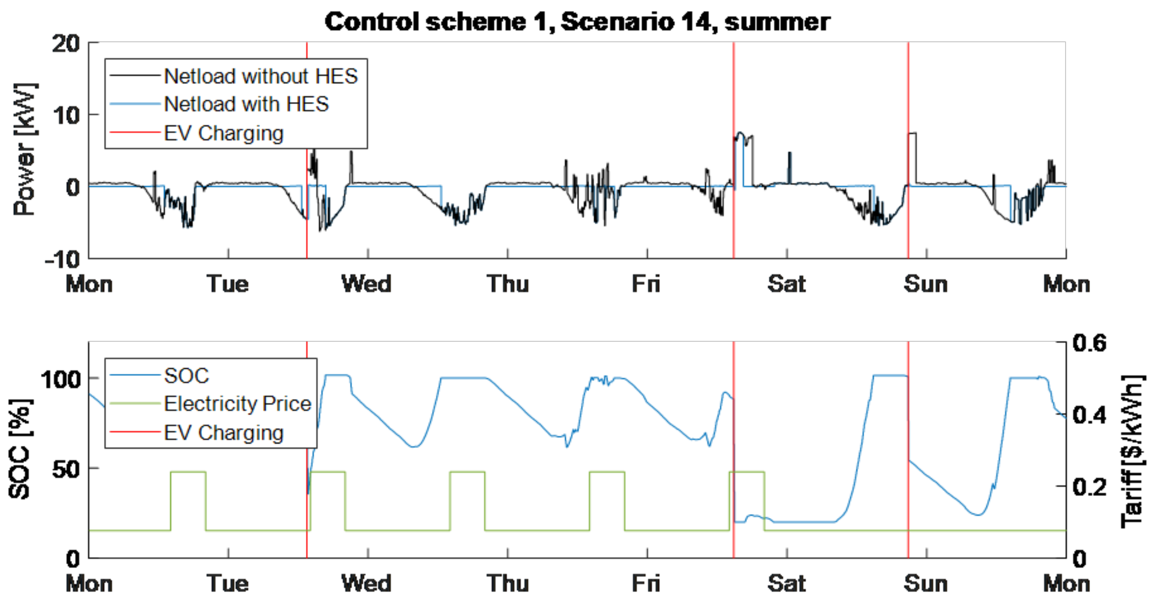


Figure 4.24: Example for control scheme 1 during summer (beginning 26^{th} of June 2017).

With the high excess solar energy generated during summer, the HES system utilization increases significantly. As the household does not use much energy during summer, the HES system is usually not depleted overnight. Furthermore, the HES system is not able to store all excess solar energy generated during the day; there is still a significant amount that is fed into the grid. During summer the SOC is usually very high and only drops significantly during fast charging events.

Control Scheme 2: Maximize Self-Sufficiency, keep Fast Charging Reserve

This control scheme is similar to the case previously discussed, only that a reserve of 40 % will be set just for fast charging at all times. Through this reserve it is always possible to add 18.5 miles to the EVs range through fast charging, which is enough range to cover the average commuter distance in metropolitan areas, which is at most 13 miles [112]. During fast charging, the battery will be fully discharged (down to the minimal SOC of 20 %) and afterwards recharged up to an SOC of 60 % to have the fast charging reserve available.

During this process the battery will recharge using solar power or, if no solar power is available, grid electricity. Again the on peak or off peak electricity prices will not be taken into account for the controls. The control scheme can be seen in figure 4.25:

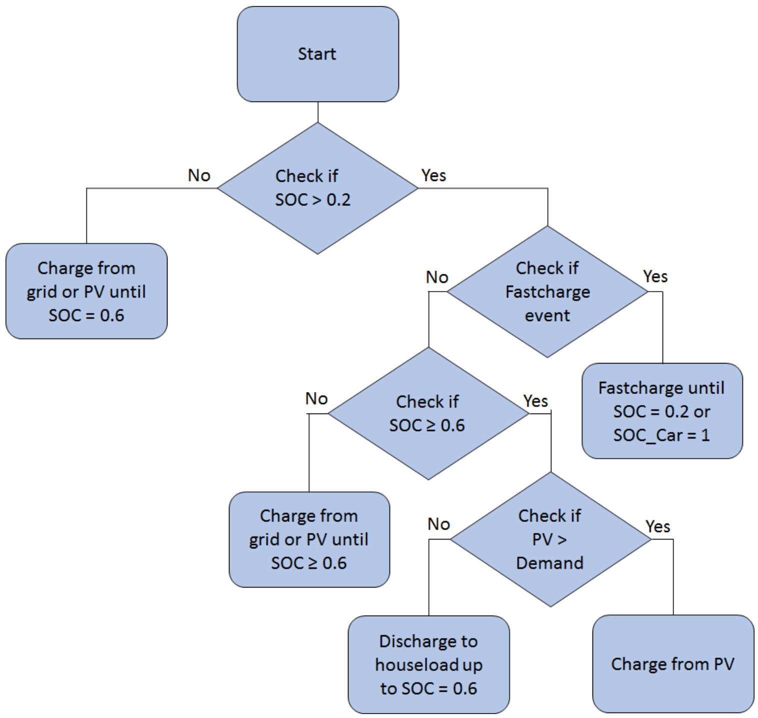


Figure 4.25: Control scheme 2 state diagram.

As can be seen in figure 4.25, the control scheme is similar to the previous case such that the system checks if the generated solar power is higher than the current demand. If this is the case surplus energy is stored in the home energy storage system, which is then used once the generated solar power drops below the demand. However, the home energy storage is only depleted up to a minimum of 60 % SOC to serve the household load, the rest is reserved for fast charging. In case of fast charging all the currently remaining charge in the home energy storage system can be used to charge the EV.

For this control scheme only scenarios are evaluated where both solar power and an EV are present in the household. The base scenarios without any home energy storage system are still included in the list, though, as these can be used for comparison. The scenarios that are evaluated for this control scheme can be seen in table 4.8:

Table 4.8: Scenarios evaluated for control scheme 2.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 8	Flat	✓		✓	
Scenario 8.1	Flat	✓		✓	2^{nd} Use
Scenario 8.2	Flat	✓		✓	New
Scenario 10	Flat	✓	✓	✓	
Scenario 10.1	Flat	✓	✓	✓	2^{nd} Use
Scenario 10.2	Flat	✓	✓	✓	New
Scenario 12	TOU	✓		✓	
Scenario 12.1	TOU	✓		✓	2^{nd} Use
Scenario 12.2	TOU	✓		✓	New
Scenario 14	TOU	✓	✓	✓	
Scenario 14.1	TOU	✓	✓	✓	2^{nd} Use
Scenario 14.2	TOU	✓	✓	✓	New

In figure 4.26 the load profile of the household and the SOC profile of the HES system can be seen for an example week during winter:

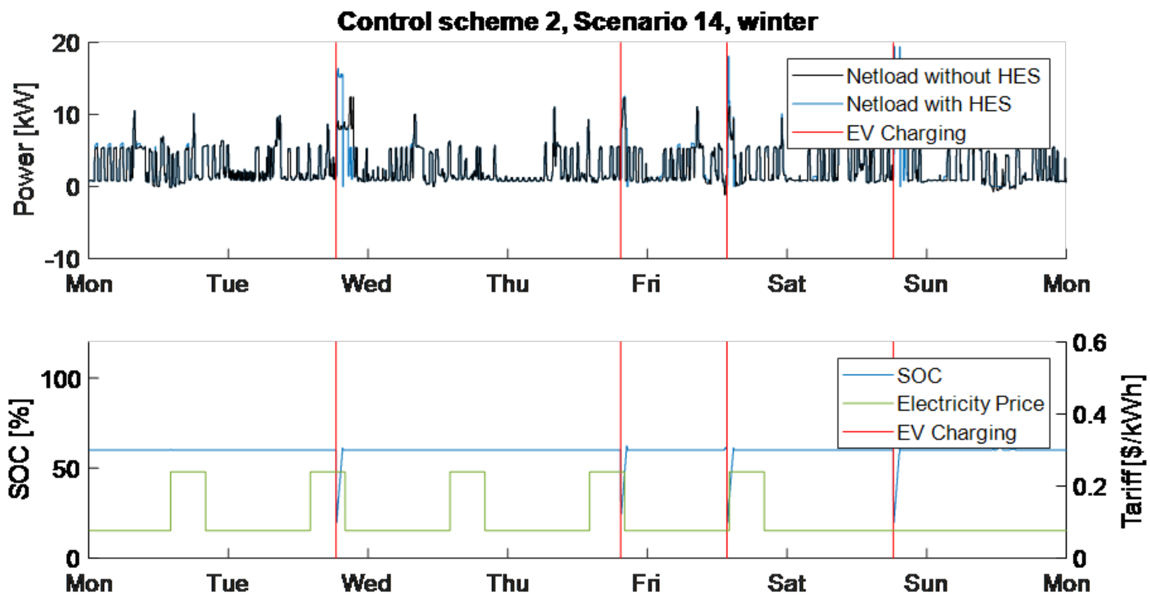


Figure 4.26: Example for control scheme 2 during winter (beginning 9^{th} of January 2017).

Again, similar to the previous control scheme, the HES system is not utilized much during winter. As a difference however, the SOC is always kept at 60 %, which always leaves 40 % of the battery capacity for fast charging. As can be seen in the downward spikes in the SOC profile during EV charging times, fast charging is always possible. After the fast charging event the battery is recharged immediately back to 60 % and awaits the next fast charging event. This recharging after the charging event is also reflected in a spike in the load profile after the charging event.

The net load profile and the SOC profile of the HES system during a week in summer can be seen in figure 4.27:

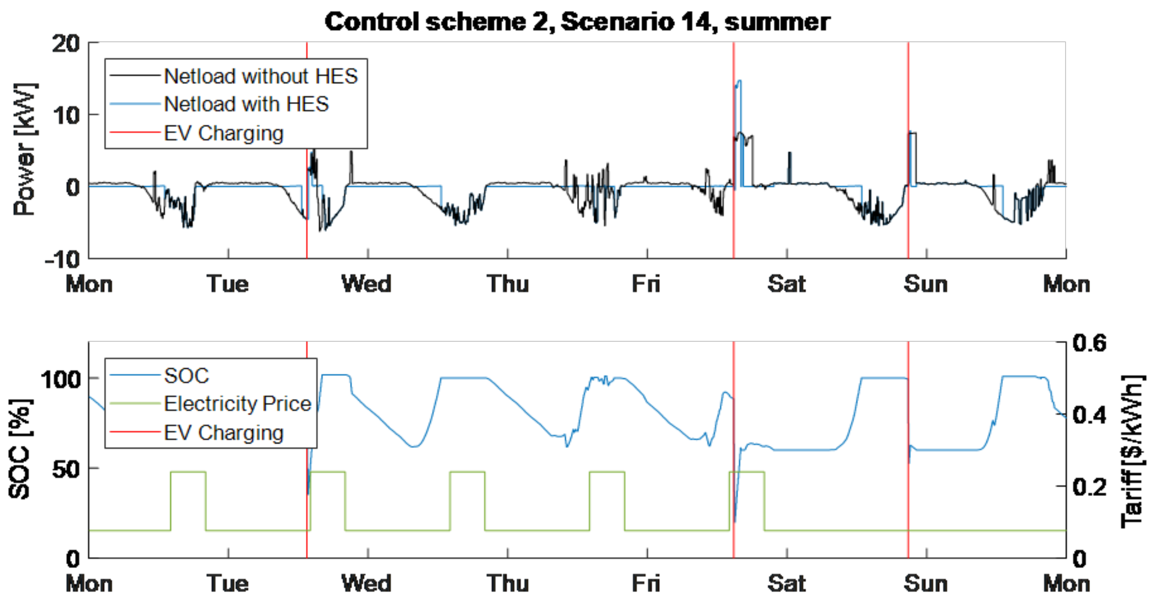


Figure 4.27: Example for control scheme 2 during summer (beginning 26^{th} of June 2017).

The net load profile is similar to the previous control scheme; however, as the reserve is always kept at 60 %, the capacity usable for storing solar energy is decreased. One effect of fast charging on the net load profile, that can be seen at the event on Friday during the summer week, is that the time of the level 2 charging spike is reduced for the net load profile with HES system, as already a high amount of energy could be transferred to the car through fast charging.

Control Scheme 3: Load Shifting

This control scheme aims to maximize the profit that can be obtained by adding the home energy storage system. For this the HES system charges up to full capacity during off peak time and discharges during peak times. Additionally the control system aims to retain as much of the generated solar power to cover for the household load as possible. If fast charging happens during off peak time, only so much energy will be transferred to the car such that it is still possible to recharge the battery fully before peak time starts. As load shifting is only possible for a TOU tariff, only this tariff structure is evaluated. For a flat tariff, the profit can only be maximized with maximizing self-sufficiency in a no net metering scenario, which has already been addressed by control scheme 1.

The control scheme if solar power is available in the household can be seen in figure 4.28:

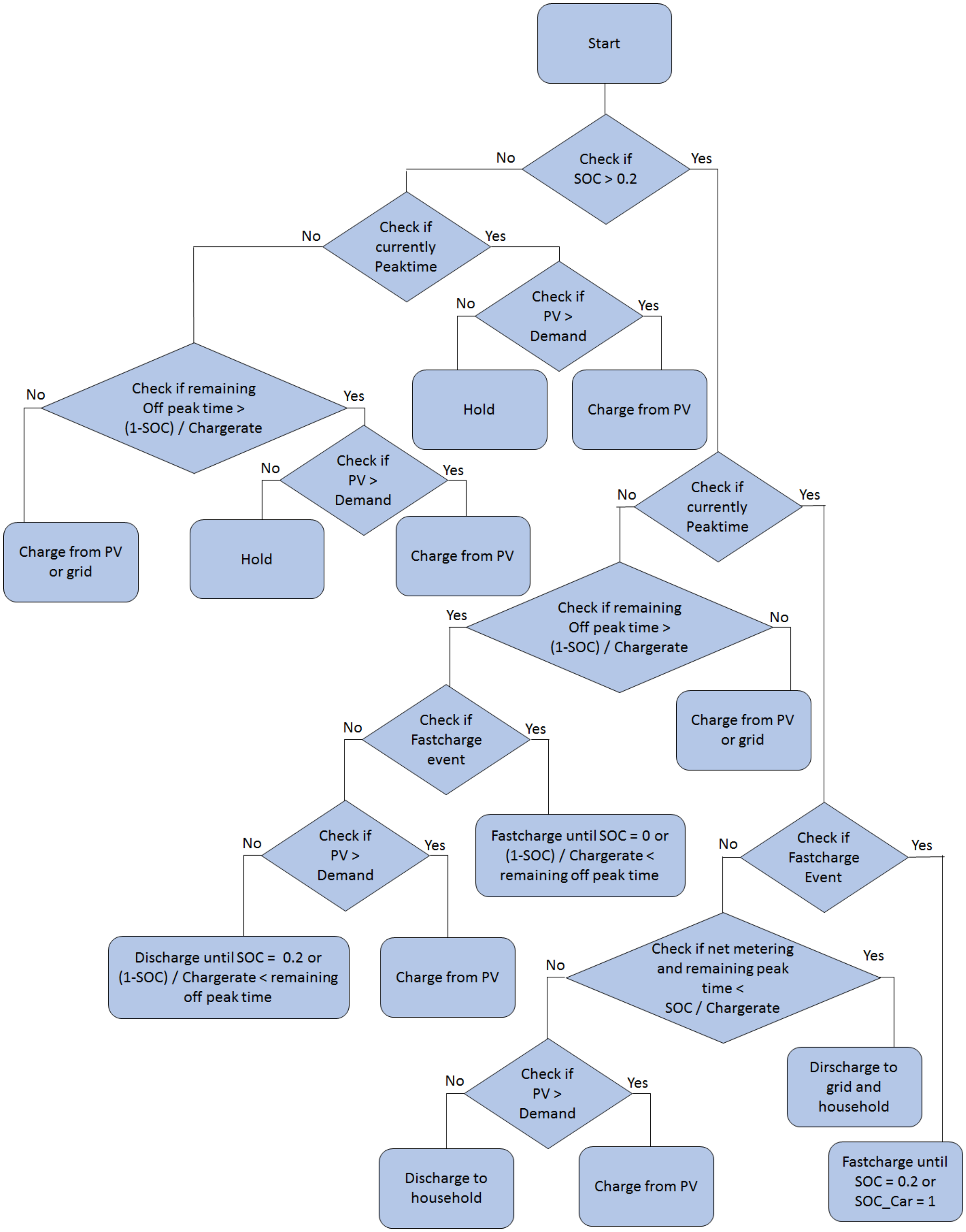


Figure 4.28: Control scheme 3 state diagram including solar panels.

As can be seen in the figure the controls determine if it is currently peak time or not. If it is peak time, the controls work similarly to the self-sufficiency case, as they will use the battery to support the houseload if the solar power generation is insufficient or used for fast charging. If net metering is active the home energy storage system discharges any remaining charge into the grid at the end of the peak time. If fast charging occurs during peak time, all charge currently available can be used if necessary. During off peak time, as before, the battery will charge if solar power is higher than current household load, and it will discharge if vice versa. However there are two main differences, if the end of off peak time approaches, the battery will use the grid or solar power to fully charge so it will start peak time with an SOC of 100 %. If fast charging occurs during off peak time, only as much charge will be used for fast charging as can be recharged from the grid or solar power during the remaining off-peak time.

The control scheme if no solar power is available in the household can be seen in figure 4.29:

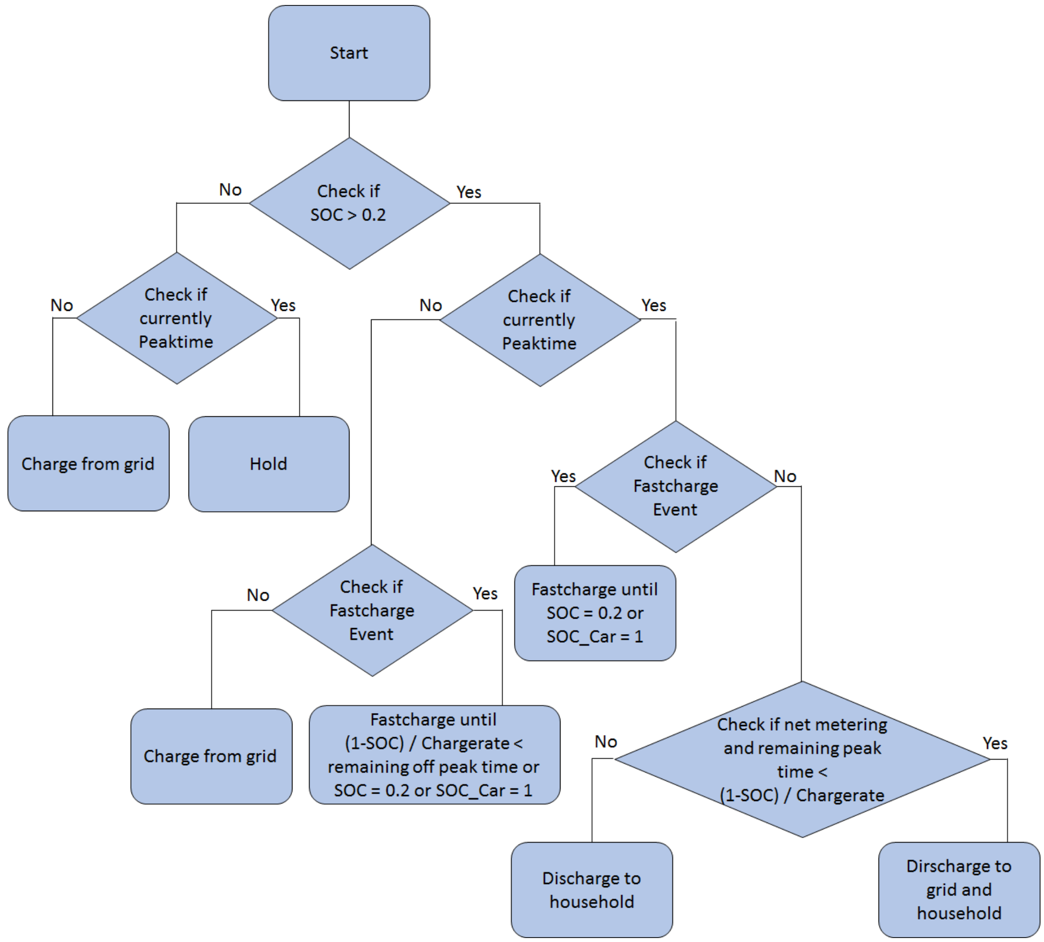


Figure 4.29: Control scheme 3 state diagram not including solar panels.

The controls scheme if no solar power is generated in the household is a bit simplified to the previous case where solar power is included. Here the battery will charge from the grid during off peak time until the SOC reaches 100 %. During peak time, this charge will be used to support the household load or could be fully used to fast charge an EV if a fast charging event occurs. If net metering is active, at the end of peak time the battery will automatically discharge into the grid until it reaches an SOC of 0 % before entering the off-peak time. If fast charging occurs during off-peak time, again only so much charge will be used as can be recharged from the grid during the remaining off-peak time.

As mentioned before, for these control schemes scenarios will be evaluated only where a TOU tariff is present. All other parameters such as inclusion of net metering, solar power or an EV will be varied. The evaluated scenarios can be seen in table 4.9 and in table 4.10:

Table 4.9: Scenarios evaluated for control scheme 3, Part 1.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 3	TOU				
Scenario 3.1	TOU				2^{nd} Use
Scenario 3.2	TOU				New
Scenario 4	TOU			✓	
Scenario 4.1	TOU			✓	2^{nd} Use
Scenario 4.2	TOU			✓	New
Scenario 5	TOU		✓		
Scenario 5.1	TOU		✓		2^{nd} Use
Scenario 5.2	TOU		✓		New
Scenario 6	TOU		✓	✓	
Scenario 6.1	TOU		✓	✓	2^{nd} Use
Scenario 6.2	TOU		✓	✓	New

Table 4.10: Scenarios evaluated for control scheme 3, Part 2.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 11	TOU	✓			
Scenario 11.1	TOU	✓			2^{nd} Use
Scenario 11.2	TOU	✓			New
Scenario 12	TOU	✓		✓	
Scenario 12.1	TOU	✓		✓	2^{nd} Use
Scenario 12.2	TOU	✓		✓	New
Scenario 13	TOU	✓	✓		
Scenario 13.1	TOU	✓	✓		2^{nd} Use
Scenario 13.2	TOU	✓	✓		New
Scenario 14	TOU	✓	✓	✓	
Scenario 14.1	TOU	✓	✓	✓	2^{nd} Use
Scenario 14.2	TOU	✓	✓	✓	New

In figure 4.30, the load profile while using this control scheme can be seen for an example week during winter:

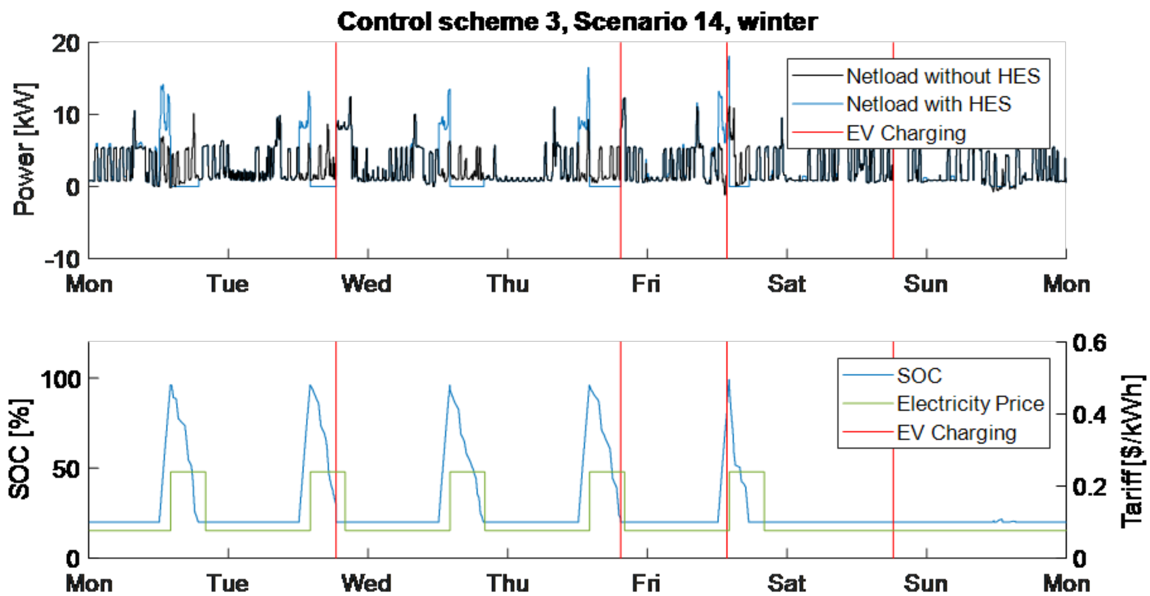


Figure 4.30: Example for control scheme 3 during winter (beginning 9^{th} of January 2017).

As can be seen in the SOC profile, the battery charges up before peak time, making sure that it reaches an SOC close to 100 % when entering peak time. During peak time the battery discharges. As there is not much solar energy during winter, the battery can only charge from the grid, adding an additional spike to the net load profile before peak time. As it discharges during peak time, it levels the net load profile until the HES system is fully discharged. In the scenario shown in figure 4.30 net metering is active; however, there is no need to discharge into the grid for profit during winter, as all the energy stored in the HES system is used by the household. One specialty of this control scheme is that fast charging will be ignored, if it interferes with the loadshifting. As an example, in the EV charging event on Friday during the winter week, the no energy is fast charged, as it would interfere with the charging before peak time. In this case only level 2 charging is used instead.

Figure 4.31 shows the net load and the charging states during a week in summer:

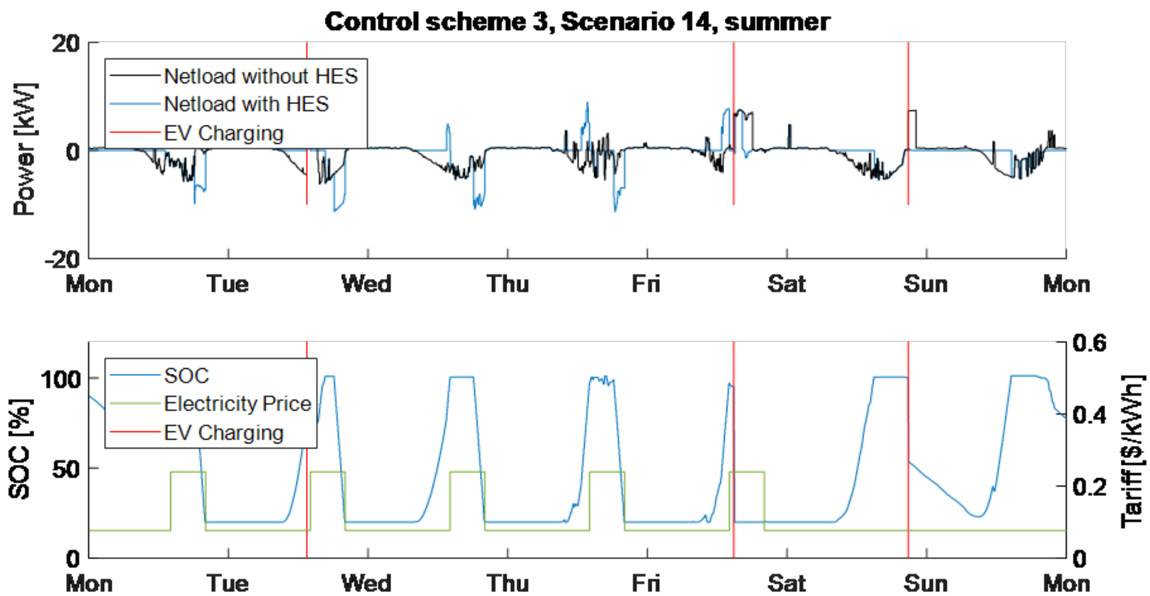


Figure 4.31: Example for control scheme 3 during summer (beginning 26^{th} of June 2017).

During summer, the battery tries to charge from solar energy before reaching peak time and only charges the remainder from the grid. As the peak time coincides with the time where a high amount of excess solar energy is produced, the energy stored inside the HES system is usually not fully used by the household. As in this scenario net metering is active, the HES system discharges its remaining energy charge at the end of the peak time back into the grid to create a profit. This leads to the negative spikes in the net load profile at the end of the peak time.

Control Scheme 4: Load Shifting, keep Fast Charging Reserve

This control scheme aims to always allow fast charging but still use load shifting to generate a profit. Similar to control scheme 2 in this scenario 40 % of the capacity will always be retained for fast charging events. If fast charging happens, the battery will be drained by all its contained energy if required even if this means that the battery cannot fully recharge again during off peak time. Should the SOC of the battery drop below 60 %, the battery will be charged by the grid, or by solar power if currently available, disregarding the on peak or off-peak time. The rest of the controls will be the same as before for the maximize profit case.

The controls for scenarios that include PV can be seen in figure 4.32:

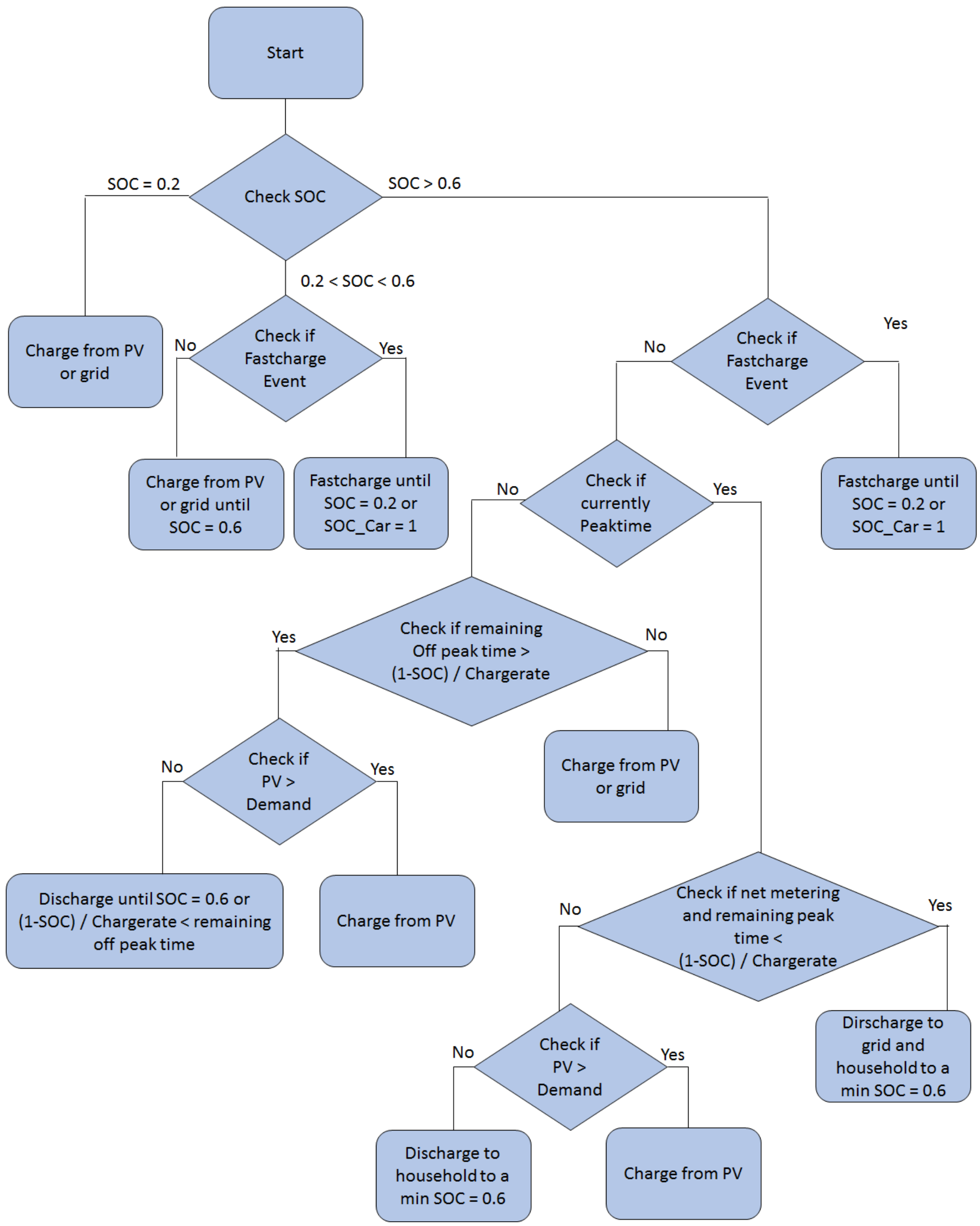


Figure 4.32: Control scheme 4 state diagram including solar panels.

Under these controls regardless of the time of day, the battery will always recharge from the grid or, if available, from solar power, if the SOC drops below 60 %. This is implemented to increase the availability for fast charging. If a fast charging event occurs, the home energy storage system can use all its available charge to recharge the EV. In this control scheme, the fast charging controls are not governed by off or on peak times. During off-peak times, if the solar power generation is higher than the current household load, the home energy storage system will charge the surplus energy and will discharge to the household load if the solar power generation drops below the demand. If the end of the off-peak time approaches, the home energy storage will charge from the grid or, if available, from solar power so it will reach a SOC of 100 % before entering the on peak period. During on-peak time the charge in the home energy storage system will be used to support the household load until an SOC threshold of 60 % is reached. In case of a fast charging event, the whole available charge currently stored inside the HES system can be used. If solar power generation is higher than the household load during off-peak time, the surplus will be used for charging the HES system. If the end of the on peak time approaches and net metering is in effect, the HES system will discharge any remaining charge into the grid until it reaches an SOC of 60 % (as 40 % is reserved for fast charging and the minimum SOC is 20 %) before entering the off peak time.

The control scheme if no PV is included can be seen in figure 4.33:

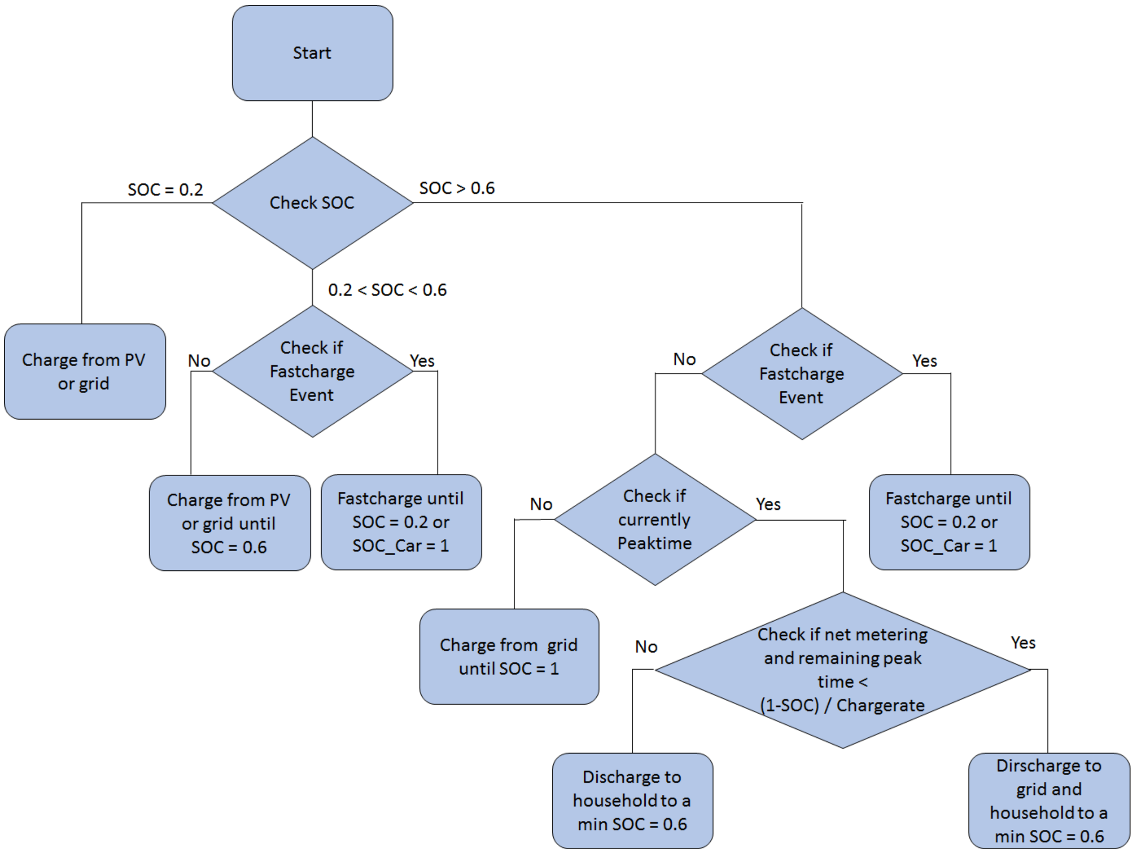


Figure 4.33: Control scheme 4 state diagram not including solar panels.

If no solar power generation is included in the household, the controls can be simplified a bit. If the SOC drops below 60 % the home energy storage system will recharge from the grid no matter if it is currently on or off-peak time. Similarly, if a fast charging event occurs, all the currently stored charge will be used for recharging the EV regardless of the time of day. During on-peak time, the HES system will support the household load until a SOC of 60 % is reached, which marks the reserve for fast charging. During off-peak time, the HES system will recharge from the grid in order to enter the on-peak time with a SOC of 100 %.

Similar to the previous control scheme, only scenarios for TOU electrical tariffs are evaluated here. As an additional condition to the scenarios, only scenarios where an EV is included in the household are evaluated. The list with the evaluated scenarios for this control scheme can be seen in table 4.11:

Table 4.11: Scenarios evaluated for control scheme 4.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 4	TOU			✓	
Scenario 4.1	TOU			✓	2^{nd} Use
Scenario 4.2	TOU			✓	New
Scenario 6	TOU		✓	✓	
Scenario 6.1	TOU		✓	✓	2^{nd} Use
Scenario 6.2	TOU		✓	✓	New
Scenario 12	TOU	✓		✓	
Scenario 12.1	TOU	✓		✓	2^{nd} Use
Scenario 12.2	TOU	✓		✓	New
Scenario 14	TOU	✓	✓	✓	
Scenario 14.1	TOU	✓	✓	✓	2^{nd} Use
Scenario 14.2	TOU	✓	✓	✓	New

The net load profile and the SOC profile for a week during winter can be seen in the next figure (figure 4.34):

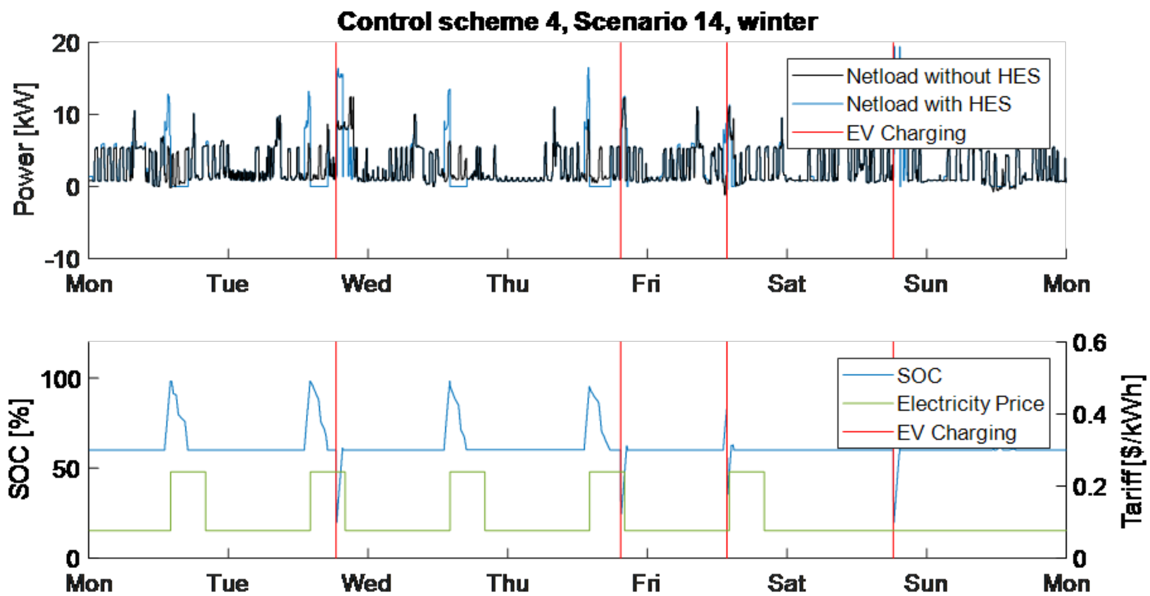


Figure 4.34: Example for control scheme 4 during winter (beginning 9^{th} of January 2017).

This figure is similar to the previous load shifting control scheme, as the battery is charged by solar power or the grid if necessary before entering peak price time and discharged during peaktime to generate a profit. However, in this control scheme a capacity of 40 % is always kept for fast charging. If a fast charging event occurs, all the energy currently stored inside the battery will be used if necessary, even if it interferes with load shifting. During winter most of the energy for charging the HES system is taken from the grid. As can be seen in figure 4.34, after fast charging, the battery will directly recharge from solar or the grid, no matter if it is peak time or off-peak time, to always store a capacity reserve of 40 %.

The load profile of the household and the SOC profile of the HES system during a week in summer can be seen in figure 4.35 :

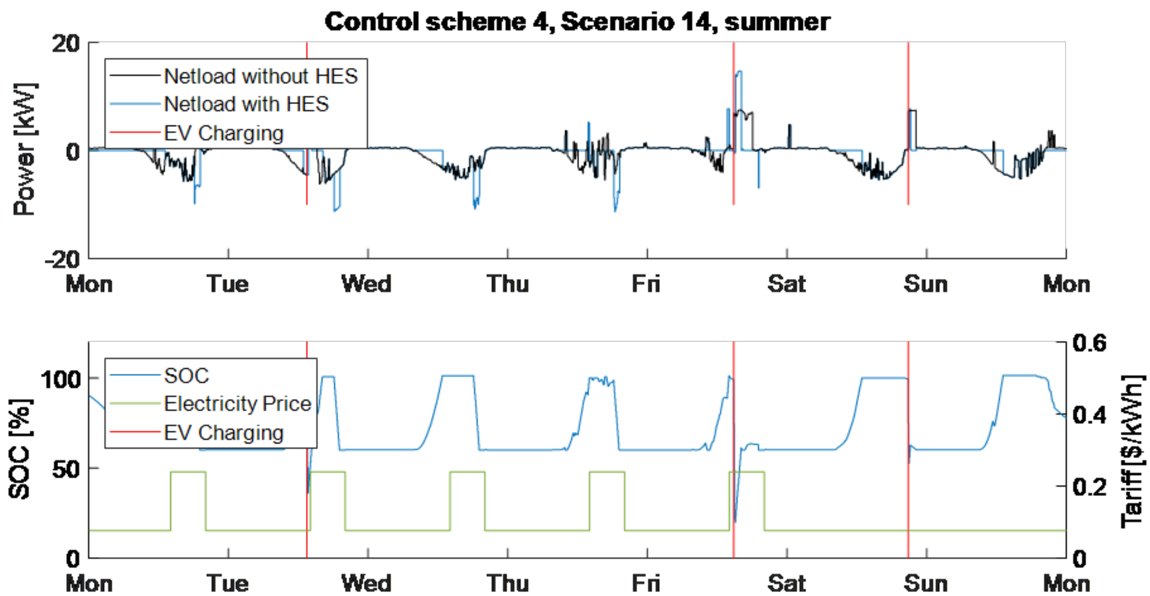


Figure 4.35: Example for control scheme 4 during summer (beginning 26^{th} of June 2017).

In figure 4.35 the net load profile for the control scheme during an example week in summer can be seen. The behavior is similar to the one in the previous figure with the difference that there is a lot more charging of the HES system through excess solar power. As can be seen in the figure, due to keeping the reserve for fast charging, there is less capacity usable for increasing the self-sufficiency through storing and using solar energy, and load shifting is also limited.

Control Scheme 5: Load Shifting, keep limited Fast Charging Reserve

This control scheme is almost the same as the previous control scheme with the only differences being that the emphasis is a bit more on load shifting and that fast charging will be limited. In case of fast charging, a maximal 40 % of the battery will be used, even if the current SOC of the battery is higher. After a fast charging event the control system will ignore the 60 % threshold to keep a fast charging reserve for 3 hours, as it is seen as unlikely that a second fast charging event would occur in such a short time span. During these 3 hours, the HES system can use all its available capacity on load shifting.

The control scheme if PV is included in the household can be seen in figure 4.36; the changes from the previous control scheme are marked in red:

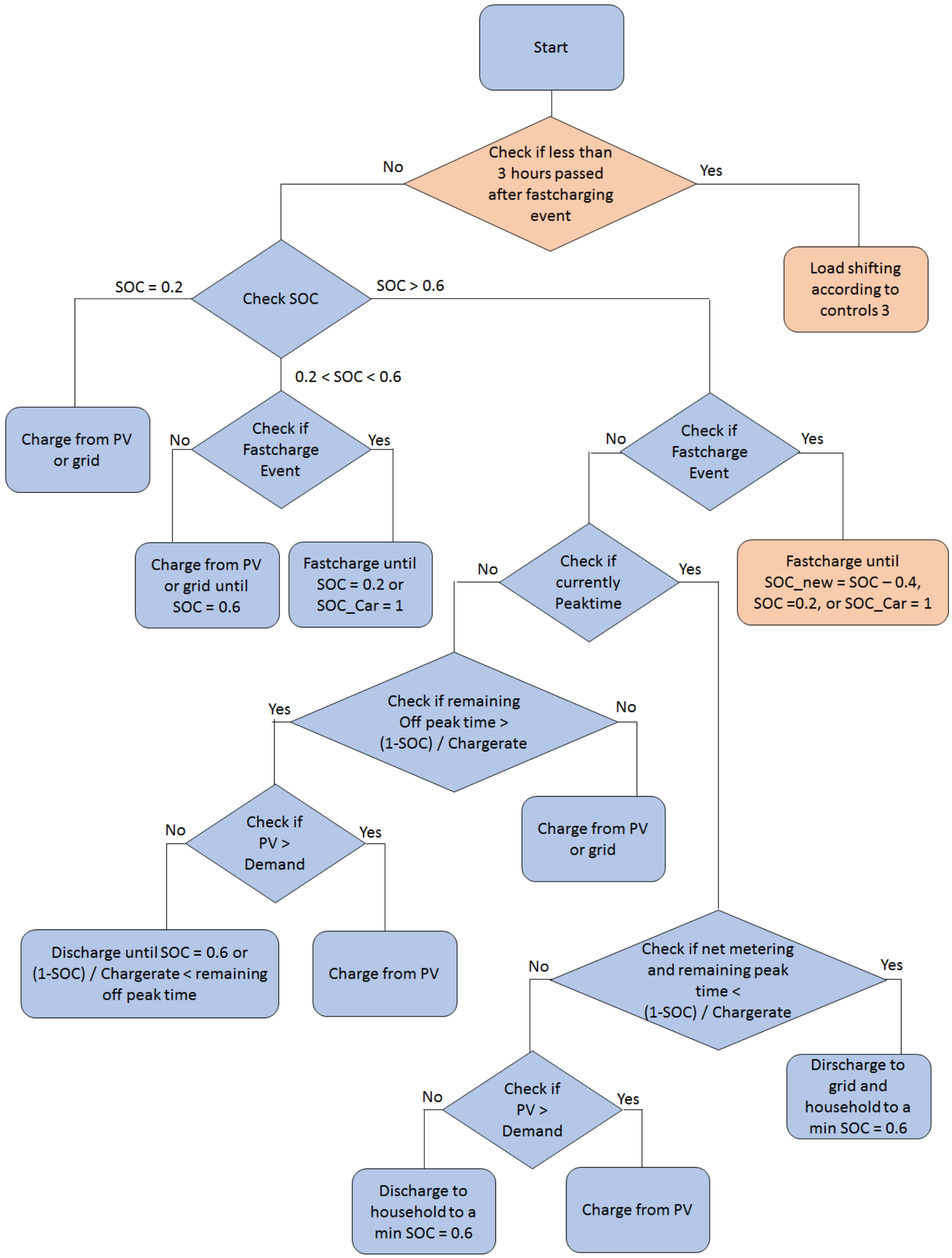


Figure 4.36: Control scheme 5 state diagram including solar panels.

As can be seen in the figure, the controls are similar to the previous case except that in the case of fast charging, only a maximum of 40 % of the battery's capacity is used. Also after a fast charging event there will be a 3 hour timespan in which the 60 % threshold for the fast charging reserve will be ignored.

The control scheme if no PV is included in the household can be seen in figure 4.37 :

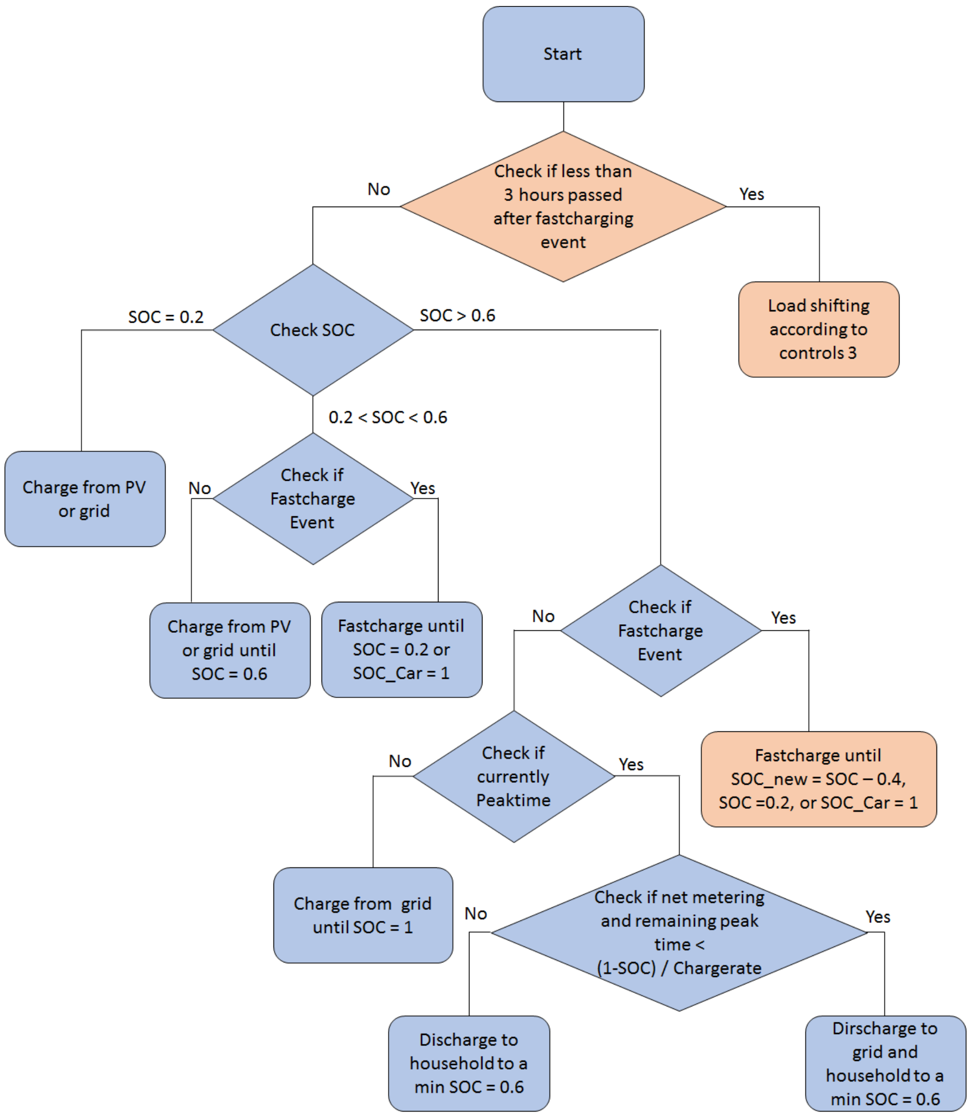


Figure 4.37: Control scheme 5 state diagram not including solar panels.

The evaluated scenarios are the same as before for the previous control scheme. Only scenarios that include a TOU tariff and an EV are evaluated for this control scheme:

Table 4.12: Scenarios evaluated for control scheme 5.

Name	Tariff	Solar Panels	Net metering	EV	Battery
Scenario 4	TOU			✓	
Scenario 4.1	TOU			✓	2^{nd} Use
Scenario 4.2	TOU			✓	New
Scenario 6	TOU		✓	✓	
Scenario 6.1	TOU		✓	✓	2^{nd} Use
Scenario 6.2	TOU		✓	✓	New
Scenario 12	TOU	✓		✓	
Scenario 12.1	TOU	✓		✓	2^{nd} Use
Scenario 12.2	TOU	✓		✓	New
Scenario 14	TOU	✓	✓	✓	
Scenario 14.1	TOU	✓	✓	✓	2^{nd} Use
Scenario 14.2	TOU	✓	✓	✓	New

In the following two figures (figure 4.38 and figure 4.39) example weeks of the net load profile and the SOC profile during winter and during summer can be seen:

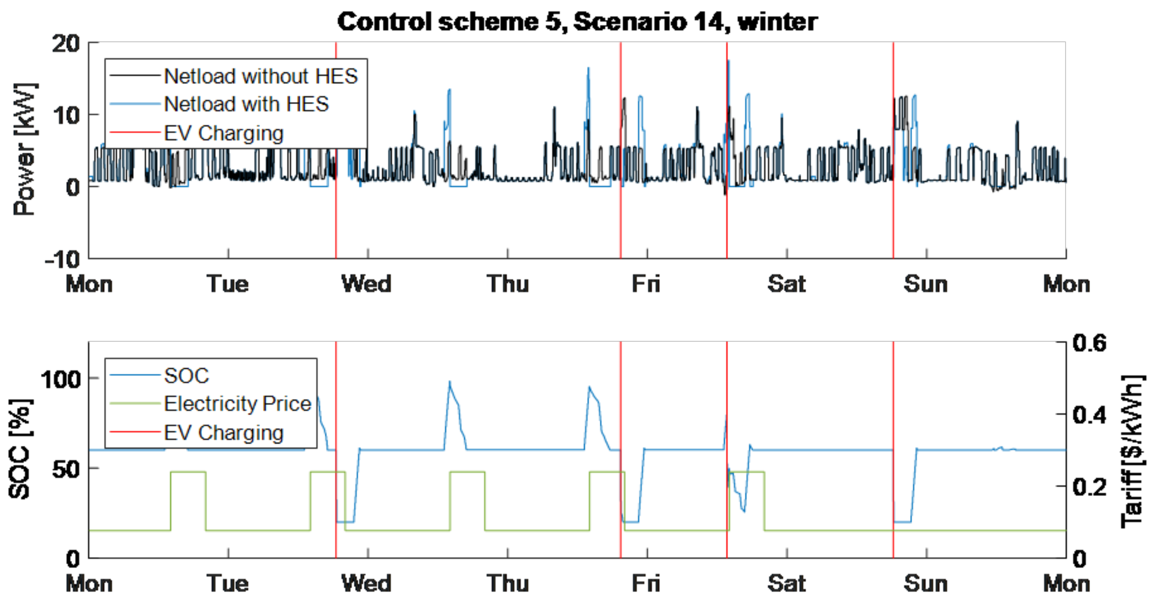


Figure 4.38: Example for control scheme 5 during winter (beginning 9^{th} of January 2017).

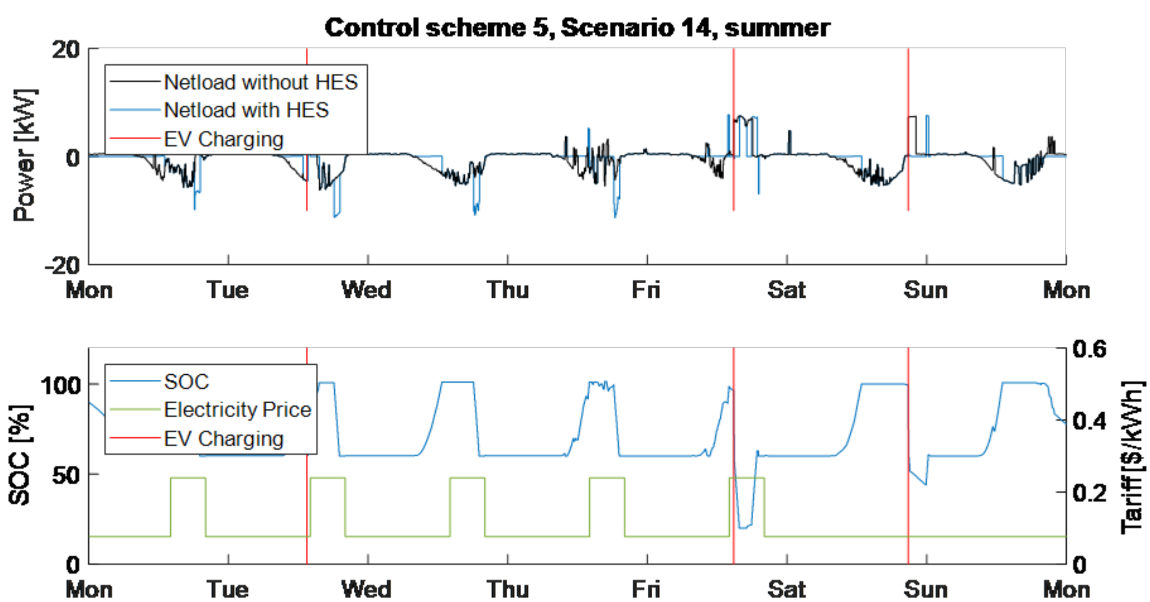


Figure 4.39: Example for control scheme 5 during summer (beginning 26^{th} of June 2017).

The behavior is similar to the previous control scheme; the main difference is the 3 hour timespan after a charging event in which the HES system focuses on load shifting only. Another difference can be seen in the figure at Friday during the summer week. In the previous control scheme, the HES system discharges all the capacity stored inside for the fast charging event until it reaches an SOC of 20 %, the minimal amount. In control scheme 5, the battery only discharges a maximum of 40 % of the battery's capacity, which is equal to the capacity reserve set aside for fast charging, even though there was more energy stored inside that could have been used.

4.8 Performance Parameters

The performance of the different control schemes and the HES system in general will be evaluated by different parameters which include:

- *Overall energy consumption:* The energy consumed within the household. This includes the energy needed to charge the EV as well as all energy lost due to inefficiencies associated with the HES system. The consumed energy will be split by its source, which is either from the grid or from the solar panels.
- *Grid energy percentage:* The fraction of the energy that is imported from the grid over the total energy consumed in the household. The lower this percentage, the more solar energy is consumed in the household, which means that the household is more self-sufficient. It is possible for this parameter to attain numbers higher than 100% as through load shifting grid energy can be imported and exported later without being used inside the household.
- *Electricity cost:* The cost for the energy consumed in the household, evaluated for one year.
- *Profit:* The profit generated over one year will be calculated. This will be defined as the difference between the energy cost with an HES system and the energy cost without the HES system. To calculate the profit, all other parameters of the scenario

will stay the same. The savings due to including an EV as no expensive gas must be purchased, will not be included in this number unless specifically mentioned. If the value for profit is negative, it means that including the HES system will increase the electricity bill rather than reduce it.

- *CO_2 equivalent emissions:* The equivalent CO_2 emissions that are caused by producing the energy that is consumed in the household. Only the consumed energy will be accounted for; exported energy will be not be included.
- *CO_2 equivalent emissions saved:* Similar to profit, the saved CO_2 equivalent emissions are defined as the difference between CO_2 equivalent emissions in a household that does include an HES system and a household that does not. If the value for CO_2 equivalent emissions saved is negative, it means that through adding the HES system to the household, more CO_2 equivalent emissions are released.
- *Fast charging:* To evaluate the fast charging performance of the battery it will be assessed how much energy the battery was able to deliver in each charging instance. For easier understanding this number will be translated into miles added to the EV's range.

After assessing each control scheme individually in the chosen scenarios for both reused battery HES systems and new battery HES systems, all results for the reused HES system will be compared with each other in section 5.7 for the parameters profit, CO_2 equivalent emissions saved and fast charging availability.

Finally, the payback time for the evaluated scenarios and control schemes for both the reused battery HES system and the new battery HES system will be evaluated. Similarly the difference in ecological impact between the reused and new battery HES system will be analyzed.

4.9 General Structure of the Implemented Model

The overall structure of the model will be explained here. In the following sections the most important individual parts of the numerical model will then be explained in more detail. The household including the home energy storage system is modeled in Matlab. The model consists of the following main parts:

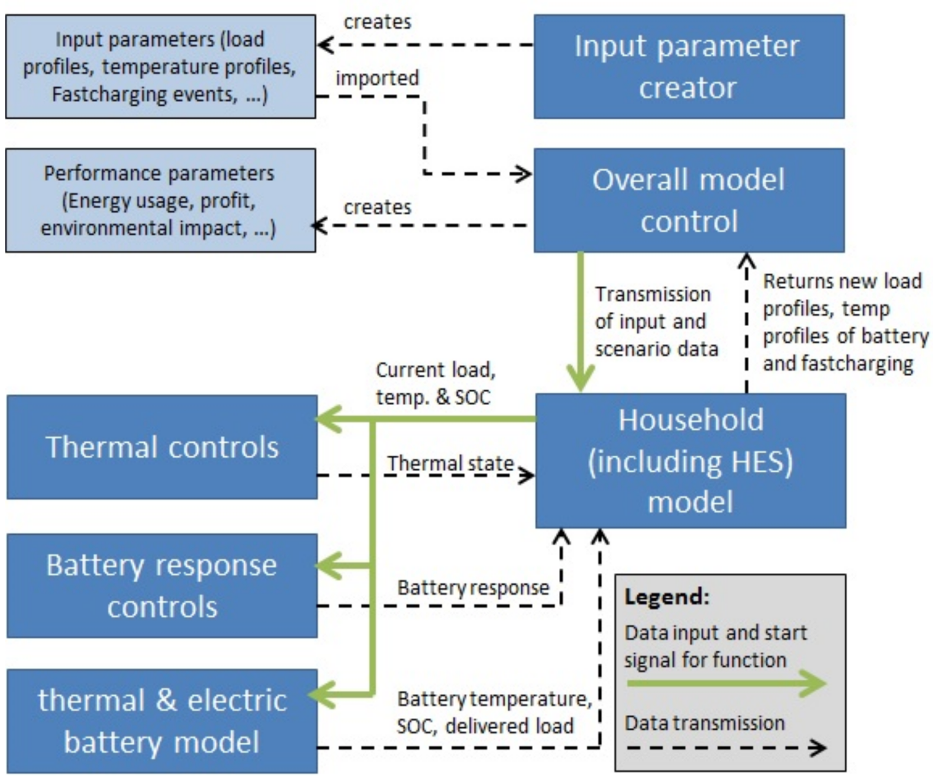


Figure 4.40: Structure of the model code.

- *Input parameter creator:* This independent script is used before the start of the simulation. The input parameters such as load profile, solar power generation profile and temperature profiles are read in from different sources, such as excel tables, and formatted in a way to ensure that they can be read in correctly and in a time efficient manner during the simulation.

- *Overall model control:* This part governs the overall structure of the model and contains the economic and ecological model. The input parameters are inserted into the model from this part and the outputs of the calculations are evaluated here. This part also reads the file containing the environmental data which, among others, includes the load profile of the house, the profile for solar power generation, the ambient temperature profile and the EV charging times and SOCs of the electric vehicle. Additionally the battery parameters are updated for aging and the parameters for the scenarios, the length of timesteps and the start and end time of the calculations can be defined here.

- *Household model:* This function imports the input parameters from the overall model control, calculates the processes at each timestep and afterwards returns the results of the model. During the calculations, this function uses the "thermal controls" to determine the thermal states (cool down, heat, hold) and the "battery response controls" to determine the current battery behavior (discharge, charge, hold) for each timestep based on the load profile and temperature at that time. After determining the control states, it starts the thermal and electrical calculations for the particular timestep.

- *Thermal controls:* This part controls the thermal management state to govern heating or cooling of the battery to ensure safe operations. Its input parameters are the ambient and the battery temperatures.

- *Battery response controls:* Depending on the overall aim of implementing the HES system into the household, different control schemes are developed to e.g. optimize the profit generated with the HES system or to reduce the energy imported from the grid.

- *Battery thermal and electric model:* This function uses the electric model and thermal model that were explained in the previous sections to calculate the temperature and change in SOC during the timestep and additionally returns the energy that is delivered to or from the battery.

- *Other helper functions:* There are additional helper functions implemented such as to calculate the current electricity price, find temperature dependent internal cell resistance.

The general order of calculations and tasks the simulation performs can be listed as such:

1. Input parameters such as load profile, solar power generation profile, temperature profile
2. Read all input parameters
3. Age battery cells, reduce capacity and increase resistance
4. Run main loop for each timestep
    a. Calculate current electricity price, household load, possible fast charging event, solar power generation
    b. Use control scheme to calculate battery response (charge or discharge)
    c. Use thermal controls to determine thermal management
    d. Calculate battery temperature, temperature dependent resistance and efficiency, current draw
    e. Solve ODE (see equation 4.8) for new battery temperature and SOC
    f. Calculate new load profile and EV charging if applicable
5. Report new profiles, calculate performance parameters for evaluation

4.10 Summary of Model Parameters

For the parameters for the thermal management and the power electronics and the battery cells, the same values as the ones used by Spence [29] were used, as the thermal model was already analyzed and validated based on these values. Keeping the values similar in this work will further allow easier comparison. A table containing these values can also be found in the Appendix A. However, some parameters were added or adjusted, for example in the controls of the battery.

The following values are the more important ones for the control schemes that were kept similar to the model from Spence:

Table 4.13: Parameters for the battery control management.

Parameter	Unit	Value chosen	Justification
Maximum SOC	-	100%	Used by [29]
Minimum SOC	-	20%	Used by [29]
Reserve SOC	-	40%	See section 4.7.2
Vehicle Charging Rate	kW	50	Typical value for fast charging used by [29]

Additional parameters that were used for the battery controls and to model its behaviour can be found in table 4.14:

Table 4.14: Overall battery parameters.

Parameter	Unit	Value chosen	Justification
Start SOC	-	20%	The model starts with minimum battery SOC
Remaining capacity of 2^{nd} use battery	-	70%	[29]
Resistance growth for2^{nd} use battery	-	30%	[29]
Battery charge rate from grid	kW	7	As the battery is taken from a EV battery, it is assumed that the charge rate from the grid is the same as level 2 charging
Power to run cooling system	W	100	[29]

Parameters for the EV added into the system and its charging efficiencies and power rates can be found in table 4.15:

Table 4.15: Parameters for the electric vehicle.

Parameter	Unit	Value chosen	Justification
Capacity of EV battery	kW	23	[89]
Vehicle Charging Rate Level 3 Efficiency	kW	97%	[89]
Battery Charge rate from grid	kW	7	[36]
Efficiency level 2 charging	-	79%	[89]
Range per kWh	Miles / kWh	3.32	[89]

Parameters to calculate the ecological and financial impact of the EV are displayed in the following table (table 4.16):

Table 4.16: Parameters for the evaluation of benefits.

Parameter	Unit	Value chosen	Justification
CO_2 equivalent of the grid mix	$kgCO_2e/kWh$	0.8282	See section 4.6
CO_2 equivalent of the solar energy	$kgCO_2e/kWh$	0.085	See section 4.6
CO_2 equivalent emissions from burning a gallon of gasoline	$kgCO_2e/gallon$	8.887	[111]
Miles per gallon average vehicle with ICE	Miles/gallon	23.41	[106]
Price per gallon gas	$/gallon	2.8	[107]
Flat electricity price	$/kWh	0.1026	[102]
TOU electricity price peak time	$/kWh	0.2240	[103]
TOU electricity price off-peak time	$/kWh	0.0720	[103]
Indiana state tax on electricity	-	7%	[102]

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results for Base Cases without a Battery (no Control Scheme)

First the base scenarios that do not include an HES system will be evaluated. For this, four different metrics will be taken into consideration namely the total energy consumed, the grid energy percentage, the CO_2 equivalent emissions associated with the energy consumed within the household and the electricity cost. The total energy consumed in the household during the year will be evaluated first. Again, produced and exported solar energy will not be taken into account here; instead this work will focus on the consumed energy only. The results for the different scenarios can be seen in the figure below:

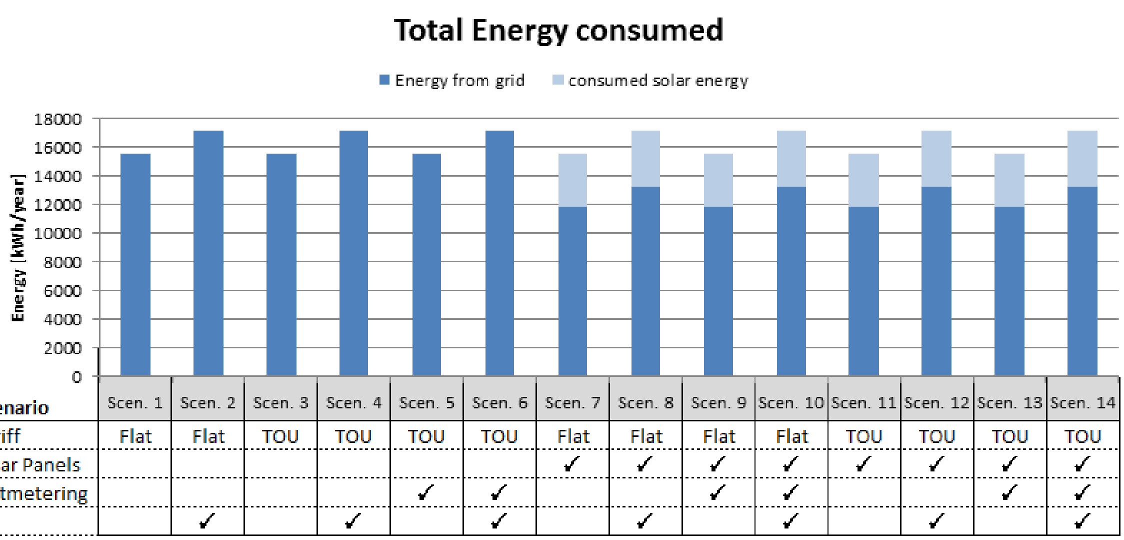
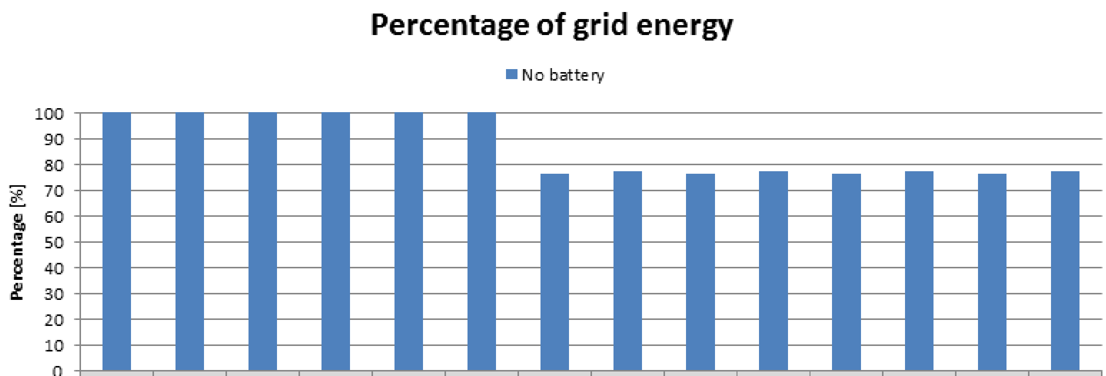


Figure 5.1: No control scheme, total energy consumed.

As can be seen in figure 5.1, the overall consumed energy only varies with the inclusion of an EV. If no solar panels are included, the overall consumed energy reaches a value of roughly 15,500 kWh per year. If the EV is included, the overall consumed energy will be higher (up to 17,100kWh per year) due to the additional electricity needed for charging the EV. The other parameters that are varied do not have any influence on the overall consumed energy. However, through including solar panels, a certain percentage of the consumed energy will be taken from the produced solar power instead of grid electricity. The dependencies on the grid for the different scenarios are shown in figure 5.2. The grid energy percentage gives the fraction of imported grid energy to the overall consumed energy.

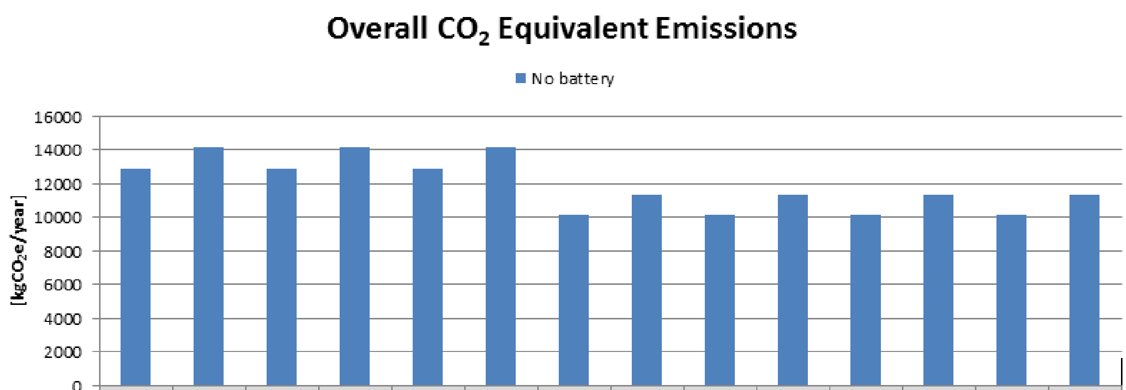


Scenario	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9	Scen. 10	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	Flat	Flat	TOU	TOU	TOU	TOU	Flat	Flat	Flat	Flat	TOU	TOU	TOU	TOU
Solar Panels							✓	✓	✓	✓	✓	✓	✓	✓
Netmetering					✓	✓			✓	✓			✓	✓
EV		✓		✓		✓		✓		✓		✓		✓

Figure 5.2: No control scheme, percentage of grid energy.

Looking at figure 5.2 it can be noticed, if no solar energy is produced, all energy consumed within the household needs to be imported from the grid, which leads to a grid energy percentage of 100 %. If solar power is added, this number is lowered to 76 %, which means that the self-sufficiency of the household increases. If an EV is included, the grid energy percentage is slightly higher (at 78 %) as more energy is needed, but the solar power produced stays the same.

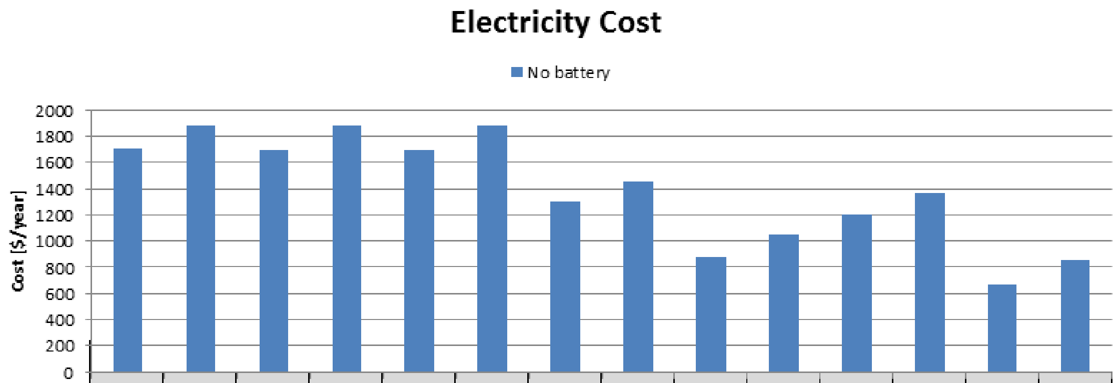
Now as the amount of solar and grid energy that is consumed within the household is known, the CO_2 equivalent emissions due to the energy consumption of the household can be evaluated. In the next figure these numbers are presented for the different scenarios:



Scenario	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9	Scen. 10	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	Flat	Flat	TOU	TOU	TOU	TOU	Flat	Flat	Flat	Flat	TOU	TOU	TOU	TOU
Solar Panels							✓	✓	✓	✓	✓	✓	✓	✓
Netmetering					✓	✓			✓	✓			✓	✓
EV		✓		✓		✓		✓		✓		✓		✓

Figure 5.3: No control scheme, CO_2 equivalent emissions.

As it can be seen in figure 5.3, the CO_2 equivalent emissions depend most noticeably on the inclusion of solar power, as solar power has a lower amount of produced CO_2 equivalent emissions associated with it compared to the electricity mix in Indiana's grid. Including solar power lowers the carbon footprint of the household from a value of 12,900 kgCO_2e by roughly 20 % to 10,100 kgCO_2e. Due to the energy increase when an EV is included, the CO_2 equivalent emissions rise as well to 14,200 kgCO_2e when no solar panels are included and 11,300 kgCO_2e if it is. To enable an easier comparison of the influence of different control schemes, this figure does not yet factor in the omitted emissions that would be produced if a conventional vehicle would be used instead. In chapter 5.9 these omitted emissions will be evaluated in more detail.



Scenario	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9	Scen. 10	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	Flat	Flat	TOU	TOU	TOU	TOU	Flat	Flat	Flat	Flat	TOU	TOU	TOU	TOU
Solar Panels							✓	✓	✓	✓	✓	✓	✓	✓
Netmetering					✓	✓			✓	✓			✓	✓
EV		✓		✓		✓		✓		✓		✓		✓

Figure 5.4: No control scheme, yearly electricity cost.

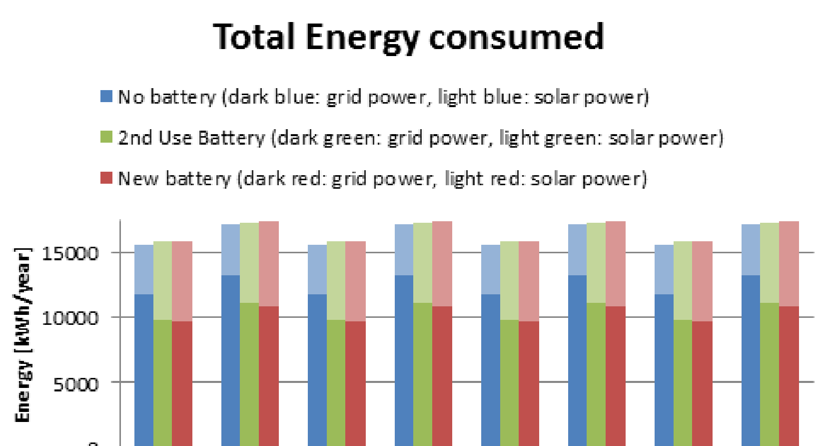
In the results for the electricity cost (see figure 5.4) it can be noticed, if the three parameters solar panels, net metering and EV are not included in the household, the electricity bill is roughly \$ 1,700 a year for both a flat tariff and time-of-use (TOU) one, not taking base fees into account. The other parameters of the scenarios influence the electricity cost heavily. First it can be noticed, that the presence of an EV leads to a higher electricity bill (increase by roughly \$ 180 a year) due to the higher consumption of energy. Again the omitted cost for gas that would have been bought for a traditional vehicle is not included yet, but will be evaluated further in chapter 5.9. As can be seen in the figure, without the presence of solar panels, there is not much difference between the TOU tariff and the flat tariff. Also the presence of net metering does not make any difference without solar panels, which can be expected, as without solar panels there is no energy fed into the grid. However this can change if an HES system is added, as load shifting is also possible without solar panels installed. Therefore scenarios including net metering were added even if no solar panels are included. If solar panels are included in the household, the electricity cost is lowered significantly, especially if net metering is active (reaching a value as low as

$ 670 a year for scenario 13). Here the time-of-use tariff leads to a lower cost compared to the flat tariff which is due to the fact that there is a big overlap between peak price time for TOU tariff and the time where a lot of solar power is generated.

5.2 Results for Control Scheme 1: Maximize Self-Sufficiency

Control scheme 1 “Maximize self-sufficiency’ will be evaluated first. As explained in section 4.7.2, the goal of this control scheme is to maximize the percentage of solar power consumed by the household. Simplified the control scheme works such that excess solar energy is stored inside the HES system and is primarily used to serve the household’s energy demand. Grid energy is only imported when the HES system is depleted and the generated solar energy is not enough to cover the household load.

The total energy consumed in different scenarios, split into grid energy and solar energy can be seen figure 5.5:

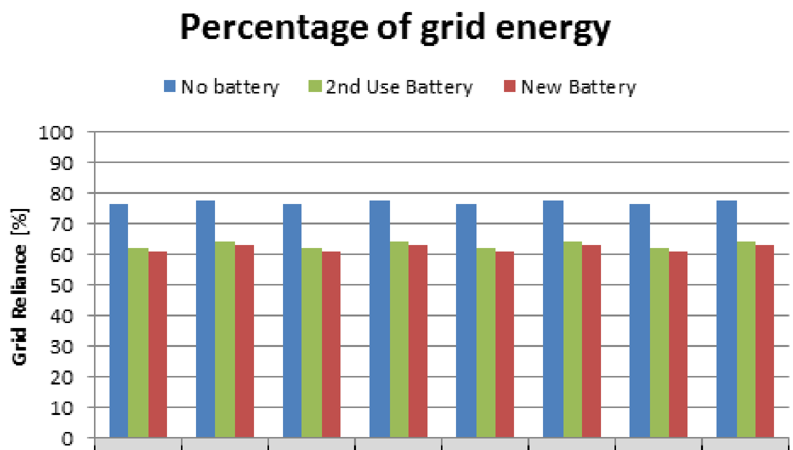


Scenario	Scen. 7	Scen. 8	Scen. 9	Scen. 10	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	Flat	Flat	Flat	Flat	TOU	TOU	TOU	TOU
Solar Panels	✓	✓	✓	✓	✓	✓	✓	✓
Netmetering			✓	✓			✓	✓
EV		✓		✓		✓		✓

Figure 5.5: Control scheme 1, total energy consumed.

In figure 5.5 for the selected scenarios, the consumed energy is presented for a case without HES system, with an HES system based on reused EV batteries (later referred to as “reused battery HES system”) and an HES system based on new cells (“new battery HES system”). First it can be noticed that adding an HES system increases the overall energy consumption in all cases but only up to a 2 % increase. This can be explained due to inefficiencies. Storing energy in a battery storage system will always lead to increased losses. The new battery HES system leads to a very similar increase in total energy consumption compared to the reused one, as there are two counteracting mechanisms at work. As the new battery has a higher capacity, this leads to a higher energy flux, resulting in a higher amount of losses. However, the new battery also has better efficiency rates than the reused one, which seems to even out the other mechanism. It can be seen that adding an HES system to the household will lead to an increase in solar power consumption, reducing the grid energy consumed by up to 18 %.

This increase in self-sufficiency will be investigated further in the following figure (figure 5.6), which evaluates the percentage of grid power compared to the overall consumed energy:



Scenario	Scen. 7	Scen. 8	Scen. 9	Scen. 10	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	Flat	Flat	Flat	Flat	TOU	TOU	TOU	TOU
Solar Panels	✓	✓	✓	✓	✓	✓	✓	✓
Netmetering			✓	✓			✓	✓
EV		✓		✓		✓		✓

Figure 5.6: Control scheme 1, percentage of grid energy.

As can be seen in figure 5.6 the grid energy percentage can be decreased significantly by adding a home energy storage system to the household. This increases the self-sufficiency and the usage of more environmentally friendly energy. Both, adding the reused battery HES system or a new battery HES system reduce the grid energy percentage. For a reused battery HES system, the percentage of grid energy reduces from around 76 % to 62 % in the scenarios in which no EV is present. For the case which includes the new battery HES system the grid energy percentage is even lower. As there is not much difference between results of both HES systems, considering that the new one has a significantly higher capacity, this suggests that the capacity of the new system might not be fully used during most of the year. Having a reused battery HES system provides therefore similar benefit at a reduced cost and environmental impact for the household. The grid energy percentage is not influenced by the parameters net metering or tariff structure, which is expected as these factors do not influence the control scheme 1. Adding an EV slightly increases the grid energy percentage due the higher energy use, but not significantly.

Overall these results are very promising, especially considering that the solar panels generate in total only roughly 7,500 kWh during the year, which is 48 % of the total consumed energy in the case where no EV is present and 44 % of the total energy in the case where an EV is included. This means that even with perfect HES system capacity size, controls and no inefficiencies, only a decrease in grid energy percentage down to 52 % or 56 % would be possible.

The CO_2 equivalent emissions of the household is evaluated in the next figure (figure 5.7):

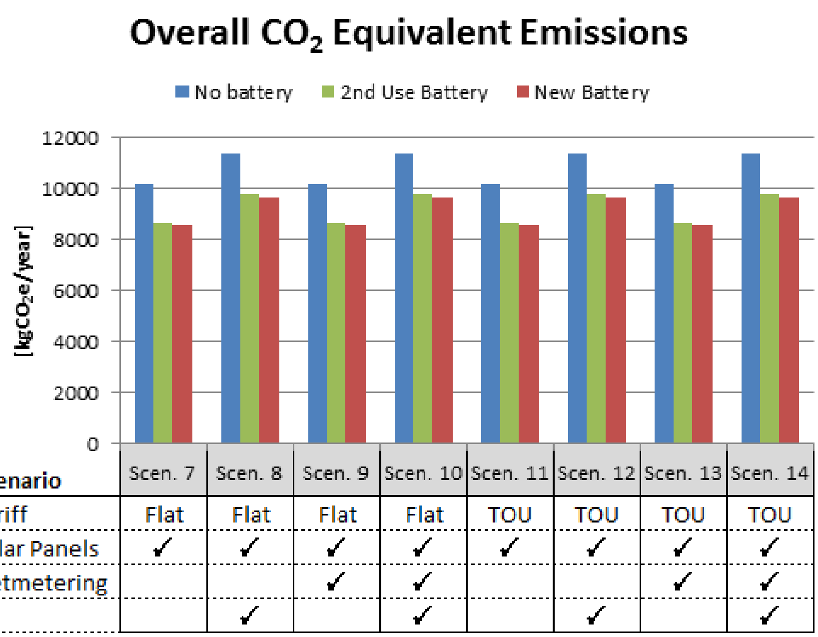
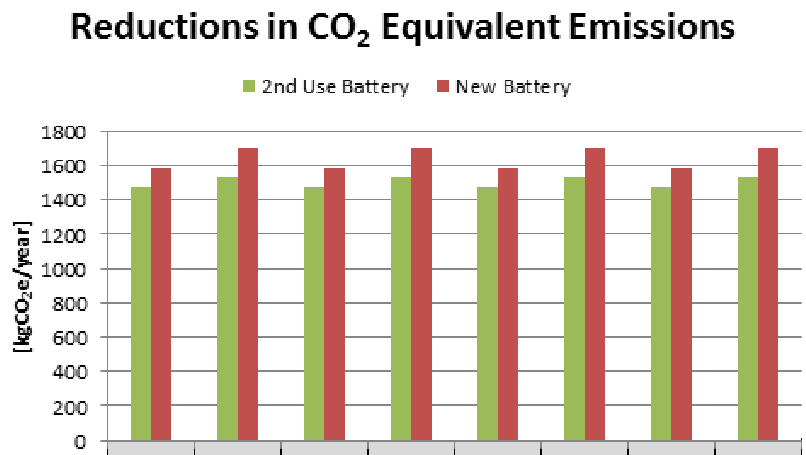


Figure 5.7: Control scheme 1, overall CO_2 equivalent emissions.

As can be seen in figure 5.7, the overall CO_2 equivalent emissions released can be reduced through the increase in solar energy used. In the best case only emissions of 8,530 kgCO_2e are released each year due to the energy consumed within the household. The difference between the two different types of HES systems is relatively small. The overall reduction in CO_2 equivalent can be seen in figure 5.8.

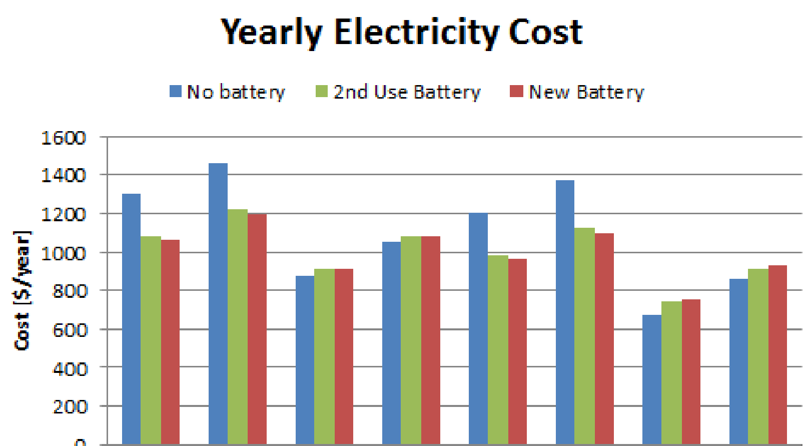


Scenario	Scen. 7	Scen. 8	Scen. 9	Scen. 10	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	Flat	Flat	Flat	Flat	TOU	TOU	TOU	TOU
Solar Panels	✓	✓	✓	✓	✓	✓	✓	✓
Netmetering			✓	✓			✓	✓
EV		✓		✓		✓		✓

Figure 5.8: Control scheme 1, reductions in CO_2 equivalent emissions.

As can be seen in figure 5.8 the CO_2 equivalent emissions can be reduced by up to 1,540 $kgCO_2e$ for the reused battery HES system and up to 1,700 $kgCO_2e$ for the new battery HES system. Comparing the reused battery HES system and the new battery HES system, using the new battery HES system results in higher CO_2 equivalents reductions. The reductions for the new battery HES systems are roughly 160 $kgCO_2e$ per year higher than the ones for the reused battery HES system, which can be explained through the increased capacity in the new system and thus the increased possibility to store solar energy. These differences as well as the overall reductions are slightly lower in scenarios where no EV is added.

The results for the electricity cost can be seen in figure 5.9:



Scenario	Scen. 7	Scen. 8	Scen. 9	Scen. 10	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	Flat	Flat	Flat	Flat	TOU	TOU	TOU	TOU
Solar Panels	✓	✓	✓	✓	✓	✓	✓	✓
Netmetering			✓	✓			✓	✓
EV		✓		✓		✓		✓

Figure 5.9: Control scheme 1, yearly electricity cost.

As can be seen in figure 5.9, the electricity could only be reduced through this control scheme if no net metering is active, which would mean that the electricity fed into the grid is not reimbursed. If, the electricity fed into the grid is fully reimbursed (net metering), including the HES system with this control scheme will even increase the electricity bill due to the inefficiencies associated with the batteries. In that case it makes more sense economically to not use the HES system. To better compare the profit that could be made in the different scenarios, the next figure evaluates the difference between the base cases (no HES system) and the cases with reused and new battery HES systems:

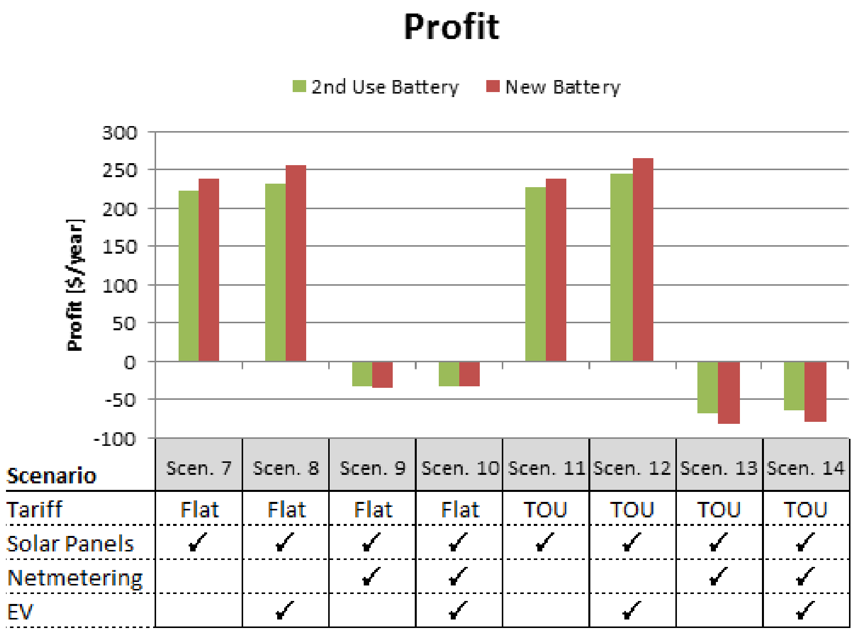


Figure 5.10: Control scheme 1, profit.

As was already noticed and can be seen more clearly in figure 5.10, in scenarios with net metering active, including HES systems with control scheme 1 increases the electric utility bill due to the inefficiencies of the system, resulting in a loss of roughly \$ 30 a year for a flat tariff and \$ 70 a year for a time-of-use tariff for the reused battery HES system. As the new batteries have higher capacities, the new battery HES system performs slightly worse than the reused ones economically, resulting in a loss of \$ 35 or \$ 80 for each tariff structure. This changes if there is no net metering included. In this case the new battery HES system performs slightly better. Overall a profit of around \$ 220 to \$ 260 per year can be made in the cases without net metering depending on the scenario and HES system. In general the TOU tariff leads to a slightly higher profit however this difference is only minimal.

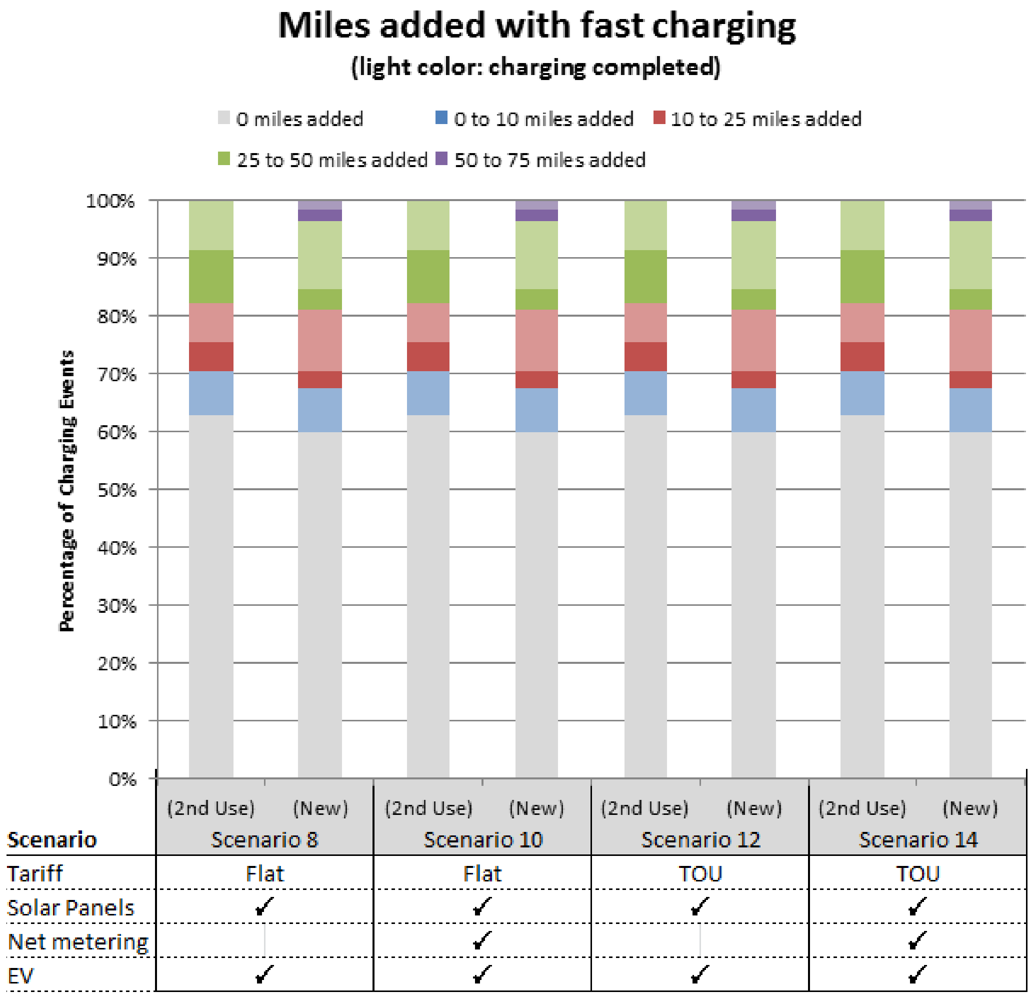


Figure 5.11: Control scheme 1, miles added with fast charging.

As can be seen in figure 5.11, in over 60 % of the charging events, the HES system was not able to deliver any power for fast charging. In the cases where fast charging is possible, both the new and reused battery HES systems are able to complete all charging events that required less than 10 miles to be added to the driving range. In around 12 % of the charging instances, the reused battery HES system is able to deliver in between 10 to 25 miles, which completed roughly 7 % of the charging instances. This value is slightly higher for the new battery HES system, which was able to nearly complete all the charging events requiring 10 to 25 miles, resulting overall in roughly 13 % of the events in which the new battery HES system is able to deliver between 10 to 25 miles. In over 17 % is the reused battery HES system able to deliver 25 to 50 miles through fast charging, which completed nearly half of these charging instances. There is no case recorded for which the reused battery HES system is able to deliver more than 50 miles. The new battery HES system is able to serve a similar amount of 25 to 50 miles delivered in fast charging instances and completes a higher proportion than the reused battery HES system. Using the new battery HES system, it is possible to add 50 to 75 miles in very rare instances (4 %), which again completes half of these.

As can be seen in the figure, in instances in which fast charging is possible, the new battery HES system performs better than the reused ones and is able to complete a large majority of these charging events. The reused battery HES system usually delivers less energy through fast charging. Overall however there is not much difference between the percentage of instances where no fast charging is possible at all, indicating that increasing the battery capacity only increases the performance in cases in which fast charging is already possible. Thus, this poor performance regarding fast charging is mostly caused by the control scheme, the load profiles and solar power generation profiles.

Discussion of Control Scheme 1

The grid energy percentage can be reduced by more than 15 %. Through increasing the self-sufficiency, a reduction in CO_2 equivalent emissions of more than 1,540 kgCO_2e for the reused battery HES system and 1,700 kgCO_2e for the new one can be achieved. The decrease of the electricity bill/ creation of a profit is very case sensitive but, generally speaking, quite low with around $ 220 of profit per year in the best case for the reused battery HES system (if no net metering is possible). Instead of making a profit, adding the HES system can result in an increase of the electricity bill by slightly more than $ 50 per year in scenarios where net metering is active. Fast charging is only possible in less than 40 % of the cases. One of the main criteria for a fast charging system is its availability, especially for unforeseen emergency situations. Therefore this low fast charging availability would not be acceptable for the customer to rely upon.

Overall the control scheme has good benefits in increasing the self-sufficiency and reducing the emissions created by the household, but it shows a less positive performance regarding economic profitability and fast charging opportunities.

5.3 Results of Control Scheme 2: Maximize Self-Sufficiency, keep Fast Charging Reserve

The control scheme evaluated in this section aims, as did the previous one, to increase the self-sufficiency by storing excess solar energy and releasing it as soon as it is needed. As a difference, however, 60 % of the battery's capacity will always remain charged to enable fast charging at any time during the year.

The results for the overall energy consumption and the percentage of grid energy can be found in the following figures (figure 5.12 and figure 5.13):

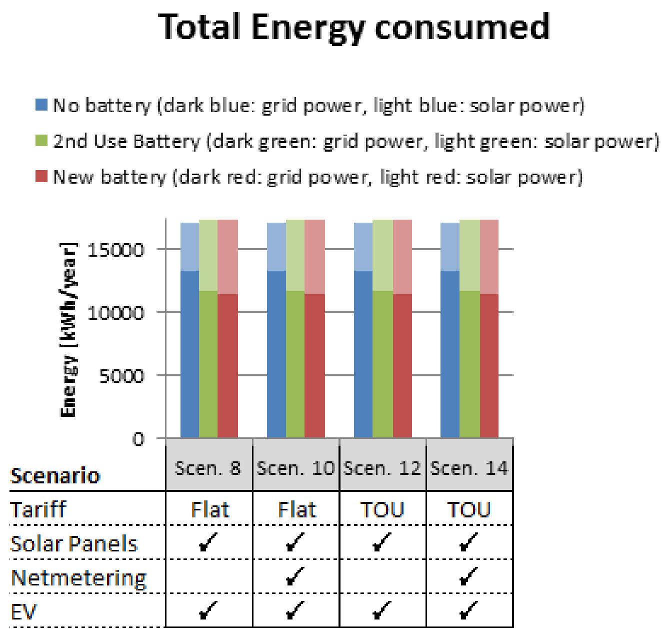


Figure 5.12: Control scheme 2, total energy consumed.

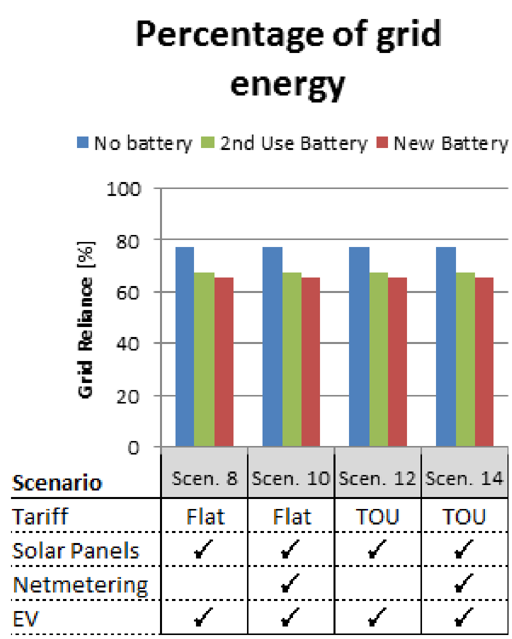


Figure 5.13: Control scheme 2, percentage of grid energy.

As it can be seen in figure 5.12 and figure 5.13, adding a battery storage system will slightly increase the overall energy consumption due to the inefficiencies. However it will also reduce the percentage of grid energy from 78 % to 67 % if a reused battery HES system is used; with the new battery HES system it is reduced slightly more (to 66 %). Comparing these values to the previous control scheme, it can be seen that the percentage of grid energy is higher compared to control scheme 1, which is due to the reserve of the battery's capacity for fast charging.

The CO_2 equivalent emissions of the household will be evaluated next:

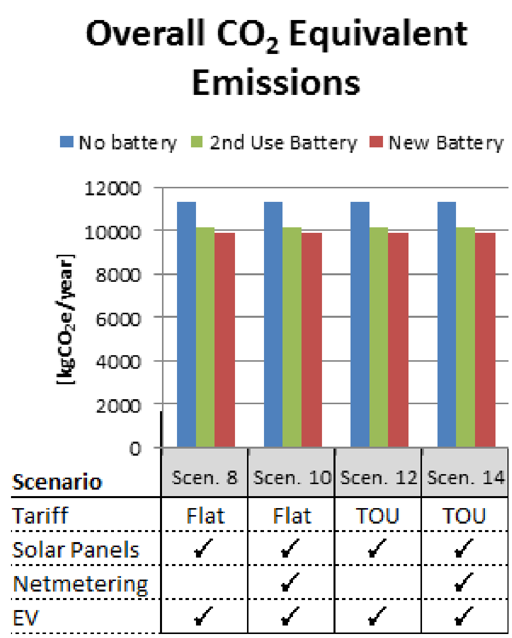


Figure 5.14: Control scheme 2, overall CO_2 equivalent emissions.

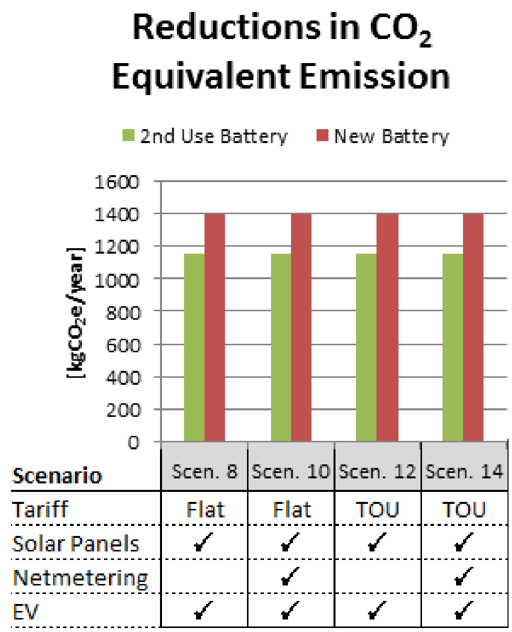


Figure 5.15: Control scheme 2, reductions in CO_2 equivalent emissions.

Again as it can be seen in figure 5.14 and figure 5.15 adding both the new and reused battery HES systems will result in a decrease in emissions due to the increase in used solar energy. Overall, reductions of roughly 1160 $kgCO_2e$ for a reused and 1,400 $kgCO_2e$ for a new battery HES systems are possible. Again, these values are slightly lower compared to the previous control scheme.

Next the electricity cost and profit will be evaluated:

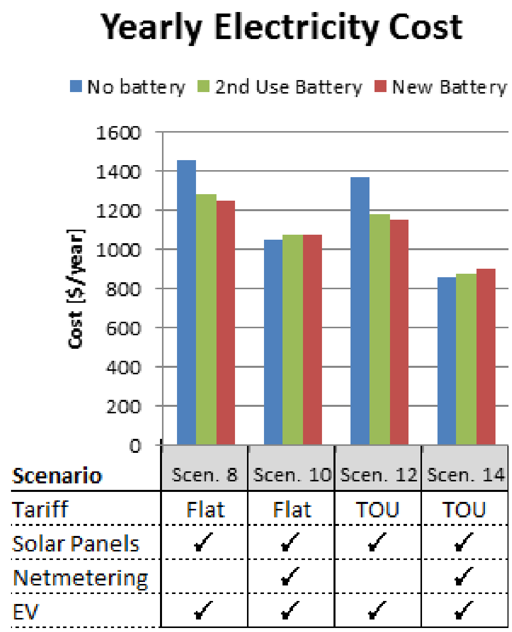


Figure 5.16: Control scheme 2, yearly electricity cost.

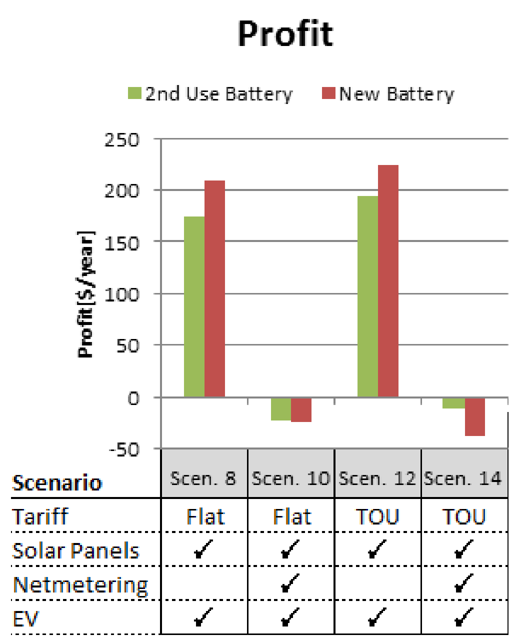
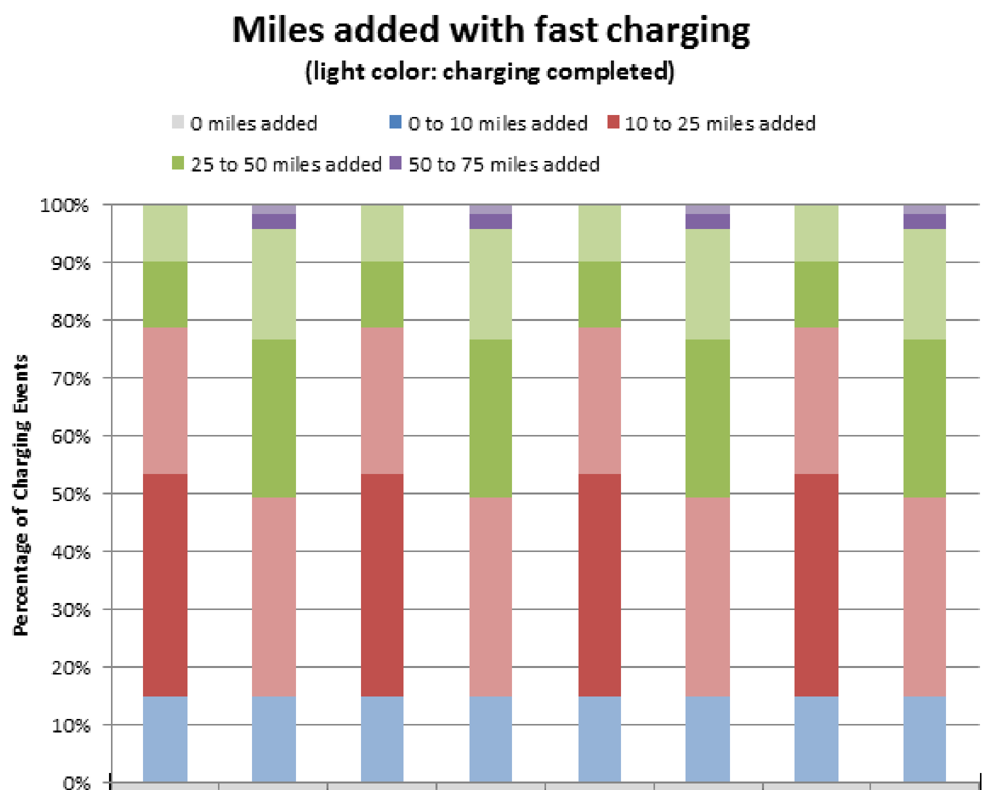


Figure 5.17: Control scheme 2, profit.

Again as it can be seen in figure 5.16 and figure 5.17, the profit depends mainly on the inclusion of net metering. If net metering is active, no profit can be made (but in this case also no extra cost occurs); if there is no net metering, the profit for the second use battery HES system is roughly \$ 170 to \$ 190 per year, for the new battery HES system it is \$ 210 to \$ 220 per year, the higher values are for the cases where a TOU tariff structure is used. Again the economic benefits are fairly low and will not be reason enough to motivate people to invest in such a system. It can be noticed that during a time-of-use tariff, the new battery HES system results in significantly higher cost in case of net metering than for the reused battery HES system. This is due to the fact that the time of solar generation and high price overlap significantly. As the reused battery HES system has a lower capacity for storing solar energy (especially if a 40 % of it is reserved for fast charging) more solar energy will be fed into the grid at high price times, which results in a lower electricity bill. Comparing this control scheme to control scheme 1, it can be noticed, that overall the magnitude decreases both for cost and also for profit.

Now the fast charging availability for this control scheme will be evaluated:



Scenario	(2nd Use) Scenario 8 (New)	(2nd Use) Scenario 10 (New)	(2nd Use) Scenario 12 (New)	(2nd Use) Scenario 14 (New)
Tariff	Flat	Flat	TOU	TOU
Solar Panels	✓	✓	✓	✓
Net metering		✓		✓
EV	✓	✓	✓	✓

Figure 5.18: Control scheme 2, miles added with fast charging.

As expected, in this control scheme fast charging is always possible (see figure 5.18). For the reused battery HES system the biggest percentage of miles added is between 10 to 25 miles (accounting for 60 % of the fast charging events with 25 % of the fast charging events being completed through adding 10 to 25 miles) which is due to the fact that the capacity reserve was chosen to provide at least 18 miles in each instance. In 15 % of the fast charging events, less than 10 miles are added, as the EV required little energy for these events, as can be seen by the fact that all of these events are completed through fast charging for both HES systems. The new battery HES system is reserving a charge equivalent to

27 miles, which allows the system to complete all fast charging events requiring energy lower than an equivalent of 25 miles. The new battery HES system further delivers energy equivalent of adding 25 to 50 miles of range in 43 % of all charging events. Similarly to the previous control scheme, for the reused battery HES system the highest category is 25 to 50 miles added while for the new battery HES system, the highest one is 50 to 75 miles added (but only in 4 % of the charging events it reached a delivered charge equivalent to that range). Overall this shows promising results regarding fast charging, as fast charging is always possible, which will greatly increase the users confidence in the system.

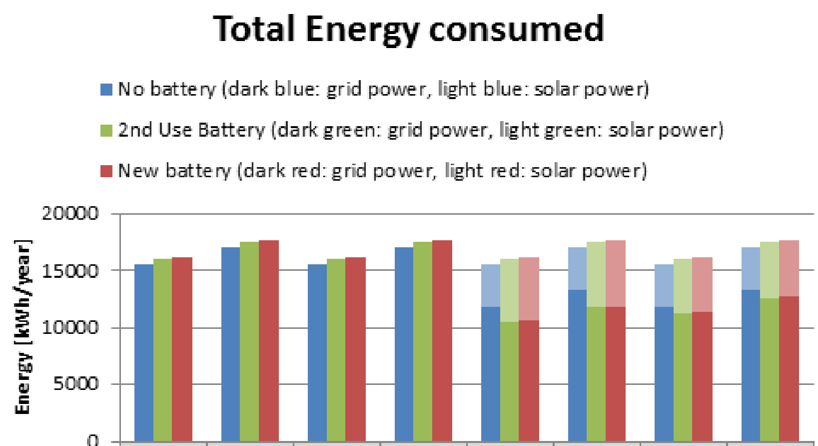
Discussion of Control Scheme 2

Reserving a certain capacity increased the availability for fast charging significantly. With this control scheme implemented, the user can be assured that fast charging is always possible, no matter the season or time of day. However, it comes at a cost; both the percentage of consumed solar energy and with it the reductions in CO_2 equivalent emissions and the possible profit (which was already low for control scheme 1) are decreased, resulting in a maximal CO_2 equivalent savings for the reused battery HES system of 1,160 $kgCO_2e$ and a maximal profit of $ 190 per year. Overall the new battery performs slightly better regarding all parameters. The reused battery is also able to give good results in terms of increased self-sufficiency and fast charging availability.

5.4 Results of Control Scheme 3: Load Shifting

The next control scheme to be evaluated is the load shifting control scheme, which aims to increase the profit. Simplified, during times with low electricity price, the battery will charge, and during times with high electricity price, the battery will discharge. Some additional control mechanism will further try to maximize the solar energy consumed. Fast charging will only be possible if it does not interfere with the load shifting.

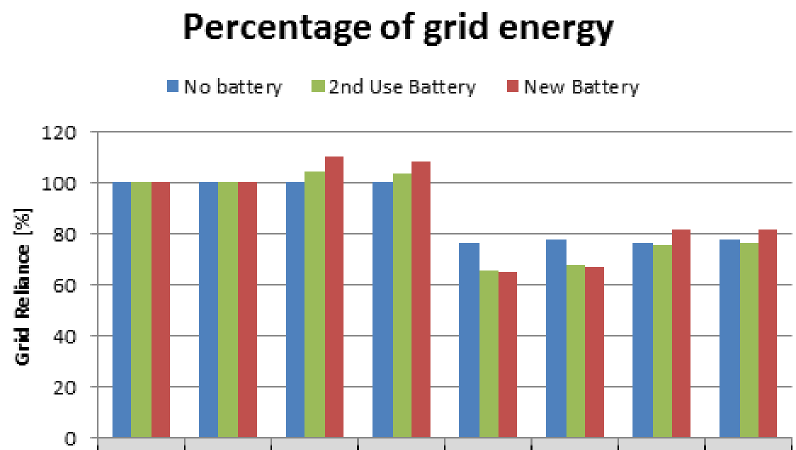
First the consumed energy is evaluated:



Scenario	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	TOU	TOU	TOU	TOU	TOU	TOU	TOU	TOU
Solar Panels					✓	✓	✓	✓
Netmetering			✓	✓			✓	✓
EV		✓		✓		✓		✓

Figure 5.19: Control scheme 3, total energy consumed.

As can be seen in figure 5.19, using an HES system will increase the overall energy consumption but decrease the amount of energy imported from the grid. This can be seen in more detail in the next figure, which evaluates the grid energy percentage:



Scenario	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	TOU	TOU	TOU	TOU	TOU	TOU	TOU	TOU
Solar Panels					✓	✓	✓	✓
Netmetering			✓	✓			✓	✓
EV		✓		✓		✓		✓

Figure 5.20: Control scheme 3, percentage of grid energy .

Looking at figure 5.19 and figure 5.20, for scenarios 3 and 4, in which no solar energy is included, the grid energy percentage is 100 % in all cases, as all the consumed energy is imported from the grid. For scenarios 5, the grid energy percentages are 104 % and 110 % for reused and new battery HES system respectively, and in scenario 6, they are 103 % and 108 %. In these scenarios adding the HES system increases the grid energy percentage over 100 %, as net metering is active, which means that the system will import more electricity from the grid than is used in the household, as it can discharge excessive energy back into the grid during peak time. If solar energy and no net metering are included, the HES system will be able to increase the percentage of solar energy used compared to the base scenario by roughly 10 %. However, if net metering is active the battery will instead feed excess energy into the grid for maximal profit, as it is fully reimbursed.

In the following figure 5.21 the CO_2 equivalent emissions released by the energy usage of the household for different scenarios can be seen:

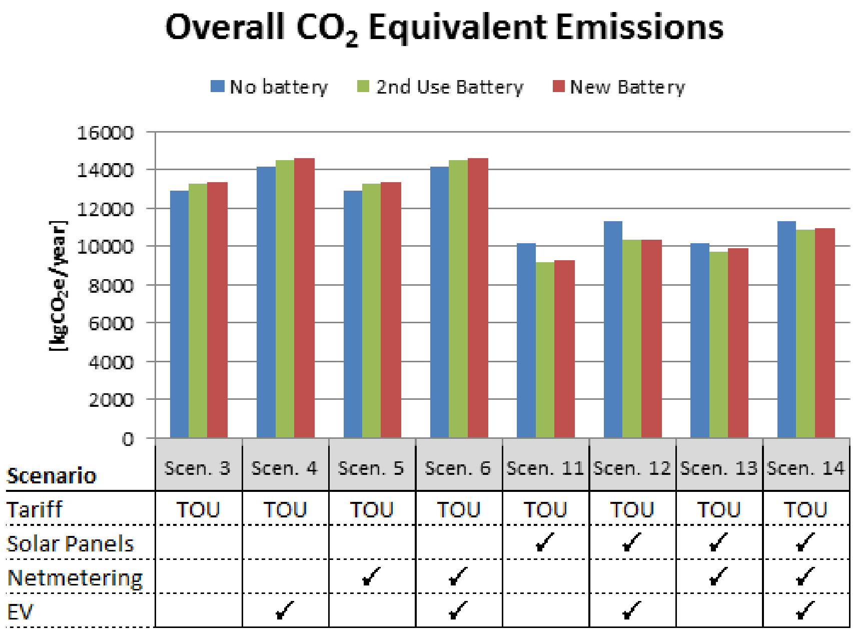
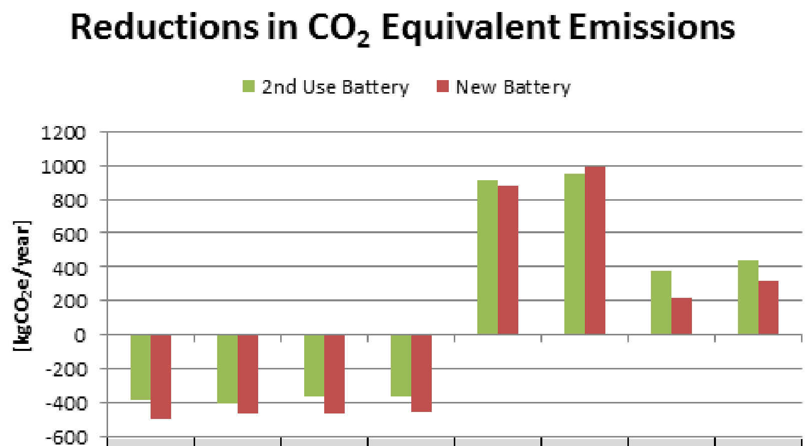


Figure 5.21: Control scheme 3, overall CO_2 equivalent emissions.

As can be seen in figure 5.21, the HES system increases the CO_2 equivalent emissions released for scenarios for which no solar panels are present due to the increase in used energy. For the case with solar panels but without net metering, the HES system is able to reduce some of the CO_2 equivalent emissions released; however, in scenarios 13 and 14 with net metering present, these reductions are only minimal. This can also be seen in more detail in the next figure 5.22:



Scenario	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	TOU	TOU	TOU	TOU	TOU	TOU	TOU	TOU
Solar Panels					✓	✓	✓	✓
Netmetering			✓	✓			✓	✓
EV		✓		✓		✓		✓

Figure 5.22: Control scheme 3, reductions in CO_2 equivalent emissions.

It can be seen in figure 5.22, as expected, adding the HES system will increase the CO_2 equivalent emissions released for cases without solar power generation, due to the inefficiencies. If solar panels are added, the HES system will result in a reduction of CO_2 equivalents released, of roughly 910 kgCO_2e to 950 kgCO_2e per year for scenarios without net metering and 370 kgCO_2e to 440 kgCO_2e per year with net metering active. If no solar panels are added, the inclusion of an HES system results in an increase in CO_2 equivalents released of 360 kgCO_2e to 500 kgCO_2e per year for the reused battery HES system. Comparing the new to the reused battery HES system, it can be noted that, due to the increased capacity, and with it the increased throughput of energy for the new battery HES system, the new battery HES system results in a higher increase in CO_2 equivalents released for scenarios without solar panels. For scenarios 11 and 12, both systems give fairly similar results, which is due to the two opposing mechanisms; As the new battery has a higher capacity it can store more solar energy which would reduce the CO_2 equivalent emissions released; however, it can also import more energy from the grid for load shifting, which increases the CO_2 equivalent emissions released due to inefficiencies. For Scenarios 13 and 14, the reused battery HES system performs better ecologically speaking, as due to the net metering, the new battery with increased capacity is able to import and export more grid energy through load shifting, which results in higher emissions due to the inefficiencies. If the reused battery HES system has a high capacity similar to the new one however, it would perform worse, as it has lower efficiencies than the new battery HES system.

Next, the yearly electricity cost will be evaluated:

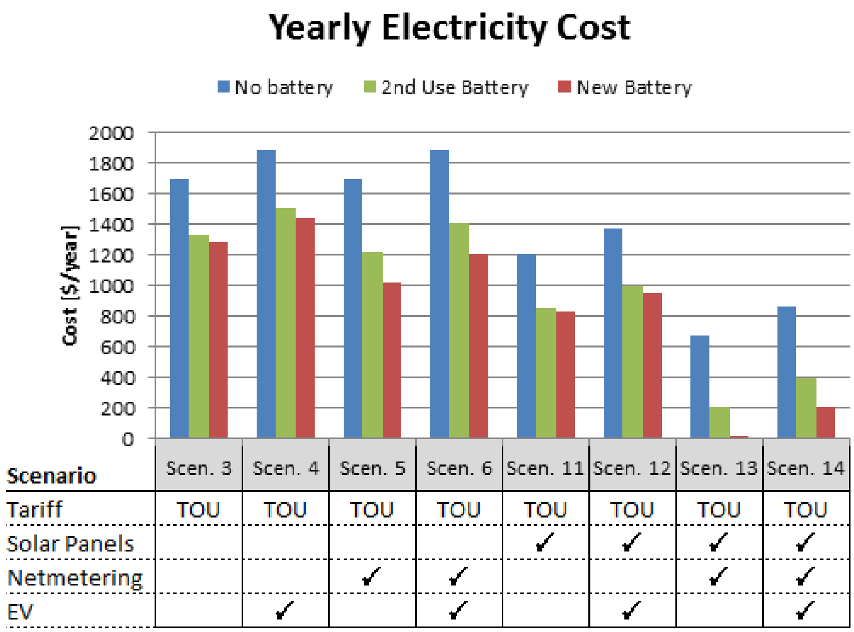
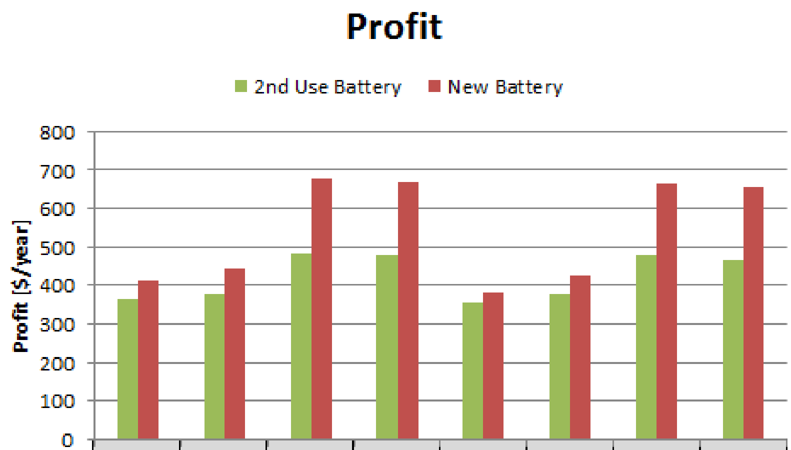


Figure 5.23: Control scheme 3, yearly electricity cost.

As can be seen in figure 5.23, this control scheme is able to significantly reduce the electricity cost in all scenarios. The profit made in each scenario can be seen in the following figure:



Scenario	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	TOU	TOU	TOU	TOU	TOU	TOU	TOU	TOU
Solar Panels					✓	✓	✓	✓
Netmetering			✓	✓			✓	✓
EV		✓		✓		✓		✓

Figure 5.24: Control scheme 3, profit.

As can be seen in figure 5.24, the profit ranges from $ 370 to $ 480 per year for a reused battery HES system; for a new one it reaches from $ 380 to $ 680 per year. The profit is particularly high when net metering is active. In these cases the new battery HES system outperforms the reused one significantly. In the other cases if net metering is not active, the profits that will be made from both systems are quite similar, with the new battery HES system returning a slightly higher profit. This shows that for tariff structures without net metering, increasing the battery capacity (eg. through using a new battery HES system) will not automatically result in a higher profit. The influence of solar panels however is only marginal, with slightly increased values for profit when solar panels are present.

To evaluate the effectiveness of the control scheme, the profit can be compared to the profit achievable in the ideal load shifting case. This can be calculated as follows:

$$\begin{aligned} \textit{Profit\_ideal} &= \textit{Capacity\_HESs\_used} \cdot (\textit{peak\_price} - \textit{off-peak\_price}) \\ &\cdot \textit{number\_of\_loadshifting\_days} \end{aligned} \tag{5.1}$$

$$(0.8 \cdot 16.1 kWh) \cdot (\$0.224/kWh - \$0.072/kWh) \cdot (365 \cdot \frac{5}{7}) = \$510 \textit{ per year} \tag{5.2}$$

The reused battery HES system is able to create a profit of $ 480 per year, which is very close to the ideal case. The difference can be explained by the inefficiencies that lead to losses of energy and to the power needed for thermal management of the battery. Overall it shows that the results given by the model are reasonable and that the control scheme seems to fulfill its purpose well. Additionally this demonstrates that the main limitation regarding the profit is not caused by the setup or control scheme but rather by the basic concept of load shifting, which generally allows only small profits for these battery capacities.

Finally the fast charging possibility in this control scheme will be evaluated:

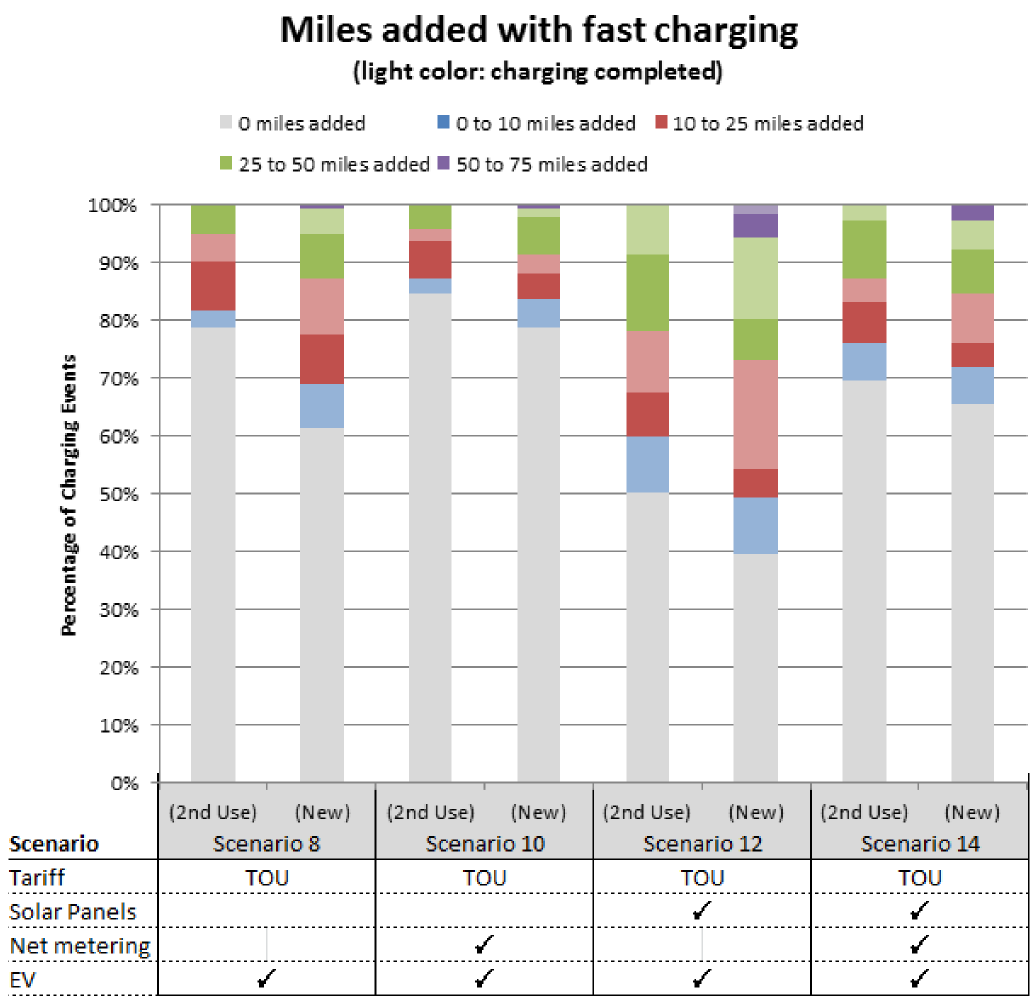


Figure 5.25: Control scheme 3, miles added with fast charging.

Unsurprisingly, as it can be seen in figure 5.25, this control scheme performs worse regarding fast charging than the previously presented ones as it will ignore fast charging events if they interfere with the profit generation. In scenarios without solar panels and inactive net metering for the reused HES system in almost 80 % of the charging events, no fast charging is possible. With net metering active, this number increases to 85 % of the cases. When solar panels are introduced, this number depends even more on the presence of net metering. With active net metering in 70 % of the cases, no fast charging is possible. If no net metering is active, the number drops to 50 % of the events in which no fast charging is possible. The highest amount of charging possible for the reused battery HES system is 25 to 50 miles added. The new battery HES system performed slightly better, especially in cases without net metering.

Discussion of Control Scheme 3

Overall this is the control scheme that generates the highest profit, resulting in a profit of around $ 370 to $ 480 per year for the reused battery HES system, which is close to the ideally achievable profit. However this comes at the price of only generating small reductions in CO_2 equivalent emissions released, if any, and almost no availability for fast charging. Overall this profit will probably not be high enough to make this system attractive for potential customers (the payback times for the different control schemes and scenarios are analyzed in section 5.8); therefore, it will be necessary to not just focus on the overall profit but also to increase the other performance parameters. Increasing the fast charging availability while still creating a profit will be explored in the next control schemes.

5.5 Results of Control Scheme 4: Load shifting, keep Fast Charging Reserve

In this control scheme, the goal again is to increase the profit through load shifting. However, similar to control scheme 2, it will always keep a 40 % capacity reserve for fast charging. Additionally, fast charging will be prioritized here even if it interferes with load shifting. During fast charging events all charge inside the battery can be used for fast charging if necessary.

First the overall energy consumption and the grid energy percentage for this control scheme will be evaluated:

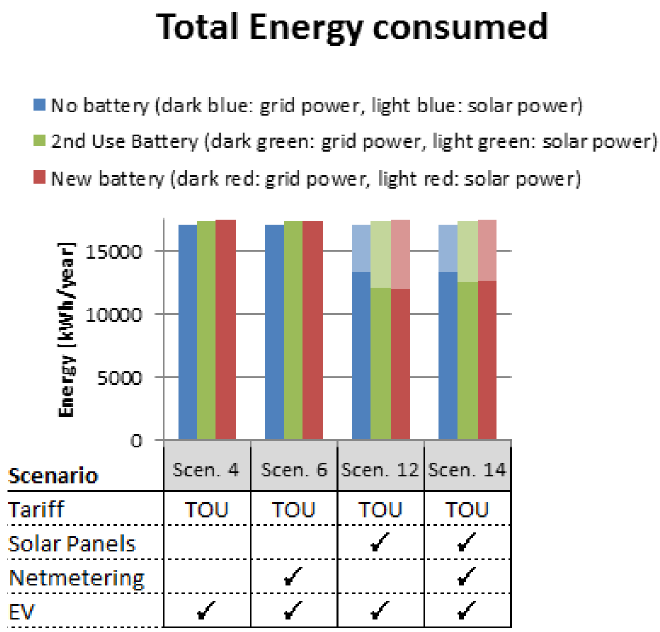


Figure 5.26: Control scheme 4, total energy consumed.

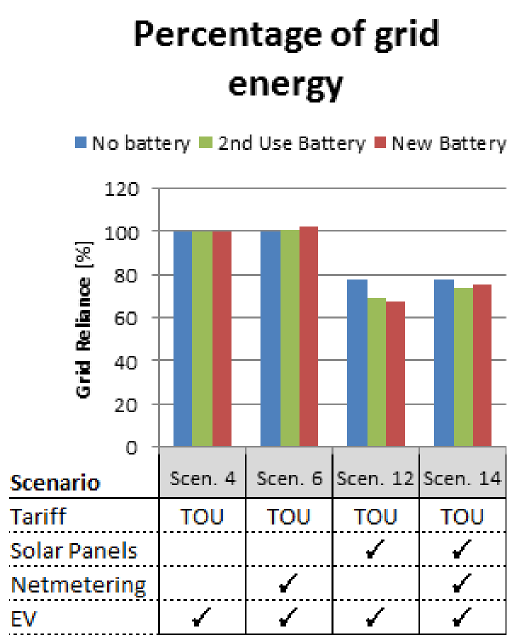


Figure 5.27: Control scheme 4, percentage of grid energy.

Again, as can be seen in the figure 5.26 and figure 5.27, the results are very similar to the previous control scheme. Adding an HES system to the household will increase the energy consumption and, if no solar panels are added and if net metering is active, will also increase the grid electricity percentage over 100 %. If no net metering is active but solar panels are included (scenario 12) the HES system will decrease the grid energy percentage (by 9 % for the reused battery HES system and 10 % for the new battery HES system). If both solar panels and net metering are included (scenario 14) the grid energy percentage will stay close to the results without the HES system (less than 4 % change).

Next the equivalent emissions released through the energy consumption of the household and the reductions in CO_2 equivalent emissions will be evaluated for this control scheme:

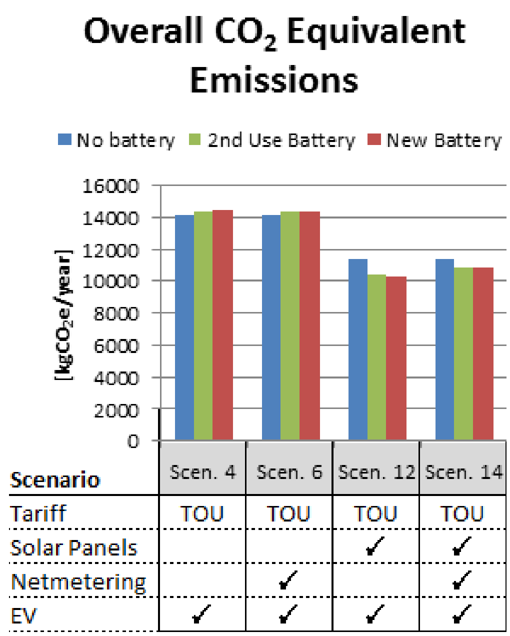


Figure 5.28: Control scheme 4, overall CO_2 equivalent emissions.

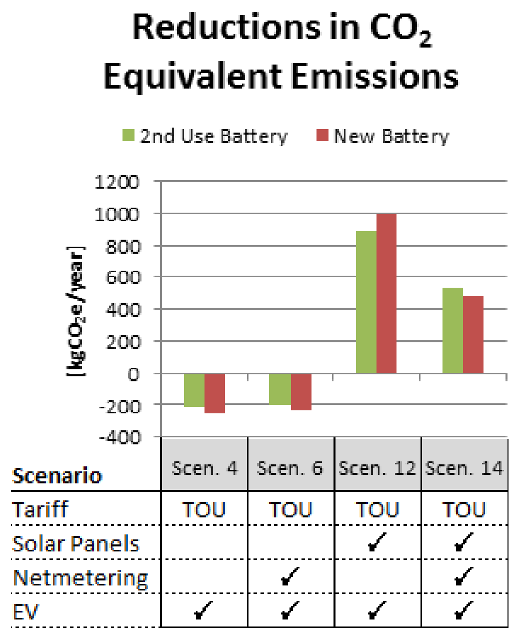


Figure 5.29: Control scheme 4, reductions in CO_2 equivalent emissions.

As can be seen in figure 5.28 and figure 5.29, adding HES systems to the household increases the CO_2 equivalent emissions released for scenarios 4 and 6. As no solar energy is present, all consumed energy needs to be imported from the grid. If solar panels are added to the household, the inclusion of HES systems into the household leads to a reduction in CO_2 equivalent emissions released, especially if no net metering is active. In the scenario in which solar panels are included and no net metering is active (scenario 12), the reductions in CO_2 equivalents reach a maximum of ca 890 kgCO_2e per year for a reused battery HES system. For a new battery HES system, this number is higher with 990 kgCO_2e. If net metering and solar panels are active (scenario 14) the reductions in CO_2 equivalents are decreased to ca 530kg CO_2e per year for a reused battery HES system, the new battery HES system performs slightly worse with 490 kgCO_2e saved per year.

Next the yearly electricity cost and the profit for controls 4 will be evaluated:

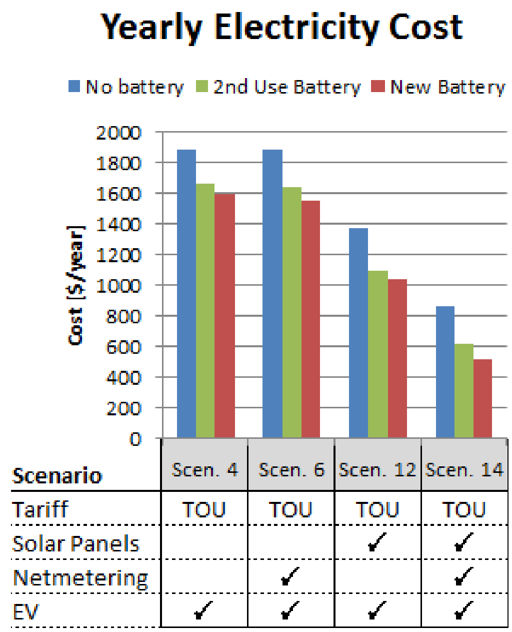


Figure 5.30: Control scheme 4, yearly electricity cost.

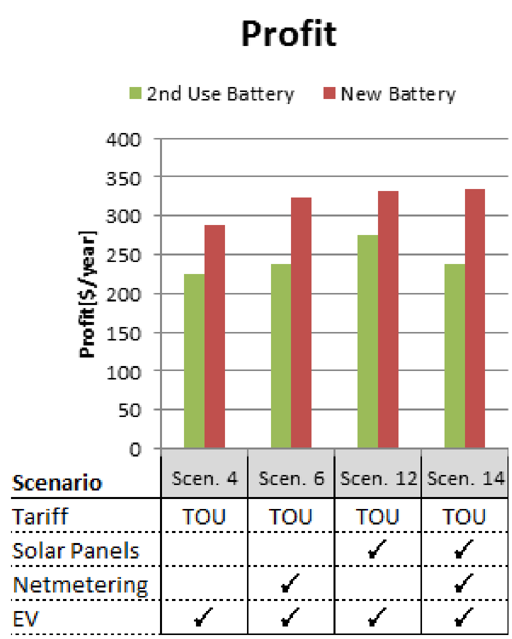


Figure 5.31: Control scheme 4, profit.

As can be seen in figure 5.30, for the evaluated scenarios the electricity bill decreases through adding an HES system to the household. The profit (seen in figure 5.31) for a reused battery HES system ranges between $ 220 per year for scenario 4 to $ 280 per year for scenario 12. The profit that can be made with a new battery HES system is higher, reaching from $ 290 a year in scenario 4, to roughly $ 330 per year for scenario 12 and scenario 14.

The results regarding fast charging for the evaluated scenarios for control scheme 4 can be seen in figure 5.32:

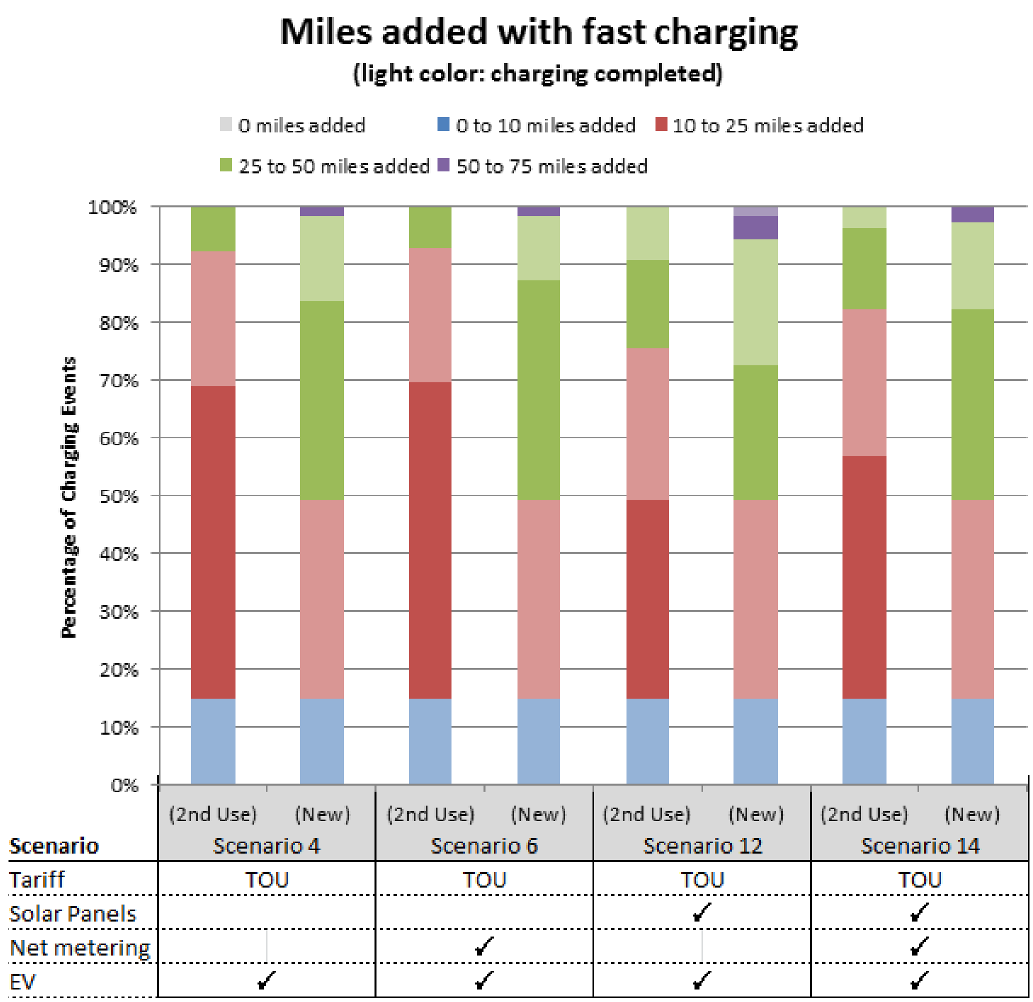


Figure 5.32: Control scheme 4, miles added with fast charging.

As can be seen in figure 5.32, the HES systems are always able to provide energy for fast charging. As the reused battery HES system always keeps enough charge in store to add at least 18 miles, all charging instances lower than 10 miles are completed through fast charging. Due to this reserve size, the biggest portion of fast charging instances (77 %) is in the range 10 to 25 miles added for the reused battery HES systems. Additionally, in 8 % of the charging instances, the reused battery HES system is able to add in between 25 to 50 miles to the EV through fast charging. For the new battery HES system the results are even better. It is able to complete all fast charging instances up to 25 miles added. In 49 % of the cases the new battery HES system is able to add 25 to 50 miles, and in some rare cases (1 %) it is able to add in between 50 to 75 miles.

Discussion of Control Scheme 4

The benefit of this control scheme is the high increase of availability for fast charging. As the battery always keeps a reserve equivalent to roughly 18 miles for fast charging, the user can always rely on this system. Over the modeled year there was no instance where the demand for fast charging could not be served with at least 18 miles added to the range. Keeping this reserve however, comes at a cost. The possible profit drops by more than a half compared to the previous control scheme, which solely focused on load shifting (maximal profit in control scheme 4: $ 280 per year). The reductions in CO_2 equivalent emissions are comparable to the previous control scheme. For scenarios 4 and 6, for which implementing the HES system will actually increase the emissions released, this control scheme had less of a negative impact than control scheme 3.

5.6 Results of Control Scheme 5: Load Shifting, keep limited Fast Charging Reserve

Control scheme 5 is similar to control scheme 4, as it focuses on load shifting, but always keeps a reserve of 40 % for fast charging. In control scheme 5 however the maximal amount of fast charged energy is constrained. Even if the battery has a currently higher SOC than 40 %, the battery will still only discharge 40 % through fast charging; the remainder of the energy required at that charging event will be then charged through level 2 charging. After each fast charging event in control scheme 5, the battery control scheme will ignore the 40 % fast charge reserve for 3 hours, using all its capacity for load shifting. After these three hours, the battery will implement the reserve constraint again and charge if necessary from the grid to reach this reserve minimum. The idea behind this is that it is unlikely that fast charging is necessary in rapid succession, as it is supposed to be an emergency solution.

The results of this control scheme in different scenarios regarding the overall energy consumption can be seen in the following figures (figure 5.33 and figure 5.34):

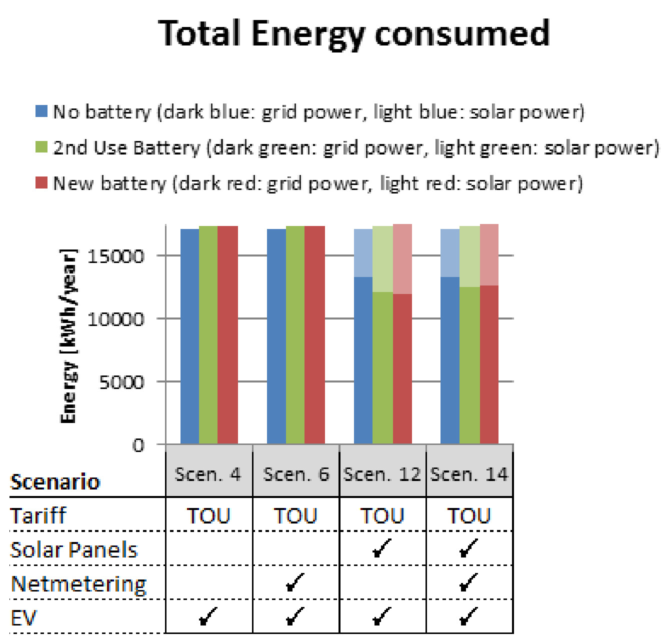


Figure 5.33: Control scheme 5, total energy consumed.

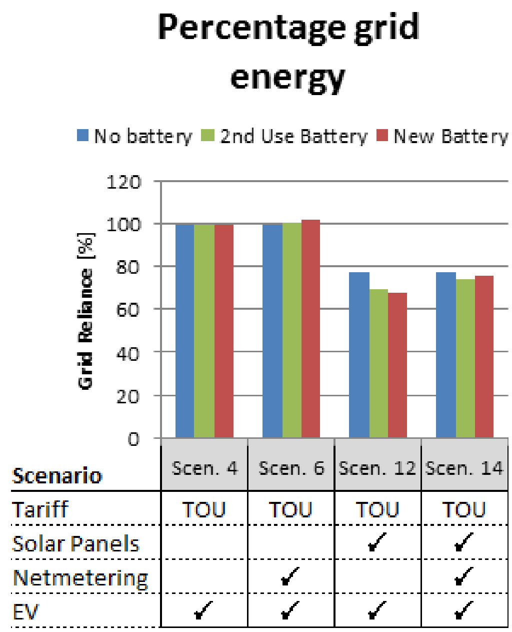


Figure 5.34: Control scheme 5, percentage of grid energy.

As can be seen in figure 5.33 and figure 5.34 the battery control scheme leads to similar results as control scheme 4. The inclusion of HES systems leads to a small increase in the consumed total energy. However, it also increases the portion of consumed solar energy in scenarios in which solar panels are present. This leads to a decrease of 5 % in the grid energy percentage for scenario 12; in scenario 14, this decrease is even smaller with the new battery HES system resulting in almost no reduction.

Next the environmental impact will be analyzed through evaluating the CO_2 equivalent emissions:

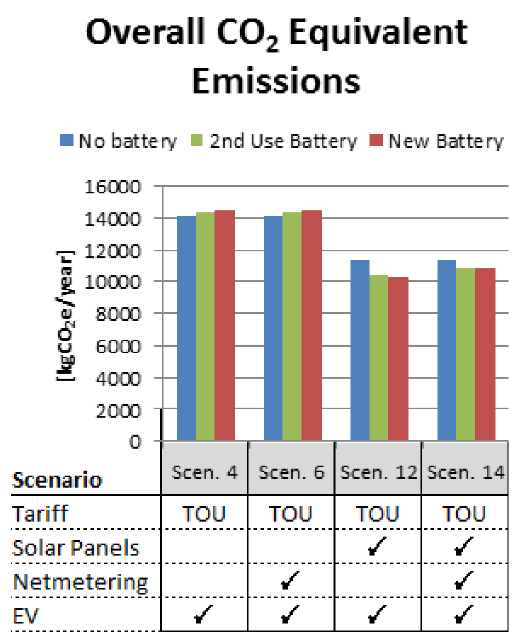


Figure 5.35: Control scheme 5, overall CO_2 equivalent emissions.

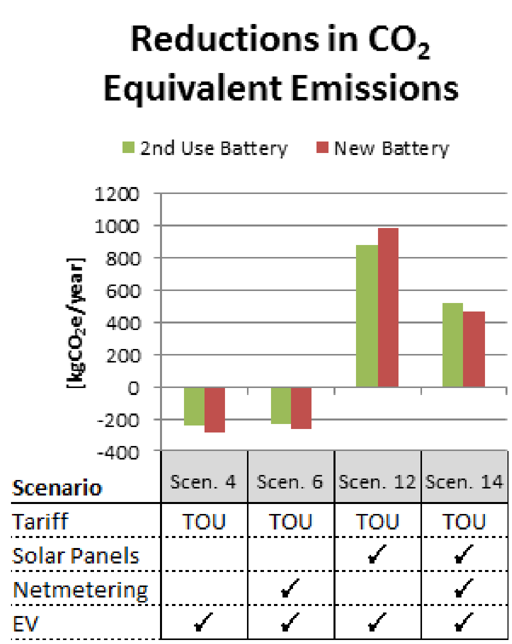


Figure 5.36: Control scheme 5, reductions in CO_2 equivalent emissions.

As can be seen in figure 5.35 and figure 5.36 in cases that include solar power, adding the HES systems lead to a saving in CO_2 equivalent emissions, while in cases without solar energy, the HES systems lead to an increase in released CO_2 equivalents due to inefficiencies. In scenarios 4 and 6, the reused battery HES systems increase the CO_2 equivalent emissions released by 240 kgCO_2e and 230kg CO_2e respectively, the new battery HES system by 280 kgCO_2e and 270 kgCO_2e. In scenarios 12 and 14, the reused battery HES system reduces the CO_2 equivalent emissions released by 880 kgCO_2e and 520 kgCO_2e respectively. The new battery HES system reduces the CO_2 equivalent emissions released by 90 kgCO_2e and 470 kgCO_2e each year. In scenarios 4, 6 and 12 the new battery HES system has either a higher positive or negative impact depending on the presence of solar panels. In scenario 14 however, the reused battery HES system results in a slightly higher savings of emissions due to its reduced availability for fast charging, as its capacity is smaller. However, if the capacity size of the newer battery would be reduced (which could also result in a lower cost for purchasing the system) the new battery HES system would outperform the reused one again due to its higher efficiencies. This suggests, that the capacity for the storage system needs to be calibrated to the system and its aims.

Next the economic impact of the control scheme 5 will be evaluated for the different scenarios:

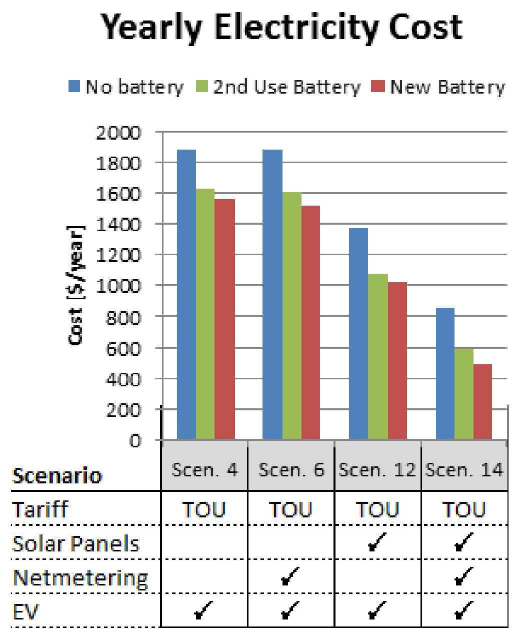


Figure 5.37: Control scheme 5, yearly electricity cost.

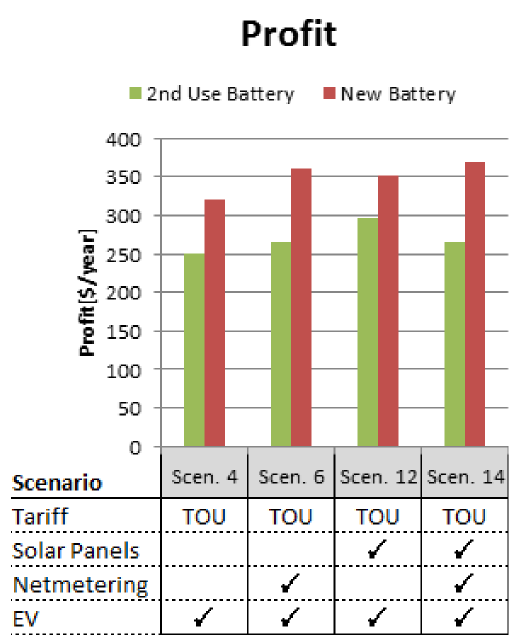


Figure 5.38: Control scheme 5, profit.

As can be seen in figure 5.37 and figure 5.38, including the HES systems results in cost savings in all scenarios, and the new battery HES system always outperforms the reused one. The profit for the reused battery HES system ranges from $ 250 per year to almost $ 300 per year with the highest scenario if there is no net metering active but solar panels are included. The profit made through including the new battery HES system ranges from $ 320 a year to $ 370 a year.

Next the fast charging will be evaluated:

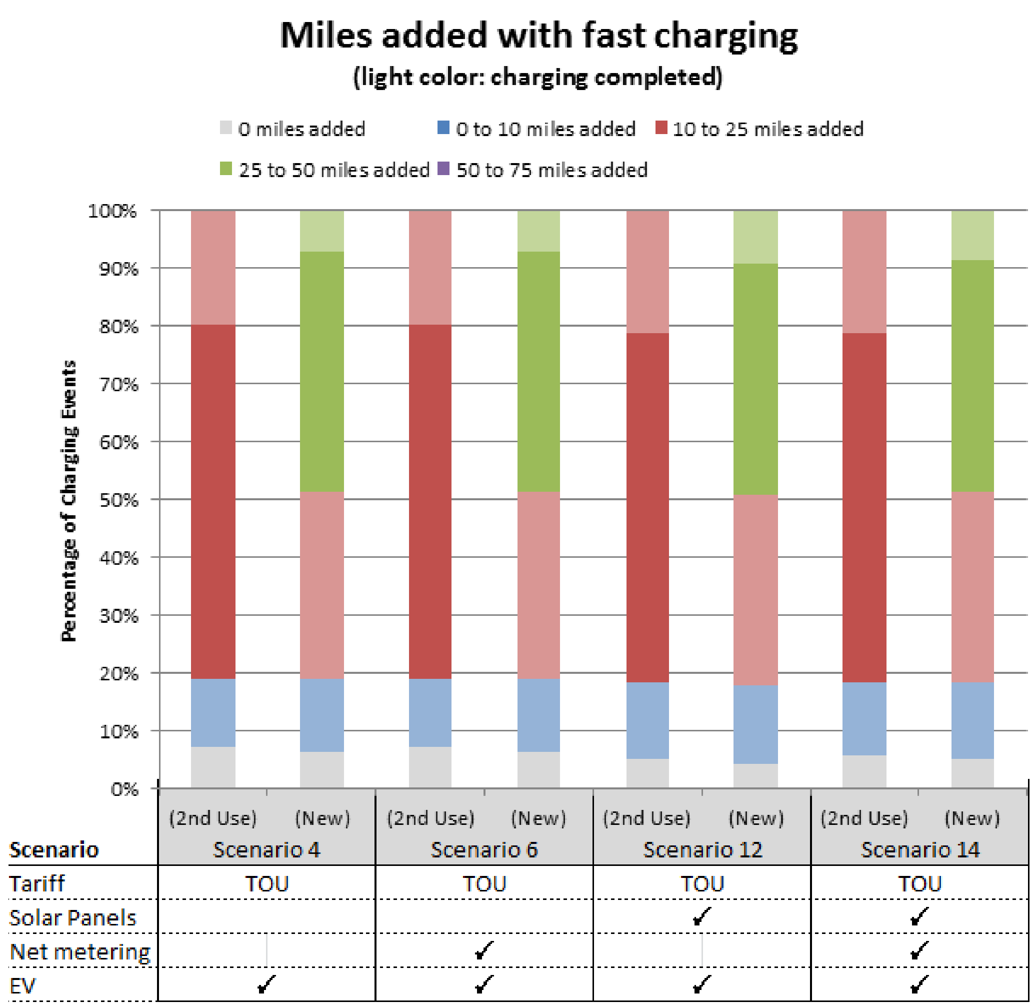


Figure 5.39: Control scheme 5, miles added with fast charging.

As can be seen by comparing figure 5.39 to figure 5.32, adding the three hour downtime leads to a number of charging instances where no fast charging is possible, which happens in 7 % of all charging events for the reused battery HES system if no solar power is present. This number is a bit lower (5 %) in scenarios where solar panels are added. In most of the cases (81 % for the reused battery HES system) the battery discharges an energy amount of equivalently 10 to 25 miles, which is due to the fact that the battery stores energy to add 18 miles through fast charging but will also limit the fast charging to this amount. In roughly 12 % of the cases the battery completes charging events that are in the category 0 to 10 miles for the reused battery HES system. The new battery HES system has a similar amount of instances (ca 5 % if solar panels are included, 6 % if not) where no fast charging is possible. In cases where fast charging is possible however, the new battery HES system performed better, as it keeps a reserve of 27 miles, which enables it to complete all charging events lower than 25 miles. In 49 % of the charging instances it delivers energy of an equivalent to 25 to 50 miles.

Discussion of Control Scheme 5

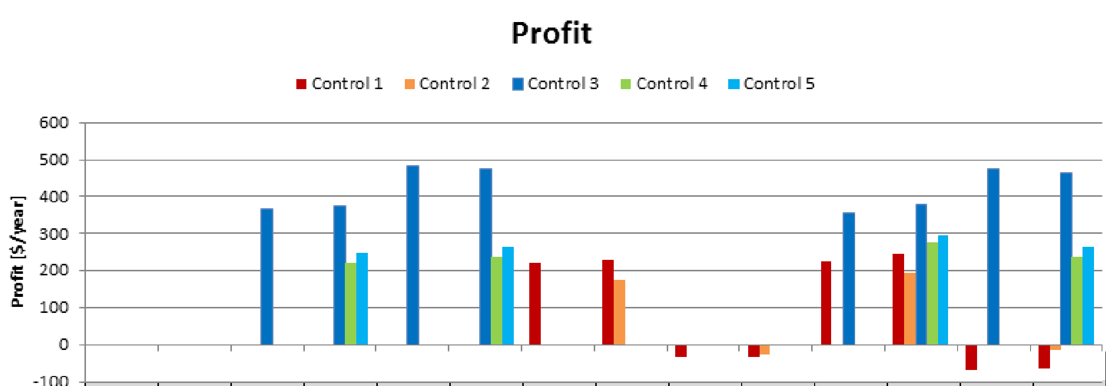
Control scheme 5 results in a slightly higher economic profit while still keeping most of the availability of the fast charging application. In this control scheme there are some instances where no fast charging is possible (in 8 % of the cases) which happens when the user wants to fast charge two times in less than 3 hours. The added profit compared to the previous control scheme is, however, less than $ 30 a year for both the reused battery HES system and the new battery HES system, which might not outweigh the poorer performance regarding fast charging availability. Regarding the environmental impact, the results stay very similar to the previous control scheme, no significant advantages or disadvantages of this control scheme can be noticed for both evaluated HES systems.

5.7 Overall Comparison of Control Schemes

After evaluating the different control schemes individually, the most important parameters, namely the yearly profit, the savings in CO_2 equivalent emissions and the availability to fast charge at least 15 miles, will be compared for all control schemes and scenarios. For simplicity this will only focus on the reused battery HES system, as the results of the new battery HES system always behave similarly to the reused ones with usually higher positive or respectively negative impacts for different scenarios.

It should be noted again that the control schemes were only applied in cases where it made sense. For example control scheme 1, which focuses on increasing the usage of solar energy, is only evaluated for scenarios that include solar panels. As another example, the control schemes that keep a reserve for fast charging are only evaluated in scenarios where an EV is present. Therefore for some scenarios only specific control schemes can be compared with eachother.

The results for the reused battery HES system can be seen in the figures below:



Scenario	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9	Scen. 10	Scen. 11	Scen. 12	Scen. 13	Scen. 14
Tariff	Flat	Flat	TOU	TOU	TOU	TOU	Flat	Flat	Flat	Flat	TOU	TOU	TOU	TOU
Solar Panels							✓	✓	✓	✓	✓	✓	✓	✓
Netmetering					✓	✓			✓	✓			✓	✓
EV		✓		✓		✓		✓		✓		✓		✓

Figure 5.40: Comparison profit.

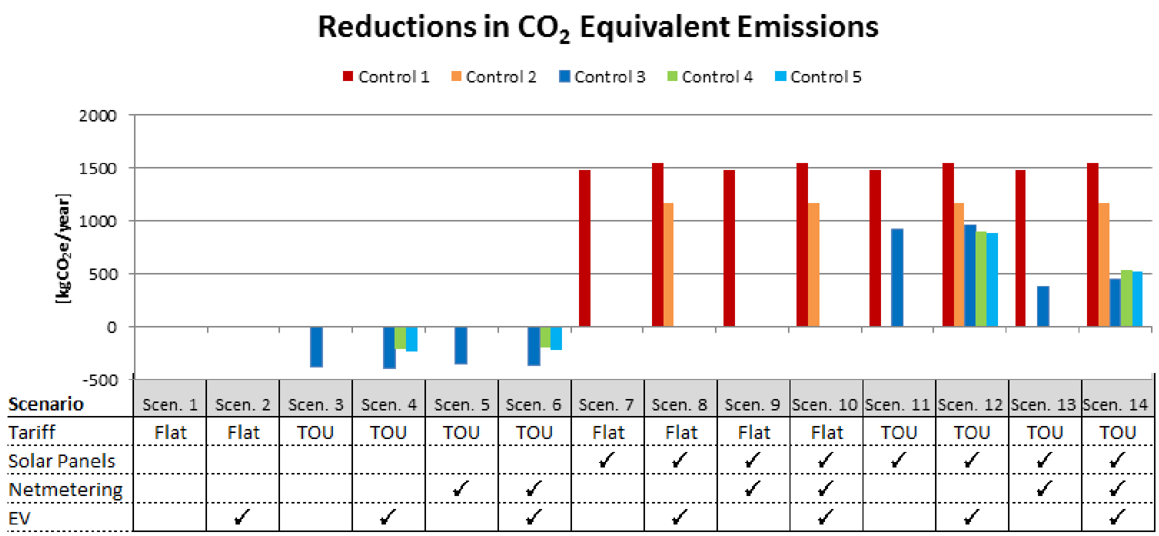


Figure 5.41: Comparison of reductions in CO_2 equivalent emissions.

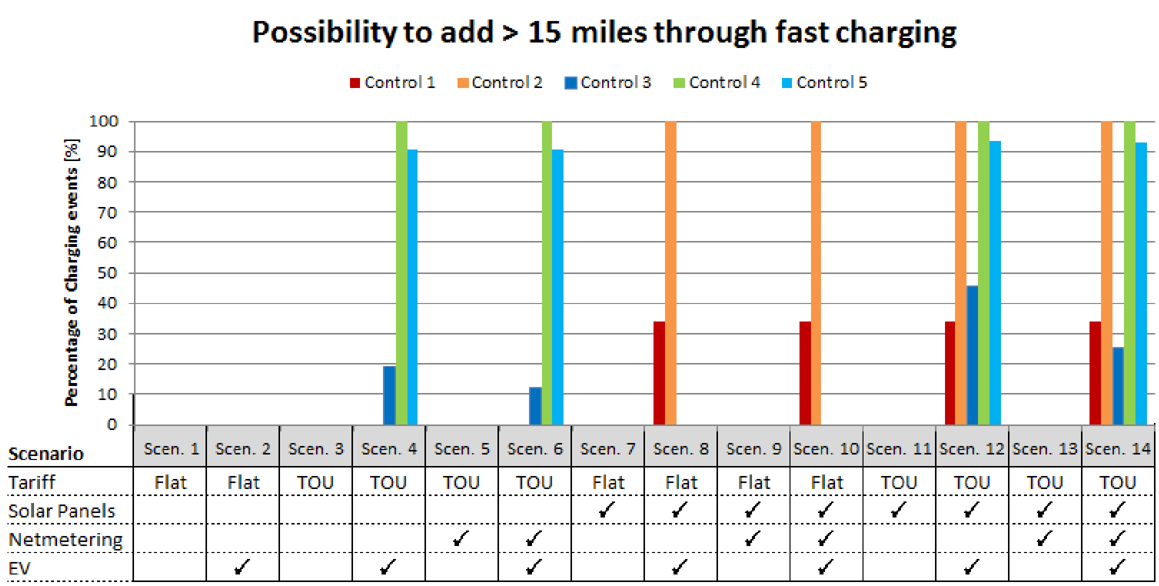


Figure 5.42: Comparison fast charging.

These figures allow easier comparison between the different control schemes. As would be expected, control scheme 3, which focuses solely on load shifting and increasing the profit, outperforms all control schemes in this regard. On second place but significantly lower is control scheme 5, which also emphasizes load shifting while keeping a reserve and a constrained fast charging output, closely followed by control scheme 4 which focuses on loadshifting and also keeps a reserve for fast charging. Control scheme 1 and control scheme 2 perform worst in regard of economic profit, resulting in the loss of money in all scenarios where net metering is present.

This high performance of control scheme 3 regarding profit, comes at a cost regarding the environmental impact. In all scenarios except scenario 12 this control scheme performs worse than any other control scheme regarding the CO_2 equivalent emission saving. For reducing the released CO_2 equivalent emissions, control scheme 1 performs best, as it is designed to maximize the usage of solar energy. All other control schemes result in significantly lower savings in CO_2 equivalent emissions compared to control scheme 1, with control scheme 2 at the second place followed by control schemes 4 and 5 which perform very similar to each other in this aspect.

Regarding fast charging, control schemes 2 and 4 perform best, as they always keep a capacity reserve for fast charging. These two control schemes were able to deliver energy equivalent to at least 15 miles through fast charging in 100 % of the charging instances for all evaluated scenarios. Control scheme 5 follows closely with delivering at least 15 miles in at least 90 % of all charging instances for the different scenarios. Control schemes 1 and 3 perform significantly worse, and the worst case is in scenario 6 (TOU, net metering and EV present) where the HES system with control 3 is only able to deliver at least 15 miles in roughly 10 % of the charging events. The best scenario for control scheme 3 in this regard is scenario 12 (TOU, solar panels and EV presence) in which the HES system is able to deliver energy equivalent to a 15 mile range in 45 % of the cases; the other scenarios in which control 3 is evaluated range in between. Control scheme 1 is able to deliver at least 15 miles in slightly more than 30 % of the charging instances in all evaluated scenarios.

5.8 Calculation of Payback Time

The overall economic and ecological benefits will be further analyzed in this section in which the payback time for the HES system under different control schemes and scenarios will be evaluated. Furthermore this section will give a more detailed evaluation of how the new battery HES system performs compared to the reused one in terms of economic and ecological impact.

5.8.1 Economic Payback Time

As explained in section 4.5.2, to calculate the payback time a price of $ 370/kWh as a low estimate and $ 490/kWh as a high estimate will be used for the reused battery HES system. For the new battery HES system a price of $ 560/kWh will be used. Considering that the reused battery HES system has a capacity of 16.1 kWh and the new battery HES system has a capacity of 23kWh, this results in a total cost of between $ 5,960 and $ 7,890 for the reused battery HES system and $ 12,880 for the new battery HES system.

To calculate the payback time no discount rate, inflation or increase of prices is taken into account. These simplifications were made as the battery degradation effect, which is currently very difficult to estimate and which has a significant impact on the battery's long-term performance is not included. Therefore the results are already associated with a high amount of uncertainty, and the payback times calculated here should be rather considered as an estimate of the dimensions the actual payback times would range in than trying to give accurate prognoses. Furthermore this also focuses only on the profit of implementing an HES system, so savings due to the implementation of an EV instead of a vehicle with an internal combustion engine will also be ignored here.

Taking the already presented profit and the prices mentioned above into account, the minimal and maximal payback time for the reused battery HES system could be calculated for all control schemes and scenarios. The results of this can be found in the following two figures (figure 5.43 and figure 5.44):

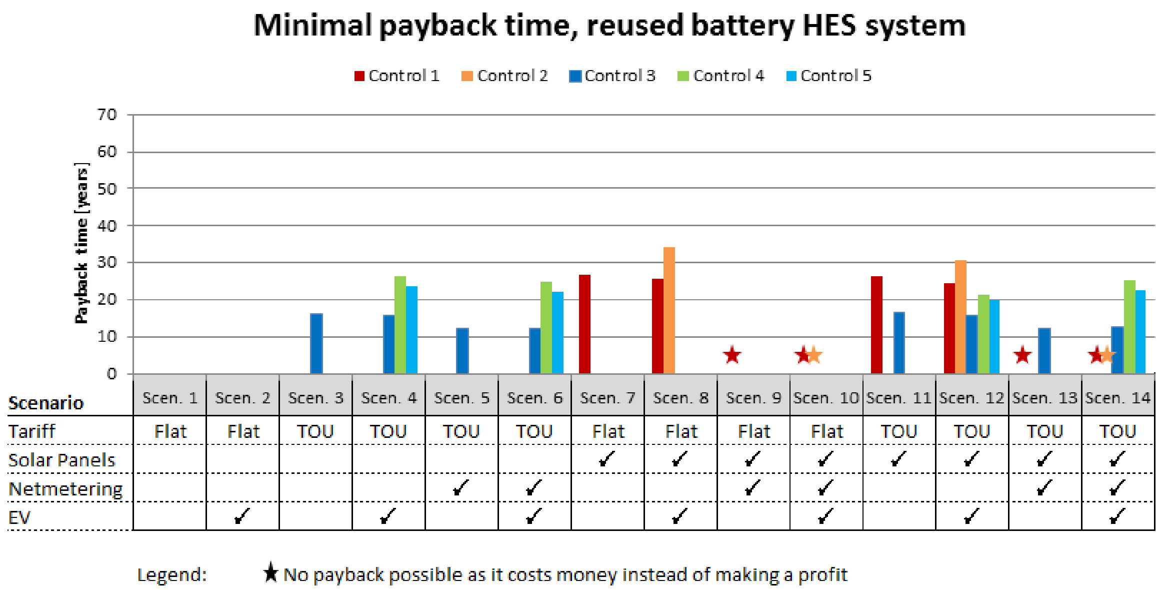


Figure 5.43: Minimal payback time reused battery HES system.

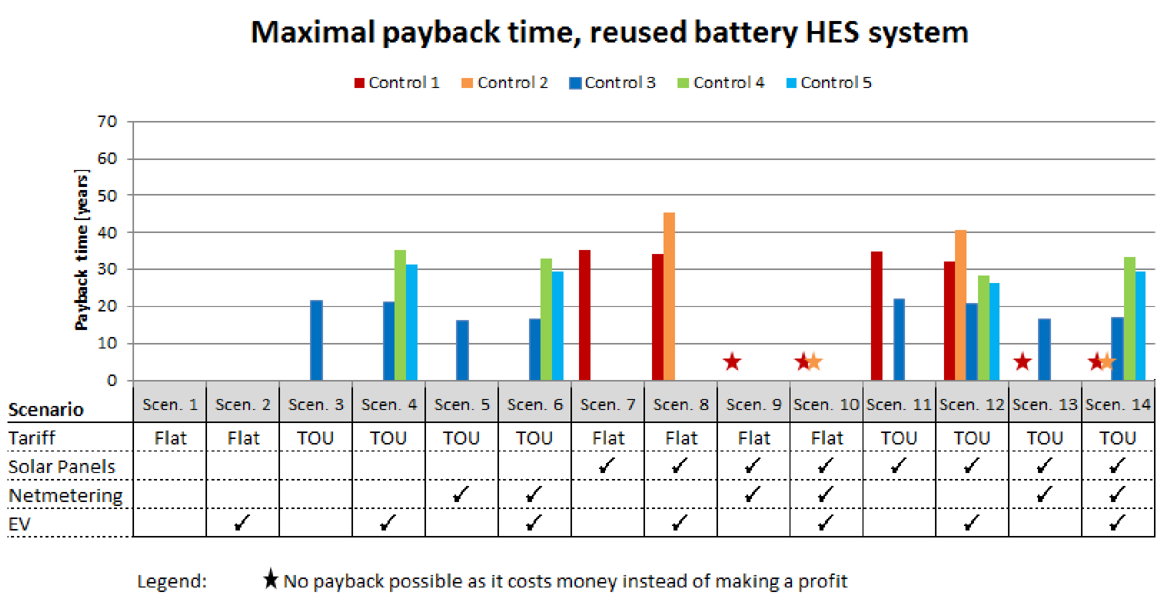


Figure 5.44: Maximal payback time reused battery HES system.

As can be seen in figure 5.43 and figure 5.44, the payback time for control scheme 3, the most profitable control scheme, ranges from 12 years in scenarios 5, 6, 13 and 14 as a minimal estimate up to 22 years in scenarios 3 and 11. The other control schemes resulted in even higher payback time; in scenarios 9, 10, 13 and 14 no payback time was achievable for controls 1 and controls 2 as implementing the HES system results in additional yearly cost instead of creating a profit for these scenarios.

The payback times for the new battery HES systems were calculated similarly and can be found in figure 5.45.

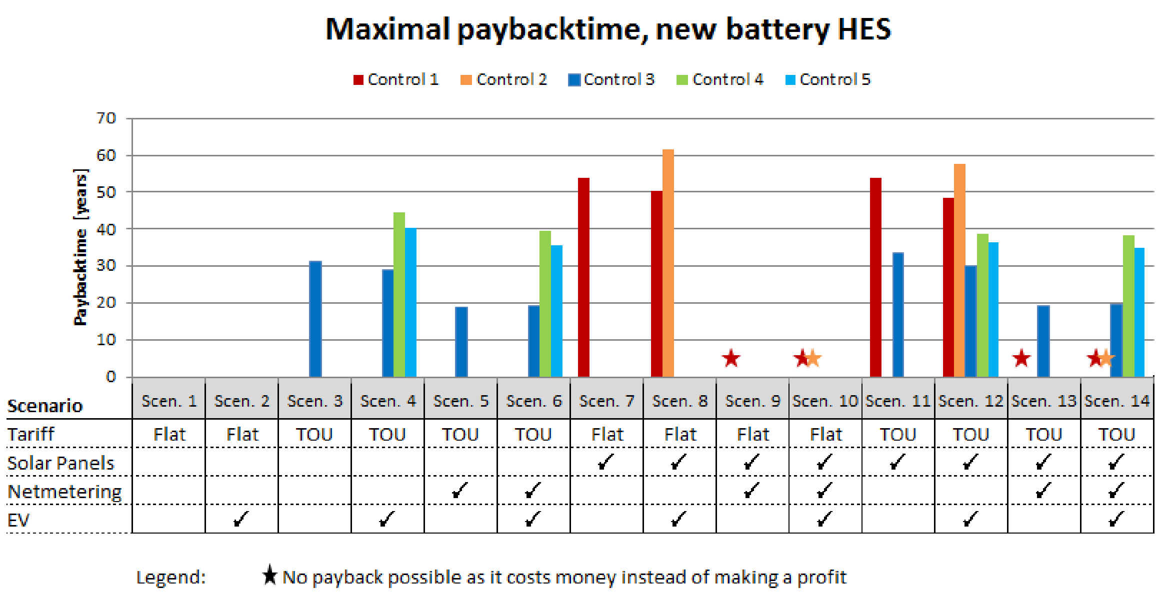


Figure 5.45: Payback time new battery HES system.

The results seen in figure 5.45 show a similar relative behavior as the ones for a reused battery HES system; however, all of the payback times are significantly higher than the maximal estimate for the reused battery HES system. The lower estimate for the payback time of the reused battery HES system is roughly half the estimate of the payback time of the new battery HES system.

5.8.2 Ecological Payback Time

The new battery HES system has shown better performance regarding the CO_2 equivalent emissions saved in almost all scenarios compared to the reused battery HES system. However, as the new battery pack would have to be specifically manufactured for this application, the manufacturing process comes with an environmental burden that cannot be attributed to its usage in the EV. As mentioned before, in this study it will be assumed that the reused battery packs will not have an associated environmental burden through manufacturing, as they have been manufactured for their primary life in an EV and would have been discarded/recycled if they were not reused in the stationary application. This recycling or discarding will not be affected by its second life except that it will happen at a different point in time.

This section will be evaluate how long it takes for the new battery through its increased savings in CO_2 equivalent emissions, to outweigh the burden associated with its manufacturing. Thus the "ecological payback time" will be calculated, and the results will be given in years. After reaching this ecological payback time, the new battery HES system will have the same ecological impact as the reused battery HES system, and any further savings in CO_2 equivalent emissions can be considered as a surplus. Again as this is just for comparison between the new battery HES system and the reused battery HES system, only the environmental impact of the battery packs are taken into account, as it is assumed that all other components in both systems are the same.

The ecological payback time for the new battery packs can be found in the following figure (figure 5.46):

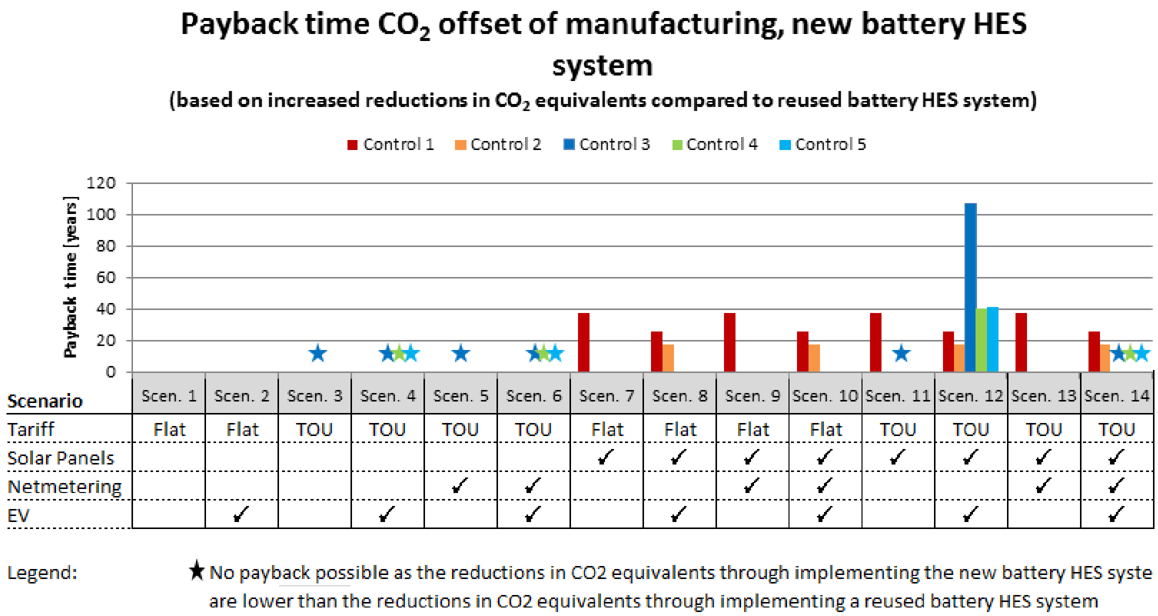


Figure 5.46: Ecological payback time new battery HES system.

As can be seen in figure 5.46 the ecological payback time ranges from 17 years up to over 106 years depending on the scenario and control scheme, and there are many combinations of scenarios and control schemes where the ecological payback is not achievable at all. It should be mentioned however that in these cases both adding the reused HES system and the new battery HES system to the household increases the CO_2 equivalent emissions, with the new battery HES system having a higher negative impact due to its higher capacity. If both capacities had the same size, the new battery HES system would have outperformed the reused battery HES system in this aspect due to its higher efficiencies. Still overall, the new battery would have a worse ecological impact due to the environmental burden associated with the manufacturing of its cells.

5.9 Economic and Ecological Impact of adding the Electric Vehicle

The previously discussed results focused only on the influence the HES system has on the modeled household, including the EV only by the added energy demand for charging. This section will evaluate the benefits the EV has on the household through replacing a vehicle using gas as its primary source of energy.

Adding an electric vehicle instead of a traditional vehicle with an internal combustion engine to the household, results in economic and ecological benefits. As the electric vehicle does not use gas but electricity which is, generally speaking, a lot cheaper than fuel, using an EV reduces the overall bill for transportation energy in the household. Through this an amount of fuel could be saved each year resulting in a profit of \$ 470. Similarly the emissions caused by the combustion of gas can be omitted through switching to an EV, which results in an amount of 1500 $kgCO_2e$ saved each year in the household evaluated in this study.

These economic and ecological savings have not yet been included in the previous results. It should also be mentioned again that the EV is not used a lot in the household evaluated (around 3900 miles driven in total for the year); in a scenario with a higher usage, the savings would rise as well.

5.10 Overall Discussion

The results show that the performance depends on the specific configuration of the scenario and the control scheme. However, some general statements regarding the influence of the different boundary conditions of the scenarios could be made:

The electrical tariff (either flat tariff or time-of-use tariff) influences the profit. In scenarios with a TOU tariff a significantly higher profit is obtainable through load shifting than in scenarios that included a flat tariff. However, if the control scheme does not only focus on load shifting, the profits in scenarios with TOU tariff and scenarios with flat tariffs will be similar.

Through the addition of solar panels, it is possible to make the household partly self-sufficient and to reduce the CO_2 equivalent emissions released. By adding an HES system in these scenarios the self-sufficiency can be increased significantly and the equivalent CO_2 equivalent emissions associated with the energy used within the household can be reduced. It should be noted, however, that the solar power generated and exported will still be used somewhere else, which is not accounted for in this model. However due to the unstable behavior of solar power production, energy fed to the grid might not be reimbursed with the current price if solar panels are deployed on a larger scale in the US, as this would put a strain on the power plants which utility companies will try to avoid. Also, less energy efficient peaking power plants might have to be used in that case, which would reduce the savings in regards to emissions. Further studies should evaluate the effects of this solar power export compared to storage in HES systems.

The influence net metering has on the performance depends heavily on the control scheme. The maximum achievable profit occurs in scenarios with net metering being active, if the focus of the battery is to increase profit through load shifting (control scheme 3). However, if the control scheme's focus is also on fast charging, net metering being active or inactive will not have much influence on the profit. In cases in which the HES system focuses on increasing the self-sufficiency and reducing the CO_2 equivalent emissions released, active net metering can even lead to an increase in electricity cost.

If an EV is included in the household, adding the HES system will allow the user to use the additional fast charging application of the HES system. Due to the increase in consumed electricity through charging, the overall energy consumption of the household rises. In cases in which an EV is included, adding the HES system leads to more reductions in CO_2 equivalent emissions than if no EV is present. Additionally, including the EV leads to further savings in CO_2 equivalent emissions released and in monetary savings, as no fuel has to be purchased and used.

The studies of the different control schemes revealed the possible tradeoffs regarding performance parameters such as profit, reduction in CO_2 equivalent emissions, and fast charging availability. Control schemes that were designed to maximize one area in particular showed a less positive (in some cases even a negative) impact regarding the other parameters. Some control schemes were designed to focus on multiple parameters (increasing self-sufficiency & fast charging or load shifting & fast charging). These control schemes achieved a more balanced performance; however, they also had significantly lower values than the peaks that were achieved by controls maximizing one area only. The control schemes that were evaluated showed the following results:

- *Control Scheme 1 (Maximize Self-Sufficiency):* This control scheme focuses on saving the generated solar power for self-consumption. Through this control scheme it is possible to increase self-sufficiency significantly (consumed solar power increases by almost 60 % through the introduction of the reused battery HES system) and to reduce released emissions (up to 1540 $kgCO_2e$ for the reused battery HES system). However, only a small profit, if any, will be generated. In some scenarios adding the HES system even leads to an increase in cost. Furthermore, the fast charging availability is very unreliable in this control scheme.

- *Control Scheme 2 (Maximize Self-Sufficiency, keep Fast Charging Reserve):* This control scheme works similar to control scheme 1 with the addition of a reserve kept for fast charging at all times. Overall it leads to fewer savings in CO_2 equivalent emissions (max of 1160$kgCO_2e$ for the reused battery HES system) and a smaller increase in self-sufficiency as compared to control scheme 1. The maximal increase of consumed solar energy is 47 % for reused battery HES system. The profit is similar to control scheme 1 as it is either very low or even negative. However, with control scheme 2, a very reliable fast charging availability was achieved, resulting in an availability to fast charge at least an equivalent of 15 miles of range added to the EV in 100 % of the charging events.

- *Control Scheme 3 (Load Shifting):* This control scheme focuses on load shifting, which resulted in the highest profit obtained from all control schemes (highest profit: $ 480 per year for the reused battery HES system). However, the reductions in CO_2 equivalent emissions released are small, and implementing the HES system into the household may also increase the CO_2 equivalent emissions. Additionally, this control scheme results in a very unreliable fast charging availability.

- *Control Scheme 4 (Load Shifting, keep Fast Charging Reserve:* This control scheme focuses on both load shifting and fast charging. Overall a smaller profit than in control scheme 3 is obtained (highest profit: $ 280 per year for the reused battery HES system), but a reliable fast charging availability (100 % of the charging events) of an energy amount equivalent to add at least 15 miles to the EV range can be achieved. The increase in self-sufficiency and the reductions in CO_2 eequivalent missions are similar to control scheme 3.

- *Control Scheme 5 (Load Shifting, keep limited Fast Charging Reserve):* Similar, to control scheme 4, this control scheme focuses both on load shifting and fast charging, but will limit the fast charging availability slightly. It leads to a small increase in possible profit compared to control schemel 4 (up to $ 300 per year for the reused battery HES system), but overall the profit is still significantly less than control scheme 3. Fast charging of an equivalent of 15 miles of range is almost always possible (at least in 90 % of charging events for the reused battery HES system). The increase in self-sufficiency and reductions in CO_2 equivalent emissions were very similar to control scheme 4.

The payback time for the cost of purchasing and installing the HES system was evaluated by estimating the price range for the reused battery HES system and the price of a new battery HES system for the parameters used within this study, and using the calculated yearly profit of each. Here it was assumed that the profit stays the same every year. The results show that the new battery HES system has a significantly higher payback time compared to the reused battery HES system. The payback time for the new battery HES system is already significantly higher than the high estimate of the reused battery HES system's payback time and up to almost twice the number of years compared to the lower estimate for the reused battery HES system. This shows that from an economic point of view it is a lot better to invest in a reused battery HES system than a new battery HES system. However, both the payback times for the reused battery HES system as well as the new battery HES system are too high (for a reused battery HES system starting at 12 years, for a new battery HES system starting at 19 years) to justify investing in these systems from an economic perspective.

To compare the reused battery HES system with the new battery HES system from an ecological perspective, the time it takes for the new battery HES system to recover its manufacturing burden through its increased savings in CO_2 equivalent emissions was calculated. Again, it was assumed that the performance is constant every year. It showed that in the best case (control scheme 2) this "ecological payback time" is at least 17 years, ranging up to 106 years in the worst case (control scheme 3 in scenario 12). In scenarios that do not include solar power, the environmental burden of manufacturing the new battery can never be recovered, as including the HES system increases the emissions released instead of reducing them. Therefore, it can be concluded, that also from an environmental perspective it should always be more beneficial to use a reused battery HES system even though it has lower efficiencies, as it is likely that the new battery HES system will reach its end of life before it can recover the initial environmental burden through its higher efficiency and capacity.

To give some credit to the new battery HES system, it is safe to assume that it would have a higher life expectancy in the new stationary usage than the reused battery HES system, since it has not degraded as much as the reused battery HES system. This is not accounted for in the calculations. However, it also might be possible, that when the reused battery cells reach their end of second life, the EV batteries that reach their end of first life will already outperform the old battery cells, due to the furthered technological advancement, even if they were new when they were inserted into the HES system. This might also make replacing the battery cells in the new battery HES system beneficial, which means that the increased life expectancy of the new battery cells might not make a significant overall impact.

The assumption of constant performance to calculate the payback times is a best-case assumption, as, due to degradation, the benefits will decrease over time. To obtain more accurate estimates, further studies should focus on experimentally testing new and used EV batteries to develop models that take the aging mechanisms into account. Also, together with the degradation, additional influences on the payback times could be further taken into account, such as the inflation rates and price development of the component costs and electricity prices.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

The first research question to be explored in this thesis was to analyze the economic and ecological impact of the addition of the HES system into the household under different boundary conditions and different control schemes. For this, a model was setup of a household including the home energy storage systems either based on new batteries or reused electric vehicle batteries, scenarios were explored with different boundary conditions such as the inclusion of solar power, the tariff structure, the inclusion of net metering, and the inclusion of an electric vehicle. Different performance parameters such as the profit, the savings in CO_2 emissions released by the energy consumed within the household and the availability for fast charging were investigated.

The results show that the impact of the home energy storage system is influenced by both the boundary conditions of the scenario and the control scheme used. As there is a trade-off between the different performance parameters, different control schemes were created either focusing on maximizing one benefit in particular or focusing on multiple objectives.

For the economical best-case scenario, an overall profit of $ 480 per year can be achieved through adding a reused battery home energy storage system. This profit is close to the ideal achievable profit through load shifting for a battery of that size. An increase in this number is only possible through either increasing the capacity of the home energy storage system (which would also increase the cost for purchasing) or through relocating to a utility company with a higher difference between peak time prices and off peak time prices.

The highest profit was mostly dependent on the inclusion of net metering and a time-of-use tariff. The results also show that the control scheme that focuses on load shifting has a significantly lower performance in saving CO_2 equivalent emissions or creating a reliable system for fast charging.

The highest savings in CO_2 equivalent emissions released by adding a reused battery home energy storage system to the household is 1540 $kgCO_2e$, achieved by maximizing the self-consumption of generated solar energy. Through adding a reused home energy storage system, it is possible to reduce the grid energy percentage of the total consumed energy from 76 % to 62 %. Depending on the other parameters of the scenario, maximizing the self-sufficiency can either lead to small economic savings (in scenarios that do not include net metering) or increase the electricity bill (in scenarios in which net metering is active). If no solar power is included, adding the home energy storage system always increases the CO_2 equivalent emissions released by the household due to the additional load caused by the thermal management and inefficiencies. Furthermore, the control scheme which focuses on increasing the savings in CO_2 equivalent emissions, has a very unstable performance regarding its availability for fast charging. In more than 60 % of the charging events no fast charging is possible.

It is possible to obtain reliable fast charging availability through reserving a certain portion of the home energy storage system's capacity solely for fast charging. Through this a charge equivalent to adding more than 15 miles on the EVs range is available at all times, which enables the user to rely on this system for unforeseen charging emergencies. This comes at a cost, cutting the profit roughly in half and also significantly reducing the CO_2 equivalent emissions saved.

The results for the different performance parameters show that, the benefits of the control scheme depend heavily on the individual scenario. An overall ranking of the control schemes is difficult, as it depends on the user's focus and preference for which performance parameter should be emphasized and is valued most.

Regarding the scenarios, a small profit can always be made except in cases which include both a flat tariff and net metering. The highest possible profit is achievable if both a time-of-use tariff and net metering are present. However, if the tariff is flat and net metering is active, adding the home energy storage system will always create a loss as solar energy can be exported to the grid without any repercussions. If solar panels are included in the household, adding the home energy storage system always results in a reduction in released CO_2 equivalent emissions. If no solar panels are present, adding the home energy storage system increases the CO_2 equivalent emissions released, as it increases the energy consumption. For all scenarios that included an electric vehicle, a high fast charging availability can be achieved through implementing a control system that keeps a reserve for this purpose.

To further analyze the economic impact as well as explore the second research question of how the reused battery home energy storage system performs against the new battery home energy storage system, the payback time for the purchasing and installment cost as well as an ecological payback time to recover the environmental burden of manufacturing the batteries was calculated. Overall it shows an expected challenge in reaching economic feasibility. With, in the best case, the payback time of the reused battery home energy storage system being 12 years and for the new battery home energy storage system being 19 years, the achievable profit does not justify investment from an economic perspective. However, in all scenarios, the reused battery home energy storage system results in significantly lower payback times than the new battery home energy storage systems. The payback time for the new battery home energy storage systems to recover its initial environmental burden through its higher efficiency and capacity was at least 17 years. These results show that although the home energy storage systems may not be economically feasible at the current time, from an economical or environmental perspective it is always beneficial to reuse electric vehicle batteries instead of newly manufactured ones for these applications.

The results for the payback times furthermore demonstrated the expected economical challenge of using these home energy storage systems for profit which justified the proposal to add fast charging as an additional application of the home energy storage system. Adding a possibility for the user to fast charge adds a unique further application to the HES system which could only be purchased for a high cost otherwise and thus increases the likeliness of customers to invest.

Overall, although the inclusion of an HES system might not be economically feasible, as the profits generated will not be able to cover the purchasing and installment costs during its lifetime, it can be concluded that reusing electric vehicle batteries for a home energy storage system will always be a better choice than using new batteries economically and ecologically speaking. As the demand for new home energy storage systems is there, even with its questionable economic feasibility, it should be profitable for companies to explore further the reuse of electric vehicle batteries for these systems, as the reuse not only saves the environment from the burden of manufacturing new batteries, it also provides an opportunity to lower the product's cost and still maintain adequate performance.

6.2 Future Work

One of the main areas that should be explored in more detail is the experimental testing of electric vehicle batteries at their end of life and the modelling of the batteries' degradation during second use. This could have significant impact on the estimates of benefits. A model could be set up to evaluate different degradation scenarios and different aging during its first life to evaluate the criteria for end-of-life batteries to be reusable in home energy storage systems.

As the results evaluating the control schemes show a tradeoff between different performance parameters such as profit, reductions in emissions, and fast charging availability, further studies should explore the customers' preferences in more detail (such as through surveys). This could be used to create a utility function to rank the control schemes and optimize these according to the customer needs. This would also help in determining if the additional proposed application of fast charging, which adds more comfort to the user, will be able to justify an investment in this system.

Furthermore, as this study focuses on one specific household, further studies could be made to assess the performance of the HES system in other scenarios which include, for example, different load profiles or sizes for the HES system or the solar panels. As the grid energy mix or the tariff also influence the economic and ecological impact, additional studies could evaluate a household at other locations with varying boundary conditions.

Appendices

APPENDIX A

ADDITIONAL PARAMETERS USED FOR THE MODEL

Parameter	Unit	Value chosen	Justification
Heat Exchanger Cooling Capacity	W/K	170	Good balance of cooling performance, cost, and size
Battery Heater	W	500	Sufficient to maintain battery temperature above 0°C
Heater Efficiency	-	0.9	
Duty Cycle	Minutes	30	Long enough to cool down battery post DCFC
Temperature Buffer	°C	5	Allows operation up to 45°C
Battery Shut-off Temperature	°C	50	Sufficiently below thermal runaway temperature
Minimum Battery Temperature	°C	0	Based on recommendations for battery temperature range
Maximum Battery Temperature	°C	30	

[29]

Figure A.1: Parameters for the thermal model.

Parameter	Unit	Value chosen	Justification
Inverter efficiency	-	97%	Based on currently available battery inverters [43, 83, 84]
DC/DC converter efficiency	-	97%	Based on currently available high power DC/DC converters [85]
Level 2 charging rate	kW	7	[15]

[29]

Figure A.2: Addidional parameters for electrical components.

Parameter	*Unit*	*2013 Ford Focus Electric*	*2013 Chevy Volt*	*2013 Nissan Leaf*	*Source*
Amp-hour capacity of pack	[Ah]	75	45	66.2	[51]
Energy capacity of pack	[kWh]	23	16.5	24	[51] for all, [52] for Volt
Mass of pack	[kg]	302.6	197.3	290.3	[51]
Volume of pack	[L]	268.3	153.8	350.6	[51]
Internal resistance of pack	[ohms]	0.065	0.098	0.111	[51]
Cooling type	-	Liquid Fin Cooling	Liquid Fin Cooling	Active – Air Cooled within Sealed Pack Enclosure	[51] for all, [52] for Volt
Max cell voltage	[V]	4.2	4.15	4.2	[51]
Min cell voltage	[V]	3	3.00	2.5	[51]
Nominal system voltage	[V]	318.2	355.2	364.8	[51]
Number of cells per pack	-	430	288	192	[51]
Number of cells in series	-	86	96	96	[51]
Number of cells in parallel	-	5	3	2	[51]

[29]

Figure A.3: Parameters for the battery pack.

Parameter	*Unit*	*2013 Ford Focus Electric*	*2013 Chevy Volt*	*2013 Nissan Leaf*	*Source*
Cell chemistry	-	LMO	LMO	LMO	[51]
Nominal cell voltage	[V]	3.7	3.7	3.7	[51]
Length of cell	[mm]	200 *	200	290	Volt and Leaf were measured in lab, Focus was assumed same size as Volt, Leaf also from [54]
Width of cell	[mm]	145 *	145	216	
Depth of cell	[mm]	5.5 *	5.5	7.1	
Internal resistance of cell	[ohms]	0.0038 +	0.0031+	0.0023 +	$= (N_{parallel} / N_{series}) * r_{pack}$
Amp-hour cell capacity	[Ah]	15 +	15 +	33.1 +	$= (1/N_{parrallel}) * Cap_{pack}$
Mass of cell	[kg]	0.359 *	0.359	0.787	Volt and Leaf were measured in lab, Focus was assumed same mass as Volt, Leaf also from [54]

[29]

Figure A.4: Parameters for the battery cells.

	Ford Focus Electric	Chevy Volt	Nissan Leaf
α [V]	62.7	67.8	55.7
U_{nom}	358	394	398
SOC_{nom}	1	1	1

[29]

Figure A.5: Parameters to calculate the open circuit voltage.

Table A.1: Additional parameters for the thermal model.

Parameter	Unit	Value chosen	Justification
Reference Temerature	K	298.15	[29]
Universal Gas Constant	J/Kmol	8.314	
E_a Experimental determined constant for calculating resistance dependent on temperature	J/mol	-28,640	[29]
R_{ref}	0.0038		Internal resistance of cell [29]
Heat capacity of Cell	W/mK	1,100	Average of experimentally determined values [29]
Natural heat convection coefficient cell side	W/m^{2}K	3	[29]
Length cooling fin cell	m	0.01	[29]
Width cooling fin cell	m	0.0003	[29]
Thermal conductivity aluminum	W/mK	215	[29]

[29]

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