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Framework for Evaluation of Home Energy Management System Approaches

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Worldwide electricity consumption and the extent of peak electrical energy utilization are on the rise as societies everywhere become more and more developed. The increase of Distributed Renewable Energy (DRE) production, Electric Vehicles (EV) and large load consuming appliances magnify these problems, and pose a potential threat to the stability of electrical power grids.

Demand Side Management (DSM) is a potential way to postpone grid reinforcements, and to prepare electrical power grids for the challenges that they face.

DSM can be implemented by including a management systems at the consumer end of the energy network, automates the control of loads and power production within the household power network. This provides capabilities to reduce electricity costs for the end user, reduce the total electricity demand through ideal management or reduce loads at peak load times for instance.

To be able to manage energy production, storage and significant loads as crucial components to the system ideally, the components are analysed with respect to the underlying physical processes that occur during their operation. This analysis, combined with research into already existing HEMS found in literature, will then be used to formulate a framework for testing and validating Home Energy Management System (HEMS) approaches.

An agent based architecture is proposed for the core of the evaluation system. This offers flexible addition of applications as agents, and will provide a simple way of building a system on top of the framework.

The management software will be based on the open source home automation platform Home Assistant, which is written in the Python programming language. Python offers a large library of modules out of the box, and is an ideal tool to create distributed software for scientific applications. Therefore, it will be used to write the flexible optimization and management module that is at the heart of the HEMS evaluation framework.

The finished System will then be validated in a simulation environment comprising a simulated PV module, an EV charging point, a BESS and simulated loads. Three different management approaches will be illustrated using distinct management algorithms, and compared using several key performance indicators.

It is shown that the proposed agent based architecture can offer a means of evaluating different HEMS approaches and algorithms.

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List of Abbreviations

AIT	Austrian Institute of Technology
API	Application Programming Interface
BESS	Battery Energy Storage System
CC	Constant Current
CP	Constant Power
CR	Cost Reduction
CV	Constant Voltage
DP	Data Point
DPC	Data Point Consumer
DR	Demand Response
DRE	Distributed Renewable Energy
DRS	Demand Response System
DSM	Demand Side Management
EMS	Energy Management System
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
GS	Grid Stability
GUI	Graphical User Interface
HEMS	Home Energy Management System
HIL	Hardware in the Loop
IoT	Internet of Things
IP	Internet Protocol
LOI	Level of Intelligence

MCC	Multistage Constant Current
MQTT	Message Queue Telemetry Transport
PV	Photovoltaic
QoE	Quality of Experience
RPC	Remote Procedure Call
SoC	State of Charge
TCP	Transmission Control Protocol
TRL	Technology Readiness Level
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

Humanity today stands before one of its largest challenges to date. Global man-made climate change could have unforeseeable consequences for future generations, potentially threatening large populated areas and vast amounts of farmable land.

This global climate change has several causes, with the expulsion of greenhouse gases like CO_2 through the burning of fossil fuels being one of the most important. The influence of artificial CO_2 emission on the atmosphere was discussed as early as 1896 by Svante Arrhenius [1]. Since then greenhouse gases and other gaseous substances that are expulsed during burning of fossil fuels and their effects on the atmosphere have been subject to extensive further studies, and experimental validations for the early theories have been found. [2], [3]

Despite being aware of the effects of CO_2 on the atmosphere and the threat it poses to humanity for more than a decade now, only little effort has been made towards a change of the status quo until recently. In 2015 all countries on earth that are part of the United Nations Framework Convention on Climate Change (UNFCCC) reached an agreement to keep the global warming below 2 ° °C by decreasing the emission of greenhouse gases into the earth's atmosphere. This was ratified by 169 countries (Until November 2017 [72]) through the so called Paris Agreement. [73] This is largely seen as a historic agreement, as it the first global political treaty on climate change that sees all the signatory parties taking action. While being considered an overall success that an agreement could be reached, there are several areas where the agreement lacks decisiveness. [4]

To reach the ambitious climate goals that have been set the use of fossil fuels has to be decreased throughout all industries and a move towards renewable energies has to be made. With electrical energy production being responsible for a big share of the global energy usage, this will result in change of the electrical energy sources that are used. [74] Another big part of the worlds energy and fossil fuel consumption is in the transportation sector. [74] Here a move towards Electric Vehicle (EV) that are ultimately supposed to be powered by renewable electrical energy, can have a big impact. [75]

With renewable energy sources for electrical energy production on the rise in both OECD (Organisation for Economic Co-operation and Development) countries and non-OECD countries [76], some renewable energy sources like wind or solar photovoltaic prove more challenging to the existing power grids than traditional electrical power plants. They cannot be controlled in the same way as today's power plants because they rely on external forces like wind and sunshine. As well as that, another development is starting to emerge: the increased market penetration of EV. [75]

With these volatile types of electricity generation and large loads on distribution grid level becoming more common the power grids of tomorrow face several challenges that traditional grids are not prepared to face without costly reinforcement.

To help make a move towards more Distributed Renewable Energy (DRE) and fewer fossil fuels possible, the electrical power grids need to be able to accommodate all of these developments.

The management of loads on the customer side, also called Demand Side Management (DSM) [5], [6] can be one solution to reinforce the grid and postpone new investments on grid infrastructure. This management can occur on at several different locations ranging from households to community housing to industrial sites.

1.1. Problem Statement

Many different techniques for DSM are emerging, while their direct comparison is difficult, the different approaches need to be tested before they can be unrolled to the electrical energy consumers. As there can be no standardised household or consumer behaviour, there is a need for a system to simulate different approaches to DSM on a consumer/household level for testing and evaluation purposes.

1.2. Methodology

At first, a survey of the current State-of-the-Art in Home Energy Management System (HEMS) was conducted as well as a physical analysis of important system components. Based on these analyses an architecture will be proposed. This system is then tested using several different control algorithms, to investigate their effects on residential electrical energy usage.

1.3. Energy Generation

Energy generation is a term that is used in this thesis to signify conversion of a different kind of energy into electrical energy. Energy itself can never be generated or destroyed, it can only be converted into a different form of energy. For instance a Photovoltaic (PV) panel does not generate energy, it actually converts the kinetic energy of single photons into electrical energy. This process will be explained further in section 2.5.1.

2. State-of-the-Art Research and Physical Analysis of Components

To be able to evaluate implications of HEMS on several levels, it is important to first understand what reasons there are to employ such a system, what components can be controlled by the different systems, and how the most important components work. For the purpose of better understanding the properties of Energy Management Systems that can already be found in literature, several such systems are to be analysed in this chapter.

2.1. Appliances and Energy components in a Future Prosumer Household

In this section, the most common means of energy production, storage and consumption in a Prosumer household of tomorrow will be outlined. As well as giving a small introduction to their function and usage, an overview of the most common means of communicating with these systems and appliances will be given. An overview of the State-of-the-Art components in such a household can be seen in figure 2.1.

2.1.1. PV Inverter, PV Module

The percentage of energy generation through PV modules has been steadily on the rise for the last several years, and is projected to continue rising for several years to come. [77] In Austria, the construction of new PV modules is being subsidised by the government institution 'Klima- und Energiefonds' (KliEn) [78] for modules with sizes smaller than 5 kW peak power production [79] and by the 'OeMAG - Abwicklunsstelle für Ökostrom'(OeMAG) [80] for photovoltaic modules larger than 5 kW peak power production [81]. In figure 2.2 it can be seen how many PV modules have been installed using subsidies from either the KliEn or the OeMAG in different regions up until April 2017 in Austria.

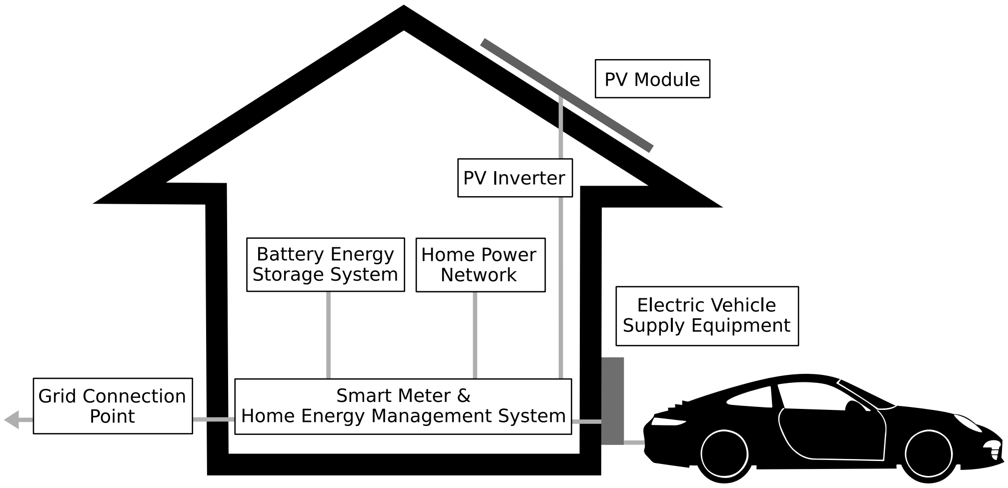
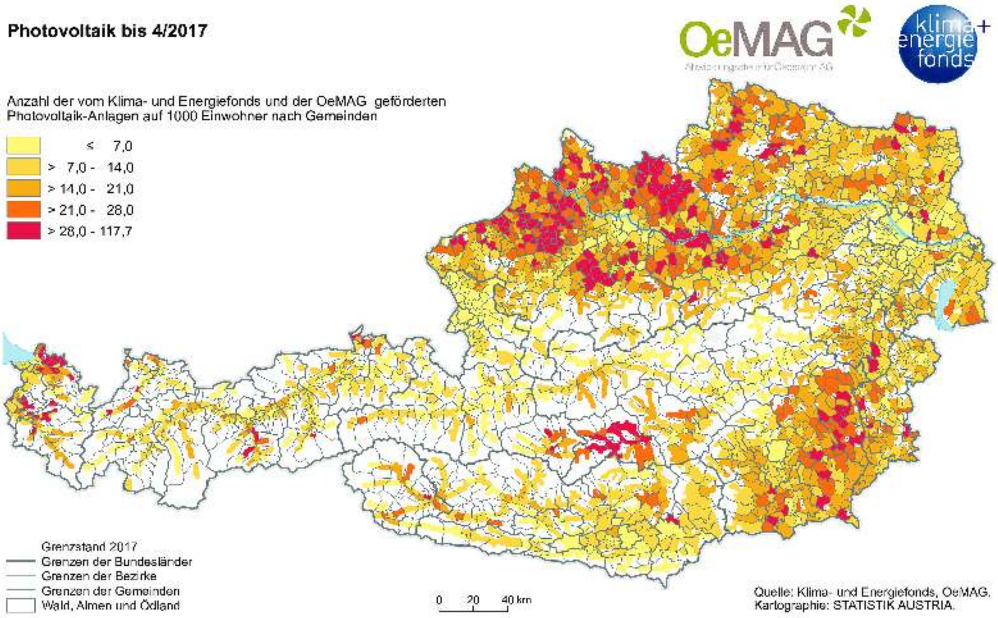


Figure 2.1.: Overview of a future prosumer household including State-of-the-Art system components.



Quelle: Klima- und Energiefonds, OeMAG.
Kartographie: STATISTIK AUSTRIA.

Figure 2.2.: Government subsidised PV-modules installed per region per 1000 inhabitants in Austria

However, PV modules can prove to be a viable investment, even without any government subsidies [7], which is why they are becoming more common in any residential setting. A Photovoltaic Inverter will be included in the system, as it is needed to be able to use the produced energy within the household. The Inverter is necessary to convert the DC power received from the PV module to AC power that is then usable in the normal household electrical power network. This conversion from DC power to AC power is executed by the PV inverter. Currently there is only one big effort to standardise the means of communicating with a PV inverter, and that is being pursued by the SunSpec Alliance®. Sunspec is an alliance comprised of several companies involved in the solar and storage industries. The way information is being handled in its models will be used in this project as the industry standard [82]. The underlying means of information transfer protocol is MODBUS TCP (Transmission Control Protocol), which is a commonly used protocol for data transmission in automated processes. An extensive explanation of the protocol can be found online, published by the MODBUS organization [83].

2.1.2. Battery Energy Storage System

Due to recent technical and economic developments, Battery Energy Storage System (BESS) are increasingly installed in PV equipped households. This allows for higher percentages of internal consumption of electrical energy produced by the PV system. [8] The increased usage of energy produced by its own PV system can result in economic benefits, even without government subsidies for the BESS. [9] Within the future prosumer household the HEMS is the key to balance out periods of high production with periods of high consumption. As well as with the PV Inverter, the SunSpec Alliance model for communication with a Home Energy Storage System is the most standardised protocol currently implemented. As well as the Protocol for the PV Inverter, it is based on MODBUS TCP [83].

2.1.3. Smart Meter

Smart Meters are Energy Metering Systems which not only record the energy consumption of the consumer but send this data to the Energy provider on a regular basis. The Data that is transmitted is usually an average recorded over 15 minutes. This can keep traffic reasonably low, while sending data with a good enough resolution to the network provider. Such a system could open up many possibilities for applications. [10] At the moment the development of Smart Metering systems in different regions is far from being uniform, and most governments follow their own plans with respect to a Smart Meter Rollout. The trend, however, is towards Smart Meters being the favorable choice over regular energy meters. [11] For communication with a Smart Meter, there are also some standardisation efforts with respect to Smart Meter communication. The Open Smart Grid Protocol$^{®}$ (OSGP) [84] represents the efforts made by the OSGP Alliance. This communication is aimed at Smart Meter Communication with the Electrical Energy Provider, rather than at direct communication with a management system. Therefore, this is not deemed important for this project. As the means of communication with the Smart Meter for an Energy Management System is not yet foreseeable, it will not be considered any further in this work.

2.1.4. Electric Vehicle Supply Equipment

The market penetration of EV has been growing for the past years and is expected to continue doing so. [75] As EV are most probably going to be playing a big part in the transportation of the future, [75] an Electric Vehicle Supply Equipment (EVSE) should be included in the HEMS as a means of interacting with the charging mechanisms for an EV. Similar to the markets for PV Inverter and Home Energy Storage System, there are efforts to standardise the communication of a central control unit with a Charging Point. The Open Charge Alliance (OCA) is comprised of several companies that are actively providing charging infrastructure services. They created the Open Charge Point Protocol$^{®}$ (OCPP) [85], which can be implemented on any hardware that allows Transmission Control Protocol (TCP)/Internet Protocol (IP) connectivity. This communication protocol provides a standardised means of communication between EV and EVSE that can be used to keep a HEMS as widely usable as possible. The time it takes for an EV to be charged can be a main obstacle for consumers to not consider buying or using an EV. This gain of flexibility when the charge time is reduced is the reason why fast charging points are becoming more popular in the home environment as well as in commercial charging settings. [75] Fast charging points in the home sector can also lead to peaks in the consumption of electric power, as they require higher throughput of electric energy.

Another concept that is worth mentioning with respect to EV and grid stability is Vehicle to Grid (V2G). In this concept it is proposed that an EV's batteries could be used as further storage capacity for renewably produced energy. These further capacities for energy storage would be charged when a lot of energy is being produced. Later, when overall energy production is lower than the demand, these batteries would provide the stored energy to the grid. The batteries would not be allowed to discharge lower than 50% of maximum charge for there to be little loss of Quality of Experience (QoE) for the owners of the EV. However, at the moment this concept is deemed too expensive as the EV's battery life span would be greatly reduced by the increased charging and discharging of the battery. As these batteries are very expensive and the cost per kWh of energy stored this way would be very high, this is currently not a viable concept. [12]

2.1.5. Household Load Mix

To classify which loads present a possible point for the optimisation of the consumers energy consumption in today's common household, several different categories of loads are presented in this section. The classification was suggested in a report by THINK, a program financed by the European Commission [86]. An overview of the classification can be seen in figure 2.3.

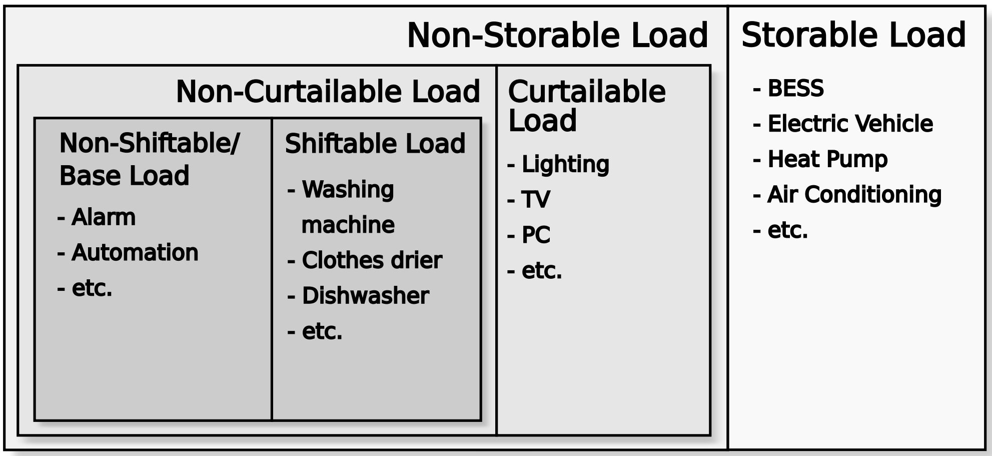


Figure 2.3.: Classifications of different loads in the household

Storable Load

The consumption of the necessary power is decoupled through storage of that energy in form of electrical energy stored in batteries of thermal energy in the household. This category includes energy storage methods such an EV, a BESS or a heat pump.

Non-Storable Load

The Non-Storable Loads within the household can be put into several different categories.

Curtailable Load The operation of curtailable loads cannot be shifted to another time without loss of QoE for the end user. These loads can however be interrupted at any time during their operation. This category includes devices such as lighting, TV, tools and computer.

Non-Curtailable Shiftable Load Shiftable loads are all which consume a certain amount of power during their operation cycle, but the time of the operation doesn't affect the outcome. These loads include several uninterruptible loads such as a washing machine or a dishwasher which offer some scheduling potential.

Non-Curtailable Base Load Non-curtailable non-shiftable load can also be specified as the base load, which cannot be influenced by the management system at all. This category includes systems like a burglary alarm or the automation system itself.

2.2. Classification of Smart Home Automation Systems

This part will outline the categories of Smart Home Automation Systems that are currently present on the market and in the literature. Systems of each category have a similar architecture and they are aimed at satisfying similar needs. The Systems will be put into 3 different categories which are not exclusive. Therefore a Smart Home Automation System can be a member of several different categories. A paper that outlines several currently present systems is [13], and an overview of several architectural approaches can be found in [14]. Not every system that is considered an energy management system in the referenced literature, will be considered one in this thesis. Some systems that manage the energy consumption of household appliances are called energy management systems, as a big part of energy consumed in the household is consumed by normal household appliances. In this paper a distinction will be made between energy management systems, demand response sensitive systems and appliance control systems.

2.2.1. Energy Management System

Energy Management System (EMS) are comprised of a central processing unit, an observable means of (renewable) energy production and a controllable means of (electrical) energy storage. In most cases the means of energy production is considered to be a PV Module, as it is currently the most common means of decentralized renewable energy production. The means of energy storage will be considered to be a Home Energy Storage System like the Tesla Powerwall®or the Fronius Solar Battery®. The Energy Management System is responsible for charging the battery with any energy production that surpasses the current electrical energy consumption. Another component often found in this kind of Smart Home Automation System is an EV. The charging of the EV needs to be managed, which is again prioritized during peak times of renewable energy production. Therefore, in order to qualify as an Energy Management System, the primary components a Smart Home Automation System must include are a PV Module (and a PV Inverter), a Home Energy Storage System and possibly an EV as a large load that is also supposed to be managed when it is present.

2.2.2. Demand Response System

Demand Response System (DRS) exist in an electrical grid where the price of electrical energy depends on the total demand for said energy throughout the grid. [15] This variable price can be exploited in three main ways; curtailing the electricity consumption, shifting electricity consumption to lower price times and maximising self use of locally produced electrical energy. [15] These ways can be used by a DRS to minimise the electricity price for the end user. If many users move their electrical consumers to lower price times, this can lead to a peak load reduction and therefore be beneficial for the grid operator, as well as the end users employing DRS.

2.2.3. Household Appliance Control System

There are different ways of enabling a system to control household appliances. In this section the two of the most prominent approaches found in literature are outlined.

Appliance Control with Remotely Managed Power Sockets

By connecting remote controllable power sockets to every socket where an appliance that one wants to control is to be plugged in, the e-appliances can be controlled in the sense that the socket they receive their power from can be turned off completely. This can be used to remove the stand-by power some appliances use when they are switched off but still plugged in to a socket. Also appliances like lights can be easily controlled this way. This way of controlling devices has the advantage that it is completely independent from any proprietary means of connection, therefore any devices that get their power from a standard plug can be used in a system that uses connected power sockets. The power sockets themselves usually offer Wireless communication to a central controlling unit. [16] presents such a Energy Management System that includes sockets controlled via ZigBee [17] wireless technology and managed by a central Hub. The implemented system in this work also implements rules to reduce stand-by power by switching outlets off once the power used by an outlet drops beneath a power threshold which represents the lowest possible power usage by the device during operation.

Appliance Control via Direct Communication with Appliances

Smart devices today often connect over WiFi or other Wireless communication protocols to a Central Unit from which they are controlled. The Central Management Unit usually provides connectivity to the internet to remotely control and supervise the system. Each of these systems offers its own way of communicating with appliances. There is no standardised way in which appliances can be addressed. Therefore, this is usually the way proprietary systems work. For instance the Google home ®, the Samsung Smart Things ®, or the Amazon Echo ® can talk directly to smart appliances if they are compatible. However, most of these systems also offer connectability for other protocols like ZigBee, or allow for inclusion of Smart plugs in the home. Another system that is primarily used for lighting control is the Philips Hue ® which makes use of a central hub that communicates via ZigBee LightLink, a solution developed especially for lighting control, for the lights that are integrated. It, however, also offers connectability with other ZigBee systems that could therefore be integrated as well.

2.2.4. Objectives of Smart Home Automation Systems

What are the reasons for you to implement an Energy Management System in your home? Patel et al. present several different optimisation approaches commonly taken in HEMS and what their aim is in [18]. It was found that the most common aims of the analysed HEMS approaches were to reduce the overall consumption of electricity within the household, peak load reduction and the reduction of the electricity bill for the end user of the system. A similar set of aims was found by Lotfi et al. in [14], they suggested that three ways in which energy can be managed locally in the home are; shifting loads to times with lower electricity prices, therefore reducing the overall electricity cost, monitoring and controlling local renewable energy sources, reducing the overall electricity consumption from the grid and storing energy from renewable energy sources to use it at forecast peak consumption times to support the grid. In [13], Beaudin et al. have found the most common objectives of HEMS are cost reduction, increase of well being, load profiling like peak consumption reduction or an increase of self consumption of renewables, reduction of electricity consumption and a reduction of emissions. These aims that were found in those papers can be put into 3 distinct categories Cost Reduction (CR), Electricity Demand Reduction (EDR) and Grid Stability (GS). These aims are further explained in table A.1 which can be found in the appendix. The different objectives the energy management systems follow are not completely independent of one another, and each of the objectives will automatically have a positive effect on the two others. However, the main objective will still be at the focus of the developer of the system, leading to potentially better results in that section, than the others.

2.3. Home Energy Management Systems

To find the current State-of-the-Art in home automation and energy management, reviewed systems will be placed into categories of what features each of the proposed system offers. This classification will help to find the most important trends in home automation and to identify the areas that provide the biggest potential for optimisation.

For further classification of the different systems found in literature, the Level of Intelligence of the systems and the Technology Readiness Level will be taken into account.

Level of Intelligence

The Level of Intelligence (LOI) of a system can be put into several different categories. This depends on how the components interact within the system, if the system is able to predict future events, how much control the system has over its state and even if it is aware of the state of all components within the system. To offer a standardised way of classification for the LOI of a system, guidelines are needed, an implementation of such a category structure has been thought up by the National Electrical Manufacturers Association. Their model can be found under [87] and the different levels that have been implemented in this model are outlined shortly in table **??** in the appendix.

Technology Readiness Level

The idea behind some systems might seem very good at first, but later in the production cycle unforeseen problems may arise which increase the time until the system is ready for use. To give some information about the technological advancement of a system the Technology Readiness Level (TRL) was introduced by the NASA[19]. These classifications have become an important measure to classify different projects outside the domain of space travel as well. The scale consists of 9 Levels of Readiness, which correspond to a level of development each proposal needs to go through before being market ready.[88] In table **??** in the appendix the 9 different TRL and what is necessary to qualify for them is outlined.

2.3.1. Home Energy Management Systems in Literature

The reviewed literature will now be classified according to the proposed categories in section 2.2. An overview of the reviewed literature and the features of each of the proposed or realised systems can be found in table 2.1. The items that are shown with limited affiliation with the Energy management category usually offer support for a PV module, but do not include the availability of an energy storage system. Most of the literature found on HEMS specialises on controlling appliances that are usually present in the household rather than managing a system that is exclusively used for energy generation and storage. Demand Response mechanisms can be found in a bit more than 50% of the proposed systems found in the literature. For each of the papers reviewed a short form of the name will be presented next to the title in brackets to make the different papers easier to find in the overview table 2.1.

Realistic HEMS using exogenous grid signals (RealisticHEMS) [20]

In this paper Ahmad et al. propose a HEMS that consists of a PV module, controllable loads and uncontrollable loads. The controllable appliances are washing machine, air conditioner, clothes dryer, water heater and dish washer. The uncontrollable appliances are personal computer, security camera, microwave oven, refrigerator, television and lights. At the beginning of the day the proposed system gets the forecast temperature and solar irradiance levels and schedules the loads according to probable energy production and energy cost. The day is divided up into 24 equal parts and the proposed algorithm finds the ideal cost saving schedule for each of these slots. The study shows that the daily electricity bill could theoretically be reduced by 22.73% compared to a household that does not use this scheduling algorithm. As the system has not been implemented yet and is just a proposed system, it qualifies for TRL 2. However, the Level of Intelligence of the proposed system is 5 as the system plans the schedule of the loads beforehand. The main aims of this system are cost reduction and peak electricity consumption.

An Intelligent HEMS with Classifier System (IntelligentHEMS) [21]

Sekizaki et al. propose a system that primarily tries to shift the loads from high price times to lower prices times, therefore offering a Demand Side Management application. The flexible loads that can be controlled and are used to shift the load are a battery and a water heater. During low price times the battery charges and the water heater warms up. These resources can then be used when electricity is more expensive. The algorithm employed is called an extended classifier system. This algorithm tries to maximize payoff with respect to the current environment (electricity price here). As the conducted experiment was merely a computer simulation, it qualifies for TRL 3. The LOI of the proposed system is 3. cost reduction was identified as the main objective of this system.

Designing a Portable and Low Cost Home Energy Management Toolkit (HEMToolkit) [22]

This system proposed by Keyson et al. consists of smart plugs with a wireless module, a residential gateway and a mobile app. The smart plugs link to the home gateway and offer information about the current energy consumption to the mobile app to provide the consumer with feedback. The wireless communication is based on the ZigBee profile, as it is more energy efficient than WiFi. As the first system prototype has actually been tested in home (ie. a relevant environment) the system qualifies for Technology Readiness Level 6. The LOI of the system is 2 as it offers information about the current energy consumption but no means to control the connected appliances. The objective of the system is to make users aware of their energy consumption, and therefore be able to reduce it.

HEMS based on Photovoltaic System (PVbasedHEMS) [23]

In this paper Yao et al. propose a HEMS architecture that includes a PV module, an energy storage system and several household appliances. The appliances include lamps, water pump, refrigerator, dishwasher, rice cooker and a fan. The management system employs a fuzzy logic based control algorithm, where current state of charge of the energy storage system, the current energy production by the PV module and the current energy price determine how much load can currently be sustained. The fuzzy logic control energy dispatch strategy proved to be viable during the testing of the prototype of the system, therefore this system qualifies for the Technology Readiness Level 6. The LOI of the system is 3, as it employs the fuzzy logic control to self optimize the current money spent on energy. The main aim that was found was to reduce the electricity bill for the end consumer.

Intelligent Multi-Agent System for Smart Home Energy Management(MultiAgentHEMS) [24]

In this paper published by Li et al. a HEMS based on many independent agents is proposed. For the management side of the system there are a HEMS agent, a Demand Side Management agent and a Supply Side management agent. For each of the systems involved in the supply or consumption of electrical energy its own agent is assigned. These agents communicate according to the hierarchy of their side of the system. The part of the system that is responsible for managing correct operation of the rest of the system is HEMS agent, and it gets information on the operation of all the other agents, which helps it to optimise the state of the system. The LOI of the system is 4 because of the collaboration present. Technology Readiness Level is 3, as the experimental verification of the concept was purely simulation based. Utilising the HEMS as a way to save energy while reducing the electricity bill for the customer and being helpful towards the stability of the power grid, are the core objectives of this system.

Laboratory Smart HEMS (LabHEMS) [25]

Paunescu et al. propose a system that employs a Demand Response mechanism to schedule appliances and therefore minimise the electricity cost. The central component in the system is a controller that is able to switch plugs on and off in response to a price signal received from a smart meter. The loads connected to these plugs are managed according to electricity pricing. The Intelligence Level of the proposed system is 3, and its TRL is 4. This systems objective is the reduction of electricity cost for its end user.

More Efficient HEMS Based on ZigBee Communication and Infrared Remote Controls (HEMSZigbee) [16]

The system that is proposed by Han et al. includes Smart power outlets that are connected via ZigBee [17] to a central hub, which can be controlled via an Infrared remote control. The system includes a stand-by power cut-off mechanism that ensures that the power outlet is turned off at the same time as the device connected to it. The system also includes the possibility to detect which device is plugged into which outlet through their unique power usage characteristics. The Technology Readiness Level of the System is 5, and its LOI is 1. To reduce the consumption of electricity within the household can be defined as its main goal.

Neural Networks Based HEMS in Residential PV Scenario (NeuralNetHEMS) [26]

In this paper Ciabattoni et al. propose a HEMS that is based on a self learning neural network prediction algorithm. The prediction algorithm forecasts how much power will be produced by the PV module that is included in the system and how much power will be consumed by the household. To classify the loads they are put into different categories, which are continuous use appliances, periodic use appliances without human interaction, periodic use appliances with human interaction, multimedia appliances and light. Another way the appliances have been categorised in this paper is smart appliances, controllable loads, monitorable loads and detectable loads. These two classifications offer a good picture of what a HEMS that specialises in minimising the energy usage on the appliance side can actually influence without reducing the QoE for the end user. It was found that this system could increase PV energy self consumption by up to 8%. The proposed combination of prediction algorithm, load manager and PV module was prototypically tested in 3 different houses, therefore this system qualifies for the

Technology Readiness Level 7. The Intelligence Level of the System is 5, as it tries to predict future events and schedules loads ahead of time. The main objective of this system was to maximise usage of power from the PV module, and therefore reduce the total electrical energy consumption from the grid.

New approach to energy management system for home based on open source software and hardware (OpenSourceHEMS) [27]

Álvarez-López proposes a system architecture for HEMS in this paper that is purely based on open source software and hardware. The proposed system consists of a PV module, several intelligent relays that are able to control power sockets and a Raspberry Pi based control unit that receives information about their state from the relays and controls them. The control system is based on Linux, an open source operating system. The proposed system qualifies for Technology Readiness Level 2, and Intelligence Level 2. There was no distinct aim of the HEMS defined in the paper, only an architecture proposed.

Optimal Home Energy Management for Mixed Types of Loads (MixedLoadHEMS) [28]

In this paper Zhao et al. propose a HEMS that includes a household, a battery storage and the need for DC power as well as AC power. The benefit of seperating AC loads from DC loads is that during conversion from the DC power produced by the PV module, some of the power is lost. Therefore if DC loads are present, these conversion losses can be omitted for some part of the system. The PV module, the battery storage system and the DC loads are all connected via a DC power cable, and this subsystem is in turn connected to the main AC house grid via an inverter which is then connected to the main power grid. The system was tested in houses with DC loads and in houses without DC loads. It was found that additionally to the presence of DC loads, the system's performance greatly depends on the dimensioning of the battery storage system and the PV module. As this system has been tested in a relevant environment it qualifies for Technology Readiness Level 6, and as it optimizes itself it classifies as Intelligence Level 3. The main purpose of this system is to reduce the electricity bill for end users.

Smart Home Energy Management Including Renewable Energy Sources: A QoE-driven Approach (QoEHEMS) [29]

Pilloni et al. propose a HEMS that focuses, along with trying to minimise the energy usage, on the QoE of the user. The system utilises an algorithm that was calibrated for the users preferences at first to make use of Time of Usage pricing mechanisms to schedule appliances when a lot of renewable energy production is present or the current electricity price is low. The results of the conducted experiments show that the Quality of Experience for the user rises significantly when this proposed algorithm is used in comparison with algorithms that don't take the users experience into account. However, at the same time the energy cost savings achieved are a little lower. The proposed system can be classified as Technology Readiness Level 7 and Intelligence Level 3. The systems objective could be determined to be the electricity cost reduction for the consumer.

Strategical Studies on Smart Home using LabVolt System (SmartHomeStudy) [30]

The project conducted by Tan et al. conducts several simulations using the LabVolt software. Several different simulation results are presented for different configurations. The configurations include a single phase grid that is tied with an inverter, a single phase stand alone with an inverter and a DC sub grid. The Technology Readiness Level for the system is 2 and the Intelligence Level cannot be specified as no true system architecture for a HEMS was proposed. The aim of the study was to provide a way of managing energy locally in a way that the grid stability is increased.

Towards and Intelligent HEMS for Smart MicroGrid Applications (HEMSForMicrogrid) [31]

In this paper by Essayeh et al. an Energy Management system is proposed that is based on Markov Decision Process algrorithm to minimise electricity cost and maximise the self produced electrical energy that is used within the Microgrid. The proposed system is then verified through a simulation run with statistical data from renewable energy generation. The Technology Readiness Level is 2, as the system was only simulated and its LOI is 3. The system takes into account the reduction of energy bills as well as the increase of distributed renewable energy consumption.

Internet of Things Based Energy Aware Smart Home Control System (IoTHomeControl) [32]

Khan et al. propose a system that is sensitive to several wireless communication networks being present in the household, for instance a WiFi network and a WSN (Wireless Sensor Network) for communication with appliances. The system tries to minimise the interference between different networks and ultimately makes them more efficient through interference reduction. A CoZNET mechanism is employed to achieve this. The Technology Readiness Level is 3, and the LOI is 1.

Point-n-Press: An Intelligent Universal Remote System for Home Appliances (PointNPress) [33]

The system proposed by Lee et al. consists of an infrared remote and infrared receivers for all home appliances. This results in an intuitive system where you can point to the device you want to control and simply press the buttons on the remote to control it. The system has been built as a prototype, therefore the system qualifies for the Technology Readiness Level 6. Its LOI is 1.

2.3.2. Proprietary Home Energy Management Systems

This section includes several systems that have been created for commercial distribution. These systems offer a finished system that is ready to be used in a home rather than an open architecture. However, due to the lack of possibilities for free alteration of the hard- and software used, they are unusable for the HEMS that is to be proposed here. These systems are simply presented as part of the analysis of the current state of the art.

LOXONE Smart Home®

The LOXONE Smart Home®is a system developed in Austria by Loxone Electronics GmbH. While it is euiped with some capabilities to add additional connections oneself, one receives access only to the top connection layer, not the operating system itself. The system is built around a Miniserver that manages the whole Smart Home and operates on Loxone OS, its own proprietary operating system. Many Smart Home appliances are supported by the Loxone Smart Home system from the start, but the company Loxone also provides support for implementing additional devices. In terms of energy management, the system offers full support for PV Systems, EV, Demand Response mechanisms as well as full appliance control in the household. In the classification proposed in section 2.2, it would provide support for every category. However, the system is not open source, and the code cannot be altered freely. An extensive documentation of this system can be found in [89].

SMA Sunny Home Manager®

The Germany based Photovoltaic System technology company SMA developed the Sunny Home Manager®to control all energy flow within a houshold in an optimal way. The system is meant to be coupled with a Smart Meter to be aware of all energy flows within the household. It offers intelligent management of energy intensive devices like battery energy storage system or a heat pump, to optimise the self-use of Photovoltaic energy. Alongside with the energy intensive appliance the system proposes the use of WiFi smart plugs or open connection protocol for smart devices EEBus [90], over which the operation household appliances can be controlled and scheduled at will of the consumer. The system also facilitates the integration of varying electricity tariffs, and the use of a BESS to minimise the price of electricity for the consumer. A Planning guideline for the smart home including the Sunny Home Manager®as intended by SMA can be found in [91]

Smart Home Appliance Management Systems

There are several Smart Home Control Systems currently on the market. Although they are not created with energy management as the primary target, they provide good support for appliance management. Google Home® [92] and Amazon Echo® [93] are two devices that offer voice control of internal functions and management of supported appliances via an API. The code of Google Home even is open source and can be looked into. Nevertheless, these systems provide a lot of proprietary solutions, and a device that is not already supported by the system cannot be integrated easily. Smart appliance control usually happens via the combination of such a system with a proprietary solution from a big corporation, for instance the Samsung SmartThings® [94], which offers connectability to every Samsung smart device. These systems might work well for managing appliances; however, for energy management of a smart home they are mostly unsuitable.

2.3.3. Open Source Software Projects

This section will introduce several exemplary open source software projects for realising home automation projects. All are open source and some have big communities that maintain the existing code and add new functionalities to the core software. As home automation has become more accessible and popular in the last few years, many examples of what can be implemented with these systems can be found online.

Home Assistant

Home Assistant is an open source home automation software project that is written in Python. [95] Python is a very flexible scripting language that offers large libraries that can be used for many specialised tasks like optimisation or data processing. This flexibility and amount of ready to use libraries makes it a viable candidate for many projects. Home Assistant offers support for many different APIs and connection protocols out of the box. The code is released under the Apache 2.0 license [96] that allows for the free sharing and adaptation of the software. An extensive documentation of the code and several example projects can be found in Home Assistants online documentation [97].

OpenHAB

The second platform is openHAB. Its software is built on the Eclipse SmartHome framework [98] which is written in Java. [99] The Eclipse Smart Home framework and openHAB are both released unter the Eclipse Public License [100], which is an open source license that allows for parts to be reused for commercial purposes. An extensive documentation on the openHAB framework and its features can be found in its online documentation. [101]

OGEMA

Another energy management platform is OGEMA (Open Gateway Energy MAnagement), which was created by several institutions of the Frauenhofer Gesellschaft in Germany. The source code for the framework is released under the GNU General Public License [102], and is therefore also reusable for non-commercial purposes. The OGEMA framework was created to introduce a standardized software platform for energy management applications. Many drivers for different connection protocols are implemented and freely usable. An overview of the specifications of the framework can be found in [103].

IoTSyS

IoTSyS is another software project that aims at home automation and the management of smart things. It was developed by the Automation Systems Group at the Vienna Universtity of Technology, and is still partly maintained by members of that group. The system is based on the IPv6 protocol [104], web services and OBIX [105] (an open source project that aims at enabling control systems to communicate with enterprise applications). It is licensed under the New BSD License [106]. The source code and the dodumentation of the project can be found on its GitHub page. [107]

Table 2.1.: Reviewed systems with features as part of the State-of-the-Art Research

Management System	**EMS**	**DRS**	**HACS**	**TRL**	**LOI**	**OBJ**
RealisticHEMS [20]	no	yes	yes	2	5	[CR,EDR,GS]
IntelligentHEMS [21]	no	yes	no	3	3	[CR]
HEMToolkit [22]	no	no	yes	6	2	[EDR]
PVbasedHEMS [23]	yes	yes	no	6	3	[CR]
MultiAgentHEMS [24]	yes	yes	yes	3	4	[CR,EDR,GS]
LabHEMS [25]	no	yes	yes	4	3	[CR]
HEMSZigbee [16]	no	no	yes	5	1	[EDR]
NeuralNetHEMS [26]	yes	no	yes	7	5	[EDR]
MixedLoadHEMS [28]	yes	no	yes	6	3	[CR]
OpenSourceHEMS [27]	yes	no	yes	2	2	-
QoEHEMS [29]	yes	yes	yes	7	3	[CR]
SmartHomeStudy [30]	yes	yes	yes	2	-	[GS]
HEMSForMicrogrid [31]	yes	no	yes	2	3	[CR,EDR]
IoTHomeControl [32]	no	no	yes	3	1	-
PointNPress [33]	no	no	yes	6	1	-
LOXONE [89]	yes	yes	yes	9	3	[CR,EDR]
SMA Sunny Home [91]	yes	yes	yes	9	5	[CR,EDR]
Google Home [92]	no	no	yes	9	2	-
Amazon Echo [93]	no	no	yes	9	2	-
Smart Things [94]	no	no	yes	9	2	-
Home Assistant [97]	yes	yes	yes	9	1	-
openHAB [101]	yes	yes	yes	9	1	-
OGEMA [103]	yes	yes	yes	9	3	-
IoTSyS [107]	yes	yes	yes	7	1	-

2.4. Optimisation Approaches

For a HEMS to ultimately make a difference, the system not only has to be controllable to an extent where a certain amount of flexibility is available, but it also has to be able to optimise the operation of the system for the achievement of a certain goal. Especially when the operation of some components needs to be scheduled at some point, complex optimisation is necessary to determine a worthwile schedule of all components. An overview of optimisation techniques used to determine the optimal operation time of components within a HEMS can be found in [13]. Two very different approaches found the literature optimisation will be introduced in the following section.

2.4.1. Scheduling algorithms optimizing operation over time periods

One common approach is to find the optimal schedule for the appliances to operate in through mathematical models of all of the components. Each appliance is defined using the duration of operation, the power it takes to operate it and whether it is interruptable or non-interruptable. These devices can then be scheduled in a way that the total electricity usage or cost is minimised. Every component in the household requires a mathematical representation of its characteristics in a formula that signifies the electricity usage or the electricity cost. The way of reaching the minimum for the desired result can differ from one algorithm to another. [13] In [34] the different kinds of loads and flexibilities in the household are first defined in form of mathematical constraints and models. These mathematical expressions are then used to set a schedule for the desired time period using an algorithm based on an artificial bee colony to determine the best solution. The work by H. Li et al. in [35] proposes an algrorithm that formulates the optimal scheduling of appliances into a stochastic programming model that takes variations in PV production and important loads into consideration. The solution of the given problem gives the optimal schedule, considering electricity prices. G. Huang et al. proposed a scheduling algorithm for operation of electrical devices in smart homes that is comfort-aware as well as cost-effective in [36]. In this work, as well as a mathematical formulation of the electrical properties of appliances included in the proposed HEMS, each device is assigned a mathematical expression for the cost for its delayed operation. With this expression the schedule that minimizes the cost function for electricity price and the comfort level is determined. All three described papers suggest a schedule for the operating time of the components. Even though all of the systems were able to lower electricity price for the examined time period, implications on the comfort of the user of the HEMS have been found to occur in [36].

2.4.2. Appliance actuation based on System State

This approach tries to define actions for each possible system conditions. The optimisation is done at runtime, where at first the state of the system is considered, and then an action is defined. The components and their actuation are part of a decision process where each decision is being taken because of system conditions. This form of algorithmic optimisation only has to know what the current state of the system is to decide how to actuate each component one after the other. In [37] J. Dong et al. present a solution to the optimal stochastic control problem for HEMS, employing a continuous-time Markov decision process that is controlled by a varying electricity price. This differs from another approach employing a Markov decision process that is taken by Hansen et al. in [38]. They developed an algorithm based on a partially observable Markov decision process to determine the series of optimal actions of the HEMS for each state of the system. This approach includes forecasting of the pricing scheme. As they have shown this can improve the optimisation capabilities.

2.5. Physical Analysis of Important Components

To be able to optimise a system it is beneficial to thoroughly understand its components and what their specific limitations in operation are. In the following two sections a small analysis of function and problems that arise with two of the most important components in a HEMS, Photovoltaic Cells and Electrochemical Battery Cells will be attempted.

2.5.1. Photovoltaic Cells for Electrical Energy Production

Due to a strong political agreement on moving to a cleaner means of securing its energy production, Photovoltaic Cells could be an important technology to help realise a fossil fuel free future. [39] Although photovoltaic cells cannot fully replace conventional power systems, mostly because of the high cost to accommodate its limited energy supply times, current developments show progress in many critical areas that could make it even more viable in the future. [40]

A brief description of the underlying principle on which photovoltaic electricity generation builds is attempted in the next section. If not explicitely stated otherwise, the knowledge has been taken from textbooks such as [41] and [42].

Role of Semiconductors in Photovoltaic Cells

To understand the underlying principle on which Photovoltaic Cells are based, some basic knowledge of semiconductors is needed.

Any solid material is made up of molecules, which are made up of atoms of possibly different kinds, which are made up of electrons and atomic nuclei. Within the material the electrons can be thought of as occurring in two different states. They can either be tightly connected to their atomic nuclei, or loosely connected to the bulk of nuclei but able to travel along through the material from one atom to the next. These states correspond to the electron being in the valence band or conduction band of the material. How these bands are arranged in a material defines its electrical properties. Generally materials can be put into three distinct categories according to their conductivity: conductors, semiconductors and insulators. Conductors are materials such as metal, where very little to no energy is needed to lift an electron from the valence to the conduction band. In semiconductors there is a gap between the valence band and the conduction band but the energy that is needed to surpass this gap is so small that for instance there is a noticeable difference between the conductivities of a semiconductor at two different temperatures. Whereas an Insulator is a material where there is a very large energy gap between the two states, where a move between the two states cannot occur.

In semiconductors, an electron can move from the valence band to the conduction band by the absorption of a photon with an energy larger than the gap width, making the electron and the hole mobile within the material. The electron holds a negative charge, and the hole can be thought of holding a pseudo positive charge. Both the hole and the electron will move randomly through the material after being formed that way. However, if a hole and an electron happen to move to the same atom in the material the electron will fall back to the valence band, and release a photon with kinetic energy equal to the energy gap size. This is called recombination of the hole and the electron.

Semiconductors can be doped, either with materials that have more or fewer electrons in the outermost atomic shells than the bulk of the rest of the material. This doping of the semiconducting material results in the material having more mobile electrons in the conduction band. If the atoms used to dope the material have more electrons in the outermost atomic shell, more electrons will be present in the conduction band of the semiconducting material. This kind of doped semiconductor is called an n-doped semiconductor. However if the atoms that are used to dope your initial material have fewer electrons in the outermost shell, they offer a hole for electrons in the conduction band to attach to and fall back into the valence band. These types of doped semiconductors are then called p-doped semiconductors. The distance between the valence band and the conduction band in the material is not affected very much by the process of doping the material, but the valence band and conduction band shift in their energy level. In semiconductors that are n-doped the energy levels sink for both bands, and for p-doped semiconductors they rise.

Photodiodes

When an n-doped and a p-doped semiconductor are combined to form a p/n junction, each side itself is electrically neutral, and the mobile charges are being compensated by fixed charge of the doping atom of the opposite charge. However the mobile charges will move towards each other and recombine. Once an equilibrium is reached, in the region around where the two sides touch, charges will have built up on each side. This is the so called space charge region, where only the doping atoms remain.

In this region an electric field will build up, that will cause holes throughout the material to move to the p-doped side, and electrons to move to the n-doped side. When the resulting photodiode, consisting of p-doped and n-doped semiconductor, is illuminated by photons with enough energy to cause a electron hole pair to form, charges on each side will start to build up. Therefore the holes will become the majority mobile charge carrier in the p-doped side and electrons the majority mobile charge carrier in the n-doped side.

To make use of this buildup of charges, the ends of the n-doped and p-doped

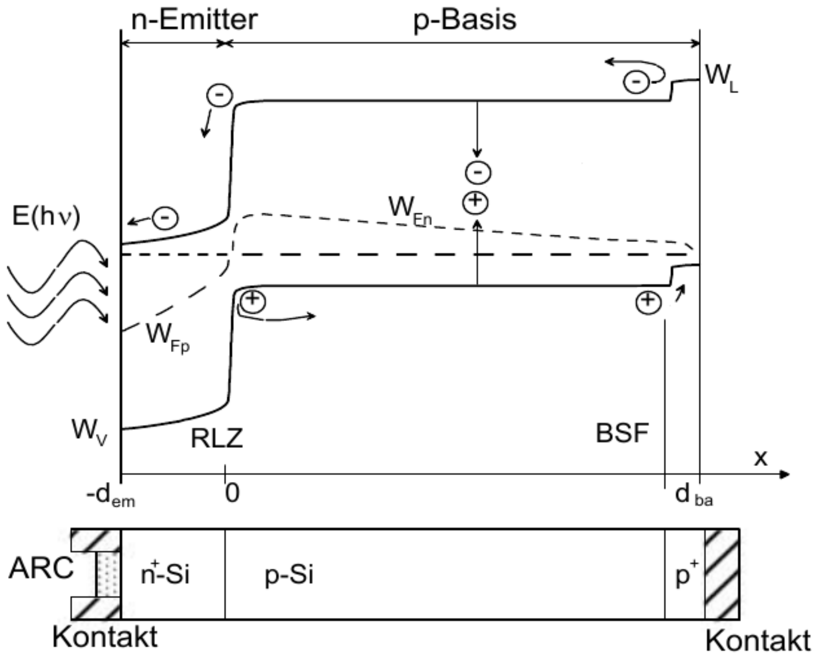


Figure 2.4.: Band structure of a crystalline silicone Photovoltaic cell [1]

semiconductor can be connected via a circuit. Over this connection a so called photocurrent will flow, as long as photons keep producing electron hole pairs in the photodiode. This is the effect that makes it possible for a Photovoltaic cell to convert the energy of photons to electrical energy.

In figure 2.4 an exemplary picture of the band structure of a crystalline Si solar cell is shown. It can be made out that the creation of space charge regions within the composite photo diode creates an energy structure where it is favorable for electrons to move to the negative contact and holes to move to the positive contact.

Limiting factors for Photovoltaic Energy

The limitations to photovoltaic systems as means of providing electrical power cannot be fully discussed in this thesis as this would surpass the scope of this work. However, a small overview of the most important limitations with respect to energy management systems will be attempted in the following.

The first and foremost limitation for photovoltaic systems to be integrated into

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[1] Reprinted from Photovoltaik - Solarstrahlung und Halbleitereigenschaften, Solarzellenkonzepte und Aufgaben, Hans-Günther Wagemann, Heinz Eschrich, Monokristalline Silizium-Solarzellen, page 80, Jan 1, 2010 with permission from Springer.

today's power grids is that the grids were constructed for the use of power sources that rely on fuel, which can be supplied whenever power is needed in the grid. [43]

Photovoltaic energy is different, as it does not require a fuel in the conventional sense, but rather that it requires the sun to shine. As this is a cyclical event which cannot be influenced directly, this is a limitation that cannot be surpassed through technological means. Even though the European Union is not located close to the equator where solar radiation is maximal, there are large potentials that vary due to geographical reasons on the European continent. [44]

Another problem with photovoltaic energy cells is that they have to be placed outside and have to withstand the sometimes harsh conditions year round. Studies have shown that naturally the photovoltaic system offers a reduced conversion efficiency due to material degradation, interconnect degradation and other aging effects. [45]

However, there are several measures available to improve efficiency of photovoltaic cells like the inclusion of a 1- or 2-axis sun tracking system to optimise the amount of solar radiation that hits the solar panel or improvements on the maximum power point tracking of the photovoltaic system. [46]

Solar Radiation

Having explored the underlying principle on which Photovoltaic cells are built, their biggest limitation doesn't arise from the way they work, but rather where the energy they convert comes from. The sun is responsible for all the photons reaching earth that can be used for the conversion to electrical energy in photo diodes. The characteristic spectrum of the light released by the sun is responsible for some semiconductors being better applicable than others for Photovoltaic Cells. This is a technical issue, which will not be further discussed here. The limitation that is most important for the application of a Home Energy Management System, is that that the sun rises in the morning and sets in the evening. The photons that are needed to produce electrical energy are not readily available whenever they might be needed.

In figure 2.5 the radiation power density of global solar irradiation for 1.5 AM (Air Mass) is compared with the radiation power density for the total irradiation outside of the earths atmosphere and the blackbody radiation spectrum at T=5800 K. The AM scale signifies how much of the atmosphere had to be passed by the radiation, until reaching the surface. AM 1 is the shortest possible distance for light having to pass through the earths atmosphere, as it is the air mass perpendicular to the

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[2] Reprinted from Photovoltaik - Solarstrahlung und Halbleitereigenschaften, Solarzellenkonzepte und Aufgaben, Hans-Günther Wagemann, Heinz Eschrich, Die Solarstrahlung als Energiequelle der Photovoltaik, page 12, Jan 1, 2010 with permission from Springer.

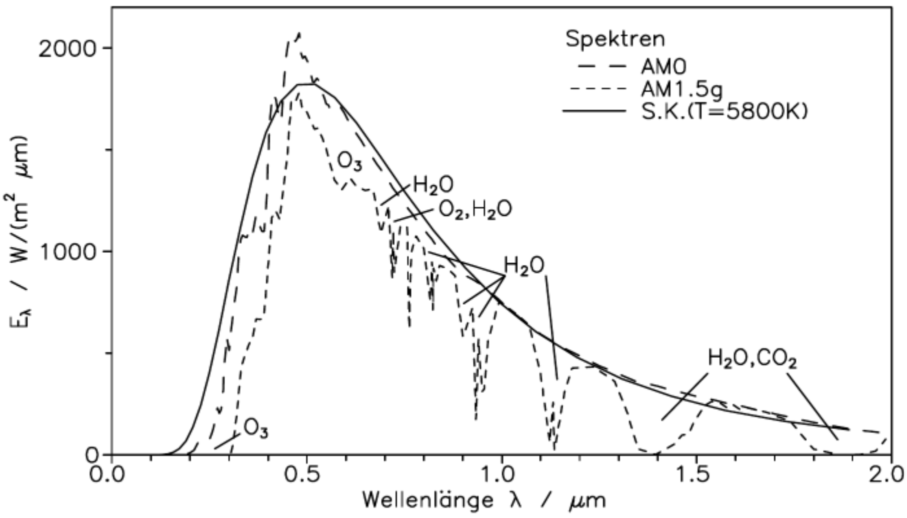

Figure 2.5.: Spectral radiation power density for blackbody radiation at T=5800 K compared with measurements of solar radiation at AM 0 and AM 1.5 [2]

earths surface. Whenever the sun is at an angle to the earths surface, the air mass that the radiation has to pass through rises. [41]

The system of earth and its movement around the sun, and the rotation about an axis is immensely complex, and is responsible for the fluctuation of available solar radiation throughout the year and throughout the day. As well as that, the radiation that is available for conversion is also largely dependent on the weather, which is far more difficult to predict than the geometrical movement of the earth, and absorption effects in the atmosphere. With all these aspects in mind, the right evaluation has to be made for the location, sizing and positioning of the PV module. [47]

As the energy resource of solar radiation is fluctuating heavily on any fixed point on the earth's surface, means to control and store electrical energy are important in combination with PV. This problem is intensified by the fact that the time where most of the electrical energy is used in the household does not necessarily coincide with the time when a lot of solar radiation is present. For that reason it makes sense to store some of the electrical energy produced with a PV module for later use.

2.5.2. Electrochemical Battery Cells for Electrical Energy Storage

The most common means of storing electrical energy in a household is with a battery. In the following, the principle on which batteries are based to identify potential limitations they bring along with them will quickly be outlined.

Batteries are galvanic cells that can convert chemical energy to electrical energy and electrical energy to chemical energy. They are the most common means of storing electrical energy over time periods from days up to months. The time a battery can keep its charge is largely dependent on the specific composition of the battery.

Galvanic Cell

The Galvanic cell is an electrochemical cell consisting of an anode (negative electrode), a cathode (positive electrode), an ion conducting electrolyte and an electron current carrying connection between anode and cathode. This type of cell is the basis for all fuel cells and batteries. When no fuel is added to the cell from external sources during the operation of the galvanic cell, we speak of a battery. And when the process that occurs during the discharging of the battery can be reversed so a state with the same chemical composition and structure as before the discharging process is reached, the galvanic cell can be classified as a rechargeable battery or an accumulator. The next section will focus on The lithium ion rechargeable battery as this is the most common battery used in BESS and EV batteries today.

Rechargeable Lithium Ion Batteries

Each different type of galvanic cell involves different materials involved in oxidation, reduction and conduction processes. Therefore each anode and cathode material comes with its own challenges to overcome. Lithium ion batteries are very popular because they offer a large specific capacity relative to other batteries, while offering good structural stability over many charging/discharging cycles. The prizes of these types of Li ion batteries are expected to drop as spending is increased to Research and Development in these areas. [48] By 2020 the market share of Li ion batteries to be used in EV and stationary energy storage is expected to reach up to 80% [49], making it one of the most promising technologies in these sectors. One common composition of a lithium ion cell chemistry can be seen in figure 2.6 and will be further investigated to determine possible limitations of this means of energy storage.

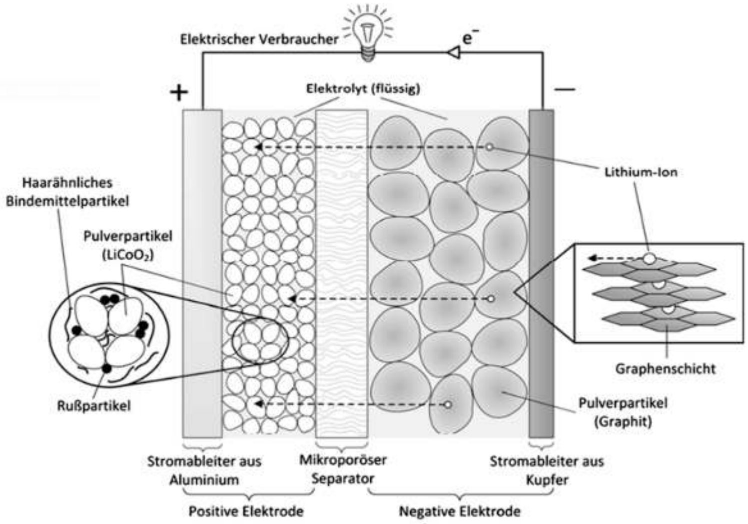

Figure 2.6.: Common configuration of a Li ion battery cell [3]

The most common anode consists of graphite layers between which Li ions can be intercalated during the discharging process of the battery. A common cathode consists of $LiCoO_2$ which can become $Li0.5CoO_2$ during the charging process. If the battery is overcharged past this structural point or insufficiently thermally regulated, the structure becomes unstable and this leads to oxidation of the electrolyte, which can lead to thermal runaway effect that can potentially be very dangerous. [50], [51] All cases that can lead to a damaging of a battery through the way it is employed are to be prevented by a battery management system. This system is responsible for a battery pack to never reach a state where it becomes hazardous to the consumer. [52] Both electrodes are in the form of powder in their natural state and are connected with a current conductor to form a composite electrode. The cathode material is connected with an aluminium foil that conducts electrons well, and is stable at the relatively high potential of the anode. The anode uses a copper foil as a current conductor, as aluminium tends to form compounds with lithium at the low potential of the anode. Usually the electrolyte in lithium ion batteries is a mixture of lithium salt and organic solvent. A popular lithium salt for battery applications is $LiPF_6$ (Lithium hexafluorophosphate), and one of the most common solvents is $C_3H_4O_3$ (Ethylene carbonate). A lithium ion battery comprised of the materials described above would offer a specific capacity of 160 Ah/kg, a closed circuit voltage of 3.9 V and an energy density of 624 Wh/kg. Other Li ion cell chemistries can offer different cell characteristics such as thermal stability, cycle life,

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[3] Reprinted from Handbuch Lithium-Ionen-Batterien, Materialien und Funktion, Kai Vuorilehto, page 22, Jan 1, 2010 with permission from Springer.

power density or energy density. [53] Therefore, each application requires different cell chemistries.

Battery behaviour during operation

The batteries operational properties vary with several parameters such as temperature and the state of charge of the battery. This has an effect on the battery cycle-life as well as the charging process of the battery. The battery that shall act as an example here is a battery of the cell chemistry described in section 2.5.2 and of the format 18650. The form factor 18650 refers to a cylindrical cell that has a diameter of 18 mm and a length of 65 mm. [54], [55] This type of rechargeable battery is widely used in power electronics and also in Tesla™ EV batteries. [108]

Due to internal changes in battery chemistry, the cell voltage and current change during the charge and discharge processes. [54]

Li ion batteries are very sensitive to temperature, which is why they need the battery management system to take care of temperature management as well. The effect of different temperature levels on the discharging of a 18650 $LiCoO_2$ cell were explored by Zhang et al. [54] The cells were found to be able to provide less energy during the discharging process in colder temperatures. This can be seen in figure 2.7

While the conditions during operation of the battery can have implications on the current performance of the battery cell, Choi et al. have found that the conditions during which the $LiCoO_2$ battery cell is charged have a far greater effect on its cycle-life. [56] A high charge rate, high charge cutoff voltages and a long period of charging at high voltages have been found to be the most damaging to such a battery cells cycle life. [56]

To ensure safe operation as explained in section 2.5.2, the battery must never surpass a certain voltage level during operation. Therefore Li ion batteries are best charged using a Constant Current (CC)/Constant Voltage (CV) charging algorithm. [57] With this type of charging algorithm the charging process is split up into two regimes. The CC regime, during which the charging occurs with constant voltage at about 0.5C, and the CV regime where the battery is charged with constant voltage. The CV charging occurs when the battery is already partially charged and the maximum operational cell voltage of the battery has been reached. In figure 2.8 three different charging paradigms for Li ion batteries can be seen. For safety reasons they all use CV charging when the internal cell voltage has almost reached the maximum safe voltage. The first charging protocol used CC charging at first, the second protocol used Constant Power (CP) charging at the beginning

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[4] Reprinted from Journal of Power Sources, Volume 160, S.S. Zhang, K. Xu, T.R. Jow, Charge and discharge characteristics of a commercial LiCoO2-based 18650 Li-ion battery, 7 pages, Oct 6, 2006 with permission from Elsevier

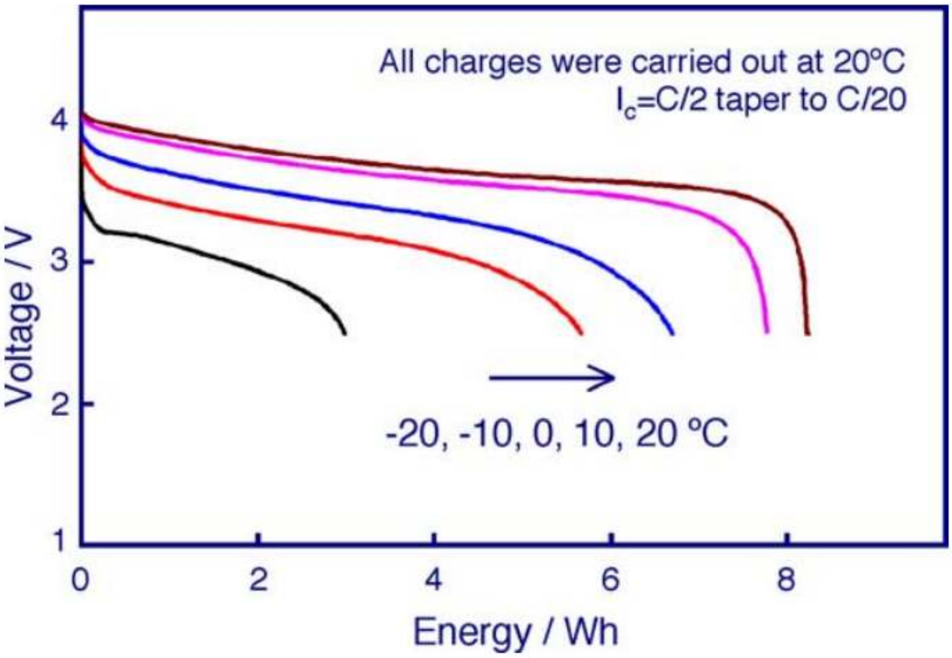

Figure 2.7.: A 18650 $LiCoO_2$ cell voltage plotted over the total energy supplied during a discharging process for different temperature levels [4]

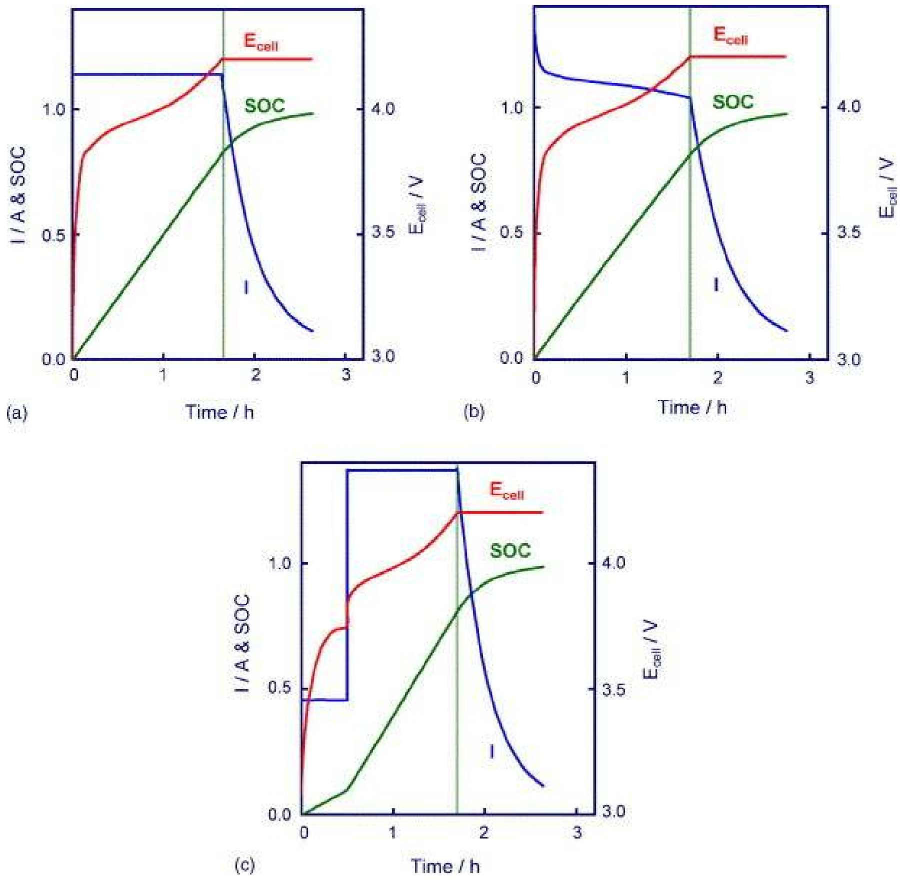

Figure 2.8.: Three different charging paradigms for Li ion batteries. a) CC/CV charging b) CP/CV charging and c) MCC/CV charging [5]

and the last charging protocol used Multistage Constant Current (MCC) charging before the CV part of the charging process. It was found by Zhang that the type of charging protocol that was used has an effect on the cycle life of the batteries used. [58]

Requirements for Lithium Ion Batteries as Stationary Energy Storage

For the application of stationary Battery Energy Storage Systems, Li ion batteries offer several good qualities such as good storage efficiency, i.e. being able to get almost all of the energy that was put into the battery during the charging process back out during the discharging of the battery. As well as that, most Li ion battery cell chemistries offer slow self-discharge and high power density. [59]

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[5] Reprinted from Journal of Power Sources, Volume 161, S.S. Zhang, The effect of the charging protocol on the cycle life of a Li-ion battery, 7 pages, Oct 27, 2006 with permission from Elsevier

Of course in the domestic sector security is always an issue if the battery is to be placed in the house. For lithium ion batteries, the largest security issue that arises is overcharging the battery to a point where thermal runaway is reached. This has to be prevented by the battery system itself through an internal battery management system, preventing the end-user from being harmed, or the battery being damaged through faults in the operation. [60]

Requirements for Lithium Ion Batteries in Electric Vehicles

A high energy density is one of the biggest concerns for batteries that are used in EV, as weight and size of the battery is crucial to be kept low while offering the largest amount of energy transported and best power transmission for acceleration possible. [53]

Also battery safety is a very important issue when it comes to EV batteries.The same measures as to battery management are taken as with batteries for stationary energy storage in the residential sector, but also other cell chemistries such as the employing of Li-metal compounds as cathode material. One compound that could offer high safety while still offering good power and energy density is $LiFePO_4$. [61]

The integration of battery cells into the car can lead to difficulties in terms of management and safety. Modern cell chemistries and advanced packaging, management and connection technologies help handle these problems. [62]

3. Home Energy Management Validation Framework

This chapter will elaborate how an agent based home energy management architecture can be utilised for the validation of HEMS approaches in simulations as well as in Hardware in the Loop (HIL) laboratory experiments.

3.1. Conclusion from the State-of-the-Art Analysis

While the reviewed systems were very different, they all had key similarities that were thought to be of importance to the implementation of a system that should be able to represent a HEMS in simulations and experiments, which will be discussed briefly.

System Components

Each reviewed system had some sort of central control unit, that was responsible for managing the operation of the system components. As well as that the systems all included some form of manageable loads as components. While some included standard household appliances others included a BESS for energy storage or an EVSE. Many of the systems included local electrical energy production, such as a PV module. Some of the reviewed systems merely proposed an architecture outline, or guidelines for optimisation in a HEMS.

Objectives

The goals of the systems found in the literature were quite different, but three main objectives were determined; the reduction of electricity costs for the end user for instance through demand response mechanisms, the increase of self use of photovoltaic energy produced locally and the reduction of peak loads to operate the system in a way that is beneficial to grid stability.

Type of Home Automation System

Most reviewed systems included appliance control in some way, some included Energy Management techniques as a focus, many also included Demand Response mechanisms. To be able to ultimately reproduce all approaches an agent based architecture is proposed. An agent based architecture allows for the addition of parts and support for certain devices throughout its life-cycle. As a first stage, the system should be able to interact with local energy production and energy storage applications as flexible loads that can be controlled without loss of QoE for the end-user. However, if required the system should be able to offer control of any appliance within the household.

Important Physical Properties of Key Components

When including PV as a means of DRE generation, the periodicity and volatility of its primary resource, solar radiation, has to be kept in mind. This limits the flexibility of PV power production as a means of providing electrical power to a household.

While this can be compensated using a BESS to increase the self consumption of self produced PV electrical power, the BESS must be properly managed to ensure safe operation and provide a long cycle life of the battery. This is mostly taken care of by the BESS itself.

3.2. Agent based architecture for Home Energy Management Validation

To be able to add as many components as desired to be managed by the HEMS the agent based architecture is ideal. A system is proposed that features a managing agent that gathers data in a fixed interval, and controls all the other agents according to the current state of the whole system. This will facilitate a simple means of optimising the system state towards desired goals.

3.2.1. Open Source Software project as the Core of the System

To support the inclusion of many different components, and offer support for many different means of connecting with devices, an open source project was chosen as backbone of the proposed HEMS testing framework. HomeAssistant [97] was chosen as the ideal candidate as it offers many already finished so called "components" that offer support for appliance platforms and communication protocols. As well as that components can be implemented for most appliances and any means of local communication the host system supports. HomeAssistant is based on the programming language Python [95], a high-level interpreted programming language, that is able to run on many different platforms. Python offers a large library of modules that are readily available for scientific computing tasks like data processing and evaluation. As well as that, there are several bindings available to interact from Python with other software. These features amongst others make it an ideal candidate for scientific computation applications. [63], [64]

AppDaemon - Python Apps for HomeAssistant

At the time of development HomeAssistant only natively supported automation through their native configuration files that are written in YAML [109], a human readable language for data serialization. For this application this form of creating automation procedures doesn't offer enough flexibility. An alternative for automations that has been created by a HomeAssistant community member is AppDaemon. [110] AppDaemon is a flexible, multithreaded Python execution environment, that is loosely coupled to the HomeAssistant core. It interacts only with the Web Application Programming Interface (API) that is provided by the HomeAssistant core system. [110] This offers the possibility to control any components that are configured with the HomeAssistant instance through Python scripts. This form of automation allows for the use of Python's powerful and versatile library of modules, and is therefore preferred over the native automations. All automation scripts that are included in this work, run within an AppDaemon instance.

As different components in the future prosumer household, don't offer a single standardized means of communication, as was explored in section 2.1, a middleware is used for relaying messages between the different components to be able to offer a standardised means of communication for all of the partaking agents.

3.2.2. Middleware to pass Information over TCP/IP Connection

In this work, all the relevant components in the Smart Home are treated as having a means of communication via the TCP/IP protocol suite. One of the most promising communication protocols for Internet of Things (IoT) or device control application that builds on top of the TCP/IP protocols, is Message Queue Telemetry Transport (MQTT). [111], [65] It is used as a communication protocol in many publications in the field of home automation and IoT. [66]–[68] MQTT's architecture is built on a topic based relaying of messages. Agents within the MQTT network can publish messages and subscribe to topics. Messages are passed along by the broker to the agents that have subscribed to the topic the messages have been published to. This concept is depicted in figure 3.1.

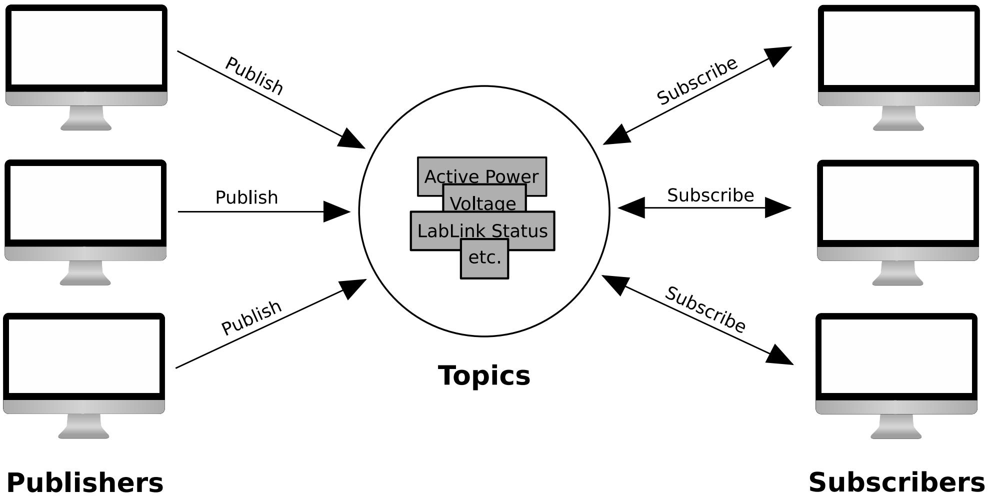

Figure 3.1.: Visualisation of the publish/subscribe mechanism used in the MQTT protocol [65]

3.2.3. LabLink - MQTT based communication library

LabLink [112], [113] is a communication library that is written in Java [99]. It is based on the MQTT protocol, and was developed to simplify the communication between laboratories and offices within the Austrian Institute of Technology (AIT) Local Area Network.

RPC and Data Points

As well as the standard messaging based on the MQTT messaging protocol, LabLink offers transmission of messages via Remote Procedure Call (RPC) [69] that are based on standard MQTT publish and subscribe paradigms. Based on this RPC communication and MQTT messages, LabLink offers the implementation of a so-called Data Point (DP), this is a way of storing data of a distinct type locally while making the data available to everyone that is registered to the same network. Whenever the value of a DP changes an update message is sent out to each Data Point Consumer (DPC) that is registered to the DP's value. Each DP can have several DPC registered to its value. The DPC can be enabled to be have the option to set the value of a DP that it is registered to remotely as well. These DP are available for four distinct data types, that can represent all relevant data that is passed within a HEMS local network. The data types are integers, floating-point numbers, boolean values and strings. In table 3.1 an overview of the used HomeAssistant components is and the corresponding datatypes is given. With the help of these components, DPC for all different types of data required can be integrated into the HomeAssistant core system. Almost all components were already present as a platform in the core HomeAssistant component library, only the **input_field_set** was entirely implemented as a backend component platform and as a frontend component. For all of the components a LabLink implementation was created to be able to make full use of the LabLink library. When a system component is implemented for the use of the system, each value that is relevant to the HEMS is implemented as a distinct DP and are later grouped up as belonging to the same device in the HomeAssistant configuration.

Table 3.1.: HomeAssistant components employed to achieve control of all necessary data types

Component	Data Type	Remote Actuation
binary_sensor	boolean	No
sensor	integer, float, string	No
switch	boolean	Yes
input_field_set	integer, float, string	Yes

LabLink Interfaces

For most components that are available in the lab at AIT, a LabLink interface exists or is currently planned to be implemented. This substantially simplifies the local data exchanges, and makes HIL experiments with laboratory equipment that is present at AIT possible. HomeAssistant offers such a LabLink interface, which was explained more closely in table 3.1.

3.2.4. Simulation Infrastructure

LabLink also offers the so-called LabLink SyncHost for synchronised simulations. When the SyncHost is used to manage a simulation each component has to send a verification message back to the SyncHost after the completion of the simulation for each timestep to make sure that all components are processing the same timestep before the next the simulation can move on to the next timestep.

The SyncHost also offers an emulation mode for the inclusion of real hardware in the simulation. When running in emulation mode, the time steps are as long as they would be in wall clock time.

The data acquired during any simulation is stored in an instance of the open source time series database InfluxDB, which is used as a data storage backend for the proposed framework. InfluxDB is a time series database that specialises in the fast and high-availability storage of data in a field type structure. [114] The fields paradigm is used to store different types of data such as current or active power in the proposed framework.

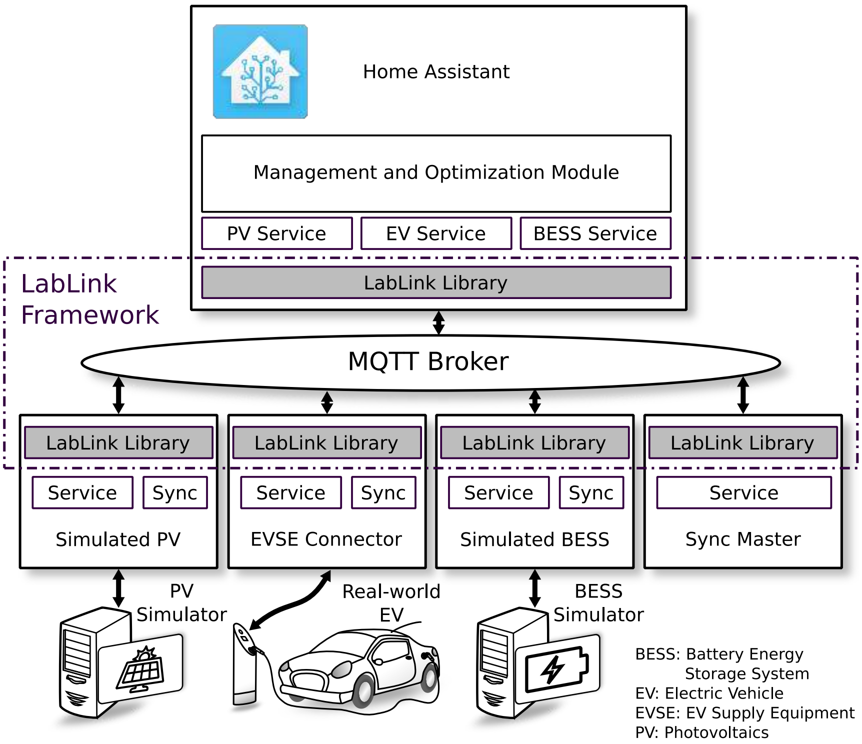

Figure 3.2.: Home energy management system architecture

Simulated System Components

For testing purposes, several possible system components such as a PV module, EV supply equipment and a BESS have been created as simulators to be included into the energy management system periphery. All of the simulators have LabLink bindings, so they can take part in synchronised LabLink simulations. An overview of a possible configuration of the base system for single household HEMS tests can be seen in figure 3.2. It includes a real-world EV and EVSE, simulated PV power production and a simulated BESS. All of these components are available to be added to the system in both real world component and simulated component.

3.2.5. Graphical Interfaces

HomeAssistant itself offers a good Graphical User Interface (GUI) for interaction with components and control of component attributes such as *switches*. An example of the slightly modified frontend used for this project during a simulation of a single household home energy management test, can be seen in 3.3.

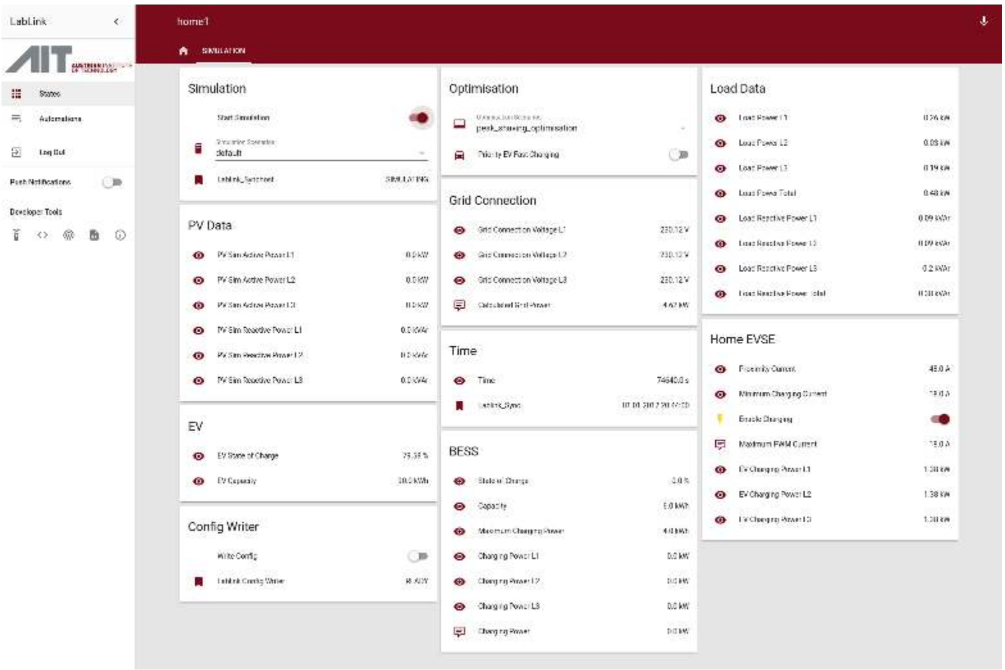

Figure 3.3.: Modified GUI for the HomeAssistant core of the system [97]

Each value that is displayed is based on one of the four data types that have been implemented for HomeAssistant both passively (as read-only DP) and actively (DP whose value can be changed from within HomeAssistant).

For preliminary analysis and surveillance purposes of simulated data the open source data visualisation project Grafana is used. Documentation for the project can be found at [115]. An example of the data visualisation GUI during a simulation can be seen in 3.4.

Figure 3.4.: Grafana GUI used for data visualisation [115]

3.3. Control Algorithms

For initial testing of the system three different simple control algorithms have been designed. Each of them controls system components according to the current system state, and no scheduling of device operating times is done. The scenario the algorithms have been set up for is as follows; A household with a load profile, in house PV power production, a BESS and an EV with an EVSE to charge it. EVSE and BESS are the two controllable components who are operated by the system, to reach the algorithms objective. The household load profile data has been taken from real world grid data collected during an unrelated project. All of the designed algorithms are based on a purely deterministic decision making processes. Certain objectives have been formulated while designing the algorithms and these are approached using linear programming models.

All of the created algorithms are based on a simple scheme that can bee seen in figure 3.5. The 3 different algorithms differ only by the calculations done during

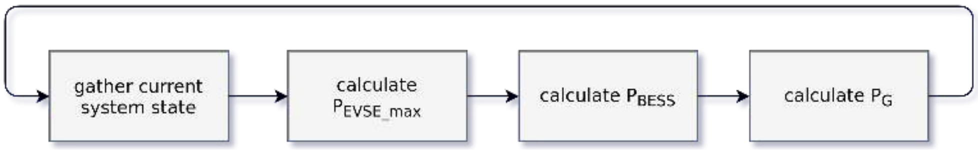

Figure 3.5.: The basic steps that the designed algorithms are based on

the steps *calculate* P_{EVSE_max} and *calculate* P_{BESS}. The signs of the different component powers are chosen so that power production is negative, and a negative grid power means a feed-in of electrical energy to the grid. A positive powers describes a load, or in case of the grid, that power is being supplied from the grid.

3.3.1. Maximising Self Consumption of PV Power

The first algorithm has the objective of maximising self consumption of PV power. A flow diagram depicting the decision processes that are being considered during its operation is shown in figure 3.6. As a first step, the current system state is gathered from the central HomeAssistant instance. Then the maximum charging power the EVSE can supply P_{EVSE_max} is calculated. When no EV is present or its battery is fully charged, P_{EVSE_max} is defined to be 0. Whenever the PV power production P_{PV} does not exceed the load power P_{Load} at that moment, and an EV can be charged, the minimum charging current the EVSE allows is chosen. Whenever P_{PV} exceeds the current household load plus the minimum charging power the EV will allow PEV_min a higher maximum charging power P_{EVSE_max} is offered to the EVSE. The EV ultimately decides how much of the maximum charging power it utilises.

P_{EVSE_max} is only limited by the maximum current that can be provided to the EV over the EVSE connection cable. This is a physical limitation, and this can usually be extended by using a different cable that supports higher charging currents, given that the EVSE supports it.

This maximum power that corresponds to the maximum current is referred to as $P_{proximity}$. Once the EVSE power has been determined, the algorithm calculates the optimal value for the battery charging or discharging power P_{BESS}. To determine whether the battery should be discharged or charged, the algorithm determines whether the PV power production exceeds the household load and the current power used by the EVSE or not.

If is the case, and the BESS is not fully charged, the charging power P_{BESS} is set to the difference between the current PV power production and the current loads in the household power network.

However if the resulting power from equation 3.1 is positive, and the charge of the BESS is higher than 0%, the system is discharged. To account for the real world limitations of Battery Cells, a maximum Battery charging/discharging power P_{BESS_max} is included. If absolute value of the determined P_{BESS} does not exceed this maximum, it is set as a new value for the BESS charging power. Otherwise, P_{BESS} will be set to P_{BESS_max}.

$$P_{BESS} = P_{PV} + P_{Load} + P_{EVSE} \tag{3.1}$$

At last, the current grid connection point power is determined via summation of the power of all the components.

$$P_G = P_{PV} + P_{Load} + P_{EVSE} + P_{BESS} \tag{3.2}$$

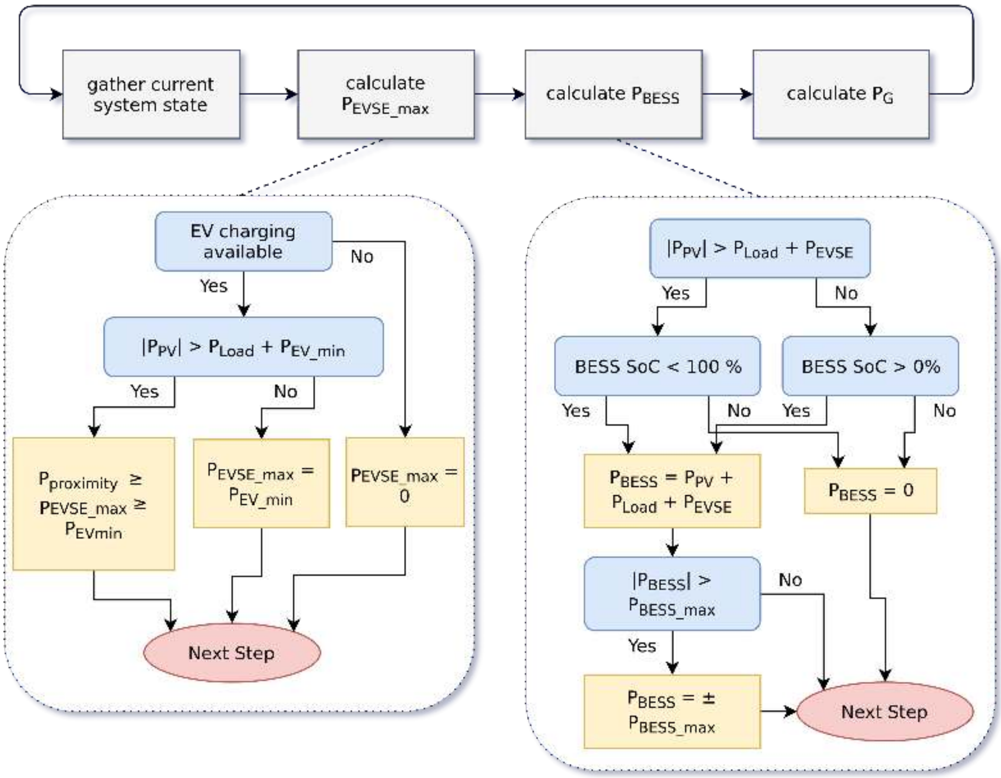

Figure 3.6.: Self consumption maximising control algorithm flow diagram

3.3.2. Grid Voltage Level Controlled Algorithm

With the objective of achieving better stability for the power grid in mind, the grid voltage level controlled algorithm was designed. It was formulated to minimise the effect peak distributed renewable energy production and EV charging have on the grid.

The main steps in the algorithm are the same as for the algorithm described in section 3.3.1. The charging itself however does not strictly depend on whether PV power is available or not.

Grid Voltage Controlled Charging Algorithm

For this algorithm a simple voltage level controlled charging algorithm is employed. Between two threshold grid connection point voltages V_G, the voltage level controlled charging algorithm distributes the charging power linearly. Below the lower threshold V_{low} and above the upper threshold V_{high} the minimum and maximum charging power is set as a new value respectively.

The charging power P_c between the thresholds is calculated using equation 3.3.

$$P_c = P_{min} + \frac{V_G - V_{low}}{V_{high} - V_{low}} * (P_{min} - P_{max}) \tag{3.3}$$

A flowchart depicting the decision tree involved in the grid voltage level control algorithm is shown in figure 3.7.

3.3.3. Limiting Peak Grid Feed-in

The third algorithm was designed to limit the peak feed-in power to the grid. This PV power production peak is variable from day to day and has to be determined every day using data from that days PV power production up to that point. To approximate this peak size a statistical approach using a standard normal distribution is used. Alternatively the power to which the peak should be limited P_{Peak} can also be set to a fixed value. It cannot be guaranteed that the whole peak can be limited using a fixed limit, as the amount of power that can be shifted using the available capacity of the BESS is not taken into account.

Approximation of PV Power Production Peak Size

The PV power production is roughly approximated using a normal distribution where 95% of produced power lies within the range between sunrise and sunset. The current position in the distribution is defined by equation 3.4. The value μ signifies the mean of the distribution, which in this case is the midpoint between the time of sunrise and sunset. σ stands for the standard deviation from the mean. These two values are enough to fully describe the distribution, and therefore also calculate the expected peak size during the operation of the system.

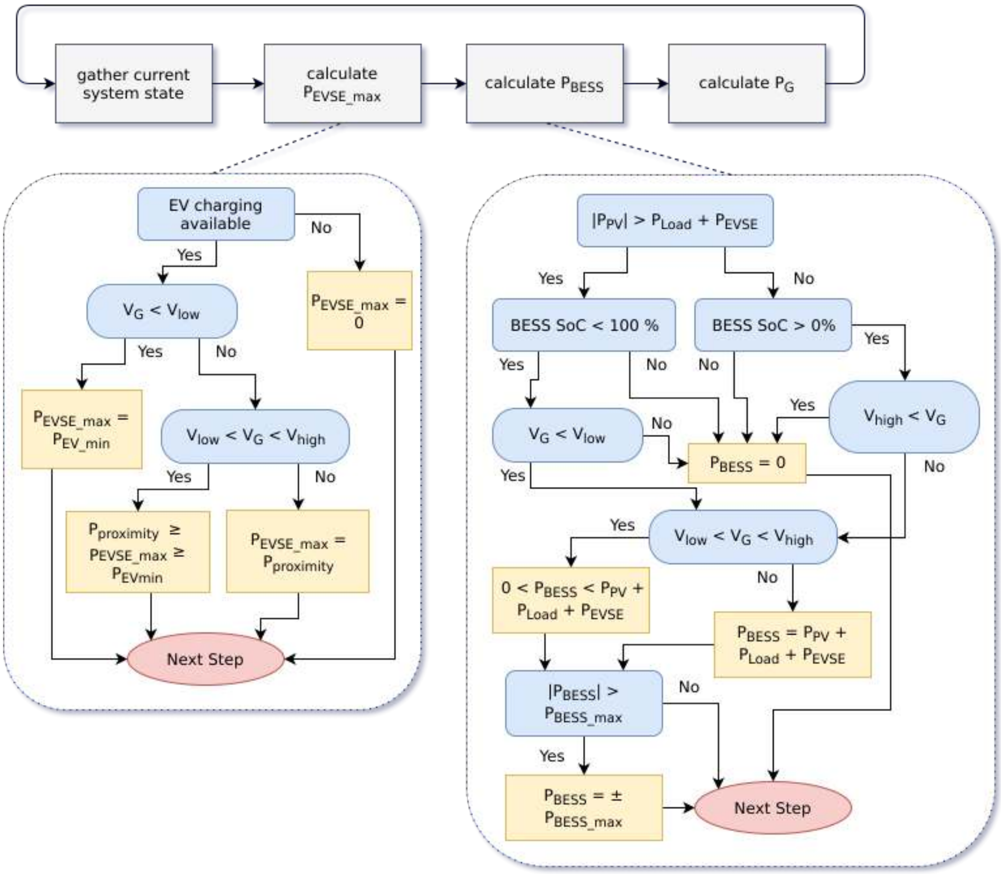

Figure 3.7.: Grid voltage level controlled algorithm flow diagram

$$x_{current} = \frac{t_{sim} - \mu}{\sigma} \tag{3.4}$$

The area under the peak and the area of the peak itself can then be calculated using the cumulative density function and the probability density function for the standard normal distribution.

The percentage of the area that lies to the left of the x position is described by the cumulative density function $\Phi(x)$. The current value on the y-axis of the standard normal distribution at the value that represents the current simulation time on the x-axis is defined by the probability density function $\varphi(x)$. Hence the area of the peak A_{Peak} can be determined using equation 3.5.

$$A_{Peak} = 1 - 2 \cdot \Phi(x) - 2 \cdot \varphi(x) \cdot |x| \tag{3.5}$$

The PV power up to now is added up in the running sum P_{PV_total}. These two values in relation, can give a value for the scale factor that is necessary to calculate the PV power as a value, not just in relation to the maximum, which is previously unknown.

This calculated area can then be observed relative to the capacity that is currently available at the BESS. Once the peak area surpasses that of the power capacity from the BESS, the peak power feed-in value P_{Peak} is set to the current value of $P_{PV} + P_{Load} + P_{EVSE}$. This ensures that any power produced additional to the value of P_{Peak} is used to charge the BESS.

The decision processes that occur during the operation of the system using the grid voltage level controlled algorithm can be seen in 3.8.

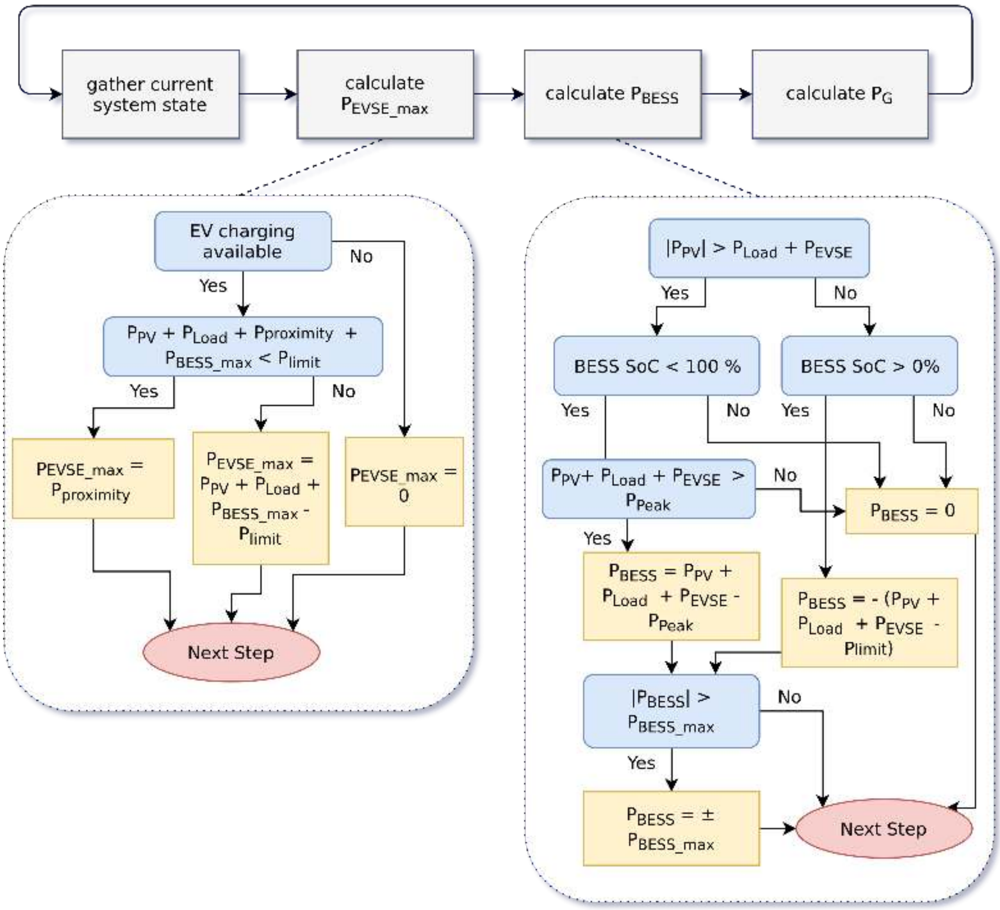

Figure 3.8.: Peak feed-in limiting control algorithm flow diagram

3.3.4. Grid Power Limitation

A grid power limitation has been implemented that is independent of the algorithm that is used for the system optimisation.

This limit for power from the grid P_{limit} is a fixed value that is defined during the configuration of the HEMS.

When P_{limit} is set the system will limit the power used from the grid to that value alongside the normal operation according to the control algorithm that is used.

4. Results and Discussion

To determine the validity of the proposed framework for testing approaches in home energy management, several simulations were conducted for a single household setup in different system compositions. These simulations were conducted for each of the control algorithms that were proposed in section 3.3.

In addition, the components that were included in the simulation environment were varied throughout the simulations. The different system compositions that were used can be found in table 4.1.

Table 4.1.: Single household simulation system compositions with included components

Name	PV	BESS	EVSE	Load
default	Yes	Yes	Yes	Yes
pv_bess	Yes	Yes	No	Yes
pv_evse	Yes	No	Yes	Yes
pv_only	Yes	No	No	Yes
load_only	No	No	No	Yes

An overview of the results gathered for the single household simulation in the default configuration for all the different control algorithms can be seen in figures 3.6 3.7 and 3.8. In these graphs the power that each device in the home power network consumes or provides is shown throughout the simulation of a single day. When power is positive, it corresponds to a consumer; and when power is negative, it corresponds to an electrical energy provider. This can be observed best with the BESS, where power during the charging process of the battery is positive, whereas during the discharging process power provided is displayed as negative power. The main components are the loads for each of the different phases L1 to L3, the PV power that is provided on phase L1 and phase L2, the BESS that is connected to phase L1 and the EVSE that uses power from all three phases L1-L3.

4.1. Simulation Scenario

For all the simulations the same setup for all the included components was used to provide results gathered under the same conditions. This scenario was chosen at random throughout the development of the validation framework. The setup of all the system components is the same for all the simulations and was chosen at random. Therefore, it will not affect the validity of the produced results.

An overview of the configurations that were used for all the system components can be seen in table 4.2. The PV Inverter supplies power to the two phases L1 and L2, the EVSE power is provided on all phases L1 to L3, and the BESS operates only on phase L1. This setup can be changed at will using configuration parameters. However, as the overall self use of power is considered, the sum over all three phases is the value that is considered in the end, hence it does not affect the results. BESS capacity was set to be 5 kW h, the EV capacity is 90 kW h and the mean energy consumption during driving was decided to be 22 kW h per 100 kilometres. During each simulation the EV made a trip of 30 km in the morning and in the late afternoon to simulate a travel to and from work respectively. The peak PV power production is 4 kW in this scenario.

Table 4.2.: Single household simulation scenario configuration

Component	Configuration	Phases
PV	4 kW peak	-
PV Inverter	-	L1, L2
BESS	5 kW h capacity and 4 kW P_{BESS_max}	L1
EV	90 kW h capacity and 22 kW h per 100 kilometres consumption	-
EVSE	3.68 kW P_{EVSE_max} per phase	L1, L2, L3

4.1.1. Self Consumption Maximising Control

To verify the approach of charging anything available in the household system as soon as there is surplus power that was produced by the local PV module, simulations were conducted for the default configuration using the self use optimisation algorithm. An overview of the results can be seen in figure 4.1. It is clearly visible in figures 4.1 and 4.2 that the maximum BESS capacity is used to shift in house produced PV power away from the production time to be used at a later time. This offers the maximal self usage of PV power in this system with the limited amount of degrees of freedom present in the simulation setup used here. The operation of the BESS is observed more closely in figure 4.2, where it is clearly visible that the provided capacity is used completely. In figure 4.3 the operation of the EVSE coupled with the state of charge of the EV is shown.

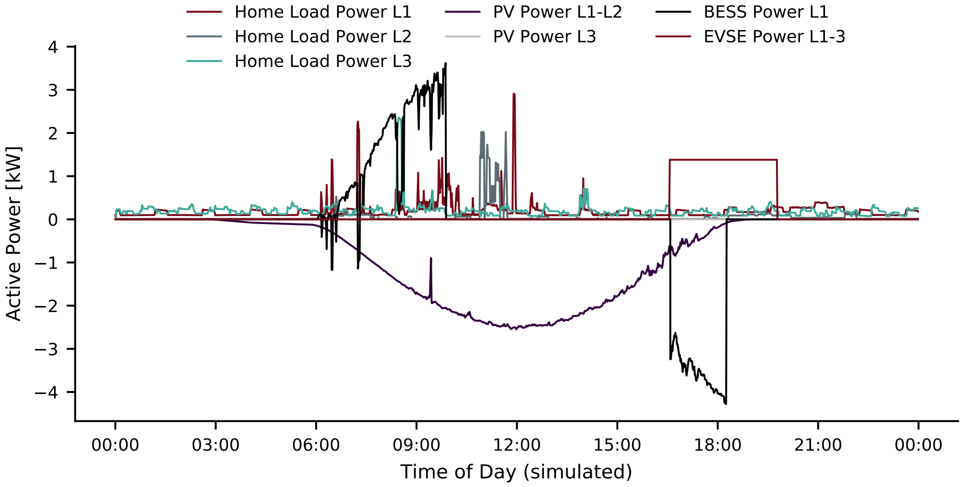

Figure 4.1.: Overview of results using default system configuration self consumption maximising control algorithm

4.1.2. Grid Voltage Level Aligned Control

For the simulations with the grid voltage level aligned algorithm a value for the current grid connection point voltage was needed. As it was not possible to include a whole grid simulation in the single household simulation, a linear correlation between the power being supplied to or taken from the grid and the current grid connection point is used as an approximation primarily for testing purposes. An overview of the results that were gathered in the default configuration using the grid aligned operation algorithm can be seen in figure 4.4. As the voltage level controlled charging algorithm itself uses a linear approach to approximate the current powers of BESS and EVSE, this leads to good results as can be expected. When the feed-in power to the grid is at its maximum, so is the charging power of the BESS, however for the setup using this algorithm the full BESS capacity was not utilised. This effect can be observed in figure 4.5. The State of Charge (SoC) of the EV during a simulation using the grid voltage level controlled algorithm can be seen in figure 4.6

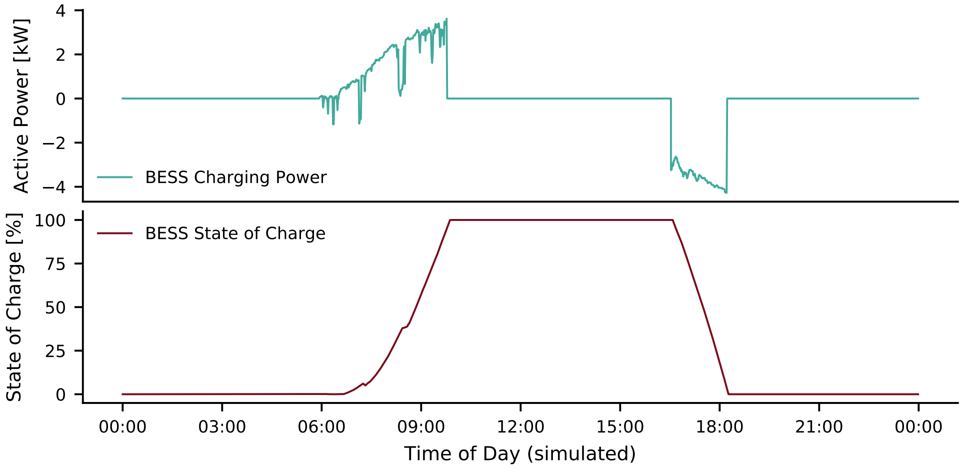

Figure 4.2.: Self consumption maximising control algorithm BESS power and corresponding BESS state of charge

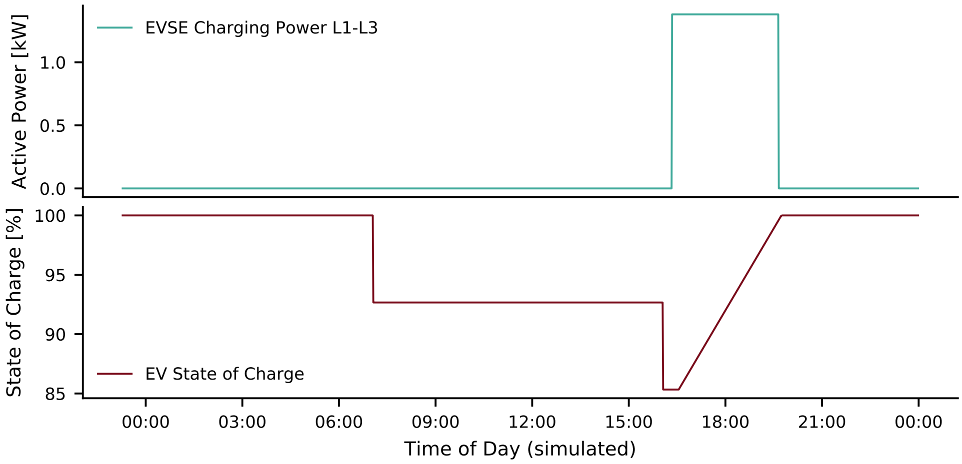

Figure 4.3.: Self consumption maximising control algorithm EVSE power and corresponding EV state of charge

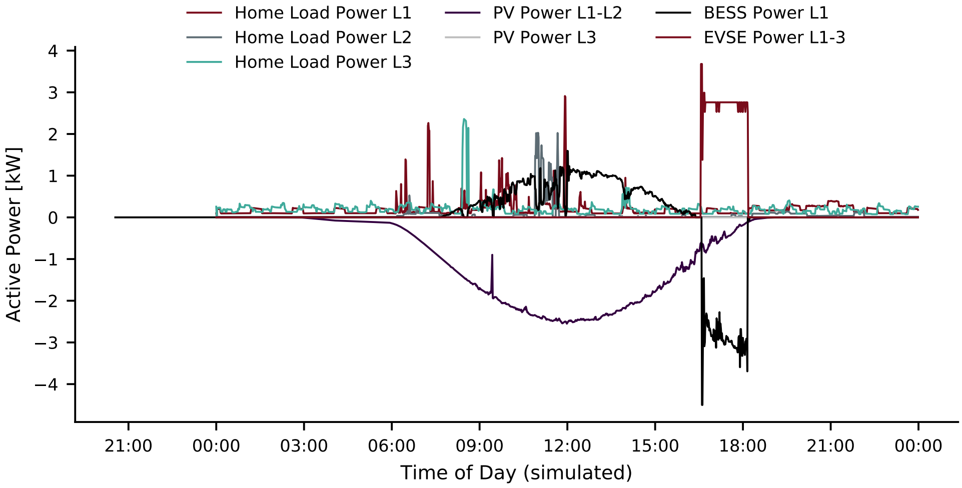

Figure 4.4.: Overview of results using default system configuration and Grid aligned optimisation algorithm

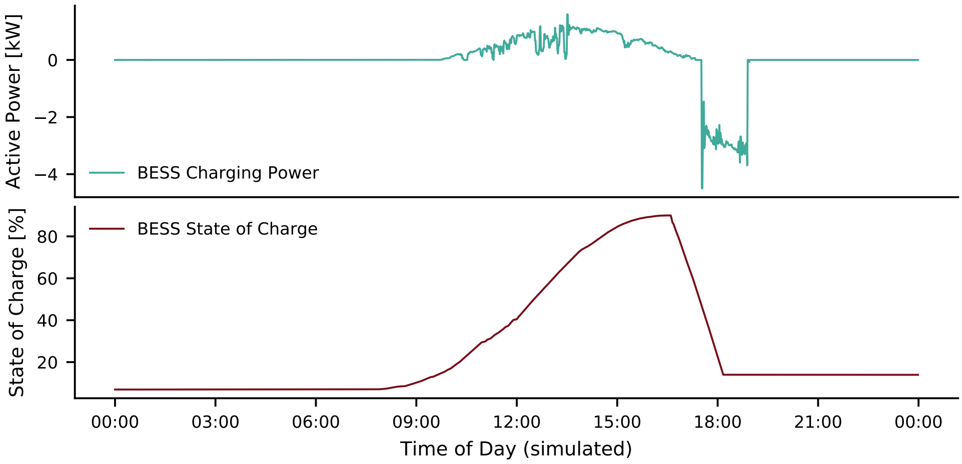

Figure 4.5.: Grid aligned optimisation algorithm BESS power and corresponding BESS state of charge

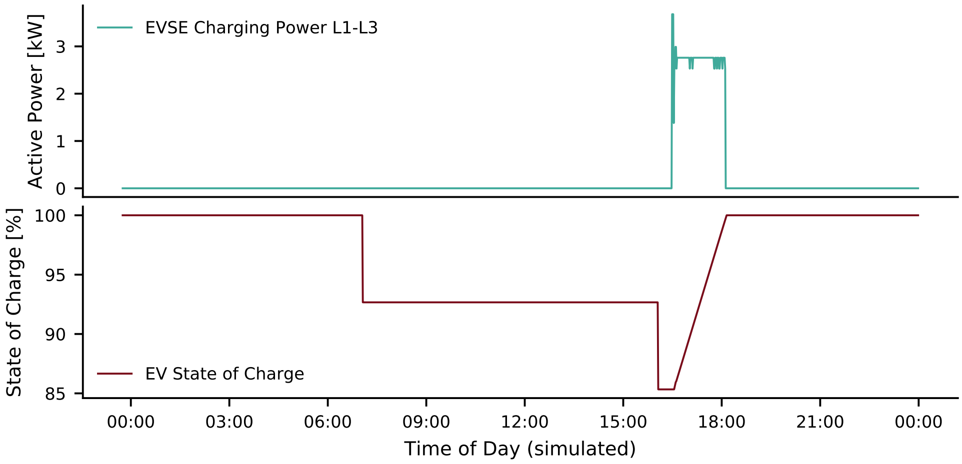

Figure 4.6.: Grid aligned optimisation algorithm EVSE power and corresponding EV state of charge

4.1.3. Peak Feed-in Limiting Control

For the peak feed-in limiting algorithm a power limit was implemented for the power supplied to the grid at any one time. The feed-in power is limited using the approximated available battery capacity determined using an approximation based on statistical methods as explained in section 3.3.3. The BESS is not fully charged after the peak PV power production, as the prediction that was used does not account for the load during the time of peak PV power production. Therefore, the BESS capacity is not fully utilised. The algorithm could be further improved to account for the household load during the peak PV power production, but this would require a means of predicting the loads during that time. An overview of the results for the default system configuration using the peak feed-in limiting control algorithm can be seen in figure **??**. The operation of the BESS with the corresponding SoC is shown in figure 4.8. The SoC of the EV with the corresponding EVSE charging power can be seen in figure 4.9 for the peak feed-in limiting control algorithm.

EV

4.2. Power Limitation

As described in section 3.3.4 a grid power limiting option has been implemented that is independent of the control algorithm. To try and simulate how electrical energy tariffs that are scaled with the maximum amount of power that is consumed

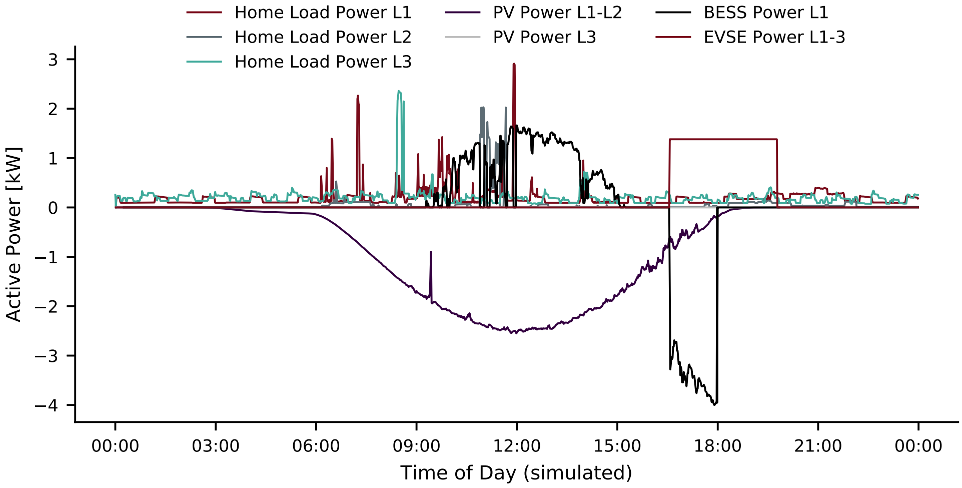

Figure 4.7.: Peak shaving optimisation algorithm

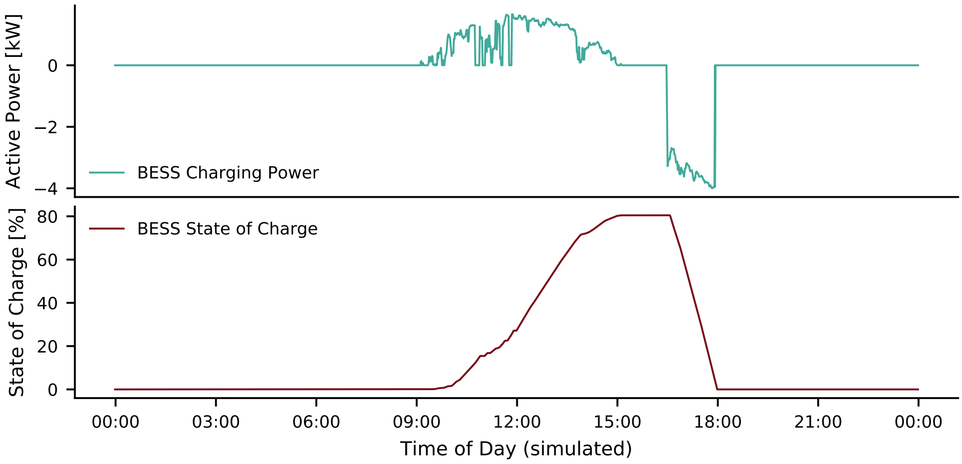

Figure 4.8.: Peak shaving optimisation algorithm BESS power and corresponding BESS state of charge

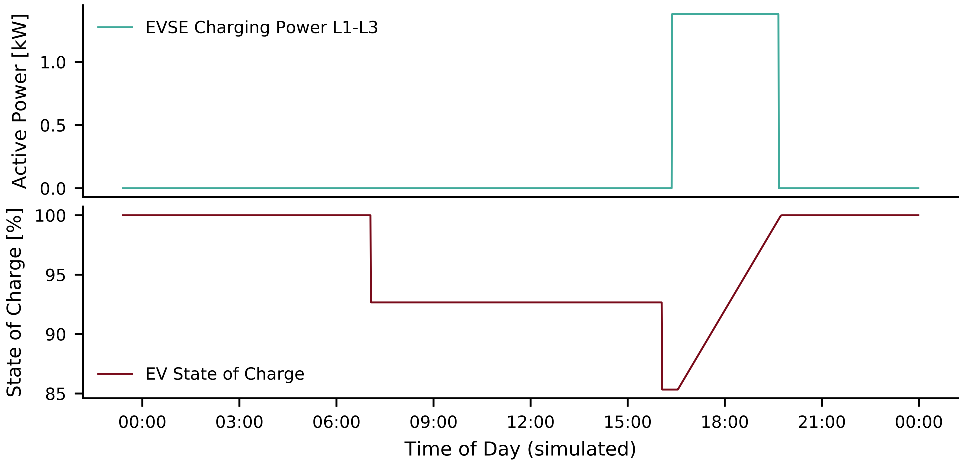

Figure 4.9.: Peak shaving optimisation algorithm EVSE power and corresponding EV state of charge

from the grid at the connection point of the household, such a power limitation factor is introduced to each of the control algorithms, limiting the power they can use from the grid to $P_{limit} = 3.5\,\mathrm{kW\,h}$. The results that provide an overview of the simulations and the results showing the BESS and EVSE operation are displayed in chapter B of the appendix.

The overall power that is fed into the grid or used from the grid and the grid connection power limitation level can be seen in figures 4.11, 4.13 and 4.15. It can be seen that the power limit is not surpassed by the self consumption maximising and the grid voltage level controlled algorithms, only the peak feed-in limiting control algorithm used power in excess of the power limit for one timestep.

One problem that occurs when a power limitation is combined with the charging of an EV is that the EV can be unable to charge itself fully in certain scenarios. This can differ between single phase and three phase electric vehicle charging points. The minimum charging power of a single phase charging point is $\frac{6\,\mathrm{A}\cdot 230\,\mathrm{V}}{1000} = 1.38\,\mathrm{kW}$, the minimum charging current available for single phase electric vehicles. For three phase charging points the minimum charging current is three times that for single phase chargers $1.38\,\mathrm{kW} \cdot 3 = 4.14\,\mathrm{kW}$. This means that for a power limitation of $3.5\,\mathrm{kW}$, there will be no charging available when no PV power is produced and the BESS is completely discharged.

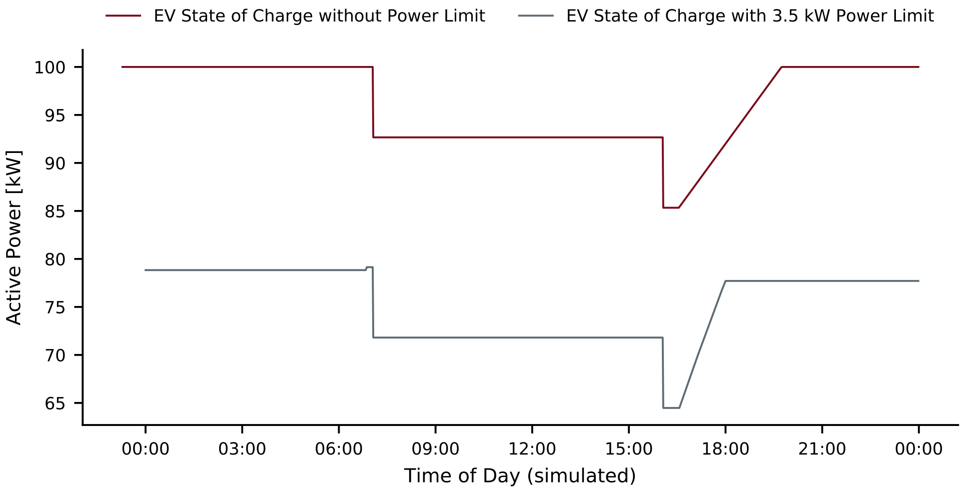

Figure 4.10.: EV SoC comparison between power limitation and no power limitation for the self consumption maximising control algorithm

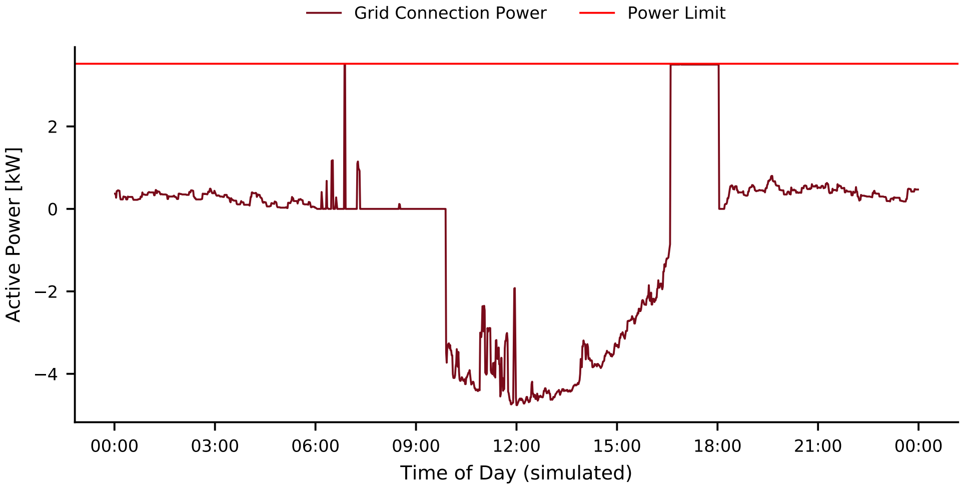

Figure 4.11.: Grid connection power over simulation time with power limitation in place for the self consumption maximising control algorithm

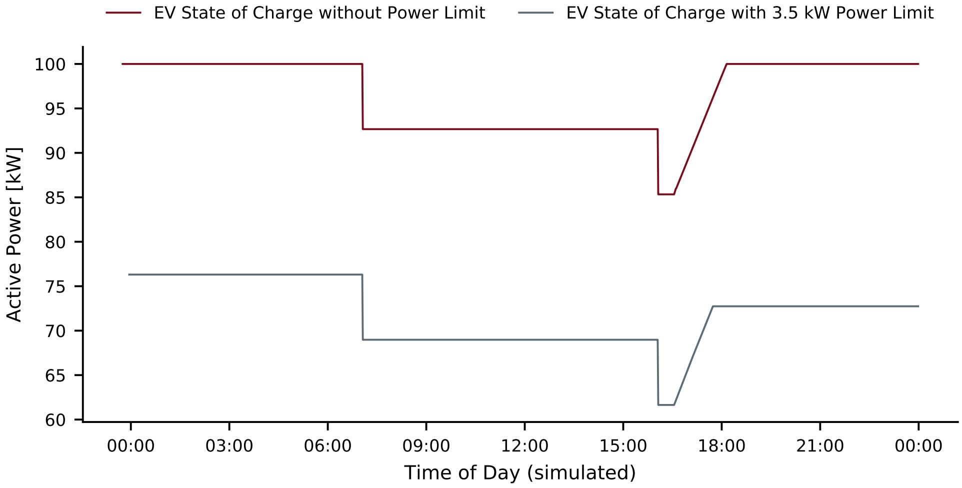

Figure 4.12.: EV SoC comparison between power limitation and no power limitation for the grid voltage level controlled algorithm

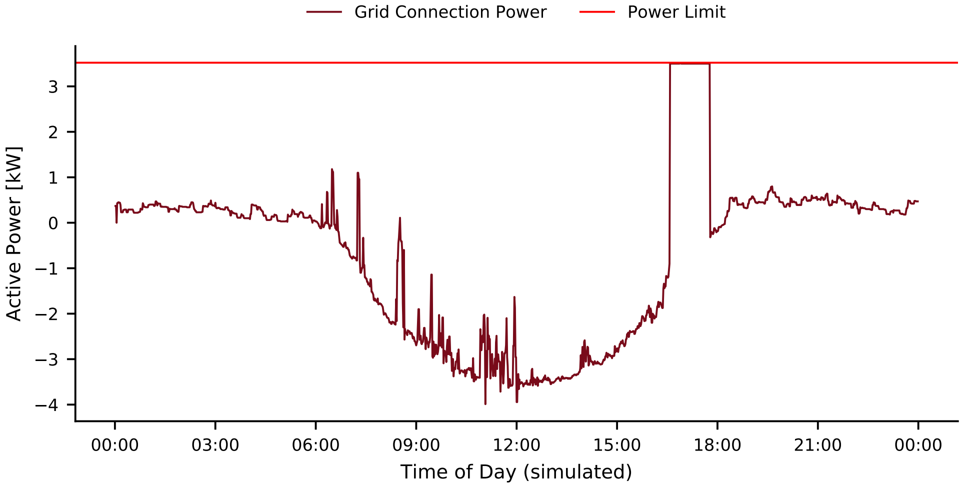

Figure 4.13.: Grid connection power over simulation time with power limitation in place for the grid voltage level controlled algorithm

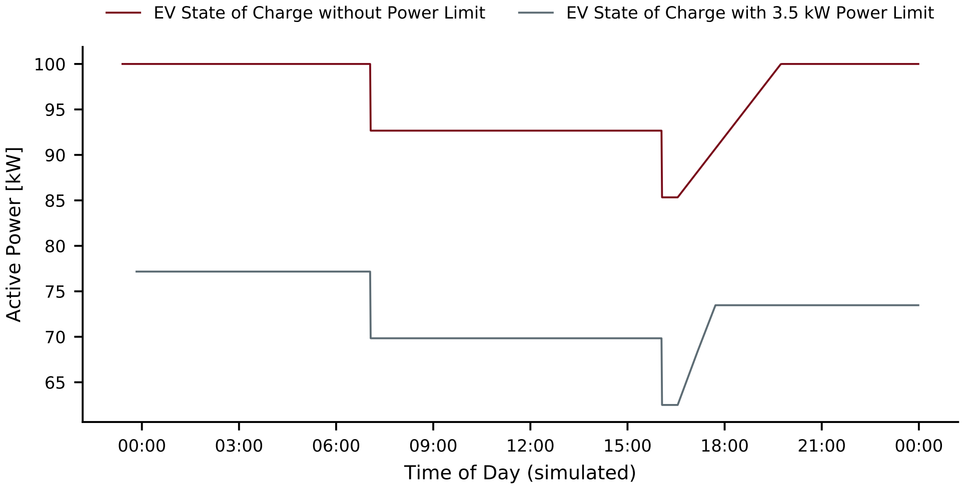

Figure 4.14.: EV SoC comparison between power limitation and no power limitation for the peak feed-in limiting control algorithm

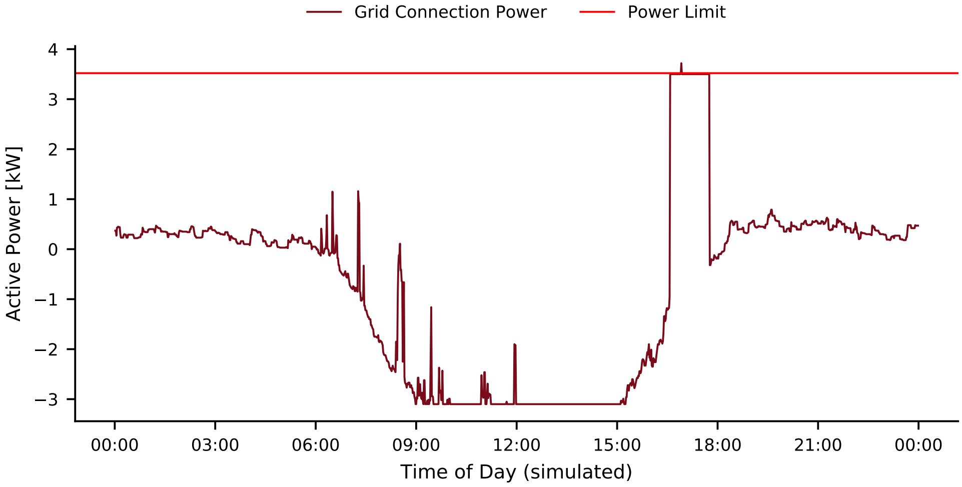

Figure 4.15.: Grid connection power over simulation time with power limitation in place for the peak feed-in limiting control algorithm

4.3. Evaluation of the Single Household Results

To analyse the three different control algorithms further, the corresponding simulated grid connection point data was analysed for each of them. These simulations were conducted using the default configuration. Figures 4.16 and 4.17 show the different control algorithms put in relation with an algorithm that offers no optimisation control. The nomenclature for the different algorithms is not consistent in this chapter, and the algorithms will be referred to using different names at this point. The self consumption maximising algorithm is also referred to as the 'self_use' algorithm, the grid voltage level controlled algorithms is also referred to as the 'grid_aligned' algorithm and the peak feed-in limiting control algorithm is also referred to as the 'peak_shaving' algorithm. This reflects the names that were chosen during the implementation of the first tests. The versions of the algorithms including a power limitation are marked with the trailing 'limit' in their name. Figure 4.16 shows the amount of total power used from the grid $P_{G,tot}$ in relation with the total power supplied to the grid $P_{fi,tot}$, in a day. Whereas in figure 4.17 the maximum power used from the grid $P_{G,max}$ is compared with the maximum feed-in power $P_{fi,max}$ for each algorithm.

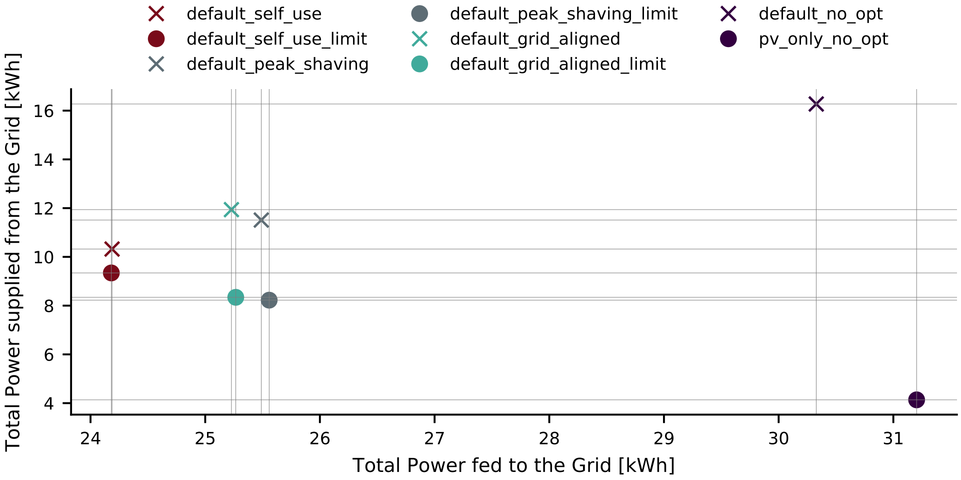

Figure 4.16.: Comparison of different algorithms in amount of total power taken from the grid and fed into the grid within a day

$$P_{self\_use} = \frac{P_{PV,tot} - P_{fi,tot}}{P_{PV,tot}} \tag{4.1}$$

The percentage of power that is used within the household electricity network and not fed into the grid is defined by equation 4.1. It can be seen that the self use

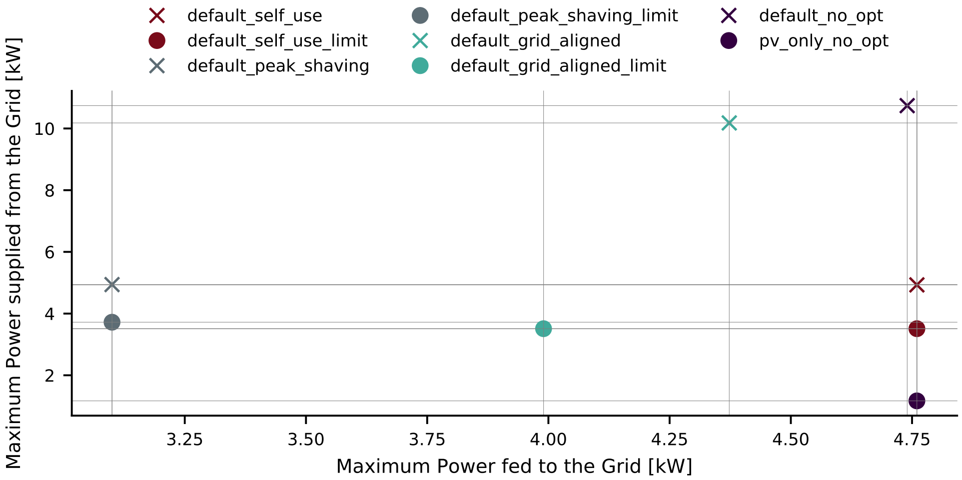

Figure 4.17.: Comparison of different algorithms in terms of maximum power taken from the grid and maximum feed-in power throughout one day

control algorithm was successful at increasing self consumption of locally produced PV power. The increase of self consumption compared to the reference case without a control algorithm and storable load was 18.6 %. This is the maximum increase of self use possible with this size of battery. The 'pv_only_no_opt' does not include the extra load of an EV that needs charging, in contrary to 'default_no_opt'. This is reflected in that 37.787 kW h · 18.6 % does not equal the total capacity of the BESS that was used in the simulation, but rather the larger value of 7.028 kW h. If the self use percentage of the 'default_self_use' simulation is compared with the 'default_no_opt' simulation however, the same calculation with the different increase in self use, 37.787 kW h · 16.3 % = 6.159 kW h this results in a value much closer to the actual capacity of the BESS used. The small discrepancy of 0.159 kW h is to be expected, as the control algorithm discharges the BESS when load fluctuations occur in the beginning of PV production and the BESS is slightly charged and the load momentarily surpasses the PV production. In comparison with the 'grid_aligned' and 'peak_shaving' algorithms the self consumption of power was increased only by 2.8 % to 3.6 %. This could be expected, as all of the simulations included BESS of the same capacity. The results for the different algorithms, with the default case without an optimisation and without a BESS included and the case where no EV is present in the system (referred to as 'pv_only_no_opt') can be seen in figure 4.18, and is displayed in table 4.3 as well.

$$P_{G\_residual} = \sum_{t=1}^{1440} (P_{Load} - P_{PV}) | (P_{Load} - P_{PV}) > 0 \tag{4.2}$$

The residual power for the grid that is defined by equation 4.2, can be used as a key performance indicator (KPI) for the different algorithms, as well as the percentage of power that is used within the household electrical power network. The results for the different algorithms are displayed in figure 4.19 and can be seen in table 4.3 labelled $P_{G,tot}$. As is to be expected all the cases where an EV is present require more power from the grid. As well as that, the cases where no power limitation to power from the grid is present use more grid supplied power. A result that is somehow surprising is that while being the best performing control algorithm without a power limitation present, the 'self_use' algorithm used more power from the grid than the other algorithms with the power limitation in place. This was the case because it used the minimum charging power for the EV, when there is no PV power present. Therefore, the self consumption algorithm was able to charge the EV longer than the other control algorithms. The grid voltage controlled algorithm and the peak feed-in limiting control algorithm used the maximum charging power possible, with the power limitation from the grid in place. This resulted in the BESS to be empty faster, and the minimum charging power exceeded the power limitation at an earlier point for these control algorithms.

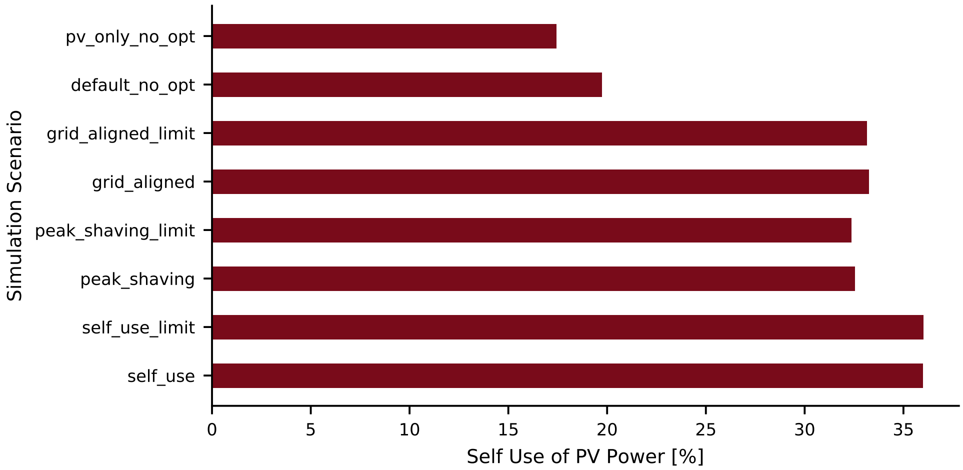

Figure 4.18.: Comparison of different algorithms in terms of percentage of PV power that is used in house

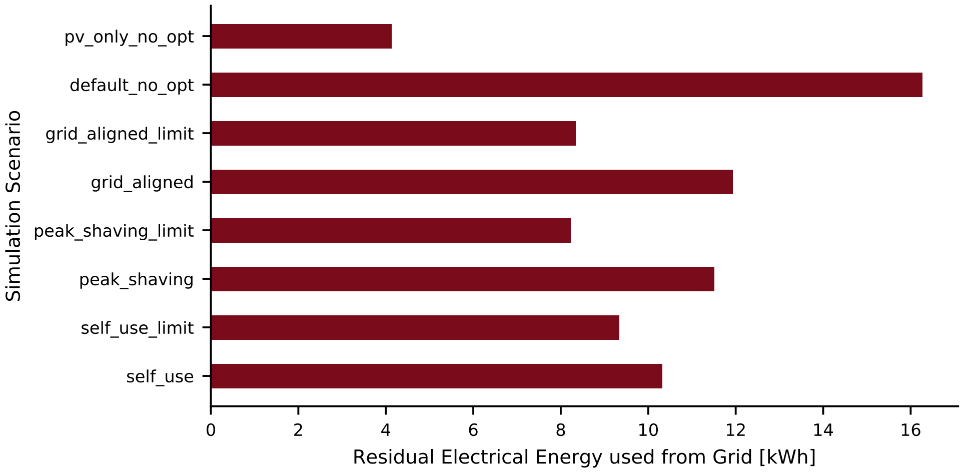

Figure 4.19.: Comparison of different algorithms in terms of Residual Grid power that was used after optimisation

Table 4.3.: Single household simulation results for the three different control algorithms in default configuration

Algorithm	$P_{G,tot}$	$P_{fi,tot}$	$P_{G,max}$	$P_{fi,max}$	$P_{selfuse}$
self_use	61.9 %	79.6 %	45.9 %	100 %	36 %
self_use_limit	56.1 %	79.5 %	32.7 %	100 %	36 %
grid_aligned	69.1 %	83.8 %	46 %	65.1 %	33.2 %
grid_aligned_limit	49.4 %	84.1 %	34.6 %	65.1 %	33.1 %
peak_shaving	71.6 %	83 %	94.8 %	91.9 %	32.5 %
peak_shaving_limit	50.1 %	83.1 %	32.7 %	83.8 %	32.4 %
default_no_opt	100 %	100 %	100 %	100 %	19.7 %
pv_only_no_opt	25.4 %	102.9 %	10.9 %	100 %	17.4 %

5. Conclusion and Limitations

In the following, the thesis will be reviewed and the most important highlights will be presented. In addition, the limitations of this paper will be discussed.

5.1. Conclusion

The State-of-the-Art analysis in home energy management conducted as part of this thesis revealed that all of the different HEMS that were reviewed during the analysis included a central control unit that was responsible for the management of the system operation.

It was possible to determine three distinct different objectives the HEMS followed, with some having more than one single objective. The determined objectives are Demand Reduction, Cost Reduction for the end user, and Grid Stability. Following one of these objectives can also benefit one of the other aspects of a HEMS, but this was not the prime objective that was in mind during the implementation.

Different types of devices to control were identified and classified with the amount of flexibility they offer in being controlled. The devices that offered the most flexibility were found to be storable loads, and devices of this type like a BESS and a EV were used for the testing of the proposed system.

The actuation technique that was identified to be more suitable for the testing of the proposed system was found to be the control of components according to the current system state, without any planning included in the actual core system. This can be included at a later time as an external input component without changing the core architecture.

From a strictly physical point of view, the system controlled by a HEMS is a lot more complicated than the controlling capabilities indicate. Each of the components analysed on their own show a great deal of complexity that limits the possibilities of control from a central management instance. For this reason, each of the observed components needs a certain form of interface to the home electrical power network. For the BESS that interface would be the power rectifier and inverter that include certain limitations which cannot be overridden by the management system.

The partially random nature of solar radiation that is the source for PV electrical energy production leads to an electrical energy system that is only able to provide power throughout certain periods during the day and whose daily output is very difficult to predict. This uncertainty and periodicity of PV power production can be moderately compensated by the introduction of a BESS into the home electrical power network, which can balance out some of the power production with later consumption, when no more PV power is available.

However, a battery being a complex electrochemical system in itself introduces some additional complexity to the system. Thankfully, modern BESS include a battery management system that will not allow operation outside of safe system parameters.

An agent based architecture was chosen as the basis of the system to provide the possibility to reproduce many approaches to HEMS and be able to vary the components that are being controlled by it. The key to being able to evaluate the different systems is the infrastructure surrounding the core system that were provided and developed. The web frontend and the data visualisation tool Grafana provide important first analysis and control methods during the operation of the system.

When extending the proposed HEMS evaluation framework, the agent based architecture can provide clear advantages. The addition of agents is handled via the LabLink MQTT communication library. This process is straightforward and facilitates the expansion of the proposed system. The core can also be easily configured to work with different components that offer a LabLink interface. This simplicity in adding components on the go can prove to be important to the systems further development and usage.

From the results presented in chapter 4 it can be concluded that the proposed architecture for testing of HEMS approaches is able to represent different control paradigms for energy intensive applications in a future prosumer household. It was shown that the results gathered using the framework developed here provide information on different aspects on the households electrical energy consumption such as the percentage of self consumption and the residual power used from the electrical power grid. These results can verify the feasibility of different algorithms for deployment, depending on the objectives for the HEMS.

All three proposed control algorithms provided satisfying results considering their limited complexity. The self use control algorithm was successful at maximising the self consumption of PV power. This was of course facilitated by the limited number of system components and their simple operation method. The peak shaving control algorithm was able to reduce the feed in peak of PV power using simple statistical approximation of the peak size. The grid aligned control algorithm was able to control the system components only with the grid connection point voltage level as an input. They all performed rather well with a power limitation for power from the grid in place, only the peak shaving algorithm shortly over used power from the grid. This was probably caused by too short reaction time for this algorithm during the simulation.

It was shown that the system developed throughout this thesis could serve as the basis for further research into the field of DSM and HEMS.

5.2. Limitations

The main focus of the thesis was to provide a framework for further experiments in the field of HEMS. To test the framework, a simple scenario was chosen using key components that were thought to be relevant to the topic. This reduced the complexity of the system and the effort of modelling of different components, while providing a scenario to evaluate the effectiveness of the system. The core architecture however, will be just as relevant for a larger number of system components.

Due to time consuming implementation of the core architecture, elaborate tests of the system with lab equipment were postponed to the phase of further development. Initial connection tests showed that lab equipment can be integrated with the core system, and work just as well as simulated components as long as they offer a LabLink interface.

6. Outlook

The framework that was developed in the context of this thesis offers many possibilities for further development and experiments in the field of Demand Response (DR) and DSM. Experiments into the increased deployment of such systems could shed light on the composition of what the traditional power grids are facing, and whether certain DSM measures could be enough to prepare the electricity infrastructure.

Another way to improve the current testing framework is to increase the LOI of the designed system to be able to represent HEMS approaches that use a higher level of intelligence to include more complex mechanisms such as scheduling algorithms or forecast methods. In the current state, the framework exhibits self actuation and some level of optimisation of the system state; this means it has a LOI of 3. If the system included some means of plan development or prediction of PV power for instance, this would increase the LOI of the system and increase the variety of HEMS approaches that can be tested and validated with it.

Such a system with a higher LOI might then be able to provide ahead of day operation schedules for consumer appliances like a washing machine or a dishwasher. In addition it might be possible to determine the probable PV power output using neural networks and deep learning algorithms. The architecture provided here paired with a variable PV simulation could serve as an optimal candidate to simulate data that would be needed for such a deep learning algorithm.

The inclusion and modelling of certain energy intensive household appliances could also increase the number of residential energy management approaches that can be tested. This could be the basis for further research into the effects on the QoE for the end user of a HEMS. Such research could give indications on how fast HEMS could be adapted in residential settings. Certain household appliances might significantly reduce the QoE for the end user if they are operated completely automatically, as they require interaction at the beginning or end of the operation such as a washing machine or a dishwasher.

One further development that is already being implemented and is delivering some preliminary results, is the combination of the HEMS evaluation architecture with large scale grid simulations and an EV mobility simulation. This could provide further insights into the effects that large scale integration of HEMS and EV might have on electrical power grids.

6.1. Large Scale Simulations

Together with different parts of the AIT LabLink infrastructure, it is possible to conduct different interesting experiments, ranging from Hardware-in-the-Loop experiments with real world lab equipment to large scale grid simulations with different system configurations. Such a Large Scale simulation coupled with a State-of-the-Art grid simulation could show possible effects higher penetration of future prosumer homes and EV could have on grid stability.

An overview over the employed large scale simulation environment can be seen in figure 6.1. The power used/provided by the grid connection point P_G and the grid connection point voltage level V_G are exchanged with the grid simulation by each of the docker containers representing a household. The maximum allowed charging current that can be used by the EVSE I_{EVSE} is exchanged by each of the docker containers with the node in the large scale EVSE simulation that corresponds to the location of the household's EVSE.

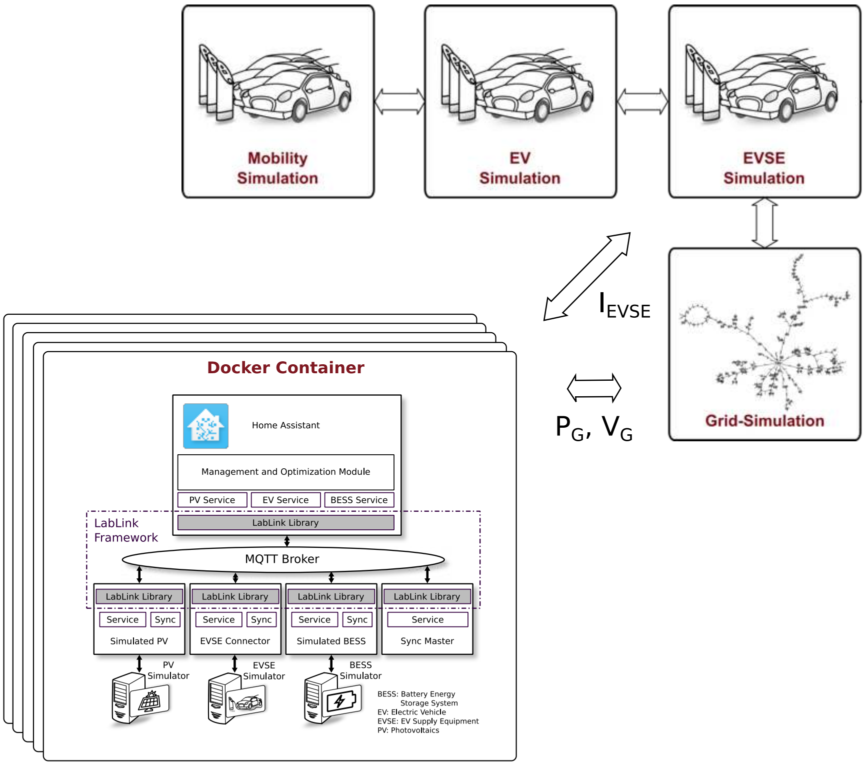

Figure 6.1.: Large scale simulation environment overview

6.1.1. Docker

To conduct such a Large Scale Simulation, the single household simulation setup was combined in a Docker container. Docker is a way of quickly and efficiently spawning lightweight virtual machines derived from an image called "containers". It was developed for software testing on different platforms. [70] Container based systems like Docker can provide a more efficient solution for high performance computing applications than traditional virtual machines. [71] These containers can then be multiplied at will as long as the computational power permits it. The big advantage of Docker is that similar containers with small differences can be easily started up and removed again. This permits the simple configurations of a large system, and have each system run its own simulators for each system component.

6.1.2. Additional Simulation Infrastructure

The Docker setup combined with a PowerFactory grid simulation and an EV mobility simulation provide a relatively realistic environment to simulate grid effects. PowerFactory is a grid simulation software that takes the power at each node of the current grid model that is configured with the software and returns the grid voltage at each node. This computation is done during each simulation step. Data of the household loads is also already included in PowerFactory and will be taken from there for computations within HomeAssistant.

The EV mobility simulation that was used for this large scale simulation was devised for another Thesis conducted at the same time as this one, and includes different EV models with distinct, realistic charging curves. These curves are based on data from charging cycles of different types of EV. The EVSE component from the single household simulation also acts as a wrapper for the EVSE included in the EV mobility simulation.

6.2. Preliminary Results: Large Scale Simulation

To verify that these control algorithms can be beneficial to the local grid stability, large scale simulations were conducted using a grid simulation that controls the local voltage levels at each of the households according to the current demand and supply in the grid.

During the large scale simulation alongside the grid simulation and the EV Mobility simulation, there were 53 running Docker containers of which 46 contained full single household simulation setups, and 7 containing only a PV simulator. 200 LabLink clients were actively taking part in the simulation conveying about 2000 messages per second over the MQTT broker. These clients provided a total of 1480 LabLink DP. One timestep of the simulation took 0.8 s to 1.2 s to complete.

The preliminary evaluation of voltage levels at critical nodes in the simulated power grid showed effects of the use of HEMS in a portion of households on the whole grid. It can be seen that the different control algorithms have different effects on the voltage levels during the simulations.

6.3. Outlook: Large Scale Simulation

Even though the first results gathered using the large scale simulation environment described in section 6.1 were positive, not enough results were gathered for the results to be conclusive. The framework combined with such a large scale grid simulation and other simulations provide a means of conducting various large scale integration tests in the fields of DSM. A possible experiment that was conducted using the proposed large scale grid simulation architecture could be used in the future is to test the effect of DR pricing systems on voltage levels, and whether these different pricing levels can cause oscillations in the grid when the penetration of automatic DR systems is high.

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Appendices

A. State-of-the-Art Research Tables

A.1. Home Energy Management System Objectives

Table A.1.: Objectives of HEMS

Objective	Description
Cost Reduction (CR)	In this approach, the HEMS is designed to reduce the overall energy cost for the end-user of the system, for instance by scheduling appliances for times when lower electricity prices are expected, if a dynamic pricing scheme is employed.
Electricity Demand Reduction (EDR)	Systems with this approach to energy management try to reduce the overall electricity consumption of the household, for instance by moving operating times of loads toward times with local renewable energy production.
Grid stability (GS)	To improve grid stability the energy management system tries to prevent peak load consumption and/or peak renewable energy feed-in, for instance by storing electrical energy produced locally and using it at peak load times.

A.2. Levels of Intelligence

Table A.2.: Levels of Intelligence that were used for classification of HEMS

LOI	Description
Level 0	**Manual Operation;** Intelligence Level 0 classifies a system that offers neither observability nor controllability. Systems that fall into this category allow for no direct automatisation, but need direct human operation.
Level 1	**Electronic Digital Communications;** A system that falls into Level 1 of Intelligence is a system that allows for electronic digital communications, either one way or both ways. This means that the system either allows for remote state reporting, remote actuation, or even both.
Level 2	**Self Actuation, Basic Automation;** The key feature that classifies a Intelligence Level 2 System is self actuation. This can mean basic automation, and closed loop control sequences that allow for self actuation possibilities.
Level 3	**Self Optimisation;** Intelligence Level 3 Systems exhibit self optimisation and adaptive behaviour. They can be aware of a desired operating state and pursue a chain of action that will bring the system towards the desired state. Independent decision making characteristics and reconfiguration possibilities are needed to classify in this Level of Intelligence.
Level 4	**Collaboration;** Systems that offer collaboration between distributed intelligent systems to serve a common goal are what sets systems with Intelligence Level 4 apart. The systems components follow hierarchical operating states and allow for networked intelligence. Each of the components understand data from other components and can react accordingly in response.
Level 5	**Prediction and Plan Development;** To classify for Intelligence Level 5, there has to be some planning being done by the system itself to optimize the output. This includes measures to improve overall quality of the electricity supply, like corrective actions that try to prevent fluctuations or outages in the supply network. Analysis, diagnosis and predictions of renewable generation for instance could be crucial features.

A.3. Technology Readiness Levels

Table A.3.: Technology Readiness Levels that were used for classification of HEMS

TRL	Description
1	Basic principles observed and reported. This is the lowest level of technology maturation. Here scientific research begins to be translated into applied research and development.
2	Technology Concept and/or application formulated. After the research of basic principles, an application for the observed characteristics can be found. At this level the application is still speculative.
3	Analytical and experimental critical function and/or characteristic proof-of-concept. Active research and development is initiated at this step. This includes analytical studies as well as laboratory-based studies to physically validate that the analytical predictions are correct. These studies should constitute proof-of-concept validation of the applications formulated in TRL 2.
4	Component validation in laboratory environment. After a successful proof-of-concept has been delivered, basic technological elements must be integrated to validate that these components will work together to achieve concept-enabling levels of performance.
5	Component validation in relevant environment. This step largely increases the fidelity of the component being tested. The basic technological elements must be integrated with reasonably realistic supporting elements so that the system as a whole can be tested in a simulated environment.
6	System model or prototype demonstration in relevant environment. In order to qualify for TRL 6, a systems validity needs to be shown in the relevant environment, only if the demonstration is successful will the component qualify for TRL 6.
7	Full-scale, prototypical system demonstrated in relevant environment. This step requires the demonstration of an actual system prototype in the relevant environment.
8	Actual system completed and qualified through test and demonstration. The technology has been proven to work in its final form under the conditions it is expected to work in. In most cases this TRL represents the end of true system development.
9	Actual system operated over the full range of expected conditions. The technology is in its final form and operating under full range of expected conditions.

B. Single Household Results with Grid Connection Power Limitation

The results presented in the following were conducted with a power limitation for the use of electrical power from the electrical power grid, as described in section 3.3.4. The simulations were conducted for each of the algorithms in the default single household system configuration. The system parameters were unchanged from all the other simulations and can be seen in table 4.2.

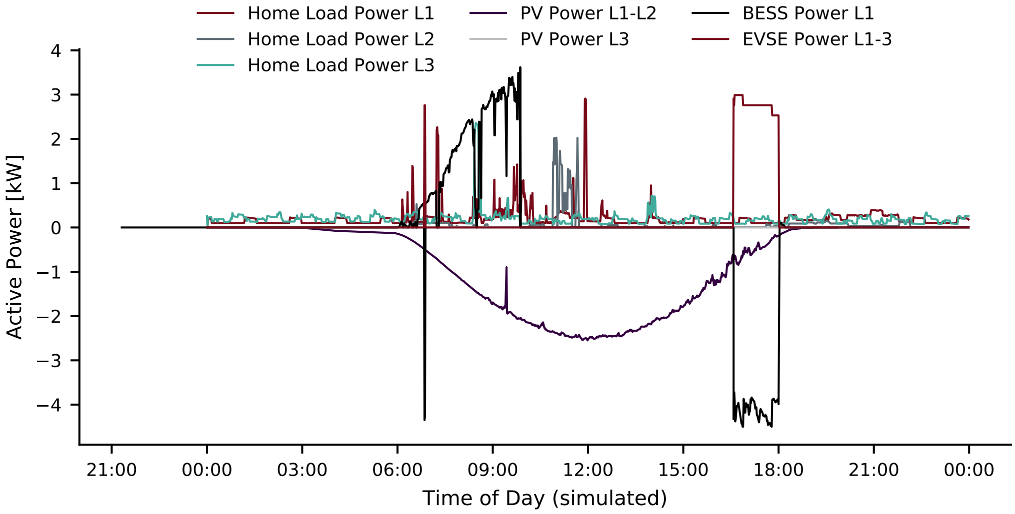

Figure B.1.: Overview of results using default system configuration and self consumption maximising control algorithm with power limitation.

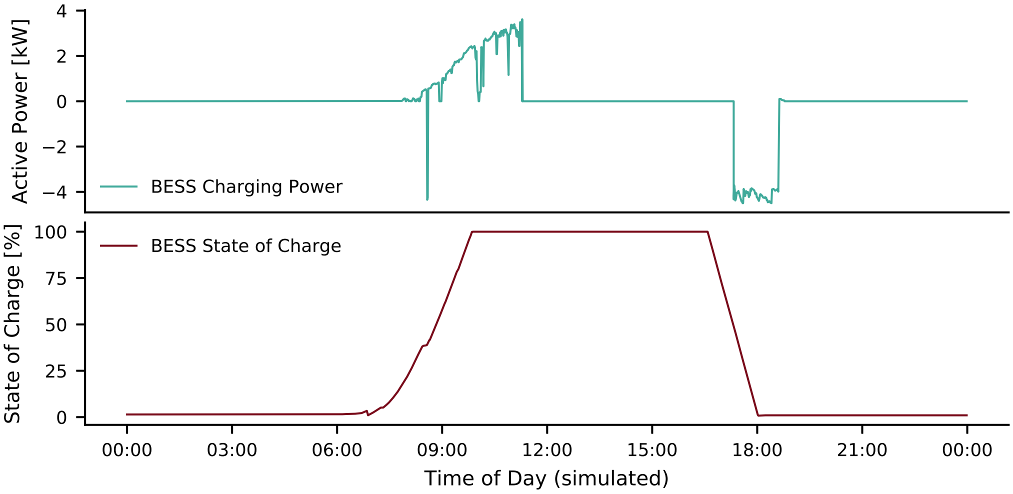

Figure B.2.: Self consumption maximising control algorithm with power limitation BESS power and corresponding BESS state of charge.

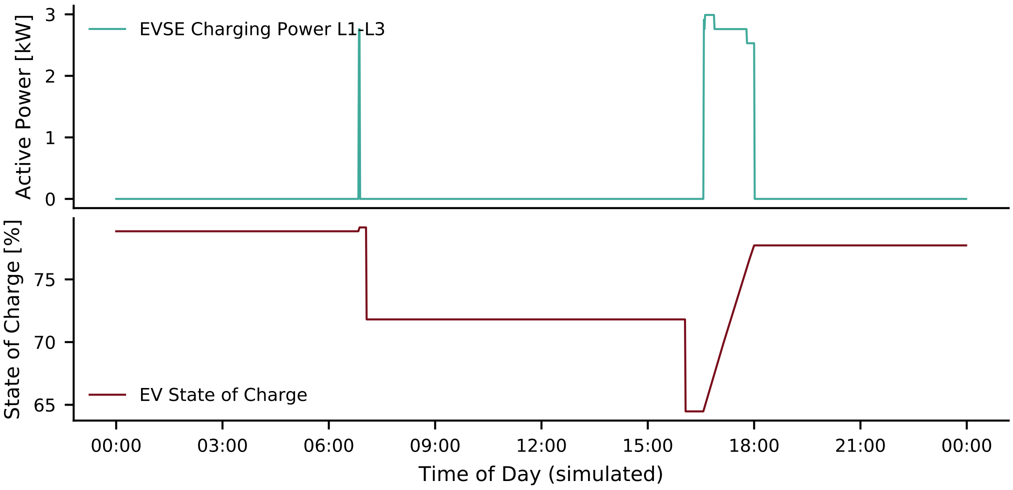

Figure B.3.: Self consumption maximising control algorithm with power limitation EVSE power and corresponding EV state of charge.

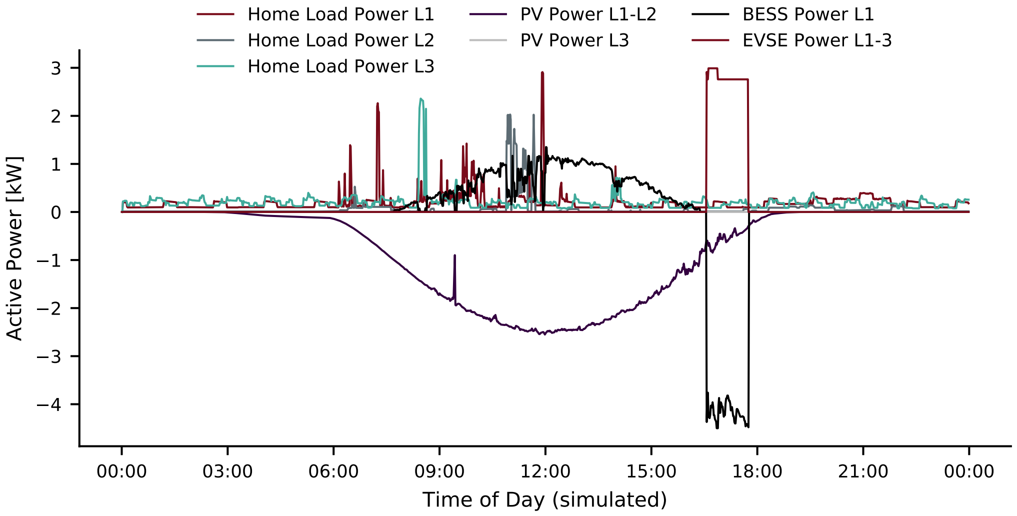

Figure B.4.: Overview of results using default system configuration and grid voltage level controlled algorithm with power limitation.

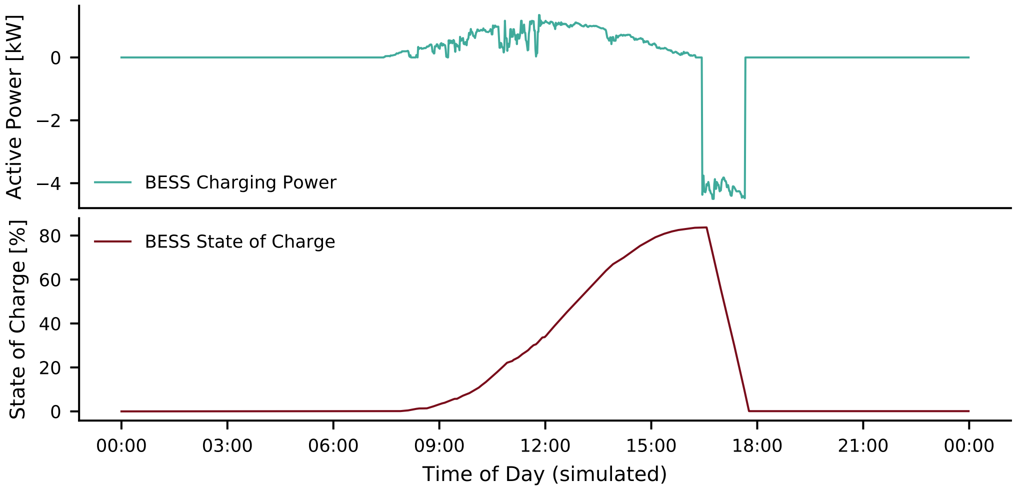

Figure B.5.: Grid voltage level controlled algorithm with power limitation BESS power and corresponding BESS state of charge.

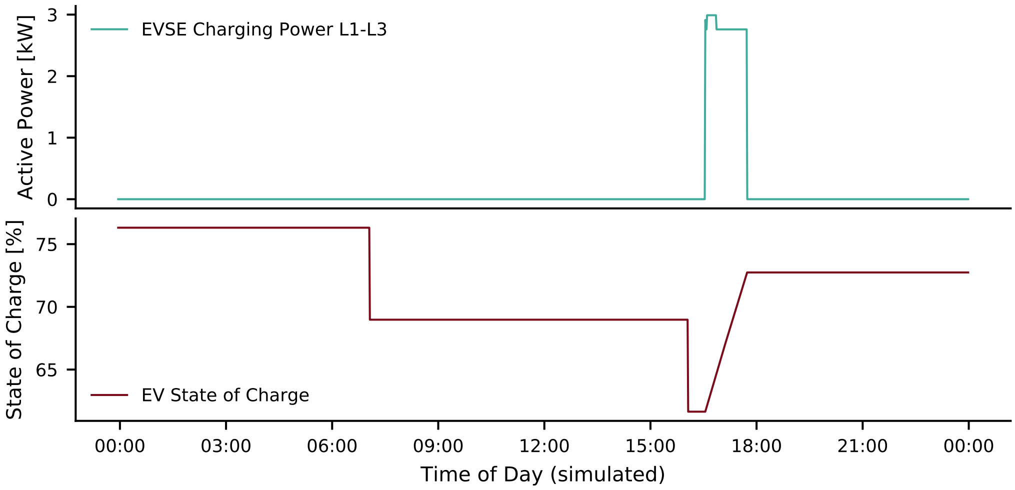

Figure B.6.: Grid voltage level controlled algorithm with power limitation EVSE power and corresponding EV state of charge.

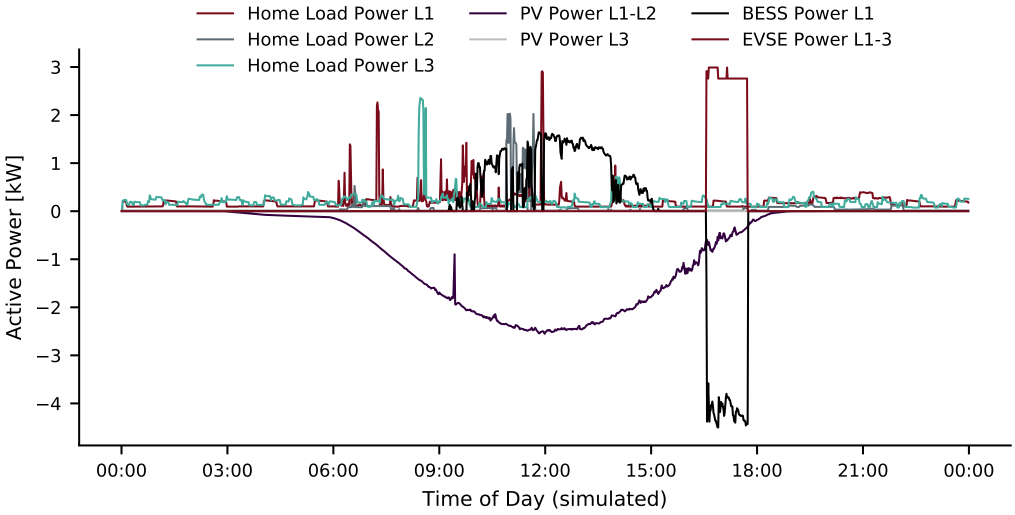

Figure B.7.: Overview of results using default system configuration and peak feed-in limiting control algorithm with power limitation.

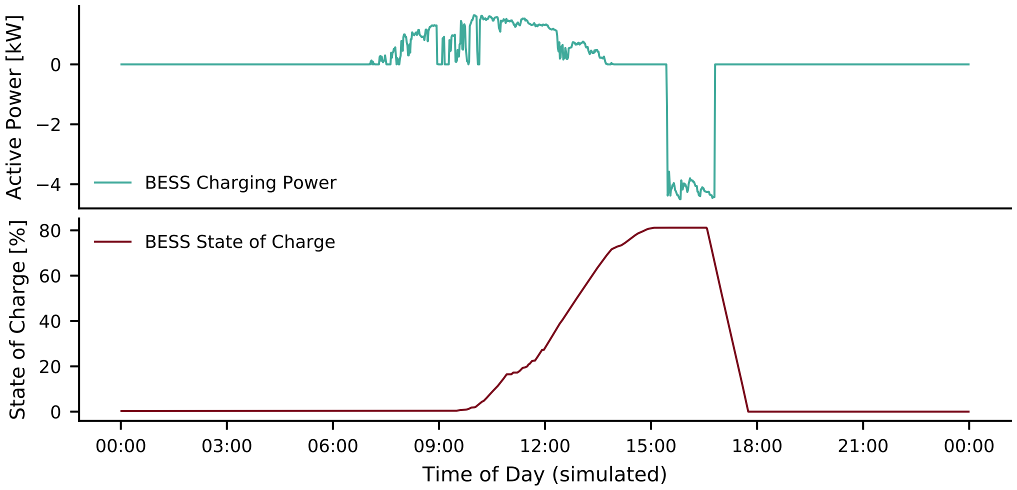

Figure B.8.: Peak feed-in limiting control algorithm with power limitation BESS power and corresponding BESS state of charge.

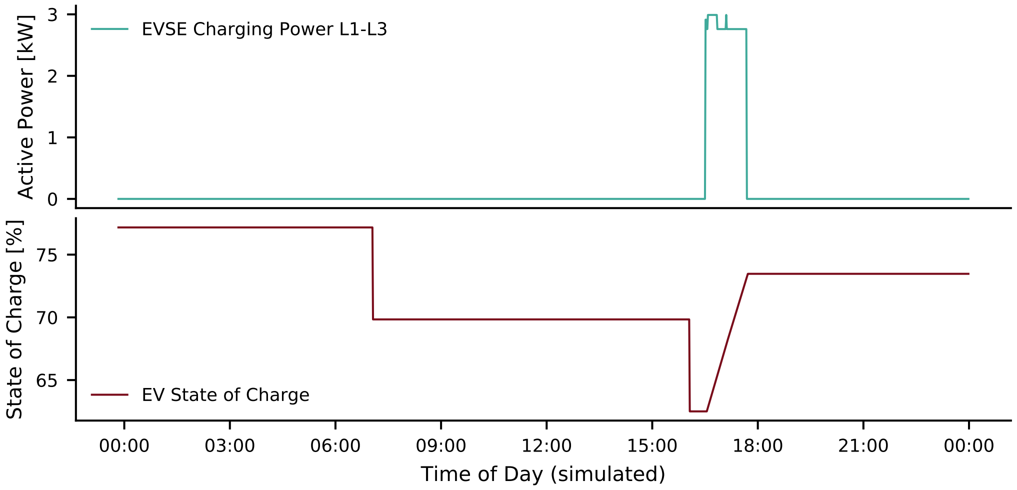

Figure B.9.: Peak feed-in limiting control algorithm with power limitation EVSE power and corresponding EV state of charge.