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Multi agent control based energy optimization of a prosumer household and a community with bidirectional electric vehicles

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Master Thesis

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ABSTRACT

Residential sectors have experienced an increase in solar photovoltaic installations in the last decades, due to which the prices of installation have reduced significantly, however, the feed-in tariff has also been lowered considerably. Many people have already invested in an electric vehicle and the numbers are increasing as accessibility and reliability have increased whereas the cost has decreased as compared to previous years. The problem emerges of overloading the local grid with high penetration when the photovoltaic systems are generating energy or when there is high peak demand when those cars are charging as there is a mismatch in time of generation and demand. This study presents how bidirectional electric vehicles can optimize the self-consumption of solar photovoltaic and increase the self-sufficiency of the loads in a household and a community, which are a group of households, by using controlled charging strategies. The optimization is performed using controllers in three different hierarchical levels: car, household and community. The car controller is a bidirectional charging station where the electric vehicle is connected, it takes user preferences that are used by the household controller to perform energy optimization by handling the mismatch between the generation and demand. The community level controller performs an on-the-top optimization along with the household and car controllers which curtail the power flow between the community and the electricity grid. The impact on the self-consumption and self-sufficiency of the community with a community charging station, where all the electric vehicles of the community are parked at one place for charging, is also studied in this thesis. The effect of the proposed control framework is investigated on a reference distribution grid (MONA grid, type 5) simulated in the software package DIgSILENT PowerFactory whereas the control framework is developed in Python. Real load and photovoltaic profiles were used to execute the simulations. The results show that there was a 40% and 36% increase in the self-consumption and self-sufficiency on a household level whereas a 51% and 31% increase on the community level when a coordinated control system was implemented.

Keywords: bidirectional electric vehicle, vehicle-to-grid, prosumer, solar photovoltaic, self-consumption, self-sufficiency, household, community, multi agent control

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviation	**Explanation**
α	Number of EVs connected to the LC in EO control mode
β	Number of EVs connected to the LC in SOC-control control mode
API	Application Programming Interfaces
$Batt_{nom}$	Battery capacity of the electric vehicle
$Batt_{useable}$	Battery usage capacity of the electric vehicle
BEV	Battery Electric Vehicles
CC	Community Controller
CO_2	Carbon dioxide
$Comm_{deficit}$	Community deficit
$Control_{initial}$	Initial control mode
COP21	The 21st Conference of the Parties
COP26	The 26th Conference of the Parties
CR	Car controller
DC	Direct Current
$Deficit_{energy}$	Energy the EV requires to reach its SOC target
$Deficit_{EO}$	Deficit of the household excluding the cars in EO mode
DOTG	Dependency on the Grid
EEG	Erneuerbare-Energien-Gesetz (German Renewable Energy Act)
EO	Eigenverbrauch Optimierung – Contol mode
EV	Electric Vehicles
HEV	Hybrid Electric Vehicles
HTW	Hochschule für Technik und Wirtschaft, Berlin
I_{grid}	Current at terminal the car is connected
LC	Local Controller
$LC_{Deficit}$	Total deficit of the household
LC_{over_con}	LCs which are over consuming power
LC_{over_gen}	LCs which are over generating power
$LC_{perfect\_eo\_con}$	LCs which are in perfect EO mode and consuming power
$LC_{perfect\_eo\_gen}$	LCs which are in perfect EO mode and generating power
$LC_{perfect\_eo}$	LCs which are in perfect EO mode
$\mathbb{N}$	Set of natural numbers
N	Number of LC connected to the CC
n	Number of CR connected to the LC
P_{eo}	Power the LC would like to support the CC with
P_{EV}	Power the EV is charging or discharging with

P_{give}	Maximum power the LC can generate
P_{load}	Power consumed by the loads in the household
P_{nom}	Nominal charging power of the EV
P_{PV}	Power generated by the PV system in the household
P_{set}	Active power set by the CR for the EV
P_{set_cc}	Additional setpoint given by the CC to the EV
P_{set_lc}	Setpoint given by the LC to the EV
P_{take}	Maximum power the LC can consume
P_{wt_LC}	The power distributed by the CC to the LCs
PHEV	Plugin Hybrid Electric Vehicles
PV	Photovoltaic
Q_{set}	Reactive power set by the CR for the EV
s	Smoothing function
SC	Self-Consumption
SOC	State of Charge
$SOC_{Idle\_reduction}$	Amount of reduction in the SOC of the EV after returning from Idle mode
$SOC_{initial}$	SOC of the car when it arrives at home
SOC_{max}	Maximum SOC an EV can charge to
SOC_{min}	Minimum SOC a EV can discharge to
SOC_{target}	The SOC of the car when it has to leave the house
SS	Self-Sufficiency
STC	Standard Test Condition
$Time_{leave}$	Time the car will leave the house
$Time_{remaining}$	A counter to indicate the start of Idle mode
V_{grid}	Voltage of the terminal the car is connected
V2G	Vehicle-to-Grid
WFH	Work from home

1 INTRODUCTION

The Paris Agreement, an international treaty on climate change, which is signed by 196 countries at the United Nations climate change conference (COP21) held at Paris in December 2015. The agreement aims to limit global warming below 2°C rise in temperature by reducing greenhouse gas emissions to achieve a climate-neutral world by 2050 [1]. At the COP26 event held at Glasgow in November 2021, the targets were made to hold the temperature rise by 1.5°C as the 2°C mark could even cause extreme catastrophic disasters. These goals would only be possible if the current emission is halved over the next decades. The most efficient ways to do so are by protecting the forests, reforming the global trade strategies, installing renewable power plants and adopting zero-emission vehicles among other ways [2]. The transport sector has been accountable for a major share of carbon dioxide (CO_2) emissions [3], in 2015 it contributed to 24% of the total CO_2 emission in the world. The transport sector can be categorized into air, water, railway and road. Within these categories, the maximum CO_2 emission is observed in the road sector accounting for 72% of the total emission within the transport sector [4, 5]. Electric vehicles (EVs) along with controlled charging strategies and distributed renewable energy sources are one of the solutions to the above stated problem.

EVs are more efficient than the traditional internal combustion engine vehicles and as people have become climate-sensitive, the acceptance of EVs has increased to a great extent. Favourable government regulations and increased charging infrastructure in some countries have encouraged people to buy EVs which have become cheap as compared to the previous years and are easily accessible. As per the 2021 year-end report of the German Federal Motor Transport Authority, there has been a 28% reduction in new gasoline fuled vehicles and a 36% reduction in diesel engine vehicles, on the other hand, the purchase of plug-in hybrid vehicles and battery EV has increased by 62% and 83% respectively as compared to 2020 [6]. The German government has a goal to have at least one million EVs on the road until the end of 2022 and seven to ten million EVs by 2030 [7]. With the increase in EVs, charging them would increase the energy consumption from the electricity grid. Electricity and heat production accounts for 42% of total CO_2 emissions in the world [8]. Problems of high peak loads might occur during the charging of such a large number of EVs in the grid. This could be solved by implementing time-shifting EV charging techniques which can reduce the peak loads [9]. Charging the EVs from the grid i.e. from the central power plants doesn’t reduce the CO_2 emissions, however, if they are charged with renewable energy sources they would have lesser emissions as compared to the ones being charged from the power plants. As the title of the thesis says ‘household and a community’ the most favourable and economical renewable energy source for them is a solar photovoltaic (PV) system.

Solar PV system installations have been increased since 2000 in Germany as profitable policies were announced which were in favour of the PV system owners [10]. Since then the prices of PV system installation have gone down extensively. In 2000, the German Renewable Energy Act called the “Erneuerbare-Energien-Gesetz” (EEG) had introduced the feed-in tariff which paid the PV system owners money, per kilowatt-hour bases, for the amount of PV energy generated by them which was fed into the grid. It started with 51 EUR cent/kWh for a contract period of 20 years. Over the years the feed-in tariff was reduced, but in 2012 the policies made a drastic change which reduced the feed-in tariff by 20% [11] resulting in a drop in the PV system installation as compared to the previous years [12]. In recent times as per EEG 2021, the feed-in tariff price for 1 kWh of PV energy is 7.92 EUR cents for a 10 kWh system and reduces as the system size increases [13], this makes it economically unfeasible for PV system owners to feed power into the grid. The current price a German consumer pays for 1 kWh of energy is 32.16 EUR cents [14], which makes it very important for the PV system owner to consume as much energy as possible which is being generated by PV rather than feeding it into the grid or even consuming energy from the grid. The biggest drawback in a PV system is the mismatch between the time of generation and consumption [15]. Most of the time when PV is producing power, there are not enough loads in the house to consume all the power, due to that, it is fed into the grid.

A battery backup installed in the house can increase the PV consumption by storing the PV power when generated during the day which can be used later when PV is not available. With increased self-consumption (SC) of PV due to the batteries, the self-sufficiency (SS), a factor indicating the amount of loads being sufficed by the PV energy, also increases. A study by the Fraunhofer Society shows that when a lithium-ion battery is introduced to a PV system the SC increases by 82% as compared to the conventional system without batteries [16]. An Australian study of 5 apartment buildings with real load profiles shows that when a battery is introduced to the PV system the SS increases by 12% and it even shaves overall building peak demand by 30% [17]. A stationary battery can be replaced by an electric vehicle to increase the SC and SS of the household in a similar manner, as 22 hours on an average a car is parked at home or at the office with 16 hours of uninterrupted parking as per a mobility survey in six European countries [18].

EVs as a replacement for stationary storage to consume the excess PV have been investigated in [19], [20], [21] and [22] on a household level. All the papers mention an increase in the loads when an EV is added to the house. The SC of PV did improve a little but not to a great extent as EVs are normally present at home during the late evenings, nights and early mornings. As there was always a mismatch between the EV charging and PV production, the SS has reduced when an EV was introduced [19]. In [21], SS and SC were found to be lower when introducing an EV in the house as compared to when it was not present. To increase the SC, the EV will have to charge during the day which will require a change in social habits or an increase in charging stations near the workplace as PV is produced normally when people are at work [20]. "*Cars and mobility are powerful emotional triggers and thus the proposition to curtail or shift mobility is a difficult one…."* [23]. Smart charging techniques have to be implemented to see better results of EVs being used as battery storage systems for a household. In [24], results of uncontrolled and controlled smart charging techniques of EV are shown for a household with PV. SC and SS of a household are higher with a controlled strategy as compared to the uncontrolled strategy by 8.7% and 6.9% respectively and it even decreases the peak loads to a larger extent. Even with controlled strategies, there is a lot of interaction of power between the household and the grid which still make the system fully dependent on the electricity grid. To reduce the interaction further, loads too have to be sufficed by the EV to be independent of the grid i.e. the EV will need to have capabilites of bidirectional power flow to consume the PV and to serve the loads in the house.

Concepts of Vehicle-to-Grid, where the EV can charge as well as discharge, has been used in [25], [26] and [27] for a household. Techno-economic analysis for a span of ten years is shown in [26], where a bi-directional charging EV can reduce the operational expense by 37% but has effects on the EV battery lifetime which is reduced by 12%. Controllers were used for implementing the V2G strategies in the household. In [25], a household with PV and EV is simulated which results in a 13% increase in the SC value with bi-directional charging strategies as compared to unidirectional charging.

Studies on a community level i.e. of a group of households are done in [19] and [21] where each household is assumed to have at least one EV connected to it. No optimized charging techniques are used to increase the SC and SS of the community. It has been found that the SS of the community reduces when EVs are introduced to the households but the SC increases. In [24], distributed and centralized charging strategies are used to improve the SC and SS of the household and the community. Centralized charging is when a central unit decides on the charging power of the EV. It requires a complex algorithm and an advance communication infrastructure, whereas the distributed or decentralized charging of EV is done on a user level which is less complex and has low privacy violations. Centralized charging strategies overperformed distributed charging strategies which were indicated with an increase in the SC value of the community.

Research on bi-directional charging is only performed on a household level, none of the papers presented in the literature talk about bi-directional EV used to optimize the community's SC. V2G strategies used on a community level to suffice the loads in the community and to increase the PV consumption is not shown in any paper. As well as no models in the literature try to minimize the dependency of the household or the community from the grid. Community charging stations, a place where all the EVs of the community are parked and charged from a single control unit, are not simulated in any research paper on focusing to increase the SC of the community.

In this study, a controller based hierarchical model was developed to improve the SC and SS of a household and a community using bi-directional EVs connected to each household in a first step. Controllers are modelled to optimize the household and the community to make it less dependent on the grid. Community charging stations will be simulated in a second step to see an effect on the SC and SS values of the community. In the thesis, the following research questions will be answered:

1. What will be the impact on self-consumption and self-sufficiency of a household when a controller based bi-directional charging electric vehicle is used for energy storage?
2. Is there any change in the self-consumption and self-sufficiency of the community when it is optimized using centralized bi-directional charging strategies?
3. Will a community charging station impact the self-consumption and self-sufficiency of the community as compared to home charging stations?

The thesis will not include a study on the impact of the controllers on the stability of the grid, as well as no economic analysis will be done to study the profitability of the consumer.

The thesis is structured as follows: Chapter 2 gives a theoretical background to the reader to understand the methodology. Chapter 3 describes the methodology of the Energy Optimization Model along with the controller architecture. Scenarios for the simulation are also defined in this chapter. The results are presented in chapter 4 of a single household and a community with home charging and community charging stations. Conclusions based on the results are made in chapter 5.

2 THEORY

In this chapter, the theory required for the reader to understand the thesis is presented. The theory will include a short introduction on the electric grid used for the simulation followed by a brief introduction on solar photovoltaic and electric vehicles and explaining to the reader how self-consumption, self-sufficiency and dependency on the grid are calculated. The software used in the simulation are explained at the end of this section.

2.1 Grid Structure

A reference grid is used by researchers to simulate a model or a controller and examine the results. The main reason reference grids are used is because real grid data of the distribution grids are not available or not open access. One can say if the results on the reference grid are in order then their model or controller would work on a real grid too. In this thesis, an opensource reference grid from the project MONA 2030 [28] is used for simulations. The project focues on optimization of transmission and distribution grids with high renerable energy feed-in. There are a total of 9 grids based on the size of the city, population and if it's in a rural or urban location. Grid type 5 has been selected for this study based on the number of houses in the model and has features similar to a small town as per [28].

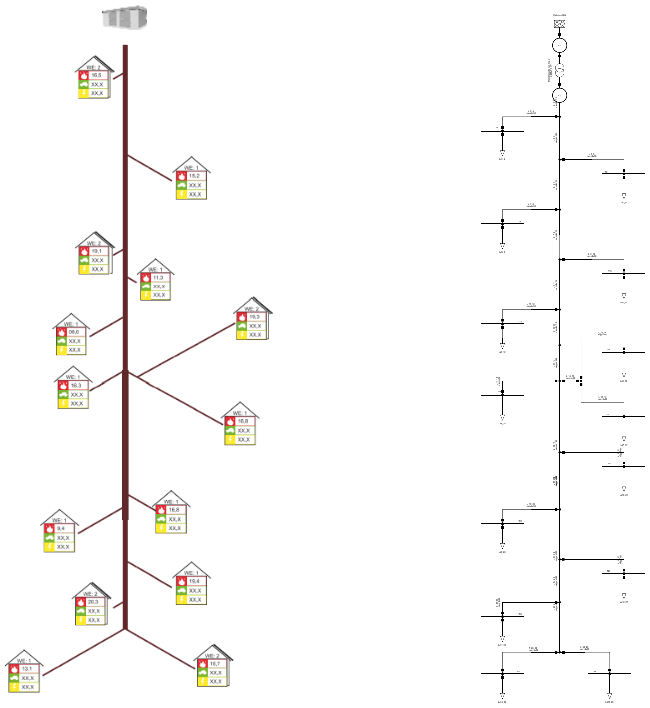


Figure 2.1: MONA grid type 5 [28] (left); PowerFactory model of MONA grid type 5 (right)

The structure of the grid can be seen in Figure 2.1, it has 14 households connected to one feeder. The length of the lines and other specifications come with the project MONA

2030 model. At the end of the line, there is a 400 kVA transformer connecting the low voltage grid of 0.4 kV to a medium voltage grid of 10 kV.

2.2 Solar Photovoltaic

Solar PV systems are electricity generating plants that require a solar PV panel to produce direct current (DC) power and an inverter to convert the DC power to alternating current which can be used by the consumer (Figure 2.2). The solar PV panels are made of PV cells which are semiconductor devices that convert light into electricity, an array of these cells connected in a combination of series and parallel fashion make a PV panel. The output of the PV panel varies based on the degradation of the PV module, variation of solar radiation, the module temperature, shading or soiling on the PV panel and the model's orientation and tile [29].

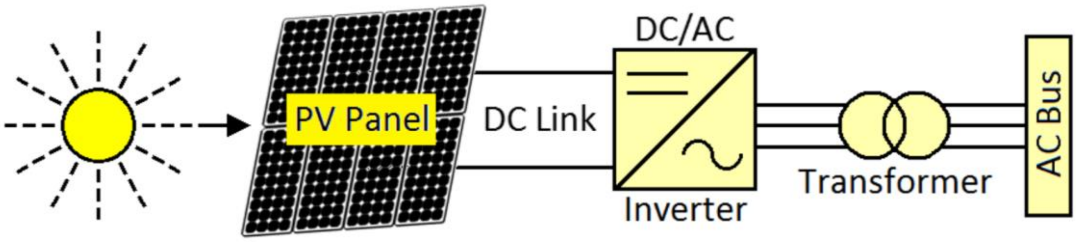


Figure 2.2: Solar PV system arrangement [29]

PV systems are mainly categorized into three types: on-grid, off-grid or hybrid systems. On-grid systems are connected directly to the electricity grid, they have a net meter that monitors the amount of power generated by the PV system and the power which is fed into the grid. Depending on the countries policies, the feed-in power is paid based on a per kilo watt hour basis or as a credit which a consumer can claim when there is no PV power available. An off-grid system is a PV system that has a battery backup and is not connected to the grid, it stores the excess PV energy into the battery which is utilized when PV power is not available. Hybrid systems are a combination of on-grid and off-grid systems, they have a battery for backup power as well as are connected to the grid. As the thesis is focused on a household level, PV systems are normally installed on the rooftop of the households which can be of any of the 3 categories mentioned. As per [30], most of the PV systems installed in Germany are under 10 kW, as they get a better price in the feed-in tariff compared to the bigger systems as per §48 (2) of the EEG 2017 [31].

2.3 Electric Vehicles

A Hungarian inventor, Anyos Jedlik, designed the first electric car motor in 1828, two years later two researchers Robert Anderson and Thomas Davenport developed an electric car in 1830 [32], since then EVs are in the market and in the last decade they have been highly accepted by many people in the world because of their low emissions as compared to internal combustion engine vehicles. EVs are operated by electric motors which replace the internal combustion engine that burns fuel to generate power. They can be categorized as Battery Electric Vehicles (BEV), Plugin Hybrid Electric Vehicles (PHEV) and Hybrid Electric Vehicles (HEV) [33]. BEVs run only on batteries and an electric motor, the battery can be charged using grid electricity, house outlets and even by solar PV panels. PHEV are a combination of BEVs and a traditional internal combustion engine that can be used if the battery is empty or to even recharge the battery in some cases. HEV has two systems, one is an internal combustion engine with a fuel tank and the other is an electric motor with a battery. They cannot be recharged from the electricity grid, all the energy to charge the car comes from the gasoline engine and regenerative braking. Regenerative breaking is a process that uses the EV’s motor to assist in slowing the vehicle and to recover some of the energy normally converted to heat by the brakes [33]. For this study, BEVs are considered for the simulations which not only charge themselves from the grid but even can discharge to the grid called as bidirectional EVs. Such bidirectional charging in the scientific world is called as Vehicle-to-Grid technology which can be used for energy management or optimization purposes, maintaining grid stability and reliability, and even as a restoration reserve during a blackout [34].

2.4 Self-consumption & Self-sufficiency

SC and SS are factors to determine how much PV energy is consumed by the entity (household in this case) and how much is the consumed energy sufficient to the total loads of the entity. To understand it in a better way, refer to Figure 2.3, it is a graph of power vs time of the day. The grey area is the load of the entity and the yellow is the amount of PV energy generated. A and D are regions when there is no PV production, the overlapping area C is the region where loads of the house are being sufficed by the PV generation, whereas B is the region of excess energy which is produced by the PV system and is fed into the grid.

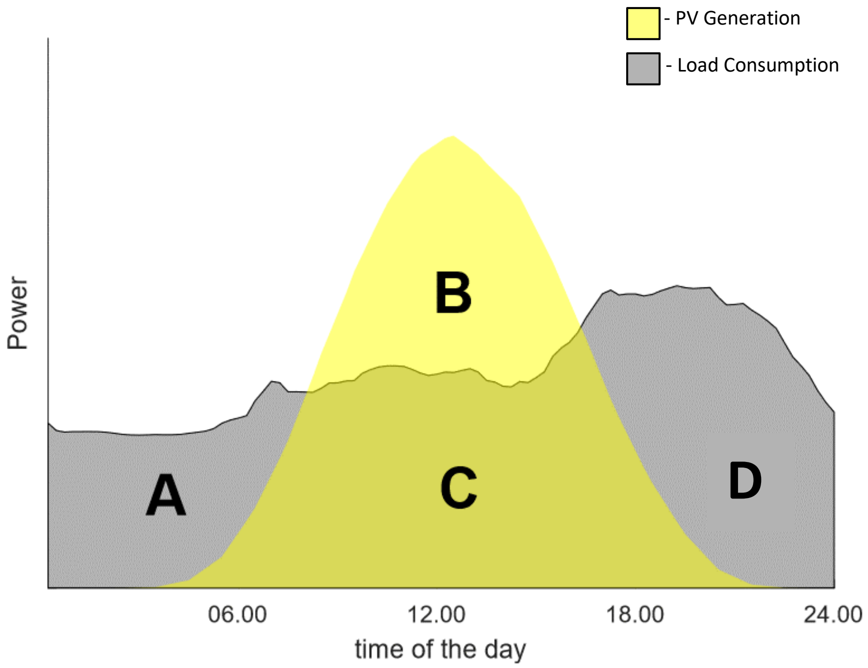


Figure 2.3: Illustration used for self-consumption and self-sufficiency explanation

As per [35] and [24], the SC is defined as the fraction of self-consumed PV energy to the total PV energy production, it can be represented by Equation *(2.1)* based on Figure 2.3.

$$Self\text{-}Consumption = \frac{C}{B + C} * 100 \quad [\%] \tag{2.1}$$

Based on the same references, the SS is defined as the loads supplied by the PV generation to the total loads of the entity, it can be represented by Equation *(2.2)* based on Figure 2.3.

$$Self\text{-}Sufficiency = \frac{C}{A + C + D} * 100 \;\; [\%] \tag{2.2}$$

2.5 Dependency on the Grid

Dependency on the grid (DOTG) is a self-made factor that indicates how much energy is being exchanged between an entity and the electric grid i.e. how much an entity is dependent on the electricity grid. To understand it in a better way, consider Figure 2.3, in regions A and D the entity is taking power from the grid, and region B is feeding power to the grid, addition of all of them is the DOTG of the entity.

$$Dependency\ on\ the\ Grid = A + B + D\ [kWh] \tag{2.3}$$

In Equation *(2.3)*, the unit of DOTG is in kWh and it can be noticed that region C of Figure 2.3, is not considered as the loads are being sufficed by the PV production so those loads are not dependent on the grid.

2.6 Software Used

The following software was used in the master thesis:

- DIgSILENT PowerFactory
- Python

2.6.1 DIgSILENT PowerFactory

DIgSILENT is a software and consulting company based in Gomaringen, Germany which is specialized in the field of electrical power systems for transmission, distribution of generation of electricity. PowerFactory is a software made by them for power system analysis of electric grids. It has functionalities like load flow simulations, real-time simulations, quasi dynamic simulations, stability analysis functions and many more functionalities that are required for advanced gird simulations [36].

For the master thesis, the MONA grid type 5 was built in PowerFactory and load flow simulations were carried out on the model. Load flow even known as power flow simulations are steady-state simulations used to analyze the power system. With load flow simulations one can find out the voltage of busbars, loading of lines, current flows, power flows, examine faults and many more indicators to study the power system. There are different numerical methods to perform load flow simulations like Gauss-Seider, Newton-Raphson and Fast Decouple. In this study load flow was carried out using the Newton-Raphson method. It is an iterative method used for solving non-linear equations. Each node i.e. connection point in the grid is represented with a non-linear equation and is approximated to a linear simultaneous equation using Taylor's series expansion. The Newton-Raphson method is the most reliable among the three methods because it converges fast to the solution and is more accurate [37].

PowerFactory has even functionalities of executing simulations from Python using the PowerFactory library. Simulations for the thesis were carried out using the Python interface of PowerFactory to execute load flow calculations.

2.6.2 Python

Python is a simple, user-friendly programming language that was created by a Dutch software programmer, Guido von Rossum, in the late 1980s which can be used for a task as simple as basic mathematics to complex programs to make real-world applications and software [38]. Python was used to build the controlling part of the model which is described in Section 3.2. Library's like NumPy, Pandas, math and os were used to construct the model along with visualization libraries like Matplotlib and tqdm were used for data visualization and processing.

3 METHODOLOGY

In this chapter the complete methodology of the thesis is described, it will help the reader to understand details about the modified grid structure, structure of the controllers and the flow of the simulation. Scenarios for the results are defined on which the simulations will be performed.

3.1 Modification of grid structure and date sets for time series

‘Prosumer household and a community’, which is a part of the title will be explained with detailed diagrams in this section. As stated in section 2.1, MONA grid type 5 will be used for simulation, and it has to be modified as per the need of the thesis. Along with that, the source of the time-series data used for loads and PV will be presented.

3.1.1 Prosumer Household

Prosumers are defined to be energy customers actively managing their own consumption and production of energy [39]. It could be a business organization, a community or a household. They rely on renewable energy sources like solar PV panels to generate electricity along with home energy management systems, smart meters, energy storage systems, electric vehicles and even electric V2G systems. For the thesis as seen in Figure 3.1, each household has been defined to have a load, a solar PV system and a bidirectional EV.

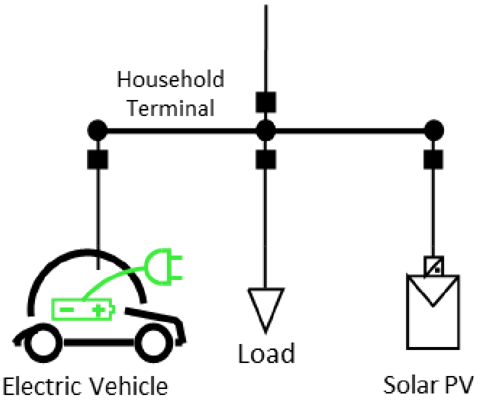


Figure 3.1: Household having loads, PV and a bi-directional EV

3.1.2 Community

A community is defined to have many households, in this case 14, as there are 14 loads in the MONA grid type 5 model, and each of those loads will be modified as a prosumer household and the new grid structure can be seen in Figure 3.2.

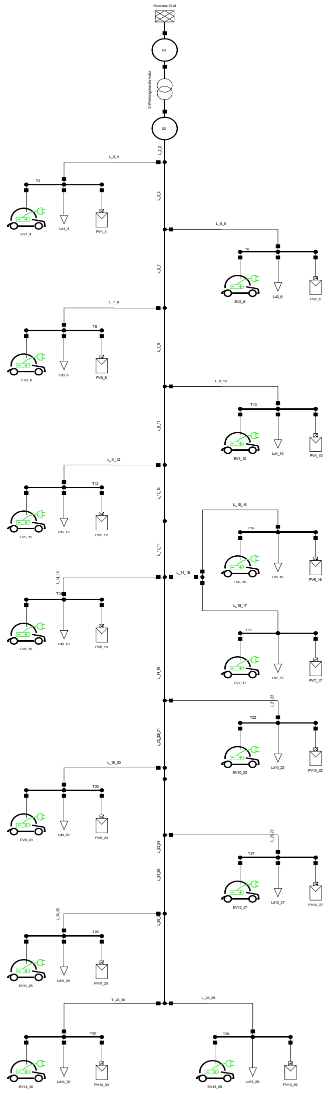


Figure 3.2: Modified MONA grid type 5 structure for a community

3.1.3 Loads

Real load profile data has been used for the loads in the modified grid structure which are taken from the *Hochschule für Technik und Wirtschaft (HTW), Berlin* database. The data has accounted for electric loads like cooking stove, washing machine, refrigeration, and lighting as well as heating loads like a heat pump to be included as an electric load. It is an open-source data of 74 German single-family households in one second as well as in one minute resolution of the year 2010. As seen in Figure 3.3 (left), the energy consumption of 74 load profiles has been shown, the red line denotes the average annual consumption of those 74 households that is 4.7 MWh which is equivalent to say that it portrays a household of 4 members in a family [40]. The histogram on the right of Figure 3.3 shows that the maximum number of houses have an annual consumption close to the average value which is 4.7 MWh.

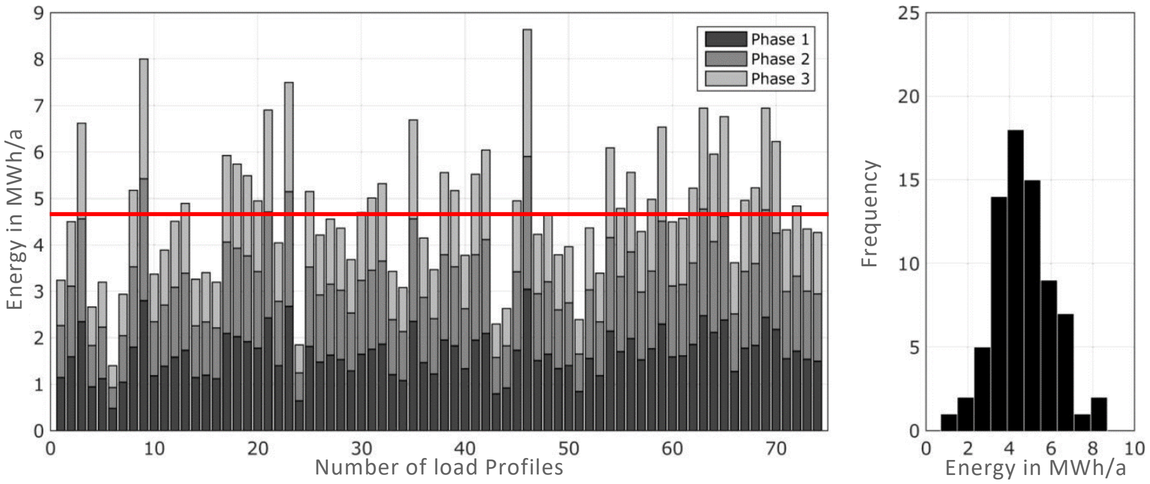


Figure 3.3: Annual 3-phase consumption of the 74 households (left); Histogram of the total consumption of each household [40] (right)

The data originally is obtained of three phases of active and reactive power each, making it six time-series data sets. They were combined to a single active and reactive power value by adding all three phases. For the thesis, the simulations were performed for the year 2021 as the weather data is available for the year 2021. The assumption made was that the loads would be the same in 2021 as they were in 2010 as there is a lack of high-resolution open-source data available for the year 2021. This assumption could even be made because the number of household loads has increased since 2010, but the efficiency of the loads has also increased over the years making it possible to use the same load profile of 2010 for 2021.

3.1.4 Solar Photovoltaics

The solar PV system was modelled using the PVLIB library of Python for each of the households in the community. PVLIB is a library made for Python and MATLAB, it is a toolbox developed by the Sandia National Laboratories and is used to design and model all aspects related to PV systems. It has three sets of application programming interfaces (API) which are the i) Core Functions, ii) the Location & PVSystem classes and iii) the ModelChain class [41]. For the thesis, the ModelChain class method was used in which it requires a time series of weather data as an input and it generates a time series power data for the given system size. As seen in Figure 3.4, the ModelChain method requires inputs like the inverter data, PV panel data, panel mounting data and weather data to give a time series power output.

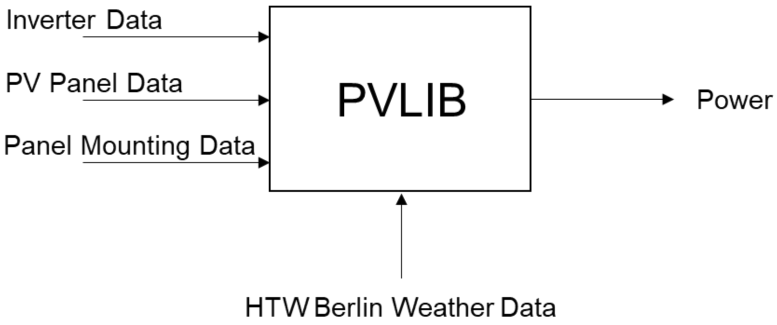


Figure 3.4: Block diagram of the ModelChain class in PVLIB

Inverter parameters like maximum DC power and inverter efficiency have to be given. The panel mounting data includes the coordinates where the PV system is located, the azimuth and the surface tile. The PV panel data includes the maximum watt peak power at standard test condition (STC) and the system size which requires the number of modules in a string and the number of strings. The weather data is a time-series data that is taken from the HTW Berlin database [42]. The data is obtained from 15 sensors located at the HTW berlin campus, it is available in multiple resolutions of direct, diffused and normal irradiance. For the thesis, the one minute resolution data was used. The values of the parameters describer can be found in Table 3.1.

Table 3.1: PV System Design Parameters

Parameters	**Value**	**Unit**
Inverter: Maximum DC power	10,000	W
Inverter Efficiency	96%	-
Location	Berlin, Germany	-
Coordinates	(52.520,13.405)	-
Azimuth	180°	-
Surface Tile	13°	-
Panel: Maximum Power (at STC)	250	W
Number of Modules in a String	10	-
Number of Strings	3	-

As per the design parameters, the PV system size is 7.5 kW_p and it is the same design selected for all the households in the community. For the simulation of the results, two scenarios were considered, one with a higher irradiation (15th June 2021) as seen in Figure 3.5 and the other with a lower (1st Jan 2021) in Figure 3.6. In the figures, the values are negative which portray a generation similar to a negative load.

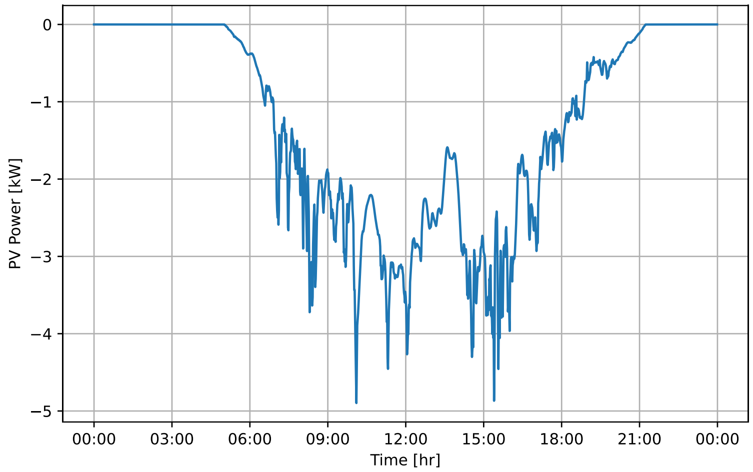


Figure 3.5: PV system output with high irradiation

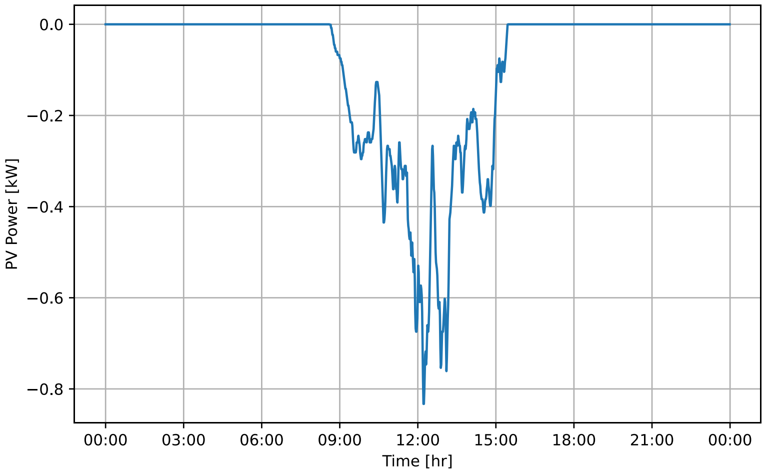


Figure 3.6:PV system output with low irradiation

3.1.5 Electric Vehicle

Honda e, an EV manufactured by Honda Motor Company Ltd. has been selected to be modelled as an EV for the study. It is a 3-door or a 5-door hatchback EV that was released in 2020 for sale in Europe [43]. The parameters considered for modelling the EV can be seen in Table 3.2 [43].

Table 3.2: Honda e specifications used for modelling

Parameters	**Description**	**Value**	**Unit**
$Batt_{nom}$	Battery Capacity	35.5	kWh
$Batt_{useable}$	Battery Usage Capacity	28.5	kWh
P_{nom}	Charging Power (AC)	6.6	kW

As the battery usage capacity is 80% of the actual battery capacity, two new parameters were introduced called SOC_{min} and SOC_{max} which specify the state of charge (SOC) limits of the battery to be 10% and 90% respectively. This implies, the EV cannot discharge lower than SOC_{min} and cannot charge more than the SOC_{max} limit.

3.2 Energy Optimization Model

The model of the thesis will be presented in this section, the part of the title ‘Multi agent control’ will be explained in brief. A detailed explanation of the control strategy used for energy optimization will be presented with flowcharts and diagrams.

As mentioned in Section 2.6, load flow simulations were performed in PowerFactory and the calculations for finding the optimized control strategy using controllers are examined in Python. The simulations were of one minute time step as all the data i.e. load profile and PV were in one minute resolution.

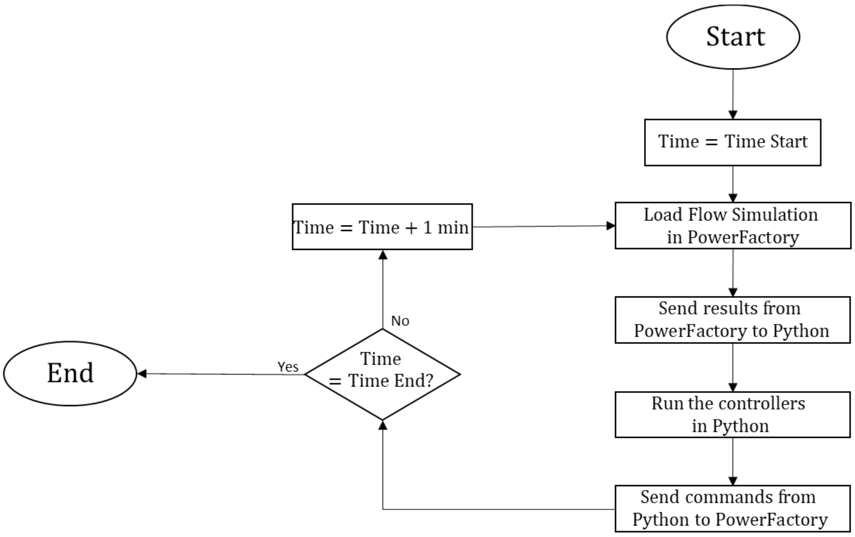


Figure 3.7: Basic flow chart of the energy optimization model

Figure 3.7 shows a basic understanding of how the simulation is taking place. During the first iteration, the time is the start time and load flow simulations are performed in PowerFactory using the PowerFactory-Python API. The results of the simulation are extracted to Python and the controller logic is simulated based on the results within Python. The instructions depending on the decision of the controllers are sent to the PowerFactory model and if time is not time end, then the next time step is simulated.

3.2.1 Controller Hierarchy and Structure

The most important components of the model are the controllers which were designed to fulfil the aim of the thesis, there were namely three controllers:

- Car Controller (CR)
- Local Controller (LC)
- Community Controller (CC)

In Figure 3.8 starting from the lowest hierarchy, the user gives instruction to the CR as it is a user input controller, as well as the CR has default values that are considered if no user input is given. The LC is an overlaying controller structure, with lower priority than the CR. The CC which is on top of the hierarchy chart has the least priority than any other controllers and is communicating only with the LC. In the designed model, the user was given the highest priority as the controllers were designed to satisfy the needs of users.

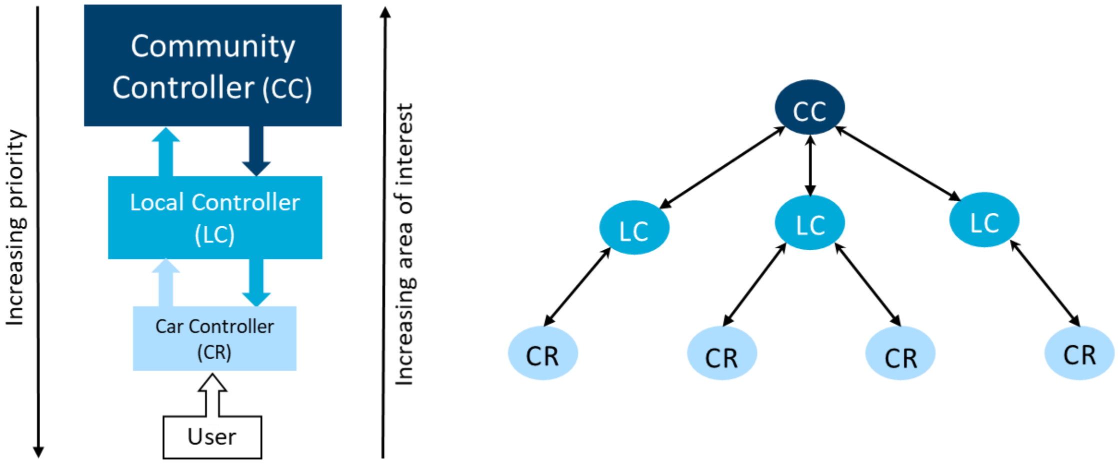


Figure 3.8: Controller hierarchy

For the designed model, there can only be one CC, but multiple LCs can be connected to the CC and one or multiple CR can be connected to each LC. The area of interest defines the boundaries of the controllers to which it can perform its control algorithm. Figure 3.9 shows the area of interest of the CC which accommodates all the LCs. The LCs boundaries lie only within each household i.e. looking at the loads, PV and the EV, whereas the boundaries of the CR are for each EV in the household.

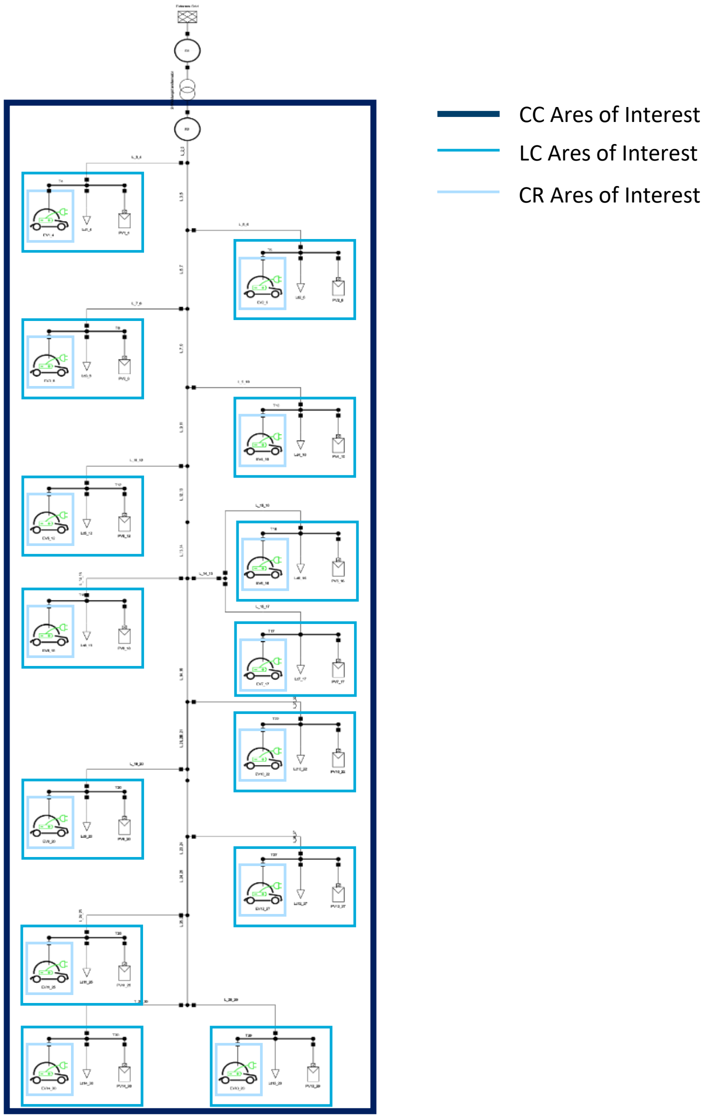


Figure 3.9: Area of interest of the controllers

Such kind of control hierarchy as per [44] is to be called as a multi agent control. It is a decentralized, scalable, and a multi-level control strategy in which each agent i.e. controller in our case is independent of the higher hierarchy controllers which means they can even function if the higher hierarchy controller breaks down or is not present. It is scalable, as one can introduce multiple LCs and CRs and still the functionality of the model remains unchanged.

3.2.2 Car Controller

The CR is connected to each EV of the respective household as seen in Figure 3.10. There can be more than one CR connected to one household if there is more than one EV.

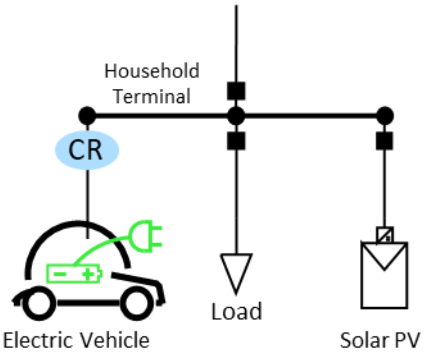


Figure 3.10: Connection point of the car controller

Figure 3.11 shows the structure of a CR, it can be seen that there are 4 input and 2 output parameters out of which some are physical flow of energy, i.e. power flow shown with a solid line arrow and some are information flow shown with a dashed line arrow.

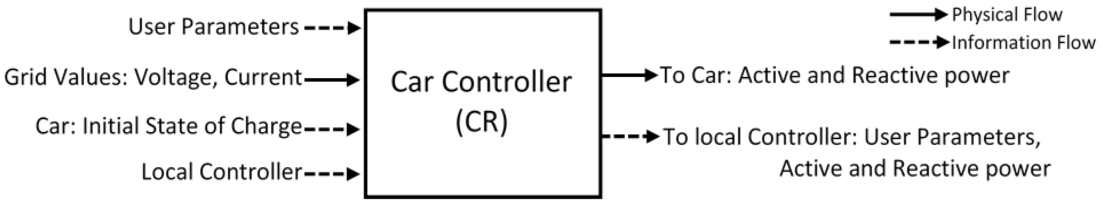


Figure 3.11: Structure of a car controller

As already mentioned, the CR gets instructions from the user so there are user input parameters which include the time when the user wants to take the car out of the house called $Time_{leave}$, the target SOC of the car i.e. till what SOC level does the car have to be charged when time reaches to $Time_{leave}$. Another input from the user is the control preference which is 0 or 1 and will be explained later in this section. The grid and the EV are physically connected to the CR as the grid has to provide the power to charge the EV. In every time step, the CR will set the active (P_{set}) and reactive (Q_{set}) power setpoints for the EV to charge or discharge. For the thesis, there is no reactive power considered for charging or discharging which makes Q_{set} always equal to zero. P_{set} passes through a smoothing function (s) which is a mathematical model that prevents any sudden changes in the power value when charging or discharging the EV. The smoothing function considers the previous P_{set} value at time = t - 1 and the new P_{set} value at time t to generate a P_{EV} value with which the car is finally charged or discharged. If s is set to one, the smoothing function doesn't affect the P_{set} value which means P_{set} is equal to P_{EV}, on the other hand, the lower the value of s the higher is the smoothing. When the EV is connected to the CR, the initial SOC ($SOC_{initial}$) i.e. the SOC of the EV when it arrives at home is saved and sent to the LC which uses it for its calculations. As the CR is connected to the LC, there is information flow to and from the LC in each time step. The parameters are explained briefly in Table 3.3 with their respective units.

Table 3.3: Input and output parameters of the car controller

User Parameters		
Parameters	**Description**	**Unit**
$Time_{leave}$	Time the car will leave the house	hh:mm
SOC_{target}	The SOC of the car when it has to leave	%
$Control_{initial}$	Control mode preference	-
Grid		
V_{grid}	Voltage at the terminal the car is connected	V
I_{grid}	Current at the terminal the car is connected	A
Car		
$SOC_{initial}$	SOC of the car when it arrives at home	%
P_{set}	Active power set by the CR for the car	W
Q_{set}	Reactive power set by the CR for the car	var
P_{EV}	Final power set for the car	W

The main responsibilities of the CR include protecting the EV from violating the SOC limits, which means to stop discharging the EV if it reaches SOC_{min} or to stop charging the EV once it reaches SOC_{max}. It even protects the EV from exceeding the charging power beyond the nominal charging power (P_{nom}). These features are common with the current home charging stations available in the market. The CR built in this thesis stands out by introducing the different control modes. There are 3 control modes an EV can be in:

- SOC-control mode
- EO control mode
- Idle mode

Each EV at every instant of time in the simulation will be in a particular control mode based on the user or based on some special conditions. During the simulation, as seen in Figure 3.12, in every time instant each EV is checked if it's in the Idle mode, it's the mode that states if the car is at home or not at home. The Idle mode check block is explained in Figure 3.13. If not idle (that means that the car is connected to the CR), it checks for SOC-control which is a mode where the EV charges itself till it reaches SOC_{target}. If that is also false, then the car checks if it's in the EO control mode, which is a mode where the car helps to increase the SC and SS of the household. The term EO is coined from the German word '*Eigenverbrauch Optimierung*' which means self-consumption optimization.

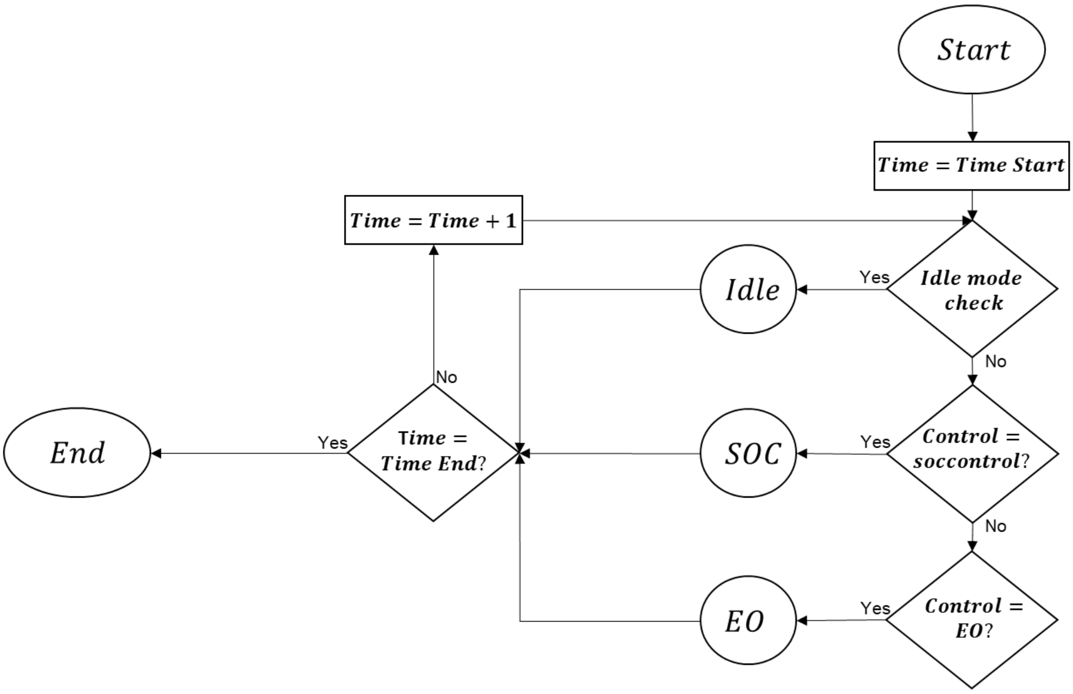


Figure 3.12: Control mode flow chart within the car controller

The EO and SOC-control are user input parameters, i.e. the users can specify if they want to put their EV in SOC-control mode i.e. $Control_{initial}$ as 0 or in EO mode i.e. $Control_{initial}$ as 1. The default $Control_{initial}$ of the CR is set to EO mode i.e.1, it can be changed by the administrator. Idle mode cannot be defined by the user as it is just a pseudo mode to indicate that the car is not present at home.

3.2.2.1 Idle Mode

The Idle mode is a state of the EV when it is not at home. It starts when $Time_{remaining}$ in Equation *(3.1)* reaches zero and ends when time is equal to *'End Idle Time'*, which is the time when the EV is reconnected with the CR i.e. returns back to home.

$$Time_{remaining} = Time_{leave} - Time \tag{3.1}$$

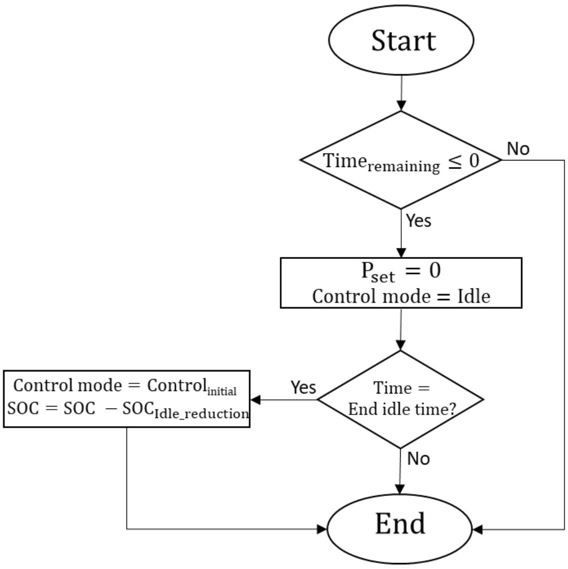


Figure 3.13: Idle mode check flow diagram within the car controller

The flow diagram of Idle mode check is shown in Figure 3.13, it is executed on every simulation step. All the EVs have to check if they are in Idle mode by passing through the $Time_{remaining}$ condition. Once the car is in Idle mode, it cannot be charged or discharged, so the P_{set} is set to zero. The car comes out of Idle mode if the time equals to *End Idle Time.* The control mode is changed to its initial control mode $Control_{initial}$ or to the default control mode. As the EV had gone out, the SOC of the EV after arriving at home will not be the same as it left the home, so the SOC is subtracted by a factory $SOC_{Idle\_reduction}$, which is in percentage and it can be defined at the start of the simulation. If an EV doesn't satisfy the first condition ($Time_{remaining} \leq 0$), then that means the EV is not in Idle mode and then it checks for SOC-control or EO mode explained in the next sections.

3.2.2.2 SOC-control Mode

SOC-control mode is made for the users who just want to charge their car till the SOC_{target} limit once the EV is connected to the CR. It does not perform any energy optimization features for the household and will act like a normal EV charging station. The EV is charged with a nominal charging power of P_{nom} and is charged with reduced power of $\frac{2}{3} \cdot P_{nom}\left(1 - e^{SOC - SOC_{target}}\right)$ if it reaches to 95% of SOC_{target} which can be called as SOC_{target_min} seen in Figure 3.14 and Figure 3.15. The exponential term gradually reduces the charging power until the EV reaches the target SOC value. The SOC_{target} limits are introduced so that during charging if the SOC of the EV reaches a value within the limits, it can be said that the SOC target has been achieved even if it has not reached the exact SOC_{target} value, it is like a tolerance factor introduced for the SOC_{target}. Once the SOC reached very close to the SOC_{target} value, P_{set} is set to zero.

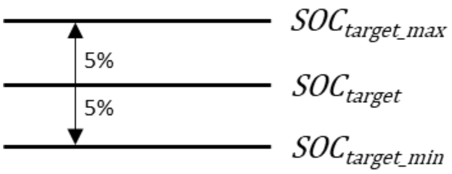


Figure 3.14: SOC_{target} *minimum and maximum limits as a tolerance factor*

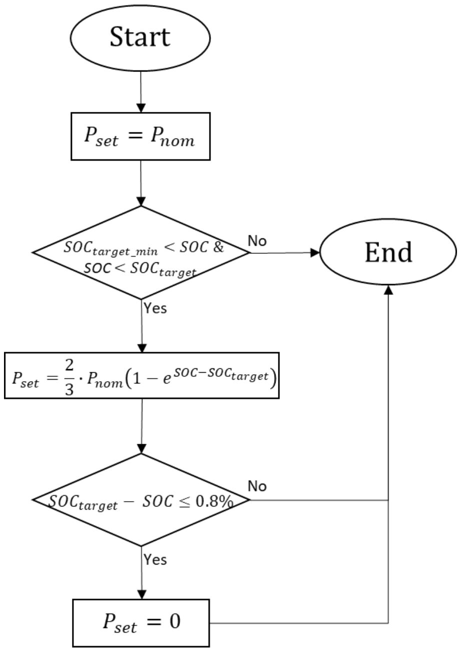


Figure 3.15: SOC-control mode flow diagram within the car controller

3.2.2.3 EO Control Mode

The EO mode is the most important mode of the EV to fulfil the goal of the thesis. It is a mode in which the EV helps the household to increase the SC and SS of the house or the community. It is designed in such a way that the EV will discharge to the loads when there is high consumption from the grid i.e. the loads are higher than the PV production, and it will charge itself if there is high generation in the house i.e. PV production is higher than the loads. By performing such functions, it will increase the SC of the PV and with the increased SC, the SS will increase too. In both cases, the household will be less dependent on the grid.

Concerning the simulations, the LC is the brain behind the EO control mode, but the CR plays a role in keeping the EV within the SOC limits and protecting it from exceeding the P_{nom} charging limit. If the EV is in EO mode, that means it is either charging or discharging, but it has to reach the SOC_{target} before it reaches $Time_{leave}$, this is also governed by the CR. To perform this function, it first calculates the deficit energy ($Deficit_{energy}$), which is the energy the EV requires to reach the SOC_{target} value, it is calculated using Equation *(3.2)*. The deficit energy is divided by the $Time_{remaining}$ value to give a power that should not exceed the P_{nom} value because if it does, it would not be able to charge the EV till the SOC_{target} value before it leaves the house. This condition is called the Time-Power condition (Equation *(3.3)*) and is checked at every simulation step by the CR. Once this condition is true, the CR put the EV from EO mode to SOC-control mode to start charging the EV.

$$Deficit_{energy} = \left(SOC_{target} - SOC\right) * Batt_{nom} \tag{3.2}$$

$$Time - Power\ Condition\text{:}\ \frac{Deficit_{energy}}{Time_{remaining}} > P_{nom} \tag{3.3}$$

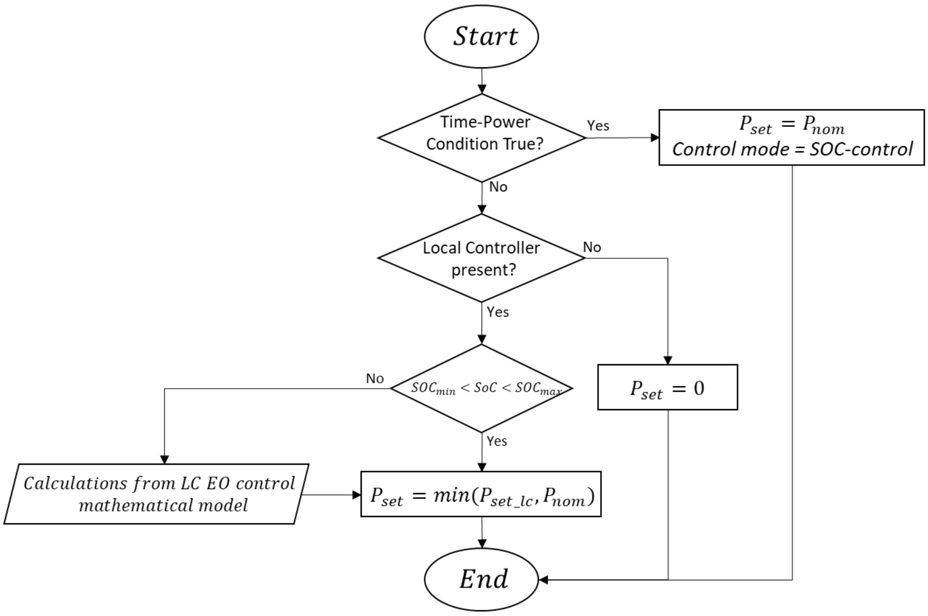


Figure 3.16: EO control mode flow diagram within the car controller

Figure 3.16 shows the flow chart of EO control mode, it activates only if the LC is present at the home, if not, then it sets P_{set} to zero. The time condition is always monitored at the start as user preference of the time to leave with the required SOC is of the highest priority. The EV is charged or discharged based on the P_{set_lc} value which is given by the LC.

3.2.3 Local Controller

The LC is the brain of the household for energy optimization, it performs all mathematical operations to increase the SC and SS of the household. It is connected to each household as seen in Figure 3.17, there could be more than one CR connected to one LC.

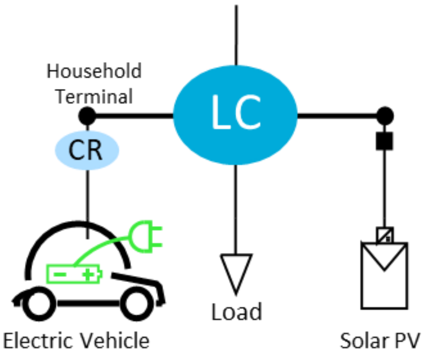


Figure 3.17: Connection point of the local controller

The LC gets data of the loads (P_{load} – power of the load) and PV (P_{PV} – power of the PV) connected to the household, it gets information from the CR which is required to execute the mathematical model of EO control mode. Figure 3.18 shows the structure of the LC, where all the inputs and outputs are just information flow and not physical cables. If there is a CC present in the system, then the LC communicates with the CC which is explained in Section 0. The clock of the system remains synchronized i.e. the LC and the CR run on the same time step.

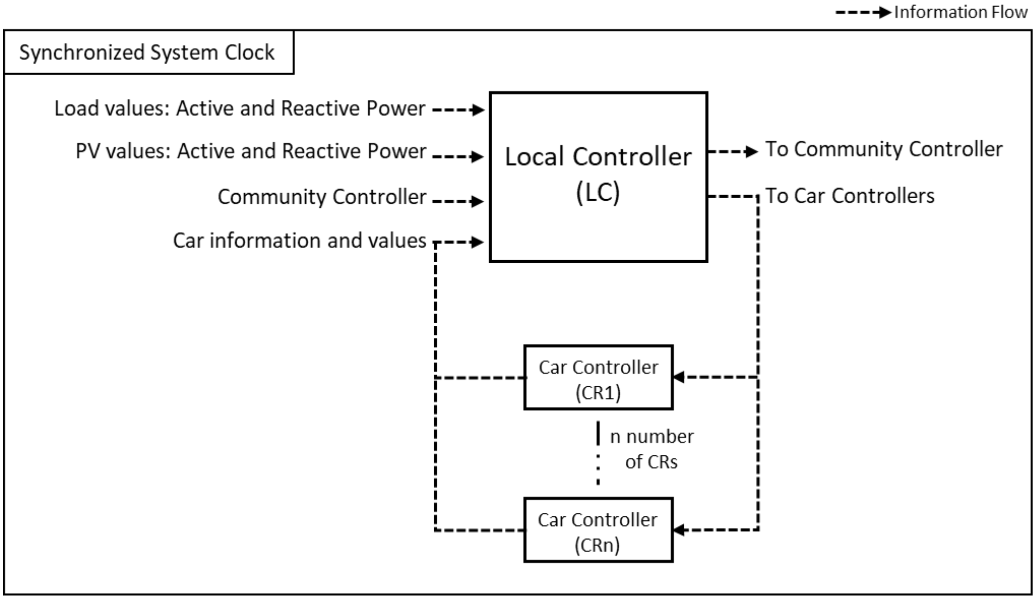


Figure 3.18: Structure of the local controller

3.2.3.1 EO Control Mode – Mathematical model

The EO mode is executed based on the deficit of the household ($Deficit_{EO}$), it is a term that is the summation of the powers of all the loads in the house except the EVs which are in EO mode. It can be calculated using Equation (*3.4*). If the loads are greater than the PV production, the value will be positive and if PV is greater than the loads, the value will be negative. If the $Deficit_{EO}$ value is supplied by the EV in EO mode, then the household will be less reliable on the grid. This value is calculated at every time instant for each LC.

$$Deficit_{EO} = \sum_{i=1}^{i=\alpha} P_{EV,i} + P_{PV} + P_{load} \tag{3.4}$$

$$P_{set\_lc,k} = -Deficit_{EO} * \frac{Batt_{nom,k}}{\sum_{i=1}^{i=\beta} Batt_{nom,i}} \qquad where\ \ k \in \mathbb{N};1 \ \leq\ k\ \leq\ \beta \tag{3.5}$$

In Equations *(3.4)* and *(3.5)*, α is the number of EVs connected to the LC which are in SOC-control mode and β is the number of EVs connected to the LC which are in EO control mode. P_{set_lc} is assigned the negation of the $Deficit_{EO}$ because if the value of $Deficit_{EO}$ is positive which means there is consumption in the household so the EVs connected to the LC in EO mode will have to supply the same amount of power by discharging to the household i.e. generate power which makes it necessary to give it a negative sign. If the $Deficit_{EO}$ is negative, then the EV will have to charge itself (acting as a load) by consuming the excess PV power. If there is more than one EV connected to the LC in EO mode, then P_{set_lc} varies based on the battery capacity of the EV.

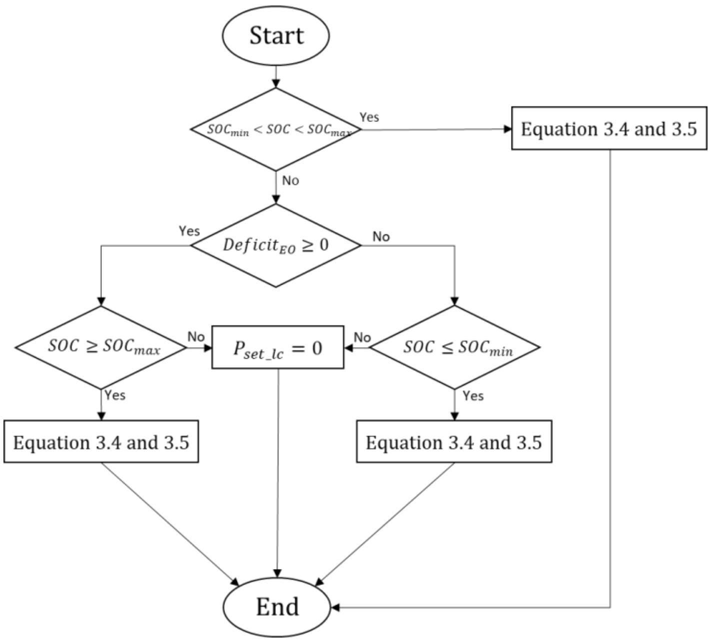


Figure 3.19: SOC limit violation of the EV in EO mode within the local controller

If the EV reaches the SOC limits (i.e. SOC = SOC_{min} or SOC_{max}), then the $Deficit_{EO}$ is checked if it's positive or negative. If it's positive, then only the EV which has $SOC \geq SOC_{max}$ can provide the necessary power to the household, on the other hand, if the $Deficit_{EO}$ is negative, then only the EV which has $SOC \leq SOC_{min}$ can consume the excess power. If the conditions are not satisfied, then the P_{set_lc} is set to zero. The explanation can be seen in Figure 3.19 in a flow chart.

3.2.4 Community Controller

The CC is on the topmost hierarchy as compared to all the controllers and has the least priority, i.e. the LC or the CR can overwrite the commands given by CC if they are violating any condition. Figure 3.20 is a small part of Figure 3.2 which shows where the CC is placed. It is connected to the lower voltage side of the distribution transformer so that it monitors the power inflow and outflow of the community to/from the grid.

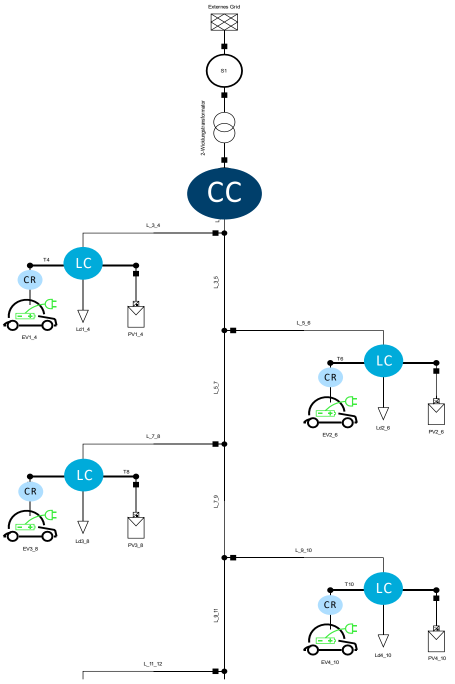


Figure 3.20: Connection point of community controller

Figure 3.21 shows the structure of the CC, it has inputs from the grid and the LC and it only gives instructions to the LC as an output. There can be N number of LCs connected to the CC.

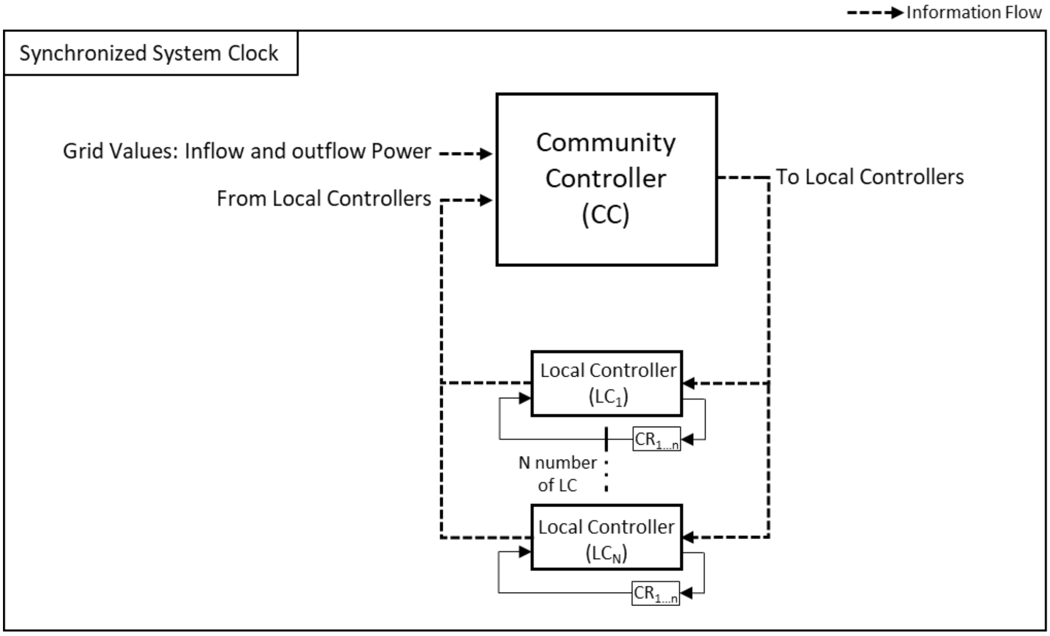


Figure 3.21: Structure of the community controller

The main aim of the CC is to reduce the power in/outflow from the community to the grid, it tries to keep the community as independent as possible from the grid. To understand it in a better way, consider one example below:

House₁: $P_{PV,1}$ @ -3 kW; $P_{load,1}$ @ 1 kW; $P_{EV,1}$ @ 2 kW (set by LC)
House₂: $P_{PV,2}$ @ -4 kW; $P_{load,2}$ @ 2 kW; no EV present

In the above example, the House₁ is optimized by the LC by setting the EV which is in EO control mode to 2 kW, but for House₂, as there is no EV present, the deficit of the House is -2 kW (over generating power). The CC plays a role here to perform an on-the-top optimization for the whole system by instructing the House₁ to take 2 kW of power making the community independent of the grid, so the new values are:

House₁: $P_{PV,1}$ @ -3 kW; $P_{load,1}$ @ 1 kW; $P_{EV,1}$ @ 2 (by the LC) + 2 (by the CC) = 4 kW
House₂: $P_{PV,2}$ @ -4 kW; $P_{load,2}$ @ 2 kW; no EV present

This is one example, other possible situations the CC optimizes are:

- LCs supporting the house which has no PV or EV
- LCs help the LC which has an EV in SOC-control mode so the power is not taken from the grid
- EVs consuming the excess PV to increase the SC of the community
- Making the community as self-sufficient as possible

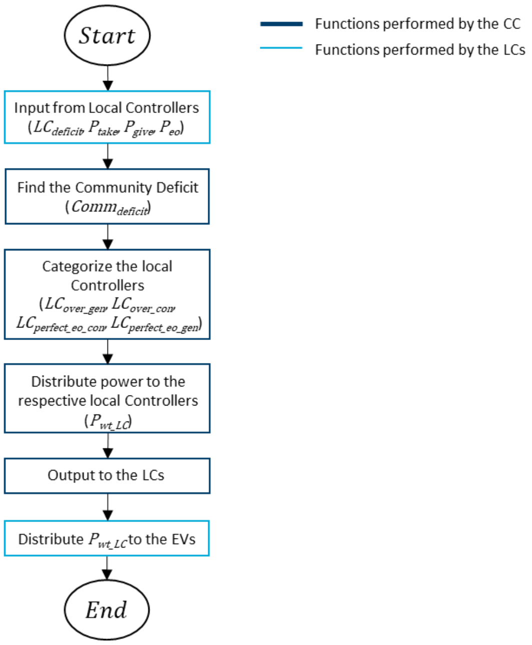


Figure 3.22: Overview of the community controller

Figure 3.22 gives an overview of what tasks the CC and as well as the LCs have to perform for the CC's functioning. Each block is a task performed either by the LCs or the CC which will be explained in detail in the rest of the section.

The CC makes decisions based on some values received from the LCs and the community deficit ($Comm_{deficit}$) which is the power observed at the lower voltage side of the transformer station. If $Comm_{deficit}$ is positive, that means the community is consuming power, and if negative, the community is generating power that is being fed into the grid. The values sent by the LCs to the CC can be seen in Table 3.4.

Table 3.4: Parameters sent by the local controller to the community controller

Parameter	**Description**	**Unit**
$LC_{Deficit}$	Deficit of the LC	kW
P_{take}	Maximum power the LC can consume	kW
P_{give}	Maximum power the LC can generate	kW
P_{eo}	Power the LC would like to support the CC with	kW

The $LC_{Deficit}$ is the inflow/outflow of power observed at the connection point between the household and the grid it can be calculated using Equation *(3.6)*, where it adds all the loads and negative loads (i.e. generation) connected to the LC. P_{take} and P_{give} are power limits of the LC which can help the CC during its optimization, the CC cannot instruct the LC to consume more power than P_{take} and produce more power than P_{give}. They are calculated using the power of the EVs in the EO mode and the nominal charging power as seen in Equation *(3.7)* and *(3.8)*, which is calculated for all the LCs. P_{eo} is a power value suggested by the LC to the CC which it would like to be sufficed by the other LCs in the community. These values are only calculated by the LCs if a CC is present, if not then they are skipped. Considering the previous example, LC of House$_1$ can suggest the CC that it has an excess 2 kW of power in the household so instead of the excess power being consumed by the EV in the same House$_1$, it can make P_{eo} as -2 stating that it has 2 kW of power that it can give to the community grid if any other node wants to consume it. Equation *(3.9)* shows how to calculate P_{eo} for each LC.

$$LC_{deficit,\gamma} = \sum_{i=1}^{i=\alpha} P_{EV,i} + \sum_{i=1}^{i=\beta} P_{EV,i} + P_{PV,\gamma} + P_{load,\gamma} \tag{3.6}$$

$$P_{take,\gamma} = \sum_{i=1}^{i=\beta} (P_{nom,i} - P_{EV,i}) \tag{3.7}$$

$$P_{give,\gamma} = \sum_{i=1}^{i=\beta} (-P_{nom,i} - P_{EV,i}) \tag{3.8}$$

$$P_{eo,\gamma} = -\sum_{i=1}^{i=\beta} P_{EV,i} \tag{3.9}$$

In Equation *(3.6)*, *(3.7)*, *(3.8)* and *(3.9)* $\gamma \in \mathbb{N}; 1 \leq \gamma \leq \mathrm{N},$ where N is the total number of LCs, α is the number of EVs connected to the LC$_\gamma$ which are in SOC-control mode and β is the number of EVs connected to the LC$_\gamma$ which are in EO control mode. If a particular EV's SOC is at its SOC_{min} or SOC_{max} limit, then the above Equations *(3.7)*, *(3.8)* and *(3.9)* need to be modified based on some conditions. If the $SOC \leq SOC_{min}$, then its P_{give} is made zero which means it cannot provide any power to the community and P_{EV} in Equation *(3.9)* is changed to $-P_{nom}$, which makes P_{eo} as P_{nom} stating that it can consume power equal to the nominal charging power. The P_{take} value remains the same as in Equation *(3.7)*. For $SOC \geq SOC_{max}$, P_{take} is made zero and P_{EV} in Equation *(3.9)* is changed to P_{nom} keeping Equation *(3.8)* the same.

Once the values arrive at the CC from all the LCs, it categorizes the LCs into four groups based on the P_{eo} and $LC_{Deficit}$ values which can be seen in Table 3.5.

Table 3.5: Categorization of the Local Controllers by the Community Controller

Category	**Description**	**Condition**
LC_{over_con}	LCs which are over consuming power	$LC_{Deficit} > 0$ and $P_{eo} > 0$
LC_{over_gen}	LCs which are over generating power	$LC_{Deficit} < 0$ and $P_{eo} < 0$
$LC_{perfect\_eo\_con}$	LCs which are in perfect EO mode (i.e. $LC_{Deficit} = 0$) and $Deficit_{EO} > 0$ (consuming power)	$LC_{Deficit} = 0$ and $P_{eo} > 0$
$LC_{perfect\_eo\_gen}$	LCs which are in perfect EO mode and $Deficit_{EO} < 0$ (generating power)	$LC_{Deficit} = 0$ and $P_{eo} < 0$

The reason for defining these categories was to not alter the state of the LC which are already well-optimized by the EO control mode algorithm of the LC. We call these LCs perfect EO mode LCs. The ones which are not optimized or cannot be optimized further (LC_{over_con} and LC_{over_gen}) will be selected first to serve the community, and then the ones which are in perfect EO mode ($LC_{perfect\_eo}$). The perfect EO mode LCs can be of two types, the perfect EO consumption ($LC_{perfect\_eo\_con}$) and the perfect EO generation ($LC_{perfect\_eo\_gen}$), they are distinguished based on their $Deficit_{EO}$ value from Equation *(3.4)*. If that value is positive, loads of this house are higher than its generation, and if negative that means there is a high generation than consumption.

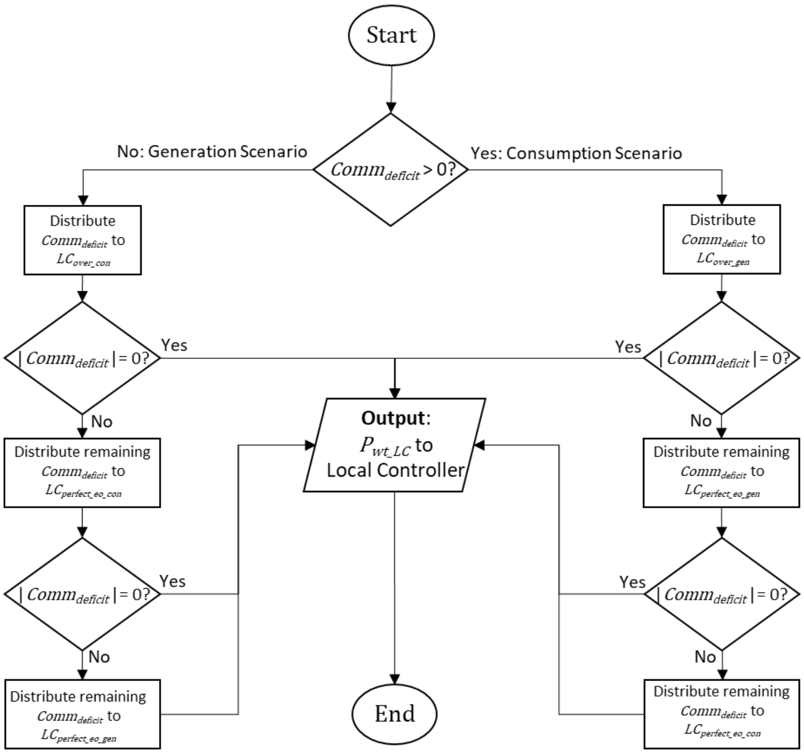


Figure 3.23: Community controller flow diagram

Once the grouping of the LCs is complete, the CC distributes the $Comm_{eficit}$ to the LCs based on Figure 3.23, it distinguishes the community as a generation or a consumption scenario based on the $Comm_{deficit}$ value and distributes the power as per the mathematical model which uses P_{eo} value as a weight factor. The model is explained in Section 3.2.4.1. For a consumption scenario, the LCs in the LC_{over_gen} group will distribute the $Comm_{deficit}$. If the LC_{over_gen} are not sufficient to serve for the whole $Comm_{deficit}$, then the remaining $Comm_{deficit}$ is distributed to the $LC_{perfect\_eo\_gen}$. If it was sufficient, then the distributed values (P_{wt_LC}) are sent to the respective LCs. If the $Comm_{deficit}$ is still not zero, then the remaining $Comm_{deficit}$ is distributed to the $LC_{perfect\_eo\_con}$. For a generation scenario, the series of events can be followed as seen in Figure 3.23.

3.2.4.1 Mathematical model

The distribution of power within the community is based on a weighted-distribution model. This kind of model distributes a value (M) to Z number of receivers, where each receiver has a weight (x) and based on the weight, the value M is distributed to them. For the thesis, M is the $Comm_{deficit}$, Z are the LCs and x is the P_{eo} value. Along with the weighted distribution, the model even considers limiting conditions of P_{take} and P_{give} of the LC to make a decision. To understand the model, consider $LC_{category}$ as any one of the 4 LC categories mentioned in Table 3.5. The $Comm_{deficit}$ value is distributed to it based on Equation *(3.10)*.

$$P_{wt\_LC,f} = \frac{-1 * Comm_{deficit} * P_{eo,f}}{\sum_{i=1}^{i=Z} P_{eo,i}} \tag{3.10}$$

$f \in \mathbb{N}; 1 \leq f \leq Z$ where Z is the number of LCs in $LC_{category}$

If the P_{wt_LC} value is greater than P_{take}, then $P_{wt\_LC} = P_{take}$, on the other hand, if P_{wt_LC} is less than P_{give}, then $P_{wt\_LC} = P_{give}$. To understand it better, consider an example where the $Comm_{deficit}$ = 1 kW (consuming power), which has to be distributed to two LCs of $LC_{perfect\_eo\_gen}$ category. The P_{eo} of the LCs and the final P_{wt_LC} can be seen in Table 3.6.

Table 3.6: Community Controller mathematical model example

Name of LC	$LC_{Deficit}$	P_{give}	P_{take}	P_{eo}	P_{wt_LC}
$LC_{1,perfect\_eo\_gen}$	0	-5.95 kW	7.24 kW	0.64 kW	-0.75 kW
$LC_{2,perfect\_eo\_gen}$	0	-3.37 kW	9.82 kW	0.21 kW	-0.25 kW

The negative sign indicates that the LCs have to generate power to optimize the community which is consuming power.

Once the LCs receive their P_{wt_LC} values, they distribute them to the EVs which are in EO mode based on the same mathematical model in Section 3.2.4.1, where $Comm_{deficit}$, P_{wt_LC} and P_{eo} in Equation *(3.10)* is replaced by P_{wt_LC}, P_{set_cc} and P_{EV} respectively as seen in Equation *(3.11)*. If there is just one EV connected to the LC, then directly P_{set_cc} = P_{wt_LC} as P_{EV} and $\sum_{i=i}^{i=\beta} P_{EV,i}$ cancel out each other.

$$P_{set\_cc,k} = \frac{P_{wt\_LC,\gamma} \; * \; P_{EV,k}}{\sum_{i=i}^{i=\beta} P_{EV,i}} \tag{3.11}$$

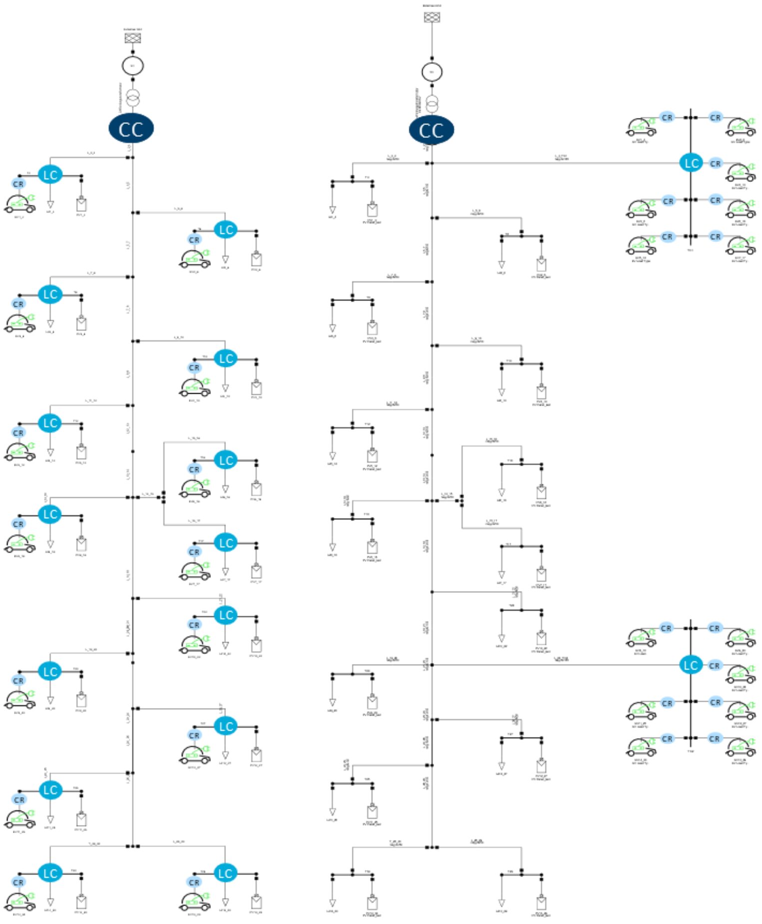
$k \in \mathbb{N}; 1 \leq k \leq \beta$ where β is the number of EVs connected to the LC_γ in EO control mode and $\gamma \in \mathbb{N}; 1 \leq \gamma \leq N$, where N is the total number of LCs

P_{set_cc} is an additional amount the car will charge or discharge with, which is given by the CC to the car to reduce the dependency of the community from the grid. The P_{set_lc} formula in Equation *(3.5)* can be modified to accommodate the P_{set_cc} value from the community controller which leads to Equation *(3.12)*.

$$P_{set\_lc,k} = \left(- Deficit_{EO} * \frac{Batt_{nom,k}}{\sum_{i=1}^{i=\beta} Batt_{nom,i}} \right) + P_{set\_cc,k} \quad where \;\; k \in \mathbb{N}; 1 \leq k \leq \beta \tag{3.12}$$

3.3 Scenario Definition

The scenarios in which the results will be simulated are shown in this section. Two grid configurations will be simulated A) EV is connected to each household (called the Home charging configuration) and B) EVs are connected to a community charging station (called the Community Charging configuration). Each of the configurations will be simulated with 3 scenarios i) with only CRs, ii) with CRs and LCs and the last iii) with all the controllers (CRs + LCs + CC). In Figure 3.24 (A), the first configuration is shown where each EV is connected to its respective household. Each EV in the household has a CR and each household has a LC connected to it, only one CC is required for the whole community. In Figure 3.24 (B), two community charging stations are shown for the whole community in which each station can accommodate 7 EVs at one time, making it a total of 7 CRs at each station. It just requires two LCs, one for each station and doesn't require any LC connected to the households.



(A) (B)

Figure 3.24: EVs connected to each household (A) and community charging station (B) scenario for simulations

Load profiles allotted to each household can be seen in Appendix A (Appendix Figure A). The total consumption per day of those profiles is given in Table 3.7. PV data is based on Section 3.1.4 with high and low irradiation. Each grid configuration (A and B) along with the scenarios (i, ii and iii) will be simulated for low and high irradiation. The total PV energy generated by a 7.5 kW_p PV system in a day of low and high irradiation can be seen in Table 3.7.

Table 3.7: Loads and PV allotted to the households for the community simulation

House	Low PV Energy (kWh/day)	High PV Energy (kWh/day)	Loads (kWh/day)
House1	2.19	31.27	4.52
House2	2.19	31.27	15.24
House3	2.19	31.27	9.96
House4	2.19	31.27	19.63
House5	2.19	31.27	17.96
House6	2.19	31.27	21.40
House7	2.19	31.27	11.86
House8	2.19	31.27	18.21
House9	2.19	31.27	15.25
House10	2.19	31.27	13.03
House11	2.19	31.27	10.80
House12	2.19	31.27	9.68
House13	2.19	31.27	16.21
House14	2.19	31.27	8.59

For the parameters of the EVs, two scenarios will be simulated, one is a work from home (WFH) scenario where all the EVs leave the house at 19:00 and return home at 22:00 and the other is a random time scenario, where each EV gets a different $Time_{leave}$ and $End\ Idle\ Time$ as seen in Table 3.8. The $SOC_{initial}$, SOC_{target} and the $SOC_{Idle\_reduction}$ selected for the simulation can also be seen in Table 3.8, other EV parameters remain the same as per Table 3.2. The two simulations of EV parameters i.e. the work from home scenario and the random time scenario will be simulated for each grid scenario (A and B) along with the sub scenarios (i, ii, iii) as well as for low and high PV irradiations.

Table 3.8: Parameters of the EV for the community simulation

				Work from Home		Random Time	
EV	$SOC_{initial}$ (in %)	SOC_{target} (in %)	$SOC_{Idle\_reduction}$ (in %)	$Time_{leave}$	*End Idle Time*	$Time_{leave}$	*End Idle Time*
EV1	75	75	20	19:00	22:00	10:00	12:00
EV2	65	75	20	19:00	22:00	08:00	11:00
EV3	55	75	20	19:00	22:00	12:00	16:00
EV4	45	75	20	19:00	22:00	06:30	11:00
EV5	35	75	20	19:00	22:00	13:00	18:00
EV6	25	75	20	19:00	22:00	21:00	23:00
EV7	15	75	20	19:00	22:00	10:00	12:00
EV8	10	75	20	19:00	22:00	09:00	13:00
EV9	20	75	20	19:00	22:00	08:00	15:00
EV10	30	75	20	19:00	22:00	23:59	23:59
EV11	40	75	20	19:00	22:00	12:00	15:00
EV12	50	75	20	19:00	22:00	08:00	09:00
EV13	60	75	20	19:00	22:00	19:00	22:00
EV14	70	75	20	19:00	22:00	18:00	20:00

4 RESULTS & DISCUSSION

In this chapter, the results of the model will be shown with different scenarios to understand how the output varies with different simulation settings. In Section 4.1, results with constant load and PV will be shown to explain minor details of the output. In Section 4.2 and 0 results with real data will be shown of the household and community respectively.

Note: *Headings stating 'With Car Controller' imply that the system neither has the LC nor the CC connected. Headings stating 'With local Controller' imply that the system has the CR connected but the CC is not connected. Similarly, headings stating 'With Community Controller' imply all the three controllers i.e. CR, LC and CC are connected in the system.*

4.1 Understanding the Model

To get a better understanding of the methodology, a single household will be simulated with constant load and a simple PV profile. The household has one EV connected to it.

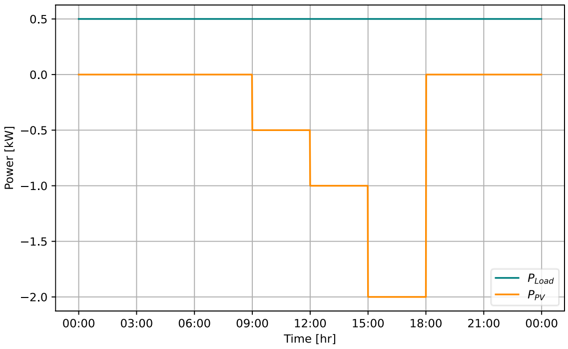


Figure 4.1: Constant loads and PV

Figure 4.1 shows the constant load and PV profile taken for the simulation. It is a 0.5 kW load and PV starts generating at 09:00 with -0.5 kW and increases in steps to -2 kW until 18:00. The parameter set of the EV for this part of the simulation can be seen in Table 4.1.

Table 4.1: EV Parameters set for the simulation

Parameter	**Value**	**Unit**
$SOC_{initial}$	50 %	-
SOC_{target}	75 %	-
$SOC_{Idle\_reduction}$	20 %	-
$Time_{leave}$	11:00	hh:mm
End Idle Time	14:00	hh:mm

4.1.1 With Car Controller

When only the CR is connected, the car charges with the P_{nom} value and there is no input from the LC to perform energy optimization. The control mode of the EV is in SOC-control, which means the EV will start charging to its SOC_{target} value once it's connected to the CR.

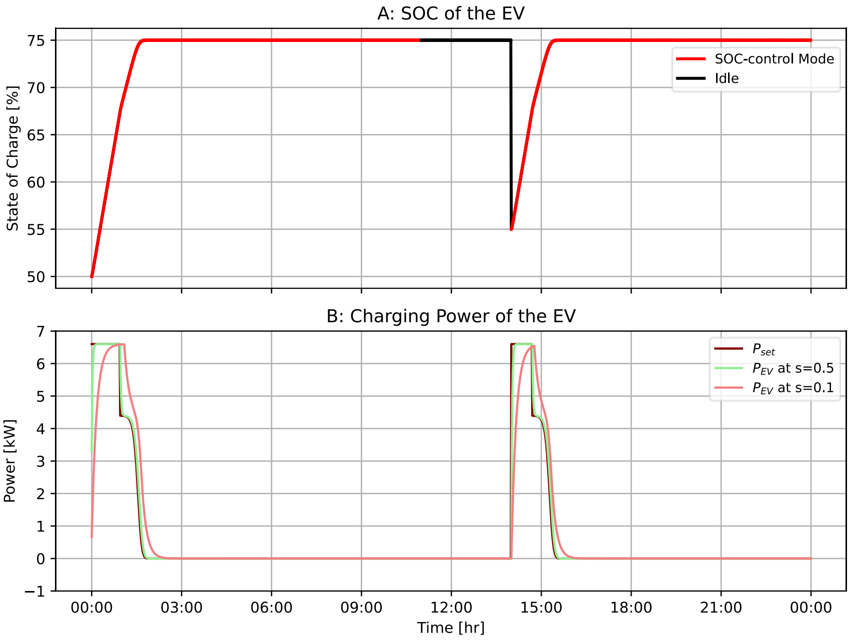


Figure 4.2: SOC (A) and charging power (B) graph of the EV with only car controller

The EV is being charged with P_{set} which is set to its nominal power (P_{nom} = 6.6 kW) as seen in Figure 4.2 (B). In Figure 4.2 (A) the SOC of the EV starts to increase, once the EV reaches SOC_{target_min}, the P_{set} value is reduced as per Figure 3.15 and a smooth curve can be observed which is due to the exponential term and it lasts until the EV reaches SOC_{target}. The EV remains at SOC_{target} until the time reaches $Time_{leave}$ i.e. it has to leave the house and it goes in Idle mode. After the EV returns home (at $End\ Idle\ Time$), the SOC of the car is reduced by $SOC_{Idle\_reduction}$, and it again goes in SOC-control mode and starts charging. In Figure 4.2 (B), the other lines represent the P_{EV} value, which is the P_{set} value after going through the smoothing function. With s set as 0.1, the power graph looks much smoother as compared to when s is 0.5, but it is not recommended as it takes longer for P_{set} to reach P_{nom} which leads to a delay in the EV's SOC to reach the SOC_{target}. For the rest of the simulations s is set to 0.5 and only the P_{set} graph will be shown in the future to the readers as there is very little difference between the P_{set} and P_{EV} graphs apart from the curved edges in P_{EV}.

4.1.2 With Local Controller

$Deficit_{EO}$ and $LC_{Deficit}$ values of the LC are very interesting to look at if a LC is connected to the household. They determine how the EV in EO mode is changing its P_{set} value which results in minimal interaction of the house and the grid.

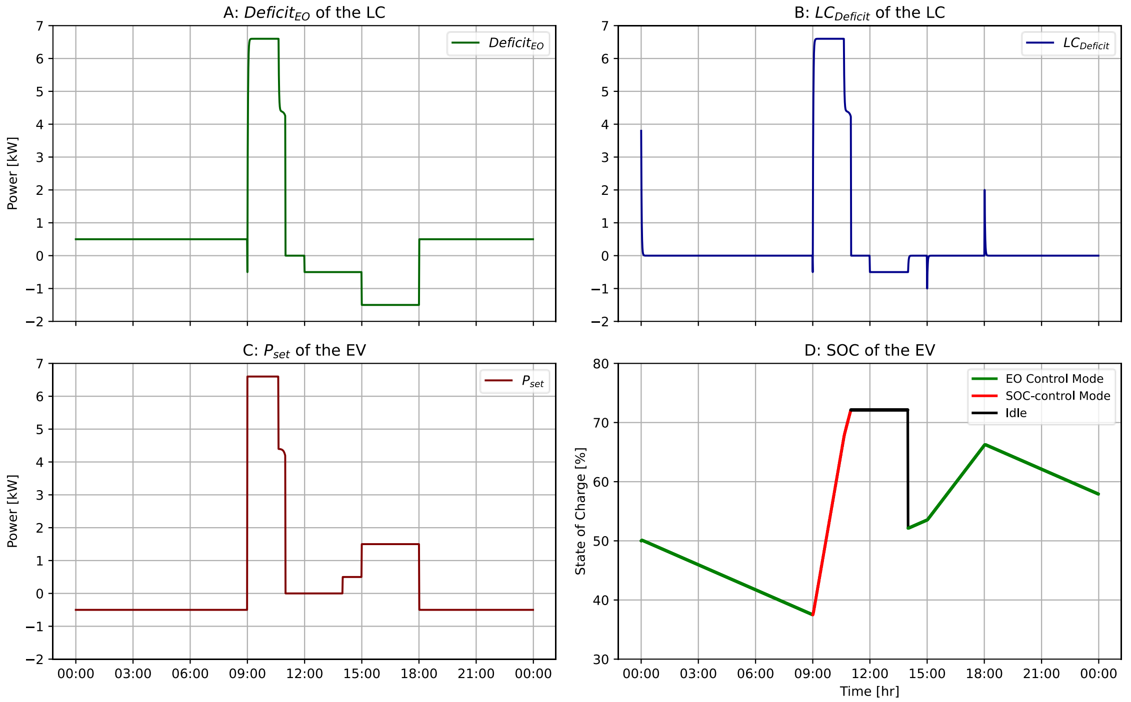


Figure 4.3: $Deficit_{EO}$ (A) and $LC_{Deficit}$ (B) of the local controller along with charging power (C) and SOC (D) graph of the EV

As seen in Figure 4.3, the EV is discharging from 00:00 to 09:00 based on the $Deficit_{EO}$ value given by the LC to the EV. According to Equation *(3.4)*, the value is 0.5 kW as there are only loads present at that time in the house so the EV discharges with 0.5 kW to make the house independent from the grid which can be visualized in the graph (B) of $LC_{Deficit}$. Once the Time – Power Condition of Equation *(3.3)* is true, the EV changes its mode from EO to SOC-control and charges with P_{nom} as it has to reach the SOC_{target} value before it leaves the house. When time equals $Time_{leave}$, the EV goes in Idle mode. After the EV returns to the house, the control mode changes to $Control_{initial}$, which in this case is the EO control mode. At 14:00 the EV starts charging with 0.5 kW as at that time it is consuming the excess PV which is being generated in the house. At 15:00, the charging power increases to 1.5 kW, as there is an excess of 1.5 kW PV in the house. Once the PV is no longer available (18:00), the EV again starts to discharge to the loads in the house. As a summary one can say that if the EV is able to charge or discharge as per the $Deficit_{EO}$ value which is recommended by the LC, then there will be no interaction of the household with the grid and the $LC_{Deficit}$ will be zero. The spikes seen in the graph of $LC_{Deficit}$ indicate sudden changes in the power of the loads or PV connected to the household. As no function of prognosis is implemented in the controllers, once the LC observes a rise or fall in the deficit of the house, it curtails it in the next time step which creates the spike. At 15:00 there is a drop as PV production increases by 1 kW and at 18:00 as well because PV changes from 2 kW to 0 kW.

4.1.3 With Community Controller

A community controller can be introduced to the existing simulation by adding another house and making it a community of two households. House1 has constant loads and PV as per Figure 4.1 and House2 has constant loads and PV as seen in Figure 4.4 (left). The community can be seen in Figure 4.4 (right) along with the placements of the CC, LC and CR.

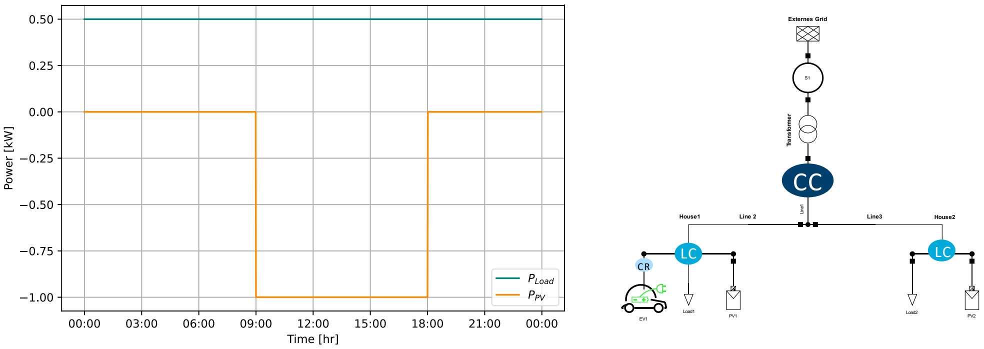


Figure 4.4: Constant load and PV profile for House2 (left), diagram of the community (right)

House2 just has loads and PV connected, it doesn't have any EV present at the household. Because of that, it doesn't require a LC to be connected to it. As per the methodology of the community controller, the EV in House1 will have to serve for itself and House2 for the community to be independent from the grid.

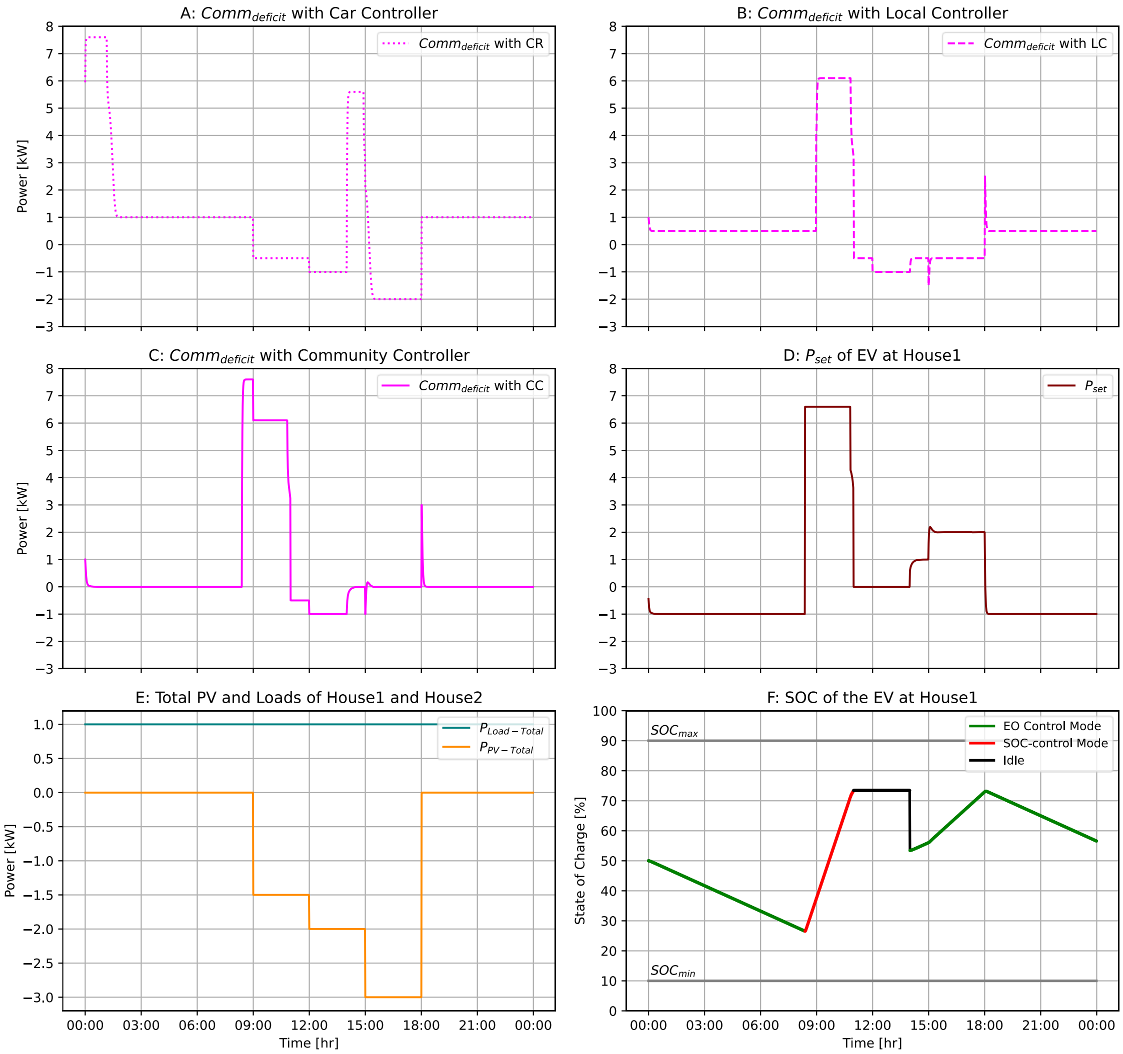


Figure 4.5: Community deficit with car controller (A), with local controller (B) and with community controller (C); P_{set} (D) and SOC (F) of EV connected to House1; total loads and PV of the House1 & 2 combined (E)

To understand the community controller, have a close look at Figure 4.5 (D) between time 00:00 and 09:00 in which the EV at House1 serves the loads of its house and even House2 by discharging and makes the community's deficit as zero (seen in C). During the same time duration, the deficit of the community with only CR (A) and with a LC and a CR (B) is greater than zero when no community controller is connected. After the EV arrives at home (at 14:00), the EV charges itself with 1 kW consuming the excess energy in the community which was generated by the PV systems. At time 15:00, the PV power in House1 increases by 1kW making the total community deficit as -2 kW, so the EV charges with 2 kW of power. Once the PV power is not present, the EV again starts to discharge to its house (0.5 kW) and House2 (0.5 kW) making it a total discharge of 1 kW to serve the community. The spikes in C and B are occurring because of the same reason as explained in Section 4.1.2.

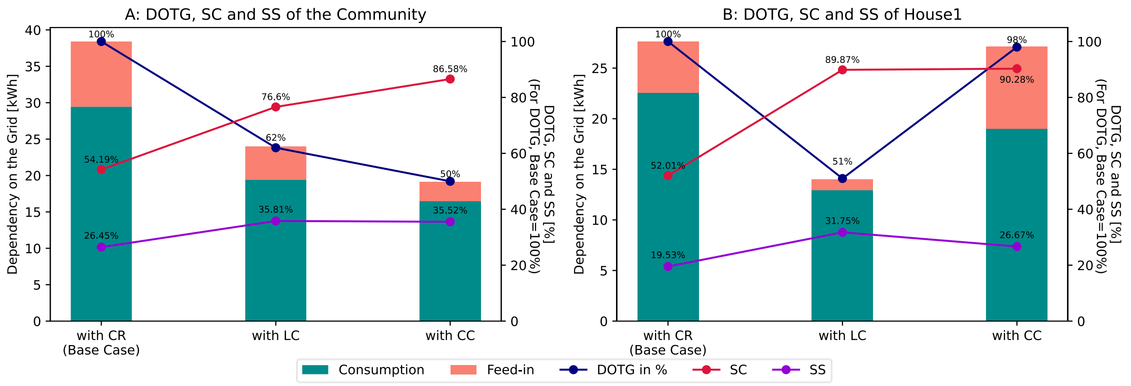


Figure 4.6: Dependency on the grid, self-consumption and self-sufficiency of the community (A) and House1 (B)

The main indicators to judge if the controllers are working fine are by examining the DOTG, SC and SS values of the community and the households. In Figure 4.6 (A) the DOTG can be seen of 3 cases which are *with CR*, *with LC* and *with CC*. The green bar represents the total amount of energy that has been consumed by the community from the grid and the peach bar is the total feed-in of energy from the community to the grid. The total bar represents the DOTG in kWh. The DOTG percentage is calculated by keeping the ‘*with CR*’ scenario as a base case i.e. it can be read as the DOTG of the ‘*with LC*’ case is 62% of the ‘*with CR*’ case in (A). The red and purple lines represent the SC and SS respectively.

In Figure 4.6 (A) the DOTG of the community is reduced by 38% when a LC is introduced in House1 and by 50% if there is a community controller introduced to the community. The DOTG is reduced as more PV power is being consumed by the community in each consecutive case. The SC of the community has increased by 32% compared to the base case by introducing all the controllers. The SS of the community is increased with a LC by 9% and it can be seen that it reduces by 0.29% when a CC is introduced. This is because the SS is a ratio of loads that are being served by the PV (part C of Figure 2.3) of an entity to the total loads (part A+C+D of Figure 2.3) of the entity as seen in Equation *(2.2)*. In Figure 4.5 (D), while charging the EV the P_{set} is set to P_{nom} for a longer time as compared to the case *with LC* as seen in Figure 4.3 (C), this is because the EV has been discharging more in the case *with CC* as compared to the case *with LC* and eventually both have to reach the SOC_{target} when they leave. Due to this, the denominator of Equation *(2.2)* increased further making the SS value smaller in the case *with CC* as compared to the case *with LC*. In simple words, as the loads are increasing since the EV is acting more often as a load, the SS has reduced.

For House2 the DOTG, SC and SS are 12 kW, 37% and 50% respectively and remain the same for all three cases as the loads and PV are constant. In Figure 4.6 (B), the same values are calculated for House1, when introducing a LC to it, the SC reaches 90% and due to that the DOTG is reduced by 49%. With a CC introduced, the SC is almost the same, but it plays a toll on the SS of the house. In the case *with CC*, the EV in House1 serves the community by generating or consuming more power to or from the community grid making the DOTG values of this specific house higher than the case *with LC*. Even the SS of House1 reduces as the loads in the house increase to consume the excess PV from House2 which increases the denominator of Equation *(2.2)* and reduces the SS.

4.2 Single Household

Results of a single household with real load and PV data will be shown in this section. The parameters of the EV remain the same as in the previous section which can be seen in Table 4.1. For the loads, the 27th profile from the 74 profiles presented earlier was selected which has an annual consumption of 4.6 MWh. As the simulations are performed for one day, the one-minute resolution load data was used which has a consumption of 11.86 kWh for the 1st of Jan 2021 (Figure 4.7). Two PV profiles were used as per Section 3.1.4 one for a low irradiation scenario and one for a high irradiation scenario. The simulation was performed for two cases i) *with CR* and ii) *with LC*.

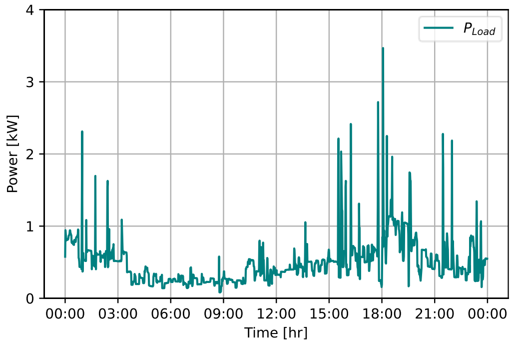


Figure 4.7: Load profile used for simulation of a single household

Results of the simulation can be seen in Figure 4.8, where the left side shows the results of the household with a lower irradiation scenario and on the right is with a higher irradiation scenario. Results for the case *with CR* are shown with a dotted line in all the graphs and the results for *with LC* are represented with a solid line.

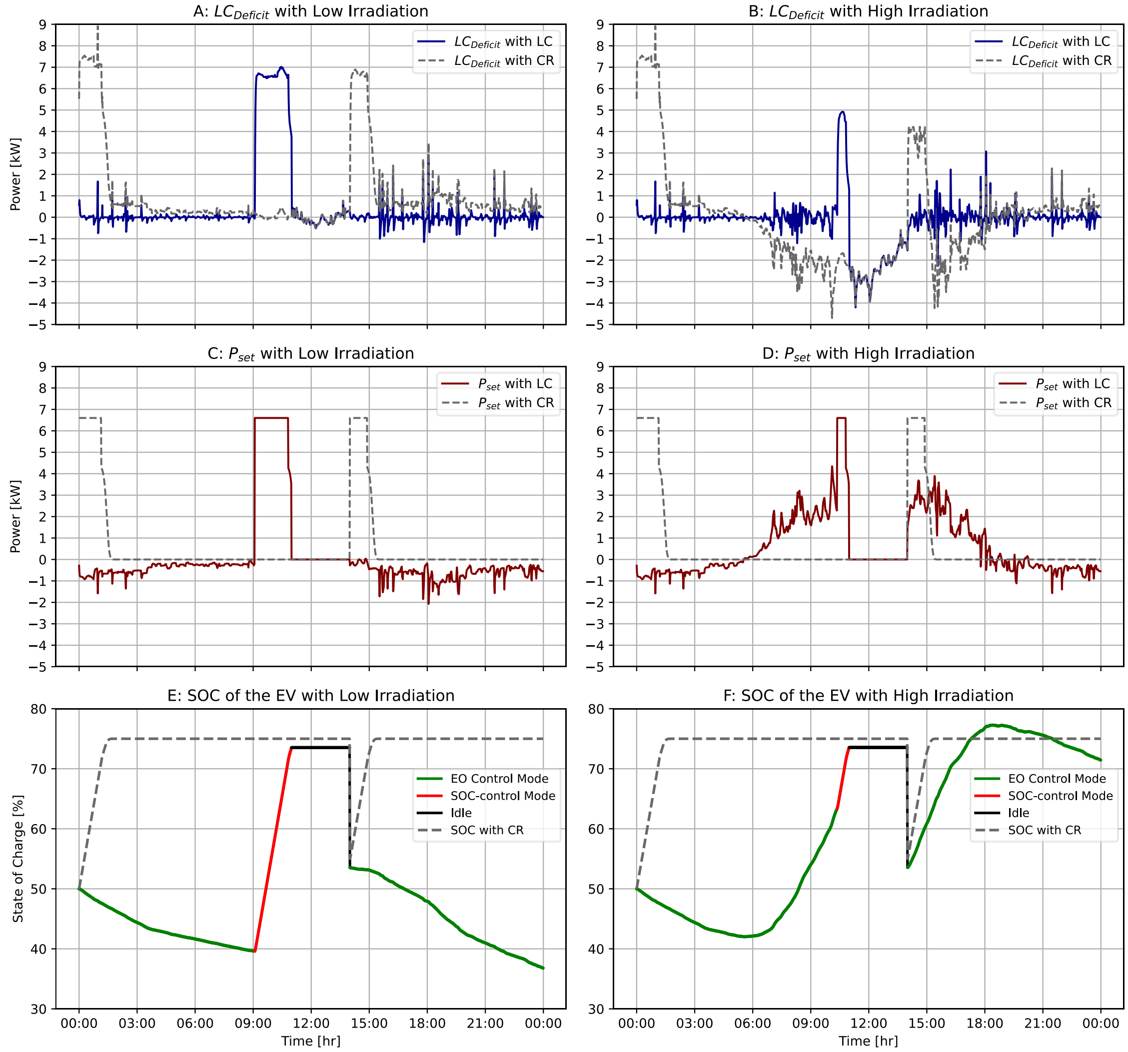


Figure 4.8: Results of a single household with real data with low irradiation scenario (Left) and high irradiation scenario (Right); $LC_{Deficit}$ of the household (A and B) along with P_{set} (C and D) and SOC (E and F) of the EV

In Figure 4.8 (A and B) the $LC_{Deficit}$ of the household in the *with CR* case is always greater or less than zero. Especially in the high irradiation scenario (B) when there is no LC connected, the excess PV is not consumed by the household but fed into the grid. If a LC is introduced to the household, it tries to keep the $LC_{Deficit}$ in both scenarios almost close to zero except when the EV is in SOC-control (that means charging just before leaving) or Idle mode. The fluctuations in the graph are due to large changes in the PV and load profiles values. When the car is in Idle mode (11:00 to 14:00), the graphs of *with CR* and *with LC* case coincide as there are just loads and PV present during that time.

The P_{set} diagram of the *with LC* case in Figure 4.8 (C) shows that most of the time the EV is helping to serve the loads in the house as the PV is very low and only present between 09:00 to 15:00 (Figure 3.6). On the other hand, the PV is dominant in (D), so the EV consumes the excess PV by charging itself as per the instruction of the LC. The EV in *with CR* case charges itself to the SOC_{target} value and remains there till it has to leave the home at $Time_{leave}$.

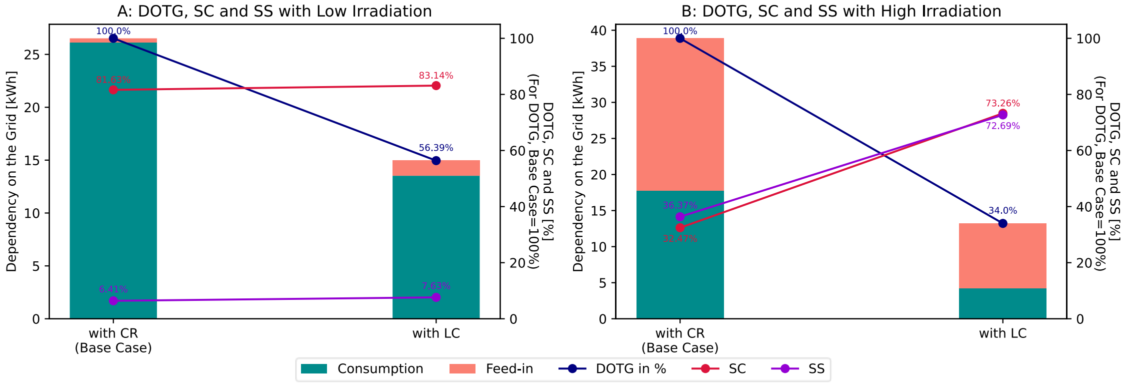


Figure 4.9: Dependency on the Grid, self-consumption and self-sufficiency of the household with low irradiation (A) and with high irradiation (B) having real load and PV profiles

The DOTG in the *with LC* case is always lower than the base case (Figure 4.9), but it's interesting to see that in a higher irradiation scenario the DOTG reduces more than the lower irradiation scenario. The consumption bar in (A) is greater in value than (B) which is because of the high PV generation in (B). In a higher irradiation scenario, the DOTG reduces by 66% and in the lower irradiating case it reduces by 44%. As there is very less PV generation in (A), the SC value is high even without a LC and after introducing a LC it just increases by 1.5%. Due to the low PV generation, the SS in both cases (*with CR* and *with LC*) remains low. In (B) the SC value increases by 40% as all the excess PV generated power is consumed by the EV as well as the SS increases as the loads for charging the EV from the grid have reduced.

As seen in this section, the high irradiation scenario gives better results than the lower, so it's considered as a base case for performing the sensitivity analysis of the LC in the next section.

4.2.1 Sensitivity Analysis

Sensitivity analysis of a single household by changing loads, PV system size and different EV parameters are simulated in this section. The base case to perform the sensitivity analysis uses the load and the high irradiance PV profile from the previous section and the same EV parameters from Table 4.1. The result of the simulation can be seen in Figure 4.10, the base case is indicated with a red box on the x-axis.

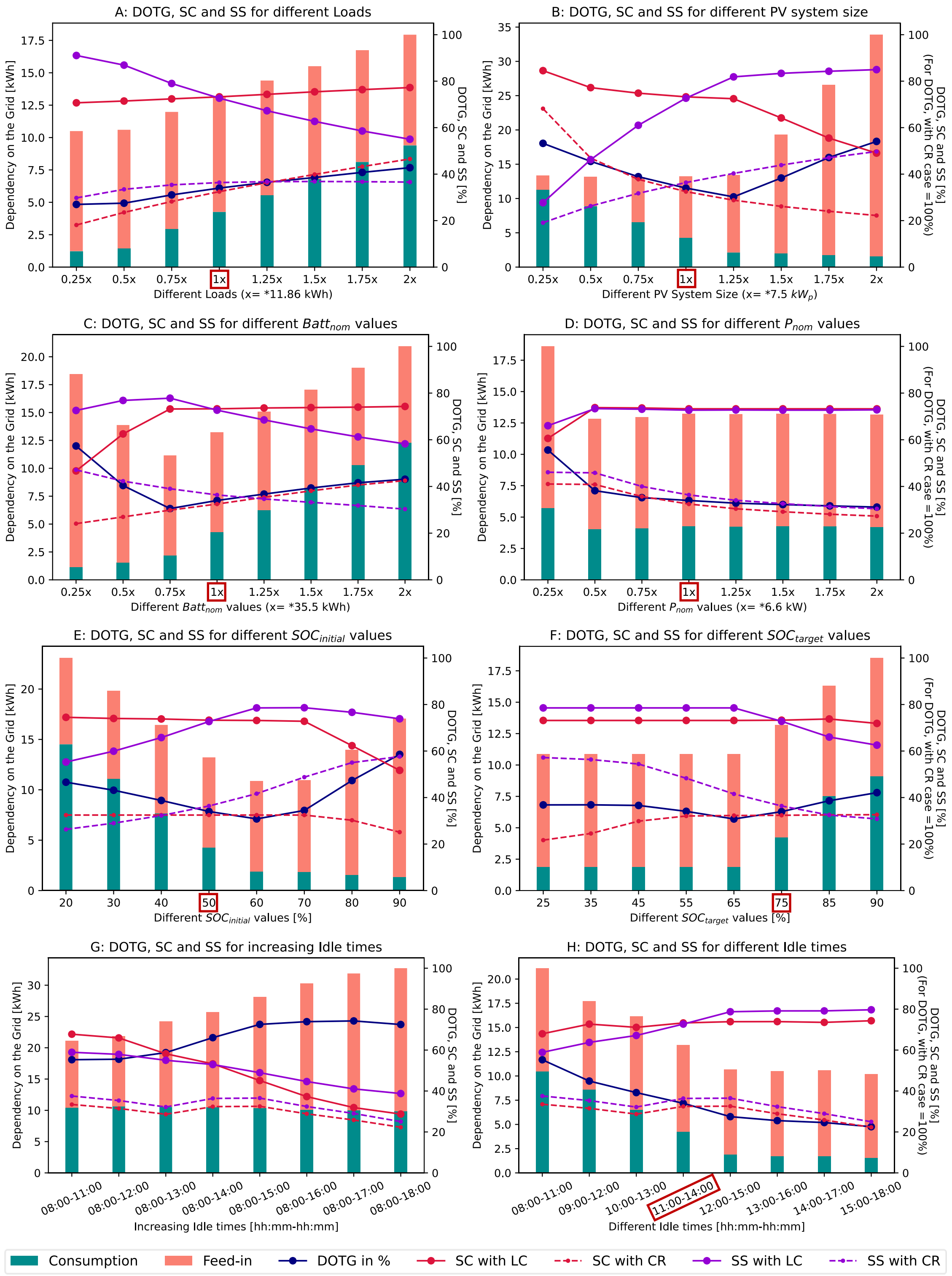


Figure 4.10: Sensitivity analysis of a single household with different loads (A), PV system size (B) and with different EV parameters like $Batt_{nom}$ (C), P_{nom} (D), $SOC_{initial}$ (E), SOC_{target} values (F), increasing idle times (G) and different idle times (H). SC and SS values for the 'with CR' case are represented by a dashed line and the 'with LC' case by a solid line. The DOTG values are only shown for a with LC case and the DOTG percentage are shown by considering the 'with CR' case of each simulation as 100%.

A general observation that can be made by looking at all the graphs is that in every graph a minimum for the DOTG percentage can be found. This means that this particular case in the respective graph is the best fit for a household with a LC to have the least exchange of energy from the household and the grid. The case with the lowest DOTG percentage even has the best combination of SC and SS values with a LC as compared to the other cases in each graph. To verify the previous statements consider graph (C), the lowest DOTG percentage is observed at 0.75x $Batt_{nom}$ value as well as the lowers DOTG values is also at 0.75x. The SC *with LC* is increasing from 0.25x to 0.75x and remains almost the same between 0.75x and 2x. The SS *with LC* is the highest for the 0.75x case as compared to the other cases. Another general observation that can be made is that by introducing a LC to the household the values of SC and SS increase considerably in all the graphs as compared to a household without a LC i.e. the *with CR* case.

In graph (A), by increasing the loads one can increase the SC of the household but that will play a toll on the SS values as the total loads in the household increase. Trends of SC *with LC* and *with CR* are the same, but different in magnitude. With increasing the PV system size the SS of the household can be increased but only until a particular point (1.25x) as seen in (B). PV system greater than 1.25x does not show much increase in the SS value as the EV reaches to its SOC_{max} limit and cannot consume any more PV power. The excess PV power is fed into the grid which can be seen by an increase in the feed-in from 1.25x to 2x resulting in a high DOTG. The trends of SC and SS are similar for the *with LC* and *with CR* case but are different in magnitude.

Increasing the battery capacity ($Batt_{nom}$) of the EV increases the consumption from the grid (as seen in graph C) because the EV has to reach the SOC_{target} when it has to leave the house. Although the SOC_{target} remains the same for all the simulations i.e. 75%, which means that the amount of energy required to reach the SOC_{target} increases with increasing battery capacity. This increases the total load of the household resulting in a decrease in the SS value. In the *with LC case*, the SC increases to a point and stops raising further, as the PV system size is the same that means there is no more energy to be charged into the car. The feed-in is the same form 0.25x to 2x becase of the unavailability of the EV to consume the PV power when its in the Idle mode. However in the with CR case, the SC always increases as the total loads are increasing which was also seen in graph (A).

In graph (D) at 0.25x of P_{nom} value, most of the time P_{PV} is greater than the $P_{nom} + P_{Load}$ which result in putting excess power into the grid and increasing the DOTG value. Moreover the SC of the *with LC* case is lower as compared to the other cases because not all PV power can be consumed by the EV in EO control mode. Increasing the charging power of the car results in hardly any change in the SC value of the *with LC* case because in all the cases apart from 0.25x, the max P_{PV} value is less than the $P_{nom} +$

P_{Load} so all the PV power can be consumed by the EV and the loads in the house. The SS follows the same trend as the SC because increasing the charging power of the car does not affect the functionality of the LC unless and until the power of loads and PV combined are less than the charging power.

The SOC of the EV, when arrived at home, most of the time won't be the same every day, so it's interesting to see the change in SC, SS and DOTG with different $SOC_{initial}$ values (graph E). With a higher $SOC_{initial}$, the SC in the *with LC* case reduces as the EV cannot consume the excess PV power and due to that DOTG increases. With a lower $SOC_{initial}$, the EV can take more of the PV generated power, but on the other hand the EV has to charge to its SOC_{target} before leaving the house which results in consuming more power from the grid leading to an increase in the DOTG value. SC in the *with LC* remains the same from 20 to 70% is because it can consume all the PV power by the same amount in all the cases. In the *with CR* case, the SS increases with increasing $SOC_{initial}$ as the EV has to charge for less time to reach the SOC_{target} which results in a decrease in the loads in each consecutive case.

Graph (F) can help the user to decide on which SOC_{target} values will there be the lease exchange of energy between his household and the grid. The different SOC_{target} don’t affect the SC values in the *with LC* case but goes a little lower at 90% because not all PV power can be consumed by the EV as it reaches its SOC_{max} limit. Between 25 to 65% of SOC_{target}, no power is taken from the grid to charge the EV when it has to leave the house as the SOC of the EV is higher than the SOC_{target} because all the PV power was being consumed by the EV as well as in some cases the $SOC_{initial}$ (50%) is higher than the SOC_{target} value. Beyond 65% the EV has to charge itself to reach its SOC_{target} which increases the consumption from the grid and results in a decrease in the SS value and increase in the DOTG value.

Not always will an EV be present at home, results of SC, SS and DOTG for different idle times can be seen in graphs (G) and (H). In graph (G) for increasing idle time, the trends of SC and SC in the *with LC* case is decreasing which is because the EV is not available at home to serve the loads or to consume the excess PV in the household. Due to that, the power for loads are being consumed from the grid and the excess PV is being fed into the grid which increases the DOTG value. The SC and SS in the *with CR* case follows the same trend, but there is a slight increase if the EV arrives between 14:00 and 15:00 as there is high PV generation during that time which is being consumed by the EV when they start charging to the SOC_{target} values when connected to the CR.

In graph (H), with the same idle time duration but $Time_{leave}$ varying throughout the day it can be said that if the EV leaves the home late when its SOC has crossed its SOC_{target} (75%) value by charging with the PV power, then the car doesn't have to charge when it leaves and doesn’t consume power from the grid, leading to an increase in the SS in the *with LC* case. Due to the same reason, the DOTG values reduces with later leaving times of the car. On the other hand, for an earlier $Time_{leave}$ (08:00 to 10:00) the EV has to charge itself before it leaves the house as the SOC is less than the SOC_{target} value resulting in a high DOTG and lower SS. For the *with CR* case, the values of SS and SC only vary based on when the car arrives at home because it will be charged once it is connected to the CR, so the trend remains the same as compared to (G).

4.3 Community

Simulations for the community were performed based on the scenarios mentioned in Section 3.3.

4.3.1 Work from Home Scenario

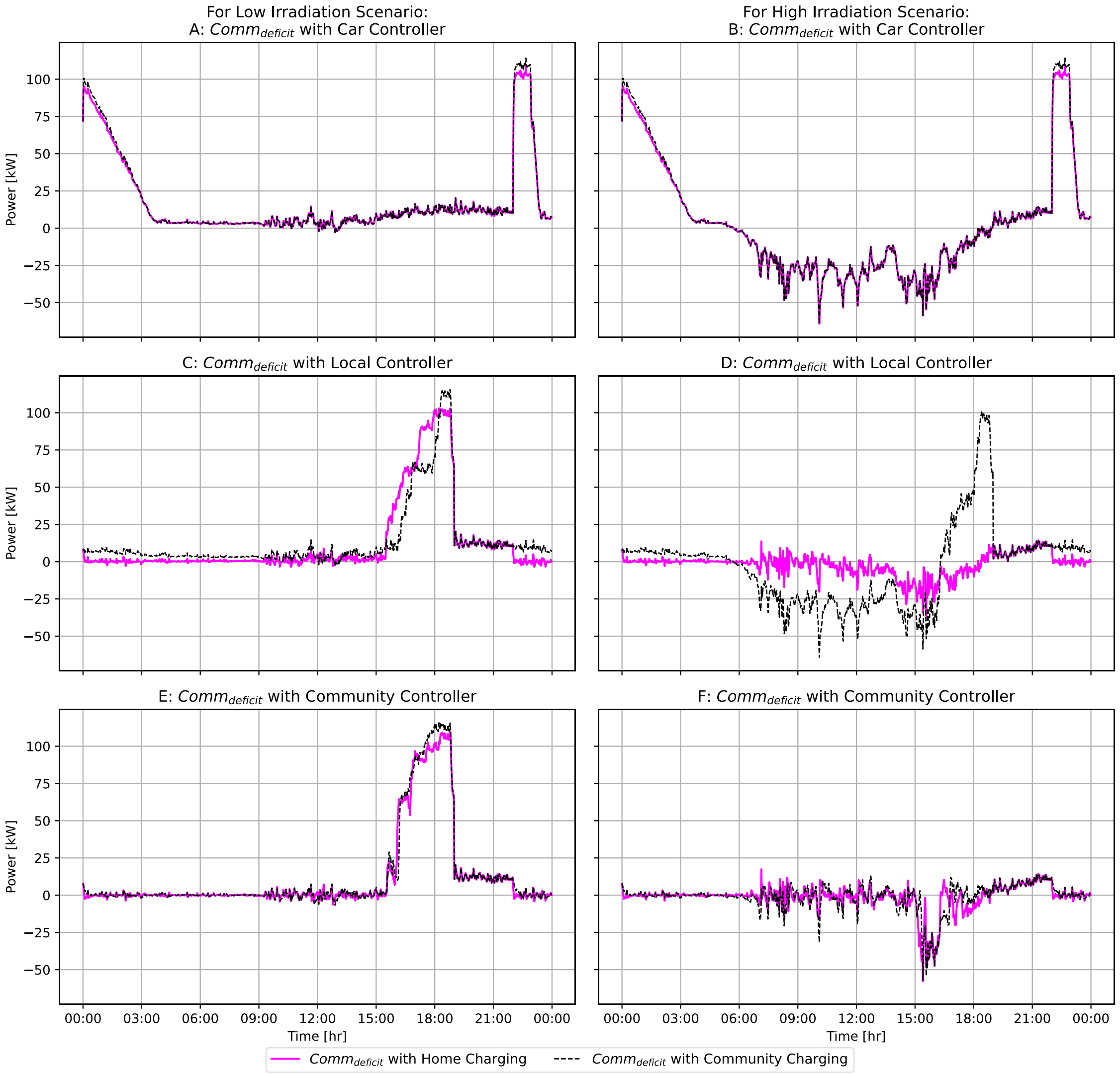


Figure 4.11: $Comm_{deficit}$ of the community when the work from home scenario is simulated with home charging (solid line) and community charging configurations (dashed line); Graphs on the left are for low irradiation scenario and right are for high irradiation scenario; A and B are results for 'with CR' case, C and D are for 'with LC' case and E and F are for 'with CC' case.

The results of a simulation with the EV parameters set as the WFH scenario are seen in Figure 4.11. With only CR connected (graph A and B), the results of the home charging and the community charging configuration remain the same as there is no LC connected to the household or the charging station. The EVs charge themselves with the P_{nom} value when they are connected to the CR which can be seen in (A) and (B) with an increase in power at the start of the simulation and at 22:00 when all the cars return home after leaving at 19:00. There is a slight increase in power in the community charging configuration as compared to home charging when the EVs are being charged, which is because of the line loading losses when all the EVs are charged at one place. The slope of reduction in the $Comm_{deficit}$ at the start of the simulation is because of the different $SOC_{initial}$ values of the car. Some EVs which have a higher $SOC_{initial}$ reach their SOC_{target} (75%) faster and stop charging as compared to the EVs with a lower $SOC_{initial}$. At 22:00, all the EVs return to the CR with a reduction of 20% in their SOC, so all of them charge together and as they charge with the same power, they reach the SOC_{target} at the same time and stop charging at around 23:00. In (B), a lot of PV power is fed into the grid as there are not many loads at that time to consume it.

When a LC is connected to each household in a high irradiation scenario (graph D), the community deficit in the home charging configuration is almost close to zero. However, the community charging configuration's $Comm_{deficit}$ value is greater than zero as the LC connected to the charging station have no information about the loads or PV of the households. For a low irradiation scenario (graph C), the $Comm_{deficit}$ values in a home chargin station is close to zero until 15:00 and then increases because as there was not enough PV to charge the EVs, they has to charge itself by shifting to the SOC-control mode which results in consuming power form the grid. As compared to the results of the *with CR case*, by introducing local controllers the absolute value of $Comm_{deficit}$ is much lower and most of the times almost close to zero.

When a CC is introduced to the system, the $Comm_{deficit}$ value of the community charging configuration also goes to almost zero as compared to the *with LC* case. Not many conclusions can be made when comparing the $Comm_{deficit}$ of the home charging and the community charging configuration when a CC is introduced as the graphs almost coincide with each other. More interesting details can be found by looking at the DOTG graph of these cases in Figure 4.12.

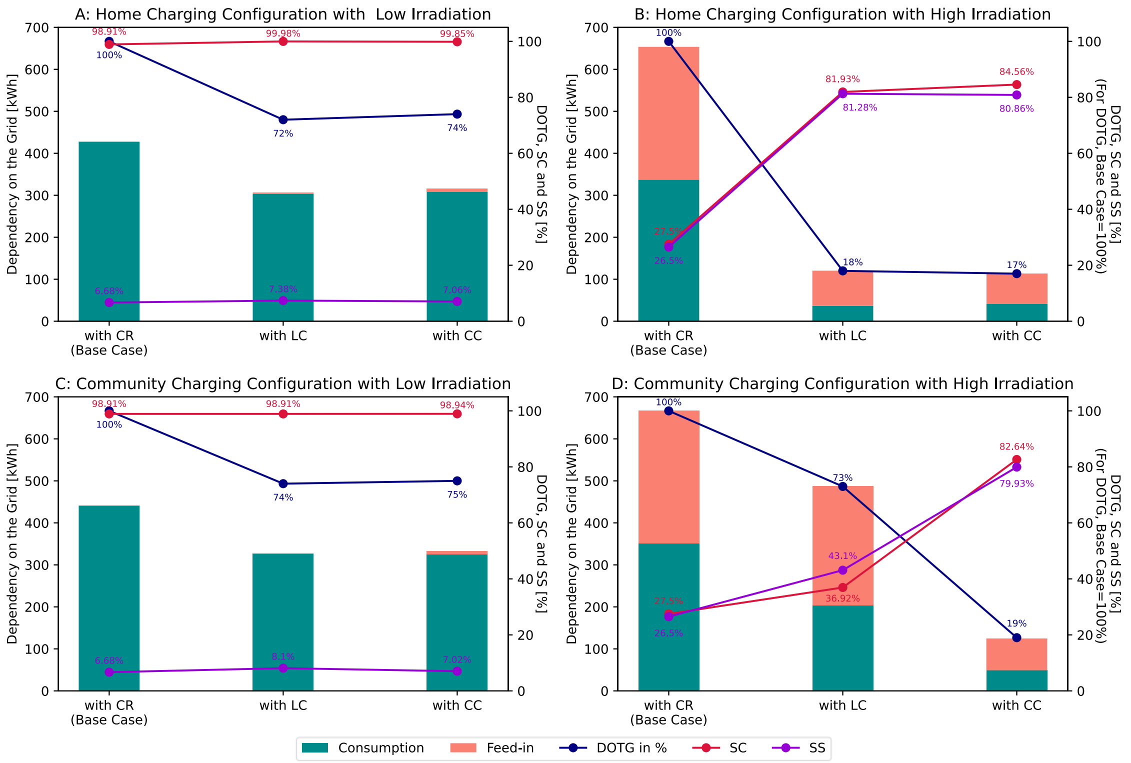


Figure 4.12: Dependency on the grid, self-consumption and self-sufficiency of the community when the work from home scenario is simulated with home charging and community charging configurations; Graphs on the left are for low irradiation scenario and right are for high irradiation scenario; A and B are for Home charging configurations and C and D are for community charging configurations.

When introducing a LC, the DOTG has reduced in all the cases as compared to the *with CR* case. For a low irradiation scenario, almost no changes have been observed in the values of DOTG, SC and SS with neither a home charging nor a community charging configuration. On the other hand, the DOTG value has increased a little when introducing a CC as compared to the *with LC* case. For a high irradiation scenario, the home charging station has better values of DOTG, SC and SS as compared to a community charging station. Nevertheless, the *with CC* case in (B) is almost similar to the *with LC* case, which means the community was already well-optimized by just having the LCs. This is because every household has an EV that is consuming the PV that is being generated. However, it would be different if not all households have an EV or if the EV at a particular household is not present at home, then the CC will perform better in optimizing the SC and SS of the community. For a community charging configuration with high irradiation, the *with LC* case did optimize the community as compared to the *with CR* case but not as much as compared to the home charging configuration. By introducing a CC to it, the values become comparable to the home charging station. When a CC is introduced in the home charging configuration, the SS value of the individual household decrease as compared to the *with LC* case. The values of SC and SS of individual houses in home charging configuration can be seen in Appendix B (Appendix Table A).

The reason is because of different $SOC_{initial}$ values of the EVs. The ones that have a lower $SOC_{initial}$ reach the SOC_{min} limit and cannot serve the loads in their household and consume power from the community grid. However, the CC instructs the EVs which have $SOC>SOC_{min}$ (i.e. the higher $SOC_{initial}$ EVs) to discharge so that the $Comm_{deficit}$ becomes zero. In this case, the EVs which are discharging will have to charge themselves later to reach the SOC_{targer} which then increases the loads of their respective households resulting in a drop in the SS value. Another case is that when there is high PV generation, the higher $SOC_{initial}$ EVs reach their SOC_{max} limit and cannot consume any further PV power, so it’s fed into the community grid. The CC instructs the EVs which can consume power to charge themselves which results in an increase in the total loads of their household leading to a decrease in the SS value. The values of individual houses in community charging can be seen in Appendix Table B and they remain the same for all the controller cases (*with CR*, *with LC* and *with CC*) because the house has only loads and PV present, the EV of the house are parked at the community charging station. The controllers perform well in optimizing the community in a high irradiation scenario as compared to a low irradiation scenario, which can be seen by a decrease in the DOTG values comparing the graphs on the left with the ones on the right. As well as with the WFH scenario, the home charging configuration has a better result as compared to the community charging configuration.

4.3.2 Random Time Scenario

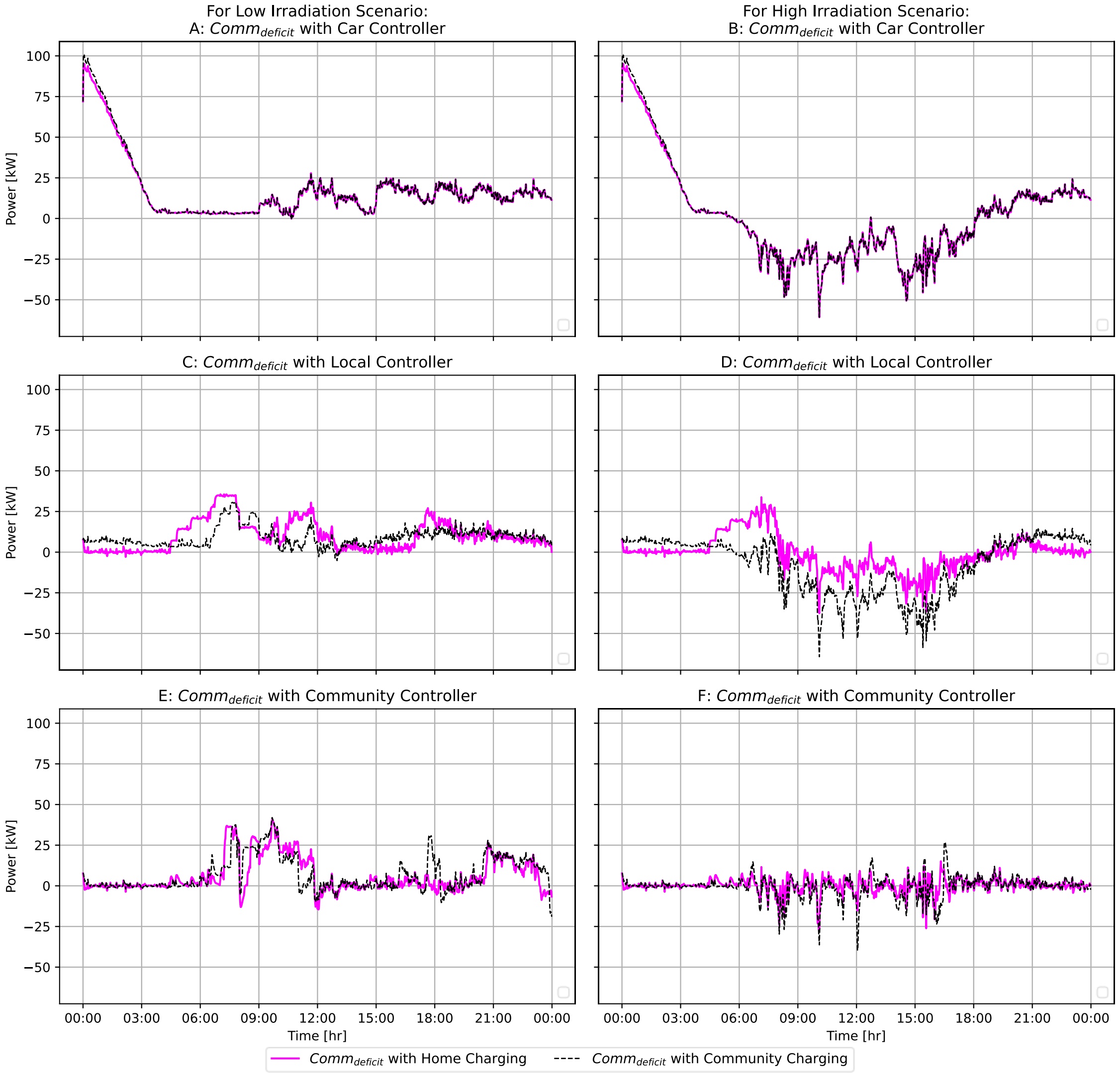


Figure 4.13: $Comm_{deficit}$ of the community when the random time scenario is simulated with home charging and community charging configurations; Graphs on the left are for low irradiation scenario and right are for high irradiation scenario; A and B are results for with CR case, C and D are for with LC case and E and F are for with CC case.

The results here have a lot in common with the results from the section before like no difference in $Comm_{deficit}$ value of the *with CR* case when comparing home charging and community charging, higher $Comm_{deficit}$ in the *with LC* case of community charging as compared to home charging among other points, but there are also some very interesting differences. It is observed that in general the peak loads have reduced as compared to the WFH situation as not all EVs have to leave the house at one time. Just by introducing a LC, the peak load goes to almost half the vales as compared to the *with CR* case. With a CC, the peak loads are even reduced further in the high irradiation scenario, but remain almost the same in the low irradiation scenario. The reason behind it is the different $Time_{leave}$ and $End\ Idle\ Time$ values of the EVs, this can vary from case to case. In the *with LC* case (C and D) between 03:00 and 09:00, the $Comm_{deficit}$ value of community charging configuration is lower than the home charging configuration because the cars which are in EO control mode discharge to the car which are in SOC-control mode if their $Time_{leave}$ is before the EO control mode cars. The only disadvantage is that those cars might reach their SOC_{min} value and have to charge later during the day when they have to leave. The *with CC* case under high irradiation scenario performs the best in maintaining the $Comm_{deficit}$ value throughout the day around zero.

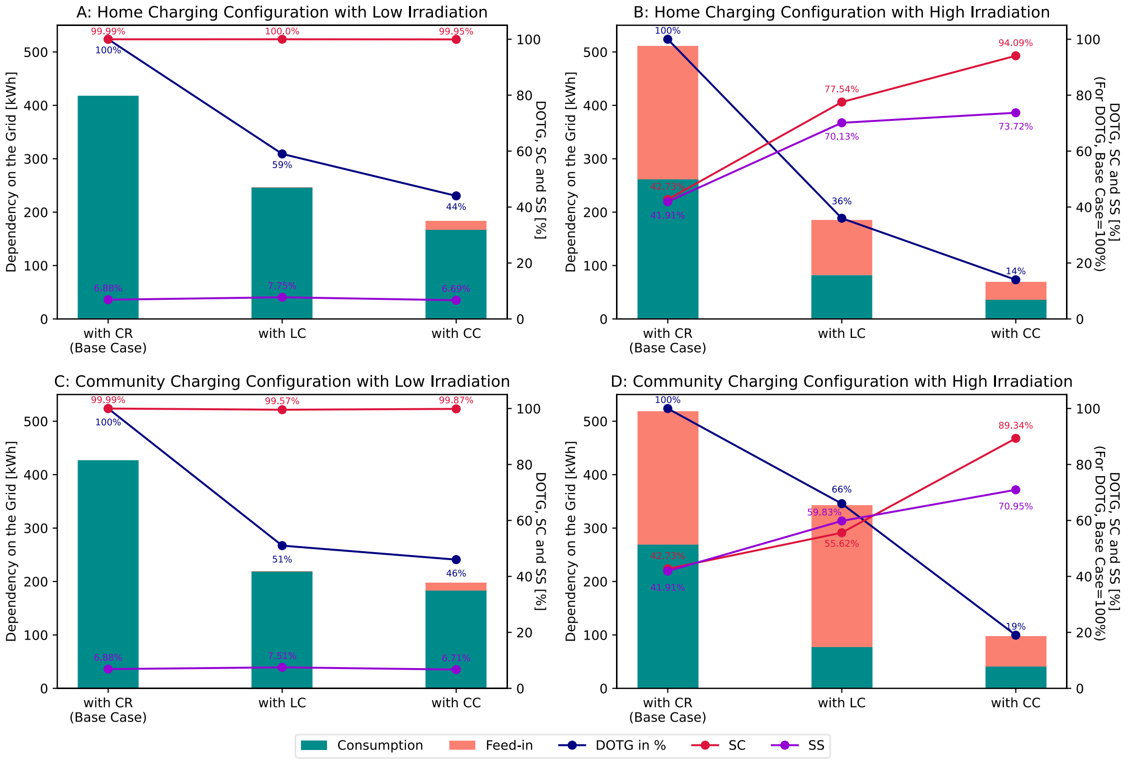


Figure 4.14: Dependency on the Grid, self-consumption and self-sufficiency of the community when the random time scenario is simulated with home charging and community charging configurations; Graphs on the left are for low irradiation scenario and on the right are for high irradiation scenario; A and B are for Home charging configurations and C and D are for community charging configurations

In a random time scenario, it can be seen that the controllers follow the same trend in reducing the DOTG and increasing the SC and SS values as compared to the WFH scenario. The random time scenario was simulated to examine the behaviour of an community close to reality where not all EVs will be present at home at all times. The results show that a community can be optimized with LCs in a home charging as well as a community charging configuration. An on the top optimization of the DOTG is possible by having a CC for the community but it results in decreasing the SC and SS values of the individual households compared to the home charging configuration seen in Appendix Table C. The reason for their decrease is because the households that have an EV help the other households who do not have an EV present by consuming their excess PV by charging themselves or by discharging to serve their loads. This increases the total loads of the respective household which results in a decrease in the SS value.

5 CONCLUSION

In this study, an energy optimization model was built for a household and a community that used bidirectional EVs as a controllable element to increase the consumption of solar PV and reduce its dependency on the electricity grid. The results show that a bidirectional EV with controlled charging strategies improved the SC and SS of a household and a community as compared to uncontrolled unidirectional charging strategies.

For a single household, the values of SC was increased by 40% when introducing a LC to the house that consumed the excess PV generation which was fed into the grid when using uncontrolled strategies. The SS increased by 36% which led to a reduction in the DOTG by 66%. It was observed that higher values of SC and SS can be achieved if the EV stays home for a long period of time and leaves the home late in the evening after consuming the PV power.

When a community was introduced with a CC that performed an on-the-top optimization of the households with LCs in the community, the DOTG was reduced by 81%. The highest SC of the community was observed as 94% with a SS of 73%. Moreover, the CC reduced the peak loads of the community by more than 50% as compared to an uncontrolled charging scenario. The CC managed to optimize the community by simulating a realistic scenario when some EVs are present at home and when some are not.

Community charging stations, where all the EVs of the community are parked at one place for charging, was optimized with a LC which was placed at the charging station. The results of the home charging scenario and a community charging scenario were comparable when introducing a CC. This concludes that fewer number controllers in the system can achieve the same level of results as compared to a large number of controllers when they are modelled in an efficient manner which makes it interesting for urban planning.

Reduction in the SC and SS of individual households was observed (as compared to the *with LC* case) in a community when a CC is connected but this can be compensated with favourable financial models built for the customers who help the community in reducing its DOTG. Real load and PV profiles were used in the simulation which makes the results realistic, future work could include using real mobility data to perform the simulations and compare the results. Examining the results of long term simulations could be done on the next step to calculate the annual SC and SS value of the household and the community. Studying the effect of the controllers on the grid stability could be a further step in modifying the control strategies which are favourable to the electricity grid.

As a closing statement, it can be said that the controllers perform well in a high irradiation scenario as compared to a low irradiation scenario, but always perform well when compared to an uncontrolled charging scenario.

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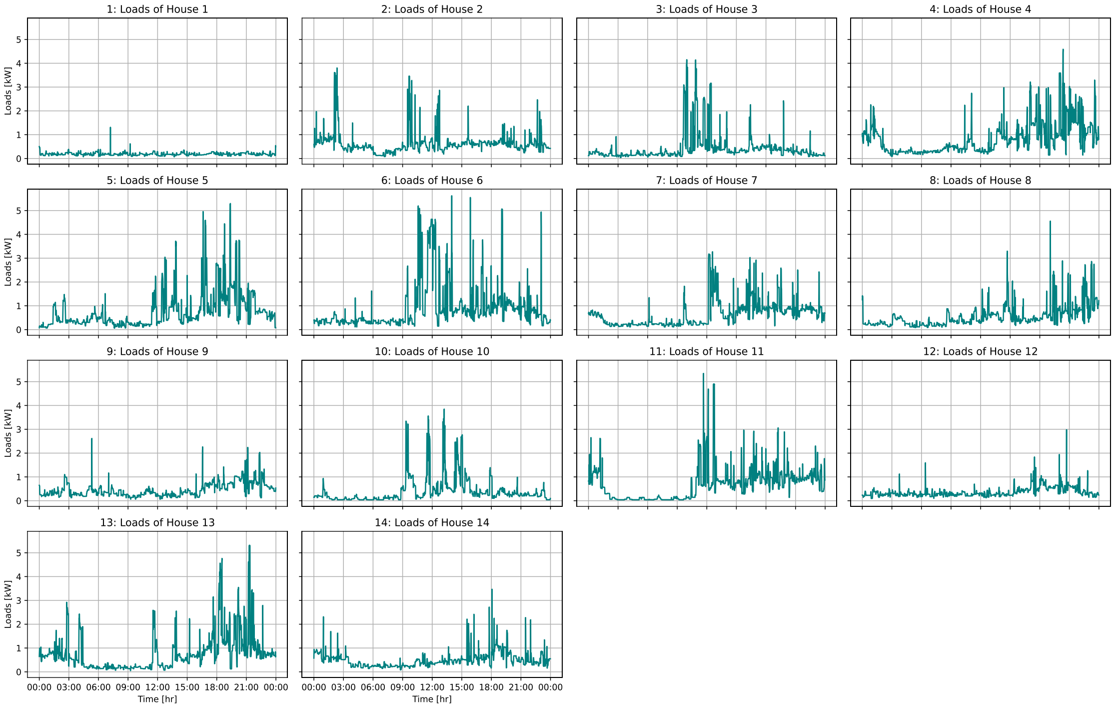
APPENDIX

A Load profiles of individual households for a community



Appendix Figure A: Load profiles of individual households in a community scenario

B Results of individual households for a community

Appendix Table A

Work From Home Scenario - Home Charging Configuration												
House	**Low Irradiation**						**High Irradiation**					
	With CR		**With LC**		**With CC**		**With CR**		**With LC**		**With CC**	
	SC [%]	SS [%]	SC [±%]	SS [±%]	SC [±%]	SS [±%]	SC [%]	SS [%]	SC [±%]	SS [±%]	SC [±%]	SS [±%]
House1	49.57	9.36	43.94	23.32	8.31	4.66	9.37	25.21	19.22	56.75	19.52	56.82
House2	89.35	7.54	6.74	0.21	4.54	-0.45	27.31	32.87	39.32	39.99	35.74	37.05
House3	86.19	7.80	7.61	1.46	5.47	0.46	25.47	32.85	39.40	53.31	34.47	47.17
House4	81.06	4.74	14.74	0.95	1.87	-0.05	30.94	25.82	57.81	45.49	49.70	39.71
House5	79.92	4.45	14.09	1.04	3.74	0.27	30.21	24.02	63.31	50.14	53.71	42.03
House6	97.91	4.63	0.77	0.28	1.04	0.34	44.13	29.78	47.75	39.03	43.52	28.64
House7	81.43	8.58	14.35	2.41	0.94	0.04	21.69	32.58	30.29	41.74	29.12	40.70
House8	68.52	4.89	26.33	1.98	9.17	0.43	24.46	24.90	44.29	40.58	42.84	38.68
House9	87.27	4.38	9.55	1.19	4.64	0.97	31.13	22.26	62.83	55.49	57.89	41.75
House10	91.26	4.62	5.03	1.30	7.60	1.39	23.00	16.61	71.56	63.31	61.22	46.80
House11	65.09	3.81	28.97	2.37	14.40	1.41	18.25	15.21	77.11	66.92	65.79	53.78
House12	81.95	5.47	12.60	1.35	4.39	0.56	25.79	24.56	64.86	64.88	51.17	51.10
House13	84.13	5.15	11.27	0.92	5.49	0.33	30.23	26.39	59.19	50.56	48.98	42.29
House14	67.83	6.04	26.57	4.09	3.61	0.77	17.59	22.32	48.06	62.06	46.10	59.56

The columns ‘With LC’ and ‘With CC’ are not actual percentages but change [±%] in the percentage as compared to the respective ‘With CR’ case. For example consider House 1 in a low irradiation scenario in the *with LC* case. The actual value of SC *with LC* is SC ‘WithCR’ (49.57%) plus the change in the SC column of ‘With LC’ (43.94%) making it a total of 93.51%. The negative sign indicates that there is a reduction as compared to the ‘With CR’ value.

Appendix Table B

Community Charging Configuration				
House	**Low Irradiation**		**High Irradiaiton**	
	SC [%]	**SS [%]**	**SC [%]**	**SS [%]**
House1	49.57	24.07	9.37	64.86
House2	89.35	12.85	27.31	56.02
House3	86.19	18.98	25.47	79.97
House4	81.06	9.05	30.94	49.28
House5	79.92	9.76	30.21	52.61
House6	97.91	10.03	44.13	64.48
House7	81.43	15.06	21.69	57.20
House8	68.52	8.25	24.46	42.00
House9	87.27	12.55	31.13	63.82
House10	91.26	15.36	23.00	55.19
House11	65.09	13.22	18.25	52.85
House12	81.95	18.57	25.79	83.32
House13	84.13	11.38	30.23	58.32
House14	67.83	17.32	17.59	64.05

Appendix Table C

Random Time Scenario - Home Charging Configuration												
House	Low Irradiation						High Irradiation					
	With CR		With LC		With CC		With CR		With LC		With CC	
	SC [%]	SS [%]	SC [±%]	SS [±%]	SC [±%]	SS [±%]	SC [%]	SS [%]	SC [±%]	SS [±%]	SC [±%]	SS [±%]
House1	75.52	14.25	6.76	13.69	9.88	-3.34	-19.65	30.40	70.18	57.38	74.15	39.88
House2	92.80	7.83	3.08	1.24	-3.45	-0.15	-5.29	33.23	78.18	30.66	69.28	19.55
House3	86.19	7.80	2.00	2.24	2.66	-0.83	-7.03	34.95	71.98	51.14	65.69	22.66
House4	91.40	5.35	4.39	1.03	-10.34	0.11	6.19	42.21	64.32	5.97	56.23	0.82
House5	79.92	4.45	16.32	1.58	16.92	0.82	8.07	51.59	62.16	13.20	56.10	-1.47
House6	97.91	4.72	0.77	0.19	0.00	0.16	14.18	49.12	77.62	17.83	74.47	6.20
House7	81.43	8.58	14.35	2.78	0.17	-3.18	-10.46	38.47	62.48	35.84	75.82	35.43
House8	68.52	4.89	26.33	1.98	0.00	-1.17	-0.55	46.69	69.30	18.79	76.27	14.79
House9	90.11	4.52	-0.12	0.70	0.68	0.60	12.46	52.55	65.51	-1.14	62.06	-6.33
House10	91.56	4.64	-0.07	1.00	-0.02	1.00	12.02	56.06	55.16	-10.27	48.63	-16.84
House11	65.09	3.81	0.00	0.73	0.00	0.69	6.23	49.75	36.97	-14.17	37.58	-19.11
House12	81.95	6.98	12.60	-0.52	0.00	-1.36	-5.53	40.87	96.18	48.58	87.82	27.45
House13	84.13	5.15	11.05	1.70	11.62	0.26	4.55	41.64	74.03	28.35	68.03	5.03
House14	68.38	6.08	26.02	4.63	-0.55	1.05	-6.63	39.03	70.79	24.78	66.26	16.90

All the colums with ‘[±%]’ indicate change not actual values as described in the start of this section.

DECLARATION

I hereby confirm that this thesis is entirely my own work. I confirm that no part of the document has been copied from either a book or any other source – including the internet – except where such sections are clearly shown as quotations and the sources have been correctly identified within the text or in the list of references. Moreover, I confirm that I have taken notice of the 'Leitlinien guter wissenschaftlicher Praxis' of the University of Oldenburg.

Aliqyaan

Aliqyaan Sakarwala
Oldenburg, Germany, 3rd February 2022