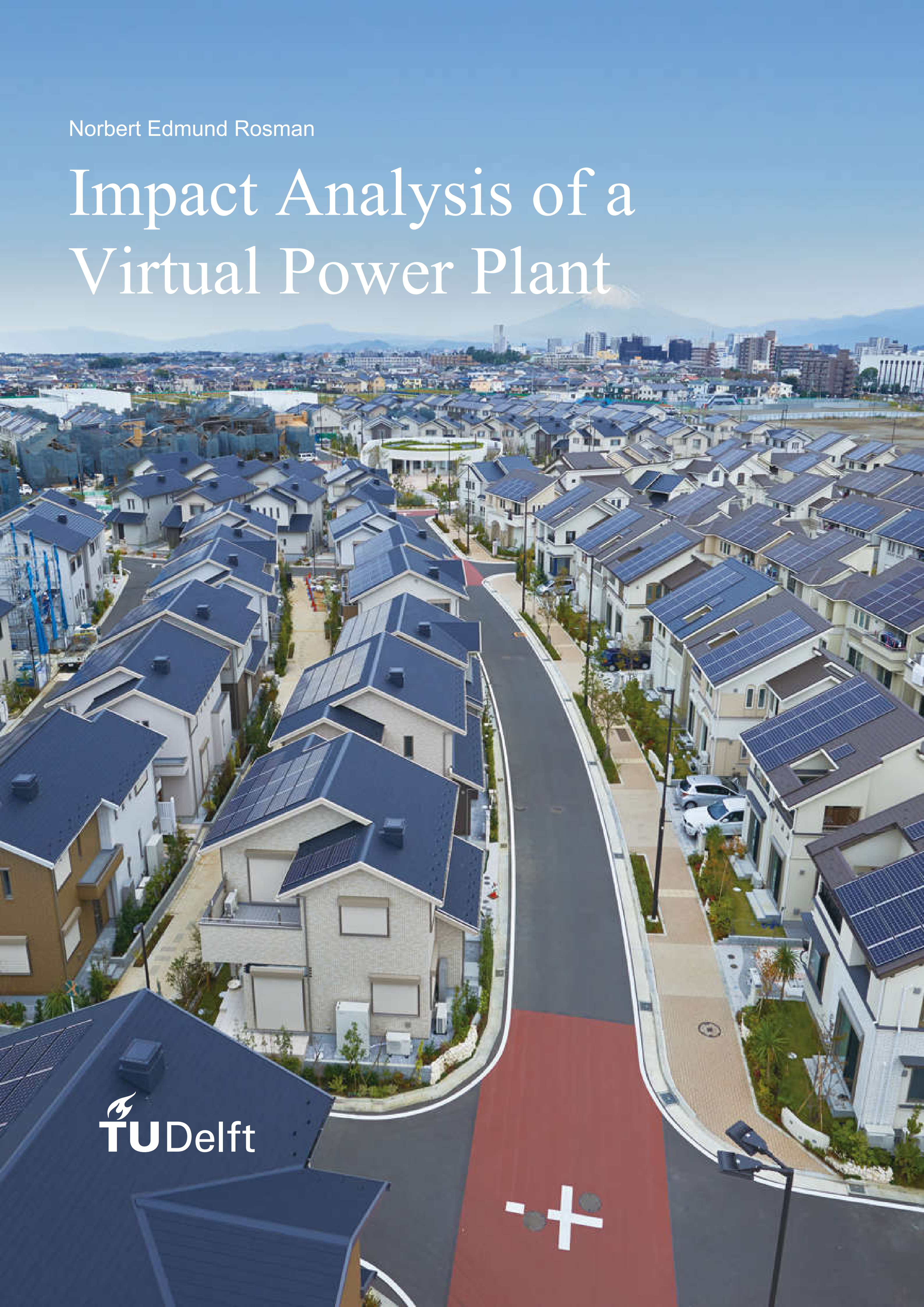
Norbert Edmund Rosman

Impact Analysis of a Virtual Power Plant



TU Delft

Impact Analysis of a Virtual Power Plant

By

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Abstract

The development of the renewable industry is still accelerating. The Netherlands contributes to roughly 1,5 GW solar PV capacity and domestic PV systems are increasingly popular. Another aggressively growing energy technology which is currently reaching its maturity is energy storage, which is also indicated as a "missing link to renewable energy" and can serve multiple other purposes like supplying ancillary services, transmission and distribution infrastructure services and many more. Aggregation of the devices from those technologies set a base concept for the VPP which was modelled in this work. The VPP by aggregation of small generating or any flexibility providing units enables their visibility on energy markets. The model of a VPP was based on the City-Zen project ongoing in one of the districts of Amsterdam in which home storage systems are aggregated to participate as a VPP on the Dutch energy market.
The model was build in Python environment where all logics was kept. Further it was interfaced with power systems analysis tool – PowerFactory in which load-flow calculations were made. The mode enabled impact evaluation of the VPP under economical and physical angle. It was concluded that currently no business case exists for such a VPP, however in the future it may be a profitable investment. The physical impact exerted by operating VPP on the distribution network turned out to be harmful and would force the DSO to upgrade the transformer or limit the number of participating houses.

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1 Introduction

In this chapter base for the further elaborations will be set. At first the background giving an overview of some of the energy technologies and concepts is presented. It will allow continuation with a section giving reasons behind existence of this work and showing its importance for different parties that would be involved in possible investment. Next the definition of problems that may occur during evolution of current work is presented and followed by the objectives within which the research questions are presented.

1.1. Background

The global growth of renewable energy is still increasing. The generating capacity added in 2016 was the highest ever reached and was estimated as 161 GW. Moreover, the strong transition to renewable energy can be observed when comparing the capacity added from renewable sources to capacity added from conventional power plants. Annually more is added from green energy than from all fossil fuels combined. RES contributed to almost quarter of global electricity production with most coming from hydroelectric power stations (roughly 17%). Energy generated from wind and biomass contributed to respectively 4 and 2% of global electricity production. Solar PV achieved 1.5% and for the first time its growth outperformed other renewable energy technologies with 47% compared to 34% wind and roughly 16% hydro. Globally, by the end of 2016, installed solar PV capacity reached at least 303 GW. The Netherlands contributes to roughly 1,5 GW and in 2016 it added 426 MW of solar PV capacity. Growth of commercial installations (above 15 kW) was still bigger compared to the residential with 2687 systems installed and capacity of roughly 385 MW. 10302 domestic installations (below 15 kW) were mounted reaching capacity of 41,4 MW. This gives average size of the system added in 2016 equal to roughly 4 kW. [1, 2, 3]

Another aggressively growing energy technology which is currently reaching its maturity is energy storage, which is also indicated as a "missing link to renewable energy" and can serve multiple other purposes like supplying ancillary services, transmission and distribution infrastructure services and many more. The technology is in fact relatively old especially the bulky segments of it like pumped hydro. However, in this work the focus will be put on younger sector, namely home storage which also with popularization of electric vehicles is currently being commonly promoted. This units are usually relatively small and are used only for local purposes in the boundaries of one household.

The existence of huge variety of different technologies, which give different flexibility and have at their disposal different capacities triggered the notion of collaboration between the owners of different energy units representing them. By working together the owners of small to medium sized energy sources could create an entity with unified power profile, which could act alike or even outperform conventional power plants. Eventually those entities were given all the rights to participate in the energy markets like conventional power plants. The entity based on the aggregation of different power sources and other units providing energy flexibility was named Virtual Power Plant (VPP).

1.2. Motivation

The concept of a VPP is relatively new and its definition has not settled yet in the literature. The most common VPP examples aggregate medium sized generating units, like wind turbines or small PV plants. However, in this work less popular approach to VPP concept will be pursued. The VPP modelled in this work will consist of home storage units along with PV

systems. This concept was introduced in the City-Zen project ongoing currently in one of the districts of the Dutch capital – Amsterdam.
Not much studies were conducted to evaluate the performance of such a VPP concept and it is not known if any business case for such an investment exists. The VPP as an entity with an access to the energy market may profit from trading. However, a household being a part of such a VPP still is subjected to regular costs of energy which is bought from energy retailer. This means that a correlation between the household energy costs and the activity on the energy market will exist and may be profitable for both or none of the parties. The estimation of the correlation may give an answer to how such an entity should be maintained. It may suggest whether the collaboration between the household owners and the VPP owner is required or maybe the business cases for both mentioned parties can be decoupled.
Furthermore, each household is a microgrid with its own characteristics and limitations. Those characteristics and limitations will influence the business case for both parties. The modelling of such household may lead to answers about the correlations between the physical limitations of the microgrid and/or the components with the final economical performance. All electrical components and especially physical storage devices degrade. As the operation and maintenance has an influence on a business case it is important for the VPP owner to know what to expect in this manner. The VPP model may give an answers to the VPP owner if and how his operation is harmful for the devices what may be transferred to costs of maintenance. On the macroscale the VPP owner may benefit from collaboration with particular types of households increasing in this way possibility of gaining profit from the positions established on the energy market.
What is more the VPP is operated in a part of the distribution network and will have direct physical influence on its condition. The VPP owner may desire operate its VPP in a way that is harmful for the grid but gives the most profits. The Distribution System Operator (DSO) may need to upgrade grid to allow desired operation of the VPP. The DSO by utilising a model of such a VPP can be answered whether the operation of such an entity in their network should be worrying.

1.3. Problem Definition

As already said the entire VPP concept is relatively new in the energy industry. The specific approach to the VPP construction modelled in this work is not popular either. The VPP model built in this work has to combine a number of different layers and points of views. The technical layer includes realistic reflection of the household with the PV system and home storage system. An endless number of different components can be used for creation of each of mentioned systems not mentioning the rest of the devices connected in the house, which inevitably have an influence on an overall performance of the microgrid. Further the economical layer, which combines the household owner, VPP owner and DSO points of view. The household owner approach is aims to minimizing its energy bill by choosing the cheapest retailer. The VPP owner wants to maintain its system the least and maximize its revenues by trading or serving other services. There is almost an endless number of possibilities of different trading strategies that can be undertaken by such a VPP owner. The DSO has to maintain its grid in satisfying condition but will decline unneeded grid upgrade. The combination of the variables and possible different scenarios in building a model of the VPP can be overwhelming and makes the modelling of such a system difficult.

1.4. Objectives

The main objective of this work is construction of a realistic model of the VPP. The model should present satisfactory performance and needs to reflect the phenomena ongoing in the VPP precisely enough to generate reliable results. The analysis of the results should give answers to the research questions shown below.

1.4.1. Research questions

1. *What is a business case of the VPP located in the Dutch distribution network, and what are potential areas of improvement?*

2. *What impact does the operation of the VPP exert on the local distribution network and storage devices degradation?*

Sub-questions:

1.1. What is the business case of the EES behaviour schemes now and in the future?
- power demand driven EES behaviour scheme,
- energy market driven VPP operation scheme,
- energy market and demand driven VPP operation scheme.

1.2. What is the business case of the area compositions now and in the future?
- High power demand with small PV
- Realistic
- Low power demand with big PV

1.3. What are the optimal converter settings required to improve business case?
1.4. What energy market should be chosen?
1.5. What are the trading settings required to improve the business case?
1.6. How does the limitation of overcurrent protection devices influence the business case?
1.7. What is the NPV and PBP of the cases above?

2.1. What problems may be expected in the local distribution network with the operating VPP?
2.2. What is the impact of the EES behaviour schemes on the local distribution network and on the degradation of the storage devices now and in the future?
- power demand driven EES behaviour scheme,
- energy market driven VPP operation scheme,
- energy market and demand driven VPP operation scheme.

2.3. What is the impact of the area composition on the local distribution network and on the degradation of the storage devices?
- High power demand with small PV
- Realistic
- Low power demand with big PV

2.4. What is the degradation of the storage devices after a year of operation as parts of the cases above?
2.5. How are the power transformers loaded with different penetration of PV and EES systems in the local distribution network for the cases above?
2.6. What are the thresholds of the penetration beyond which the distribution transformers are overloaded?

2 Theoretical Background

The purpose of the chapter is an introduction of definitions, concepts and rules providing an opportunity to properly understand the model described in the following chapter. To build a model of a VPP with sufficient precision a number of different topics has to be intermeshed. Therefore, the chapter will firstly present the concept of energy trading. Then the notion of a VPP seen from different perspectives and several approaches for defining a VPP will be introduced. It will provide insight in operation of a VPP and its classification. Further some information about placement of a VPP will be introduced, namely information about the power distribution networks. Some general concepts and specific values for the urban environment in Europe will be provided. Next some concepts and short state of an art in PV systems will be introduced. To ensure secure and reliable operation of the power distribution network and safety of people using it a proper design and protection is required. Hence, the theory of how the distribution system is designed and protected will be provided. The focal point of the project is energy storage, hence profound preface providing insight into the theory of energy storage, in particular to electrochemical batteries, is given.

2.1. Energy Trading

In recent years an energetic development of the electricity sector economy was observed, especially in European countries where comprehensive liberalization and deregulation were applied. The reason behind this movement is an assumption that the liberalization, and as a last step privatization, improves the economical efficiency in the sector. The development of the electricity supply industry can be shown in four steps, which start from monopoly model.
The monopoly model (Figure 1) can be divided into two sub-models. In both of them the utility handles generation and transmission of the electricity. However, one of the sub-models also incorporates the distribution into the utility responsibilities and in the other one the distribution is handled by one or more separate companies. In this model the wholesale market is fully controlled by the utility, nevertheless energy trade between different utilities is still available.

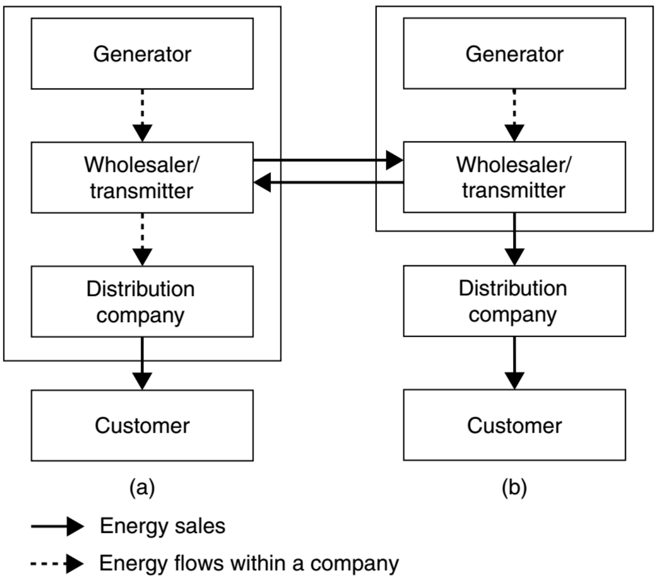


Figure 1 Monopoly market model with submodels: (a) – completely vertically integrated utility, (b) – distribution not integrated into the utility

The next evolution of the monopoly model is purchasing agency model (Figure 2) and is also divided into two sub-models. One of them is a first step to introducing competition to the wholesale market. Even though the wholesale market is still handled by the utility the generation is not fully controlled by the utility anymore. So called independent power producers (IPP) are introduced, who sell the energy to the utility, which plays a role of a purchasing agent. The second sub-model is an evolution of the first one. The generation is fully accompanied by multiple IPPs, who sell their energy on the utility, which does not own any generation capacity anymore. From there multiple distribution companies can buy energy and resell it to their consumers. The wholesale purchasing agency has to regulate the price what puts some competition incentives on the generation sector, nevertheless the price level is not regulated in the same way as in the open market. In the monopoly utility model all technical issues are settled within one entity, what in theory can minimize the operation costs. Some will also argue that this approach will ensure maximum reliability to the system. Nevertheless, in terms of generation the monopoly utility will usually tend to overestimate the generation capacity what will cause the consumer to pay for not necessarily needed power plant.

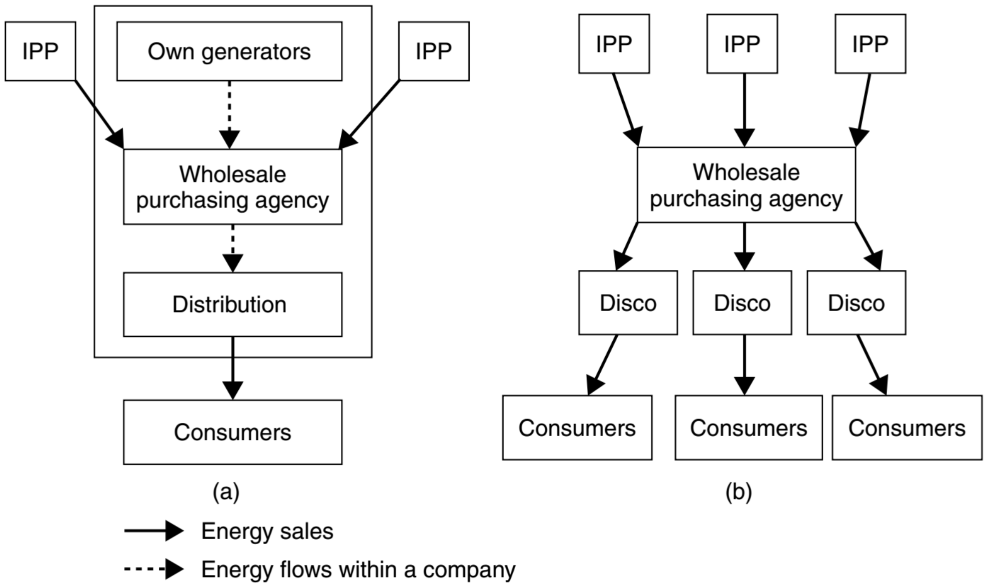


Figure 2 Utility as a purchasing agent with sub-models: (a) – integrated, (b) – non-aggregated

Following economy model called wholesale competition model (Figure 3) allows the distribution companies to buy energy directly from the generation companies mediated by the open wholesale market. The model grants permission to buy energy directly from the wholesale market to large energy consumers. The only functions that remain centralized at the wholesale level in this model are operation of spot market and operation of the transmission system.

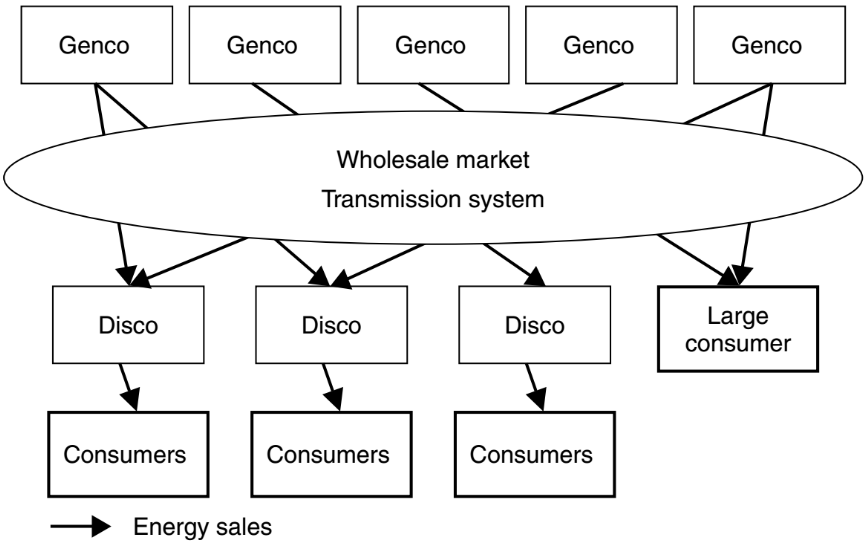


Figure 3 Wholesale competition model

Even though the generating companies are subjected to much bigger competition comparing to other models and the wholesale price is driven by supply and demand, the retail level is still centralized. The small consumers cannot change the distribution company if the price is to high, hence the retail price has to be regulated. However, the next evolution of the model deals with that problem.

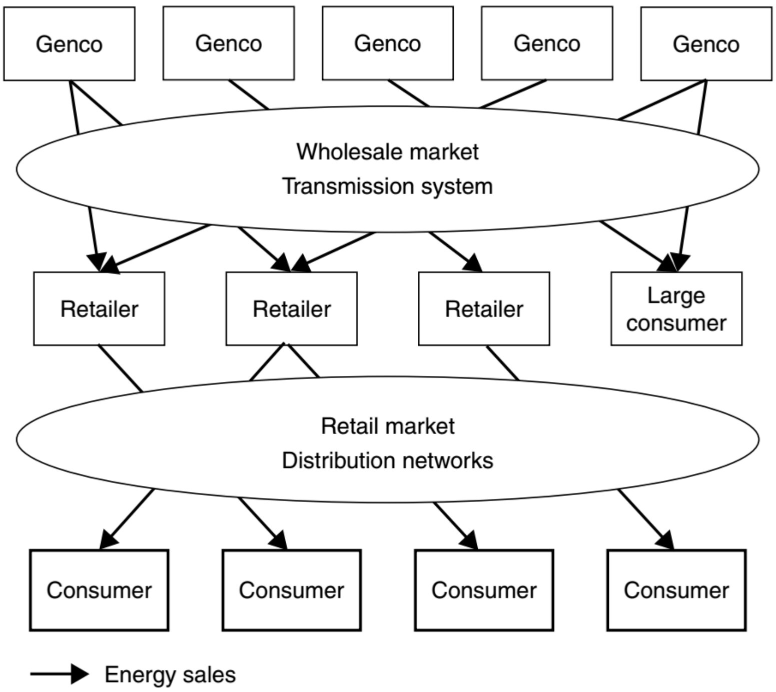


Figure 4 Retail competition model

The retail competition model introduces competition at the retail level, thereby allowing the small and medium consumers to choose their energy supplier. In this way the retail price does not have to be regulated anymore and the final design of the energy economical sector is created. This model is currently present in most of the European countries. The large consumers are still allowed to buy energy from the wholesale market decreasing the transaction costs. The retailers also buy energy at the wholesale market on behalf of their consumers and resell it. The only monopoly functions that remain from previous models are operation of transmission and distribution systems.

Summing up, all forms of the economy introducing competition and decentralized approach imply the decisions made by a group of differently oriented entities. In the models containing competition in the generation area the sum of the capacity of the independently funded power plants is hoped to match the demand more closer than in the case of single decision-making department. At the beginning of the sector evolution fear of the reliability decrease was observed, however the modern power systems prove that a model with properly operated wholesale market is capable of maintaining its reliability and that the fears were not fully legitimate. To ensure proper operation of the network its frequency needs to be stable. It means that the energy generation at all times has to be matched with the energy demand in the system. In order to achieve the balance between the generation and demand and be able to exploit the assets of competitive wholesale market, in the Netherlands the market was divided according to the time scale of transactions. The long-term markets use a notion of bilateral agreements of futures, which offer energy transactions made years in advance. The medium-term markets offer transactions made on an hourly basis days ahead (spot market) or within a day (intra-day market). The portions of energy traded on even smaller time step basis on top of the energy traded at the other markets provide sufficient accuracy to maintain the balance between the generation and demand. So called ancillary services required by the transmission system operator (TSO) are parts of the power balancing market. The offered services need to work on a time step base ranging from seconds to hours. The most relevant in Dutch context ancillary services are:

- Frequency services,
- Voltage services,
- System restoration services.

The frequency services consist of three reserves, namely Primary also called Frequency Containment Reserve (FCR), Secondary also called Frequency Restoration Reserve (FRR) and Tertiary. The Primary Control in case of a deviation from the goal frequency is automatically triggered by the European Network of Transmission System Operators (ENTSO-E). The associated TSOs are obliged to contribute to restoration of the frequency within 30 seconds. The primary control is crucial in maintaining system reliability and it is not a part of the imbalance pricing system. The FRR is triggered in an control area of the TSO, which experienced the disturbance. Its aim is restoration of the system optimal frequency and nominal cross-border exchange in the area. Usually it is activated automatically and leads to response times within five minutes. The tertiary control ensures availability of FRR in case of unplanned disturbances occurring during the operation of secondary control. The TSO requires certain amount of available capacity for the secondary and tertiary control, which are priced by the imbalance system.

The TSO in the Netherlands interacts with so called Balance Responsible Parties (BPRs), which take part in the power balancing market. The prices of the market are settled in 15 minute periods (Program Time Units – PTUs). The BPRs submit scheduled market activity day before. During the day TSO can make adjustments to maintain in balance. Then for each PTU the settlement prices are developed, which are related to the system imbalance. Those prices are also referred to as energy imbalance prices. The prices can differ greatly from those offered at the medium term markets like day-ahead market ran in the Netherlands in Amsterdam Power Exchange (APX) and integrated by EPEX SPOT, which gathers some of the European energy markets.

The characteristic value allowing participation in any of the energy markets is minimum bid size accepted at the market. Obviously, at the wholesale markets the minimum size of a bid is relatively big compared to capabilities of the small or medium sized generation units. Therefore, the options of owners of those units are limited to transactions with the retailer or avoiding costs by self-consumption of the energy consumed on the spot. Nevertheless, a concept introduced in the following part of the chapter may be a solution, which will allow to expand possibilities of small and medium generation units' owners.

2.2. Virtual Power Plant (VPP)

The concept of a VPP is still reasonably recent, hence there is no unified definition respected in the literature. Different authors base their definitions on the VPP physical system structure, control system structure or on the purpose of the VPP. Regarding the physical system structure all definitions agree that a VPP is an aggregation of distributed generation, controllable loads and/or storage devices [4, 5, 6, 7, 8, 9, 10]. Nevertheless, regarding the control system structure the definitions do not overlap anymore. In some of the definitions the control system is broadly introduced as centralized [4, 5, 8]. Other approach introduces a division of the control system structures to: Centralized Controlled Virtual Power Plant (CCVPP), Distributed Controlled Virtual Power Plant (DCVPP) and Fully Distributed Controlled Virtual Power Plant (FDCVPP) [11]. In the first structure all decisions regarding all DERs are made in a single entity. In the second one a hierarchical model of a VPP control is introduced. A lower level VPP control entity coordinates operation of a number of DERs and delegates the decisions to the higher VPP control entity. Both of the aforementioned structures are centralized and the broad definition can be used to describe them. In the third VPP control structure each of DERs is an independent entity reacting to its own operation incentives and even though the whole system may have common goal the control system is not centralized and the broad definition cannot be utilized. Some of the definitions containing VPP's purposes are strict and limit their possibilities. They introduce a VPP as a body, which has a flexibility, and controllability similar to large conventional power plants [7]. Whereas, other allows VPPs to outperform conventional power plants providing higher efficiency and more flexibility [5, 10]. Some of the goals given in the definitions are more precise describing VPP as an entity that can be used to make contracts at the wholesale market and provide services to the system operator [9]. One of the definitions perceives VPPs as an "Internet of Energy", which goal is an incentivization of the network to provide more services to the customers, therefore maximizing the end-user revenues and the development of software innovations [12].

As mentioned above VPPs facilitate trading in various wholesale markets as well as providing some services for the system operators. From those activities a duality of VPPs concepts came to light. VPPs aiming to market participation are described as "commercial" (CVPP) and those used for system management and support were described as "technical" (TVPP). [9]

Characteristic aspect of a CVPP is that its aggregated profile does not take into account the impact of the distribution grid. The functionalities of a CVPP are wholesale market trading, balancing of trading portfolios and supplying services, which are not location-specific. Depending on the system access rules the location of the DERs representing a CVPP can be different. Systems with unlimited access will allow any geographic location. Nevertheless, when the location of the energy sources is crucial for proper system operation, it can be restricted to a certain location, like part of a distribution network or a transmission network terminal. Yet, the location of DERs within the restricted area is discretionary. The CVPP allows DERs to utilize the economies of scale and market prediction tools to maximize its profit. Any CVPP can be operated by a third party or a balancing responsible entity with access to the market. In principle the information about the DERs, like operating parameters, metering data or load forecasting data are gathered in the CVPP management system along with information from the market forecasting tools to plan the CVPP behaviour. The CVPP projected profile can be divided into base scheme and the variable scheme. The profile constitutes the potential trading capacity of the CVPP at certain time. The base part of the profile represents a constant capacity which the operator of the CVPP will have in its command in the whole forecasted period if the forecasting is perfect. The variable part of the profile represents the changing

capacity throughout the forecasted period on top of the base capacity. In this way the CVPP operator may establish a strategy and decide to trade on the day-ahead or long term market with the base capacity and utilize the variable part of the profile for trading on shorter periods. After choosing the VPP behaviour the decisions are send to the TVPP. [4, 9]
In summary the CVPP allows DERs to gain a visibility on the energy markets, what would not be possible or would be difficult if the same DERs were operated as single entities. Furthermore, aggregating DERs allows them participation on the wholesale markets, including the long-term ones and potentially decreases the costs of transactions. Last but not least by utilizing the diversification of the portfolio technologies and the market intelligence the CVPP can benefit from favourable fluctuations of prices in the market. [9]
In the contrary to the CVPP a characteristic aspect of a TVPP is that its aggregated profile takes into account the impact of the distribution grid on the VPP output. Because of that even in a system with unlimited access the DERs of the TVPP will be situated within the same geographical location. In order to allow provision of TSO-related services TVPP requires information about all DERs within the local network and the network details, like topology, status or restrictions. Most probably the entity, which will provide the distribution grid information to the TVPP will be the DSO. Furthermore, the role of the DSO can evolve and it can request various services from the VPP. The aggregated profile of the TVPP combines the involvement of all controlled DERs and the influence of the distribution grid. In this way the profile is visible at the point of the transmission system connection. Therefore, it can be taken into account by the TSO along with other bids and offers from conventional power plants to provide balancing services. [9, 7, 11]

2.3. Electrical Distribution System

The electrical distribution system is the part of the grid, which purpose is to distribute the electricity taken from high-voltage, highly meshed transmission network to end users in a secure and efficient manner. It starts at the terminal substation where power transformers step-down the voltage coming from the transmission network to the level accepted in the primary distribution system circuits. The primary distribution cables or overhead lines operate at MV level and transmit the power to local substations placed in the vicinity of the end users. The transformers in the local substations step down the voltage to the level required by the customer. These networks are managed by the local utility or a Distribution System Operator (DSO) and carry the electricity to the end users, which may be residential or commercial.
In Europe distribution networks in medium to large-sized towns or cities are underground cable based and in the rural areas overhead line based. At the secondary distribution system circuits in the urban environment standard is 3-phase 4-wire with voltage level of 230/400V. The medium to low voltage substations are usually equipped with one or two transformers of rating up to 1500 kVA. In domestic areas the consumer substations are connected at a nominal voltage between 1 – 35 kV and usually not exceed 1250 kVA. The metering is utilized at the LV level. The topology of the distribution systems are usually radial with unidirectional power flow, from the utility to the end user. Nevertheless, an introduction of renewable energy sources and therefore upgrade of the role of an end consumer to prosumer may change this situation. The prosumer is not only draining the energy from the grid, but it also generates electricity locally. This will change the direction of the power flow in the network, which will be forced to operate in bidirectional power flow conditions. Therefore, to provide security and reliability of the network it may become more meshed. [13, 14, 15]

2.4. Photovoltaic (PV) System

In general PV systems may be very simple and consist only of PV panels and a load, which is operational only when the panels receive radiation. They can also be very complex and consist of multiple elements involving grid connections, UPSs, ESSs, heat pumps, diesel backup generators etc. Depending on the system composition we can determine three types of PV systems: stand-alone, grid-connected and hybrid. In the residential areas grid-connected systems (Figure 5) are most common. PV panels in this type of systems are connected to the infinite bus through an inverter, which converts DC power to AC. The inverter is usually connected to a distribution board, from where the power is transferred to the grid or to the loads connected locally. In principle, this type of PV systems do not require connection to batteries, since all energy surplus can be supplied to the grid. In this way the home installation do not only rely on the intrinsically intermittent power source like PV panels, but can be supplied directly from the grid. Nevertheless, installation of ESS in domestic environment becomes increasingly common, what allows increase of renewable energy consumed locally. [16]

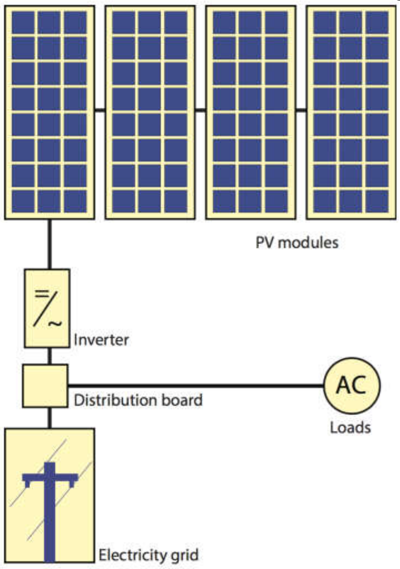


Figure 5 Scheme of grid-connected PV system [16]

2.5. Overcurrent Protection System

To ensure security of the power distribution network and people using it a proper design and protection is required. Several conditions must be satisfied by the cabling and its protection, in order to ensure safety and reliability of the installation.

Cables must:

- Transfer the permanent full load current and normal short-time overcurrents.
- Not cause voltage drops, which may reduce the performance of certain loads.

Furthermore, the protection devices must:

- Protect the cables and busbars from any overcurrent.
- Protect persons against indirect contact hazards, usually by RCD protection rated at 300 mA.

An overcurrent is a phenomenon occurring every time when for a certain load the current exceeds the maximum load current I_B. At the bottom network level the maximum load current is directly correlated with the rated apparent power of the load. Nevertheless, at higher levels of the network, when currents of several loads are combined the maximum load current changes its form. It correlates to the sum of apparent power ratings of all the loads and additionally takes into account the diversity factor and the utilisation factor. [13]

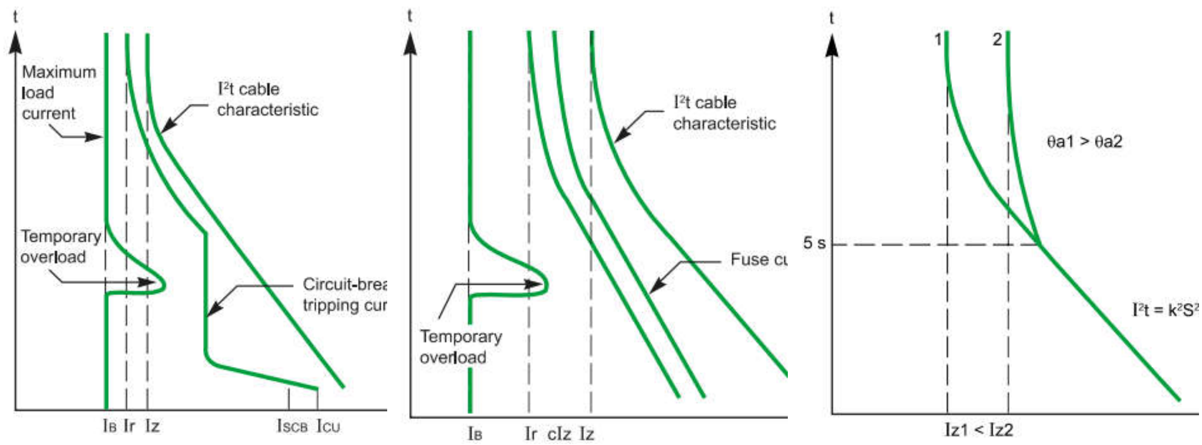
$$I_B = k_s \times k_u \sum_{i=1}^{n} I_A \qquad (3.1.)$$

Where:

I_B – maximum load current,
I_A – current corresponding to the apparent power rating of a load,
k_s – diversity factor,
k_u – utilisation factor.

When overcurrent occurs the current must be cut off with rapidity depending on the current magnitude (the bigger the current the faster it must be cut off), in order to avoid cables and the loads damage. In some circumstances overcurrents are allowed to in healthy electric circuits for example during motor starting and cables are designed to withstand those currents. The cable can be damaged by currents reaching beyond the cable characteristic (Figure 6). Current I_z represents the maximum permissible capacity that can be carried by the cable indefinitely without reducing the life expectancy. It depends strongly on several parameters:

- Cable design (materials used for cores and insulation, number of active conductors, their placement etc.)
- Ambient temperature
- Method of installation
- Influence of neighbouring circuits



a) Circuit-breaker *b) Fuse* *c) Temperature influence*

Figure 6 Overcurrent protection curves [13]

Where:

t – duration of short-circuit current [s],
I – short-circuit current [A R.M.S.],
I_r – regulated nominal current of the overcurrent protection device,
θ – temperature.

The protection device choice is based upon following rules (Figure 6):

- The nominal current of the protective device I_n must be smaller than the maximum permissible current I_z and bigger than maximum load current. (zone a Figure 6)
- The tripping current I_2, corresponding to the operation of the protective device in its conventional time, of the protective device must be smaller than $1.45 \times I_z$. (zone b Figure 6)
- The breaking rating in case of 3-phase short-circuit fault must be greater than a 3-phase short-circuit current achievable at this point of the installation. (zone c Figure 6)

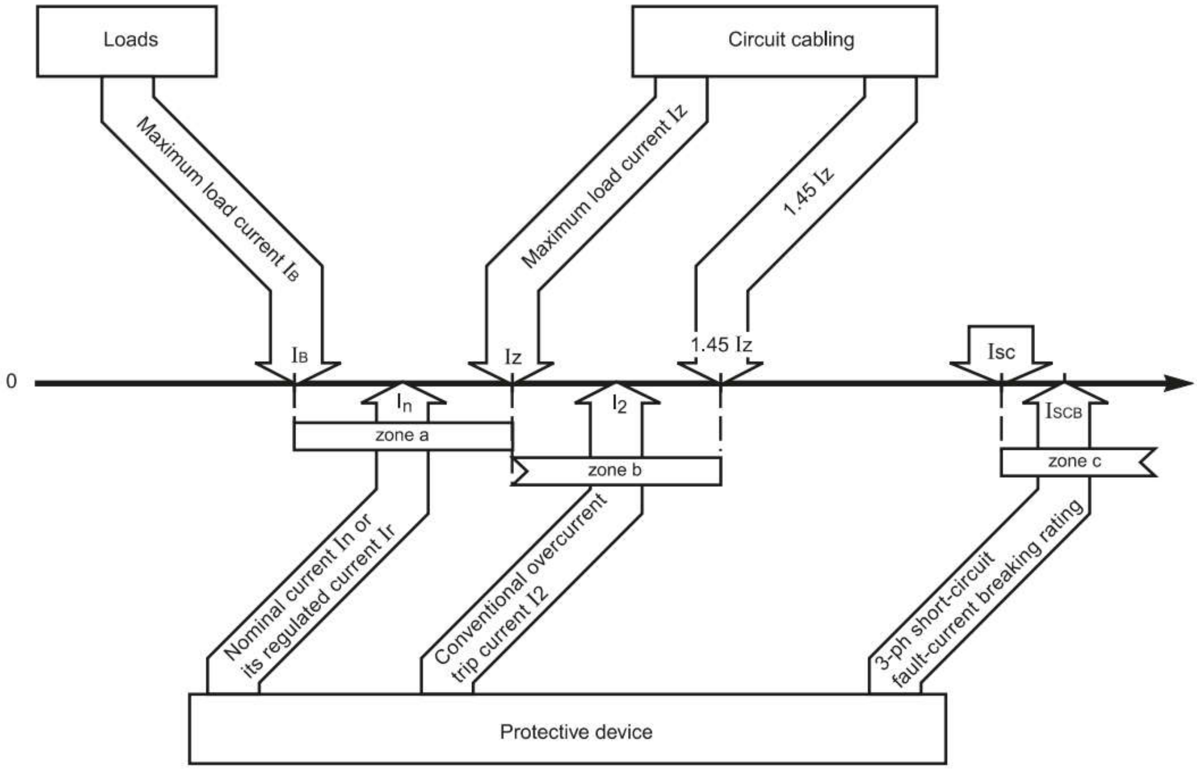


Figure 7 Overcurrent protection system design [13]

2.6. Electrical Energy Storage (EES)

In general, the electrical energy storage is capable of converting energy, in the broad sense, to electrical energy reversibly. It consists of a number of vital for its proper operation components. Even though some variations of the storage technology are implemented a general diagram of EES can be conceived (Figure 8). The energy storage device physically stores the energy. Its technologies can be classified based on what methodology of storing energy they use. We can differentiate three of them:

- Mechanical (e.g. flywheel, compressed air)
- Electrochemical (e.g. lead-, nickel-, lithium ion batteries)
- Electrical (e.g. capacitors, supercapacitors)

In many cases the power exchanged between the supply and the energy storage device has to be converted, what is done by a single electronic converter or a conversion system.

The energy storage device is in first instance controlled by low-level management system. Its input is all the data from the energy storage device current state, namely, in case of batteries cells currents, voltages, temperatures or in case of flywheels rotating speed, temperature etc. It also ensures that the device works in its safe boundaries. In the high-level management system the behaviour of the energy storage device is determined. [17, 18]

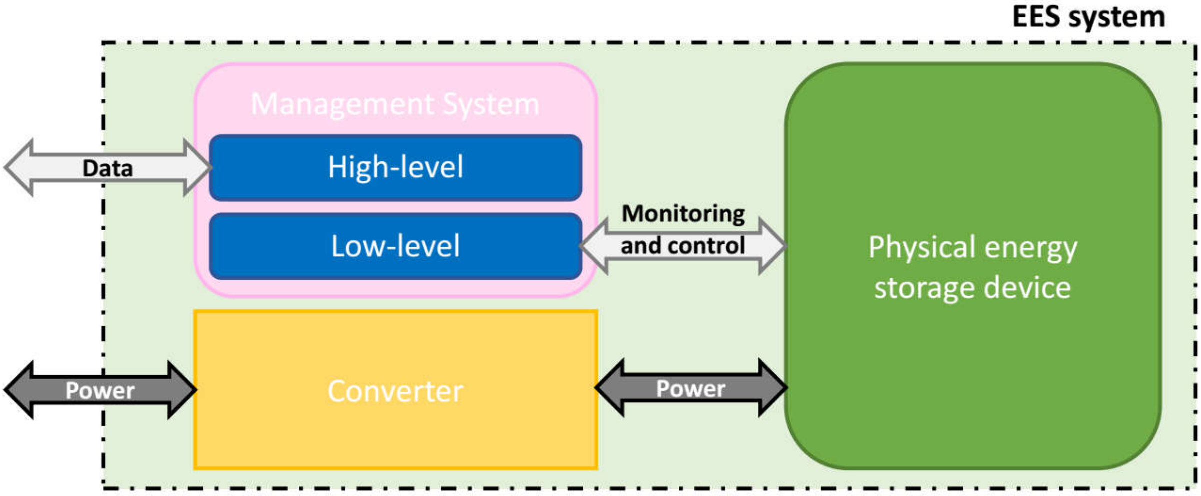


Figure 8 EES system diagram [17]

The technologies have different characteristics and are used in different applications. Different fields of applications of the storage technologies can be estimated based on the technologies' energy capacity capabilities and their power output potential (Figure 9).

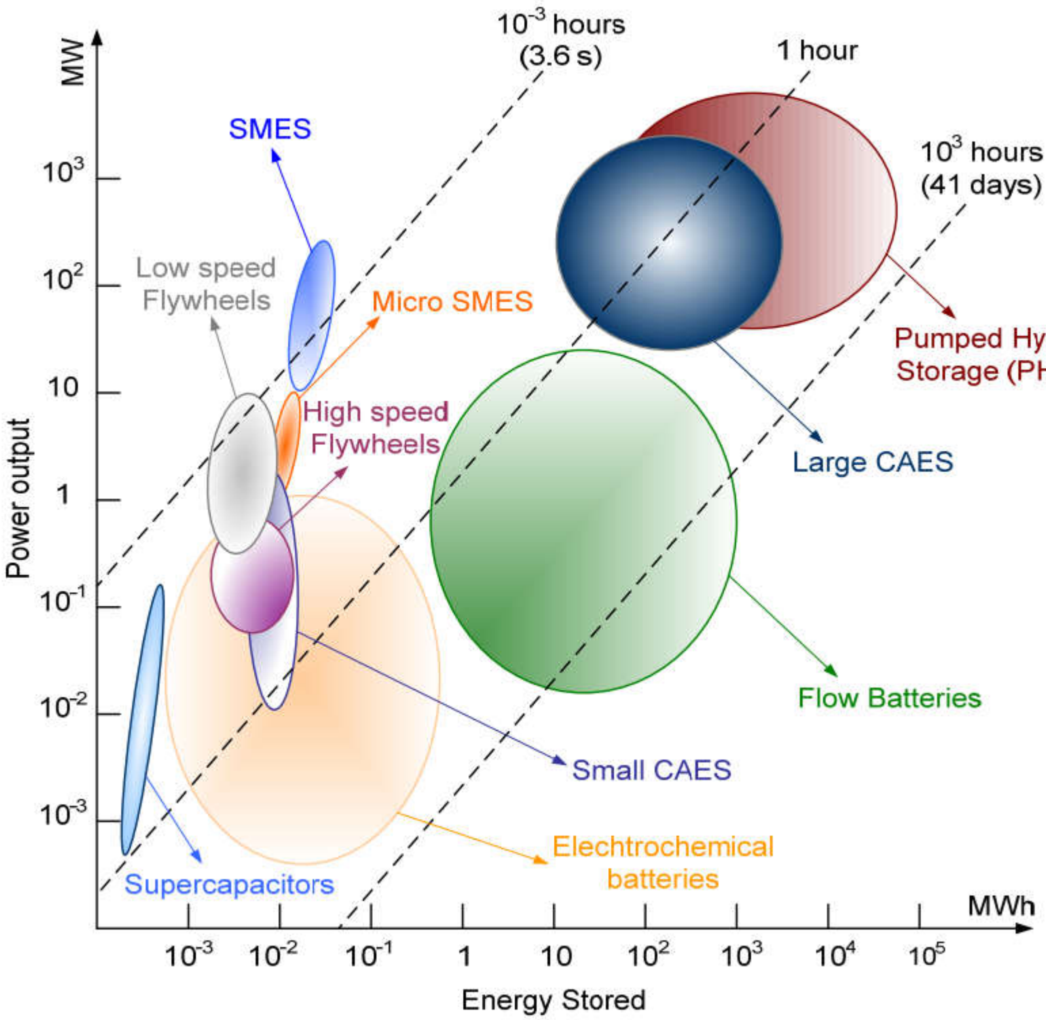


Figure 9 Energy storage devices potential [19]

The applications of stationary EES are presented in the table below (Table 1). Important fact is that EES can serve multiple purposes even simultaneously in order to increase the overall profitability of the system. This method is called application, revenue or benefit stacking.

		Power range	Discharge duration
	Bulk energy services		
1	Electrical energy time-shift	1 MW – 500 MW	2 hours – 6 hours
2	Power supply capacity	1 MW – 500 MW	2 hours – 6 hours
	Ancillary services		
3	Load following	1 MW – 100 MW	15 min – 4 hours
4	Regulation	10 MW – 40 MW	Seconds to hours, depends on market
5	Frequency response	2 MW – 50 MW	Seconds to minutes
6	Spinning, non-spinning and supplemental reserve	10 MW – 100 MW	Minutes to hours
7	Voltage support	1 MVAr – 10 MVAr	Minutes to an hour
8	Black start	5 MW – 50 MW	Seconds to hours
	Transmission infrastructure services		
9	Transmission congestion relief	1 MW – 100 MW	1 hour – 4 hours (cannot be generalized easily)
10	Transmission upgrade deferral	10 MW – 100 MW	1 hour – 8 hours
	Distribution infrastructure services		
11	Distribution upgrade deferral	500 kW – 10 MW	1 hour – 4 hours
	Customer energy management and microgrid services		
12	Power quality	100 kW – 10 MW	Milliseconds – 15 minutes
13	Power reliability (grid-connected)	50 kW – 10 MW	1 hour – 8 hours
14	Power reliability (microgrid operation)	50 kW – 10 MW	1 hour – 8 hours
15	Retail electrical energy time-shift	1 kW – 1 MW	1 hour – 6 hours
16	Demand charge management	50 kW – 10 MW	15 minutes– 4 hours
17	Renewable power consumption maximization	50 kW – 10 MW	1 hour – 4 hours
	Renewables integration		
18	Ramp rate control	1 MW – 500 MW	1 minute cyclic-repetitive –4 hours
19	Generation peak shaving	1 MW – 500 MW	1 hour – 4 hours
20	Capacity firming	1 MW – 500 MW	1 hour – 4 hours

Table 1 Stationary EES applications [17]

The application requiring the least power, from those mentioned above is, retail electrical energy time-shifting. In principle, the EES is used to gather the energy during off-peak hours (low energy price) or from the surplus of the energy generated by renewable sources and discharge during peak hours (high energy price). This type of generating profit is often referred to as arbitrage. It is also possible to increase the self-consumption rate by supplying the demand from the EES charged by the renewable sources when it is required. At the figure presenting energy storage technologies potential (Figure 9) we can observe that the only technology corresponding to the power discharge and discharge duration represented by retail electrical energy time-shift in table above (Table 1) is electrochemical battery. [17]

2.6.1. Electrochemical Batteries

The electrochemical batteries convert, in an electrochemical oxidization-reduction reverse reaction, chemical energy contained in its active materials into electric energy. They can be divided into several groups: [20]

- Standard batteries (e.g. lead acid, Ni-Cd)
- Modern batteries (e.g. Ni-MH, Li-ion, Li-pol)
- Special batteries (e.g. Ag-Zn, Ni-H2)
- Flow batteries(e.g. Br_2-Zn, vanadium redox)
- High temperature batteries (e.g. Na-S, Na-metachloride)

2.6.1.1. Electrical Characteristics of Electrochemical Batteries

The different electrochemical systems used in the battery influence its open-circuit voltage U_0 as well as to what extent it is discharged, temperature and other factors. The discharge voltage U_d, because of the electrode polarisation and ohmic voltage drops is smaller than U_0 and depends on the discharge current I_d. The voltage decreases with the raising current. The power ($P = U_d \cdot I_d$) provided by the battery increases at first with the current raise, but at certain moment after reaching its maximum it starts to diminish. A typical power curve of a battery is presented below (Figure 10). [21]

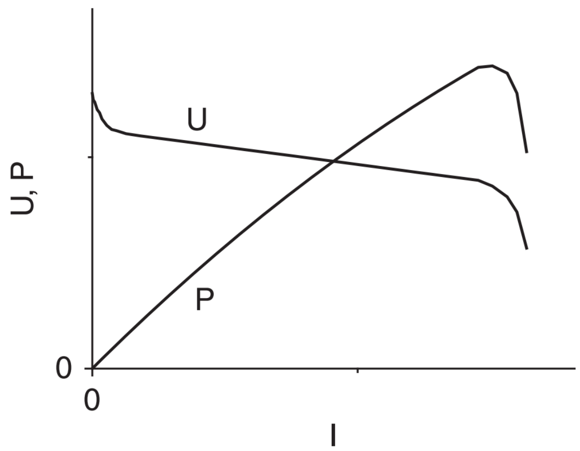


Figure 10 Typical battery power curve [21]

When the battery is subjected to discharge its discharge voltage U_d or the electric charge $Q_d$diminishes. The decrease depends on the chemical processes ongoing in the reactants or on the electrodes of the battery and/or on its increased ohmic resistance. The voltage decline may be sudden or gradual (Figure 11). Because of that the cut-off voltage is set, at which the battery discharge process is cancelled. The process is terminated even though the battery is not fully discharged in order to ensure its safe operation. [21]

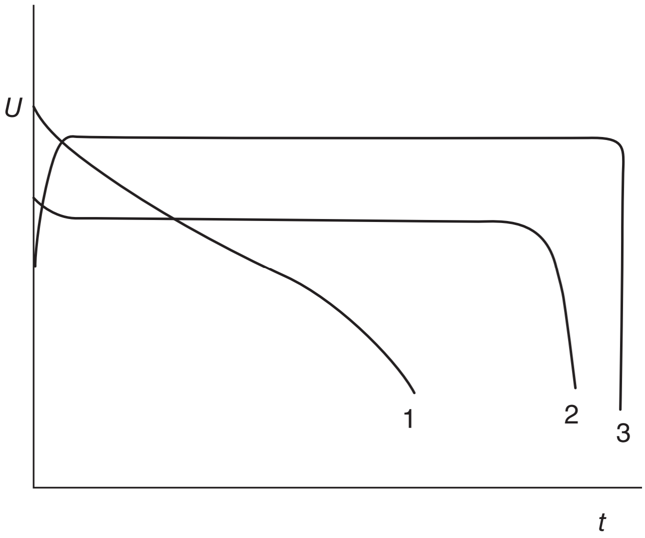


Figure 11 Typical voltage discharge curves (1 – steep, 2 – flat, 3 – with initial dip)

The discharge current of the battery depends on the external load R_{ext} and it is equal U_d/R_{ext}. Because of abovementioned fact the power discharge of the battery will be also determined by the load chose. Nevertheless, to prevent the battery from malfunction (e.g. overheating) its operating points are limited to maximum discharge current $I_{bat\,\max out}$ or critical voltage U_{crit}. With the current an important characteristic of the battery is directly associated and it is maximum discharge power $P_{bat\,\max out}$. Another important battery parameter, which not necessarily is equal to the maximum discharge power is its maximum charge power $P_{bat\,\max in}$. [21]

2.6.1.2. Battery State Measures

The electric charge is equal to the current provided by the battery in a certain time of discharge ($Q_d = \int I_d dt$) and it is given in ampere-hours (Ah). The charge delivered by the battery during a full discharge is called ampere-hour capacity C. The State of Charge (SoC) of the battery indicates the percentage of charge remaining in the battery from the its initial capacity. Therefore:

$$SoC = \frac{C - Q_d}{C} \tag{3.2.}$$

Where:
SoC – state of charge [%],
C – battery capacity [Ah],
Q_d – electric charge discharged from the battery [Ah].

The Depth of Discharge (DoD) of the battery indicates the percentage of charge that the battery has already discharged from its initial capacity. Therefore:

$$DoD = 1 - SoC \tag{3.3.}$$

Where:
DoD – depth of discharge [%],
SoC – state of charge [%].

Similarly, to the concept of amount of charge in the battery the amount of energy can be introduced. Therefore, the State of Energy (SoE) can be defined as a percentage of energy remaining in the battery from the initial energy capacity. [22]

2.6.1.3. Self-discharge

Even though the battery is not subjected to discharge after a full charging process it never reaches its full capacity, because of self-discharge. At each electrode independently self-discharge occur when the battery is not in use. They are associated with parasitic redox reactions, which since they are chemical phenomena accelerate with increasing temperature. It can also depend on the battery age and usage history. Depending on different technology used the self-discharge rate of the battery can also change along with its state of energy SoE or time. As mentioned before, to ensure safe operation of a battery a low-level battery management system has to be supported from the battery. Hence, the energy used to sustain the operation of the BMS is perceived as a part of the self-discharge of the battery. [21, 22]

2.6.1.4. Degradation

Every battery at all times is subjected to degradation caused by chemical reactions in the battery medium. The process fades its capacity, discharge and charge power. The aging process of the battery can be divided into calendar and cycle fade. The calendar fade is associated with the process ongoing in the battery, which is dependent mostly on time even in the absence of its usage. The degradation rate of cycle fade depends also on the SoE and its temperature. Nevertheless, usually the principal cause of aging of batteries is their usage. The cycle fade represents the decrease of battery parameters associated with its cycling. A full cycle is defined as a full charge and full discharge or reverse. The smaller the cycle is the less damage it causes to the battery, hence the lifetime of the battery can be significantly increased if the DoD is decreased. The two fades are certainly correlated with each other, nevertheless depending on which is the major one the unit in which the lifetime of the unit is provided can change. If the aging is caused more by time the lifetime (shelf-lifetime) of the battery should be provided in time units (e.g. months or years). However, when the fatigue of the battery takes major responsibility for its degradation the lifetime should be provided as number of cycles. The End of Life (EoL) of batteries are given in percentage of remaining capacity and for different applications and technologies are provided in European standards. For lithium-ion batteries for electrical vehicles (IEC 62660-1) the EoL is stated as 80% or for lithium cells for portable applications (IEC 61960) is 60%. [17]

2.6.1.5. Lithium-ion Batteries Performance

Very attractive option to serve retail electrical energy time-shifting in domestic areas is lithium ion battery, mostly because it provides the highest energy density among the commercially used technologies. The self-discharge depends on the material of the electrodes and for C-$LiMO_2$ 0,6% per month was experimentally obtained and for C-$LiFePO_4$ 1,2% per month. Nevertheless, as already mentioned above an additional part for the BMS support should be added to the self-discharge rate of the medium, which was estimated as 3% for C-$LiFePO_4$ batteries. The rate of self-discharge is also dependent on time and it accelerates with running time. For lithium-ion batteries first 24 hours of non-operation the remaining stored energy can decrease by 5% continuing with a rate of 2% for the medium and 3% for the BMS per month. [22, 23, 24]

An important parameter of any electrical device is its efficiency. A faradaic efficiency over a charge/discharge cycle is a ratio of the delivered electrons number to injected electrons number. In the lithium-ion batteries operating at nominal currents the efficiency is nearly 100% in certain conditions. When the current and temperature is identical during the charge and discharge and when the battery final SoE is equal to the initial SoE after the charge/discharge cycle. The measurements often show that the efficiency can be even greater than 100%, due to dissimilar conditions during charge and discharge. The faradaic efficiency described has no association with any electronics, what in practice is hard to achieve, because of inseparable BMS of the battery. An overall efficiency of a battery in a long run (repeated charge/discharge cycles) depends on many factors, namely:

- current amplitudes,
- temperature,
- range of SoE,
- others.

Nevertheless, in lithium-ion batteries it is relatively high and for C-$LiFePO_4$ is close to 95% and for different technologies it can reach even 98%. The values are referred to the beginning of life of a battery and they will decrease as battery is subjected to degradation. [22]

In the lithium-ion batteries the degradation process is mostly due to three main phenomena:

- decrease of the amount of lithium exchanged between the electrodes,
- degradation of the electrode materials,
- parasitic reactions.

In different usage profiles, namely with different values of maximum discharge or charge power, cut-off voltages, DoD, operating temperature the phenomena will be limited or stimulated. Nevertheless, the quality of the battery is of big importance, namely: the purity of the components or the electrodes capacity ratio. [22]

2.6.2. Power Converter

Often an electronic interface between the energy storage medium and the grid is necessary. Power electronic converters are crucial to the EES system as well as to the PV systems. They inject the high-quality current to the grid complying with the grid standards. Furthermore, they are responsible for charging and discharging the energy storage medium in a controlled manner. Additionally, they may provide anti-islanding protection, which disconnects from the grid when the grid support is lost or provide power for critical loads. Different types of power electronic converters are used for number of applications. Those used most often for grid connected residential EES are presented at the figure below (Figure 12 - Figure 14). [25]

The first topology taken into consideration (Figure 12) consists only of an inverter and a transformer. When discharging the battery the DC current from the battery is converter in the inverter to AC and then the transformer steps-up the voltage to match the grid voltage level. The role of the transformer is also providing galvanic separation between the grid and the rest of the circuit. It is unquestionably the simplest of the presented topologies and most probably the cheapest in design and construction. Nevertheless, to allow proper discharge mode operation the voltage of the battery needs to be higher than the step-down transformer voltage level. It narrows down usage of low voltage battery packs. Furthermore, the charging methods are in this case limited to a constant voltage charging. This kind of topologies are used in cheap car battery chargers with lead-acid batteries and they are often used for lithium-ion cells, although with more complex protection circuitry. [26, 25]

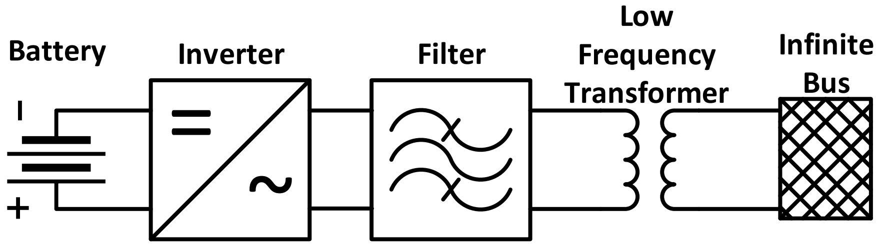


Figure 12 Battery converter topology with inverter only and low frequency transformer [27]

Next topology (Figure 13) is more complex and in addition to the previous one utilises a bidirectional DC/DC converter. This design will most probably be more expensive in design and construction, nevertheless it provides control over the DC voltage. In the discharge mode the DC/DC converter is used to boost the battery voltage above the voltage level of the transformer. This will allow the current to flow from the battery to the grid. Again, the inverter is used to chop the DC voltage and form an unfiltered AC signal. Then the waveform is passed through an output filter in order to smoothen out the imperfections. Further, the perfect AC waveform supply the step-up transformer to reach the voltage level of the grid. [28]

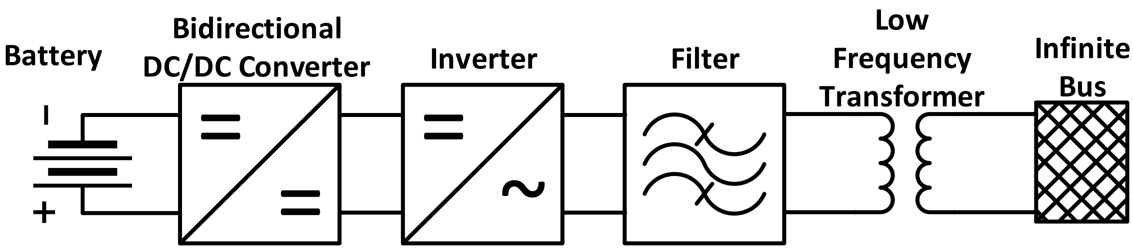


Figure 13 Battery converter topology with bidirectional DC/DC converter and low frequency transformer [27]

The third considered topology (Figure 14) consists of the same components as the previous one, namely from bidirectional DC/DC converter, inverter and transformer. Nevertheless, the low frequency power transformer representing an interface between the grid and rest of the circuitry was removed. Instead of the low frequency transformer a bidirectional DC/DC power converter was equipped with a high frequency transformer. This solution allows to significantly decrease the size of the power transformer core, what transfers into better spacing on the circuit board and lower material costs. [28]

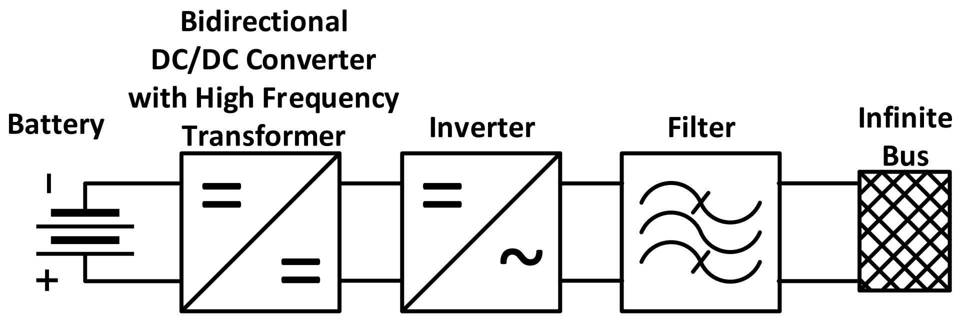


Figure 14 Battery converter topology with bidirectional DC/DC converter with high frequency transformer [27]

A significant influence on the performance of the EES has the efficiency of a power converter. It depends on many factors like losses of each component of the converter, topology, switching frequency, temperature, control system losses etc. Manufacturers in the data sheets of such devices provide mass of data about the performance of their equipment, which are essential for its proper connection and operation, including nominal voltage levels, acceptable voltage variations, frequencies, maximum output/input power and current, total harmonic distortion, power factor and mechanical characteristics. Nevertheless, the true performance factor of the converter, namely its efficiency at every operation point, is simplified to a single number representing peak efficiency of the device. This poor description may be misleading for the EES designer, because the overall efficiency of the power converter may be much lower than the one provided in the datasheet. A practical for the designer dependence is the efficiency of the converter to its power input/output. In the literature [29, 30] it can be found that the shape of the efficiency curve of DC/DC converter (Figure 15) is similar to the shape of the efficiency curve of inverters (Figure 16), which are main components of abovementioned battery converters. [29]

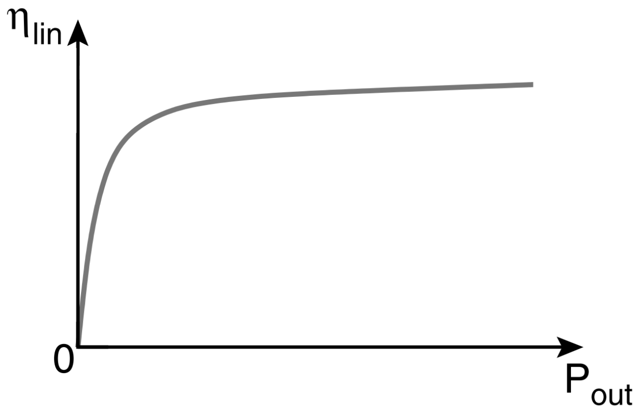


Figure 15 Typical efficiency curve of a DC/DC converter [29]

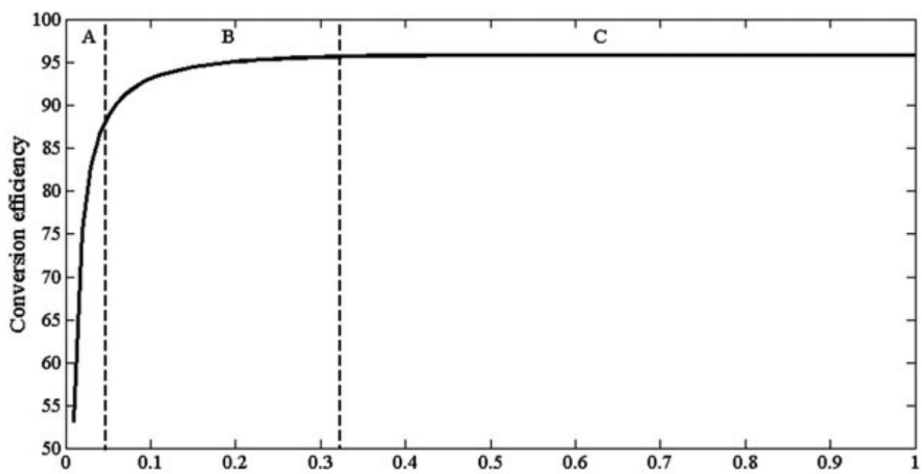


Figure 16 Typical efficiency curve of an inverter [30]

If for instance the battery is supplying a small load the converter operates under part load conditions with lower system efficiency. Without comprehension of the efficiency curve and taking into account only its maximum efficiency the converter may be easily oversized, for instance with a vision of further development of the system in the future. In this case the EES owner may be subjected to relatively high losses. This may be also changed with installation of parallel converters of smaller size. Nevertheless, with knowledge about the efficiency of the converter in every operating point the optimal converter sizing can be done successful and monitored during the lifetime of the system. [31]

2.6.3. EES management system

In general three main concepts are linked with a management system of an EES, namely:

- battery management,
- power management,
- energy management.

Each of them handles different role in the mix. The battery management system (BMS) is the lowest link of the chain, closest to the battery. It ensures safe optimal operation of the battery in terms of safety. For instance, it ensures that the battery is kept in allowable SoE limits and limits the operation of the battery if the temperature of cells is too high. The power management system (PMS) ensures proper power flow in the system. Its aim is also to ensure minimum consumption by each of the system components. For example, it will guarantee that all cells are discharged evenly and limit the charge/discharge power. Last, but not least the energy management system (EMS) is definitely the highest link in the chain. It handles the storage of energy in the system and gives signals to the lower management systems to execute the desired action if possible. The energy management system will simply determine when the battery should be charged, idled or discharged depending on the aim of the system. In case of multifunctional performance the local and external high-level controls can be combined. [32, 17]

3 Model description

This chapter is fully devoted to the VPP model created in this work. It should prepare a base before introducing the case study in which the model is used. At first a description of the core of the VPP model will be introduced. The single household model description contains all the information required to fully understand operation of the model on the component level and on the microgrid level. Further the structure of the single household simulation will be presented in a form of a flow chart and then discussed. Further section will treat about trading on energy markets as a VPP. It will introduce the trading strategies used in the model and how CVPP creates trading signals as well as the approach to the households transactions with the retailer. After complete introduction of the single household simulation a module its results analysis is presented. The analysis will allow economical evaluation of the single household performance and further entire VPP what is one of the goals of this project. In the section further the VPP models will be described. Firstly the VPP model, which analysed results will allow economical impact evaluation is presented. Further, the introduction of the physical impact VPP model will be done. Its results will be a base for the evaluation of the impact that the VPP exerts on the part of the local distribution network. Next the approach to this evaluation is discussed. The last section will treat about the optimization modules that will allow determination of the systems settings which will increase the economical performance of the VPP.

3.1. Single Household Model

The goal of the single household model is to reflect the most important phenomena occurring in a house, which is a part of a VPP. The analysis of the results coming from the model should allow evaluation of economical impact of the VPP consisting of the modelled houses. To do that the most important components of a house and EES system were modelled. Starting from the house electrical topology, including overcurrent protection limiting sometimes the performance of the EES system. Next, the loads and the PV system. Ending with all crucial EES components, like battery, power converter and the EES management system.

First, the overall household architecture will be introduced including the types of connections of the house, PV system and the EES system. Then the required inputs, like power demand and PV system output profiles, will be described. Further, the description of modelling of each physical component of the EES will be presented. This will be followed by introduction of the complete model structure. It will be presented in a form of flowchart allowing simple introduction of the simulation sequence.

3.1.1. Overall household architecture

Each house belonging to the VPP consists of PV panels connected to the house through an inverter and EES system. The PV system and the EES system can have one phase or three-phase connection. The PV system, because of high power injection from the panels, may require three-phase connection. The same situation is applicable to the EES, which may contain three-phase bidirectional power converter. The topologies of the houses with systems' one phase and three-phase connections are presented below (Figure 17). Not all connections' possibilities are presented below. The EES and PV system does not necessarily have to be connected on one phase. It may also happen that one of the systems is connected to one phase and second requires three-phase connection. Furthermore, if the cable supplying the house is sufficiently big, or the peak power drawn from the grid is expected to be low the house itself may have one phase connection. This would obviously allow connection of all the systems on one phase only.

Nevertheless, with three-phase connected house there are 16 different connection possibilities, namely:

- 3 when PV system and EES are connected on one phase
- 6 when PV system and EES are connected to different phases,
- 3 when PV system has a three-phase connection and EES has one phase connection,
- 3 when EES has a three-phase connection and PV system has one phase connection,
- 1 when both systems have three-phase connections.

Each house contains a smart energy meter, which shows the current power balance of the house at the interface with the infinite bus. It is the point of common coupling (PCC) of the household and the power exchange with the grid will be observed at this point. All data on power output of the PV system, EES and the smart meter reading are wirelessly sent to one entity, which is responsible of controlling the EES. Based on the three power inputs the value of the household consumption combined with house ohmic losses can be calculated.

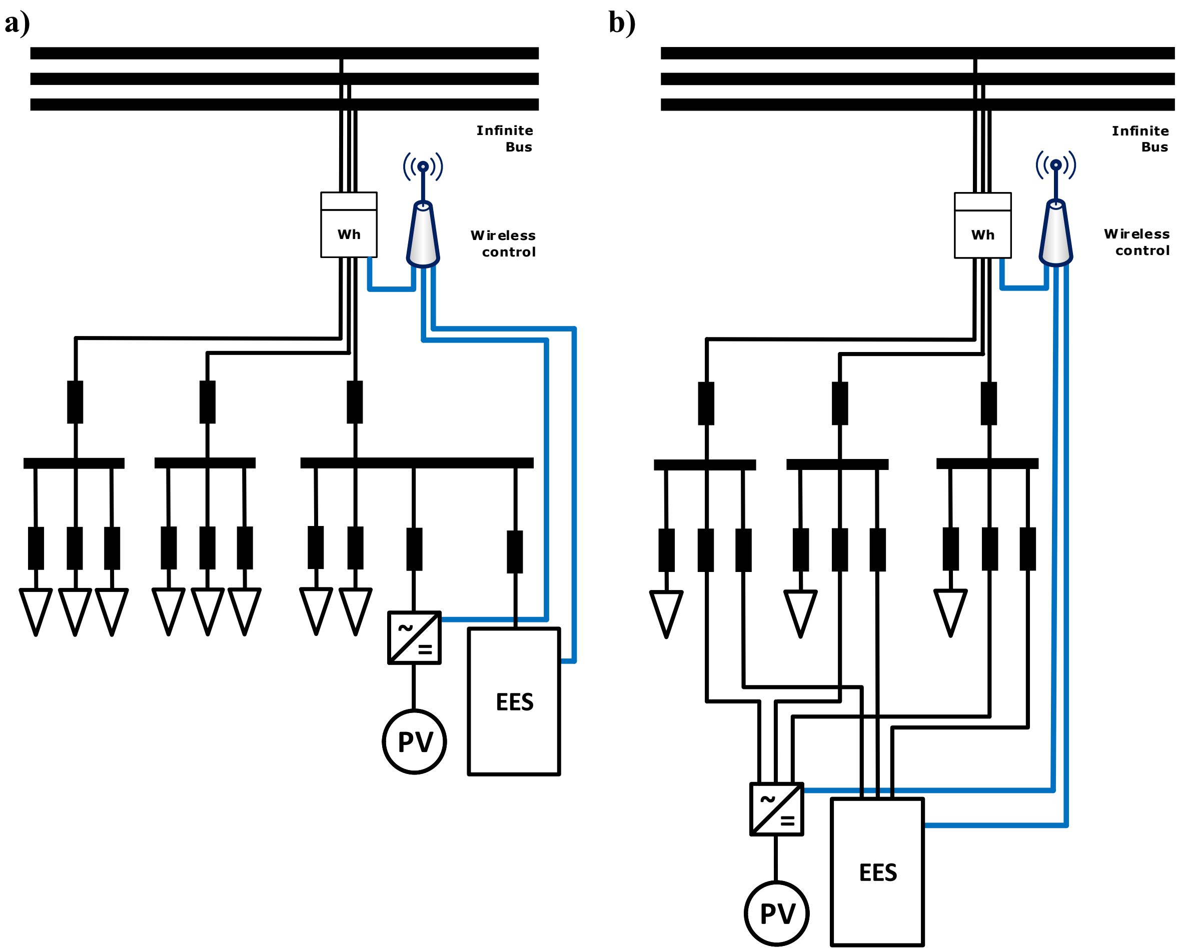


Figure 17 House architecture: a) single phase connections, b) three-phase connections

3.1.2. Profiles

Besides a mass of data regarding the performance and behaviour of each of the modelled components, which will be introduced later along with descriptions of each of them, very important inputs for the model are three types of profiles. They are stored in an Excel Workbook and are loaded from it to the model.

The first profile type represents the power consumption of a household in each time step of the simulation. Because the loading of each phase in a house is rarely symmetrically spread over all the phases for each household three consumption profiles are required. Each of the profiles will represent consumption on each phase. If the house to be simulated is one phase connected the phase of connection should contain realistic profile and profiles for other, non-existing, phases should be provided as strings of zeros. If only three-phase summarised consumption profile is available the values of the consumption in each time step can be divided by three creating a symmetrical loading. Nevertheless, it shall be noted that it will usually not reflect the real demand of the household. An example of a power demand profile is presented below (Figure 18). The periods with nearly zero consumption represent the vacations for the household residents.

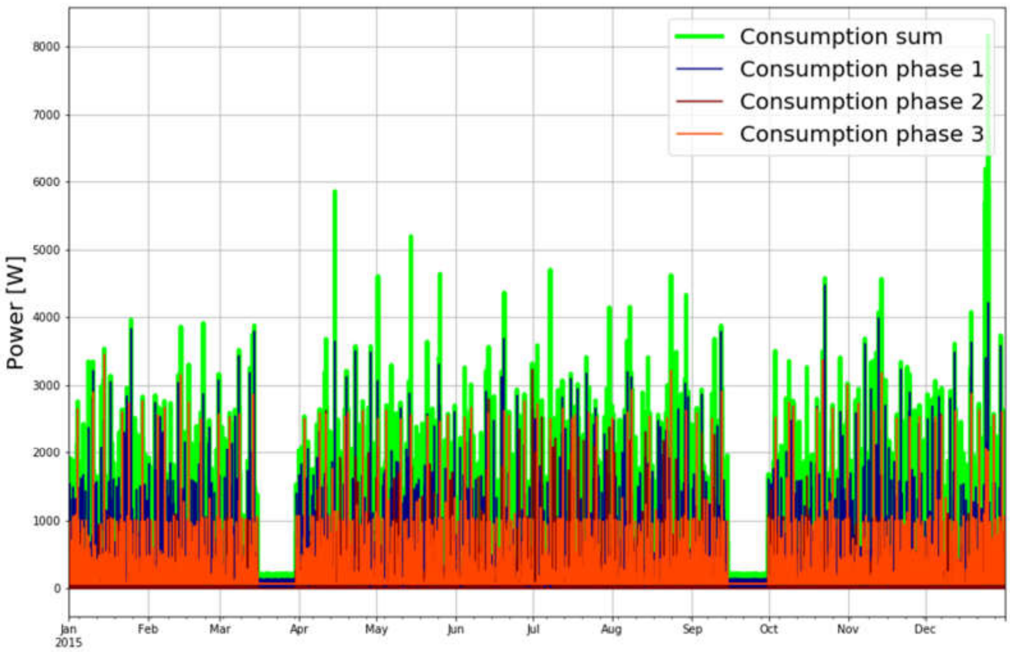


Figure 18 Typical consumption profile of a medium-sized household

Second type of profiles that have to be provided as an input to the model is power output of the PV system. The profile should represent the realistic power output of the power inverter. If the power inverter has a three-phase connection the value of PV system power output in each time step will be divided by three and spread over three phases. No separate profiles are required. It should be noted that for the sake of realism the losses of the inverter and other PV system losses should be included already in the profile. The model will not simulate the losses of the PV system, but will focus on the ESS phenomena. An example showing a yearly power output of a PV system located in the Netherlands is presented below (Figure 19).

The last type of the profiles contains the energy market prices, based upon which the decisions on trading operations will be made. Because of markets operating in dual-price systems the model was adjusted to take two different prices' profiles. One profile should contain information about the price put on the energy sold on the market and the second one on the energy bought on the market. If a single-price system is utilised the same profile should be provided for the selling and buying price profile. Obviously the prices of the energy markets are highly unpredictable and providing real price of the market may not be realistic enough. Nevertheless, instead of real market prices a price prediction can be provided to the model and the decisions on market transactions will be made on the predicted values. An example of profiles containing energy market prices are shown below (Figure 20 and Figure 21).

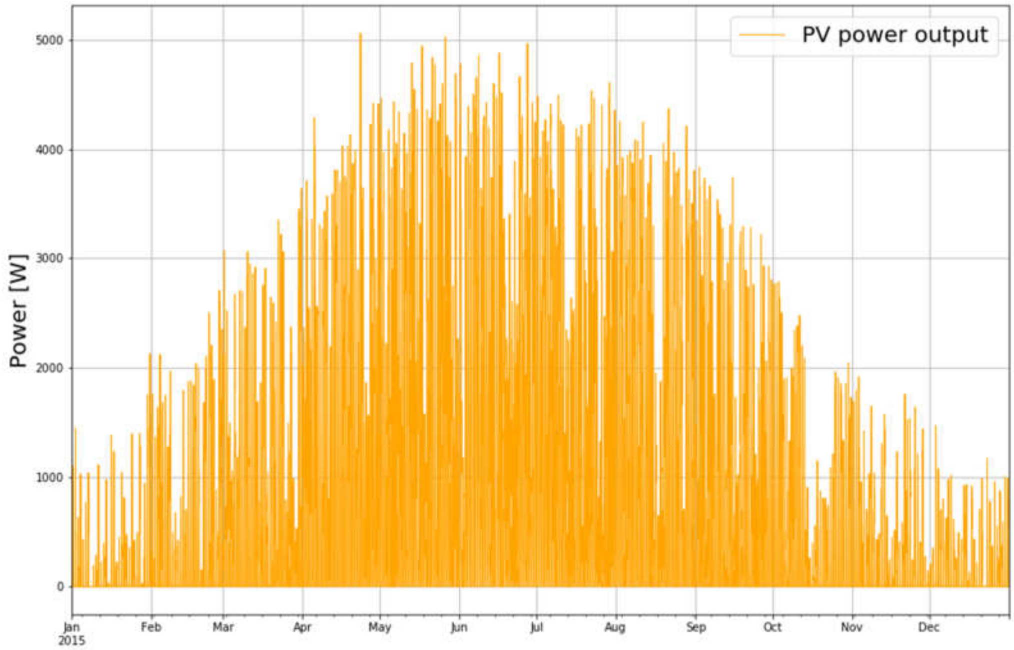


Figure 19 Typical PV system power output profile in the Netherlands

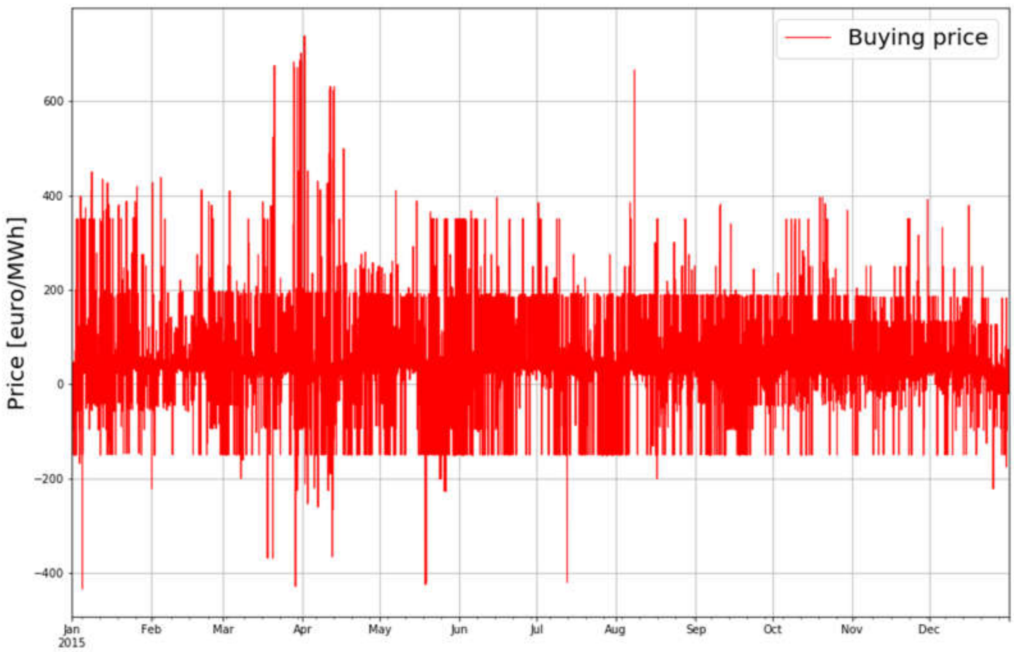


Figure 20 TenneT Energy Imbalance Price for buying in 2015 year

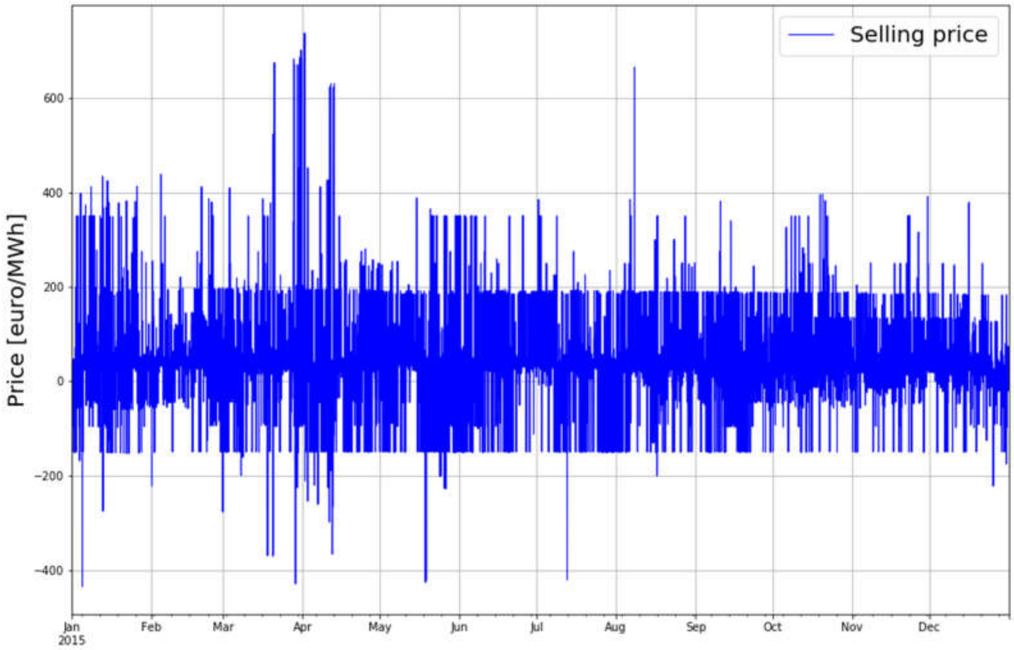


Figure 21 TenneT Energy Imbalance Price for selling in 2015 year

3.1.3. Battery model

The battery model takes into account two most important phenomena occurring in electrochemical batteries influencing the overall performance of the EES. As mentioned in the theoretical background those phenomena are degradation of the battery and its self-discharge process. The efficiency of the battery itself is not taken into account. It was shown that the efficiency of some electrochemical batteries is very high, reaching in certain situations 100%, hence it was inferred that it will not have a noticeable influence on the final simulation results.

3.1.3.1. Degradation

To simulate degradation behaviour of the battery a lithium-ion battery lifetime model was adopted. The model was developed for certain lithium-ion battery chemistry (C-$LiFePO_4$) and for certain operation scheme of the battery, namely provision of primary frequency response on Danish energy market. It was based on accelerated aging tests performed in a laboratory and the analysis involved SoE profiles measured in field while battery providing PFR. The model was developed in conformity with the theory provided in the previous chapter. The process was separated into two dimensions, namely calendar aging and cycle aging. The battery lifetime model is capable of estimating battery degradation idling in different temperatures. Nevertheless, because usually batteries used for PFR are operated in air conditioned environment where temperature is kept at level of 25°C this value was used. In the battery model developed in this work the temperature is also assumed to be constant 25°C.

The model provides calendar fade (C_{fcal}), which corresponds to the degradation of the battery capacity caused mostly by time. It is given in percentage of lost energy capacity from the initial capacity ($E_{bat\ init}$). [33]

$$E_{fcal} = 0{,}1723 \cdot e^{0{,}007388 \cdot SoE_{avg}} \cdot t^{0{,}8} \quad (3.1.)$$

Where:

E_{fcal} – capacity calendar fade [%],

SoE_{avg} – average state of energy [%],

t – time [month].

Several capacity calendar fade curves for different values of the average state of energy (SoE_{avg}) are presented below (Figure 22). It can be observed that the calendar fade depends non-linearly on time and it tends to decelerate while the aging process evolves. It can be also seen that the higher average state of energy of the battery have negative influence on the battery degradation process.

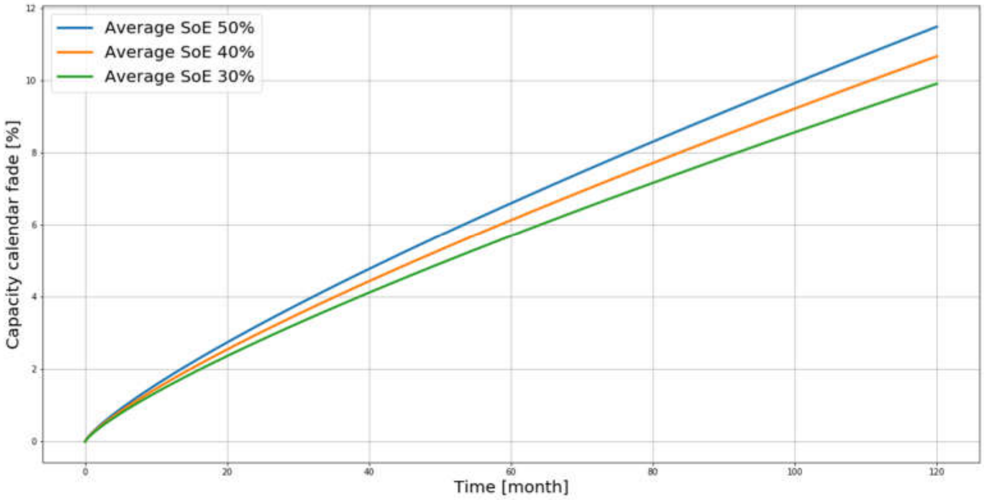


Figure 22 Typical capacity calendar fade curves

The cycle fade given by the model is associated with the degradation of the battery caused by the way the battery is cycled. Just like calendar fade it represents percentage of energy capacity loss from the initial battery capacity ($E_{bat\ init}$).

$$E_{fcyc} = 0{,}021 \cdot e^{-0{,}01943 \cdot SoE_{avg}} \cdot Cyc_{avg\ depth}^{0{,}7162} \cdot Cyc_{eq\ number}^{0{,}5} \quad (3.2.)$$

Where:

E_{fcyc} – capacity cycle fade [%],

SoE_{avg} – average state of energy [%],

$Cyc_{avg\ depth}$ – average cycle depth [Wh],

$Cyc_{eq\ number}$ – equivalent cycles number.

The calculation of number of cycles may seem relatively straightforward and it is true when all cycles done by the battery are full 100 % deep cycles. Nevertheless, in reality it is rarely the case. Hence, an equivalent number of cycles has to be calculated and applied.

There are several ways of calculating it, like level crossing counting, peak counting, simple range counting or rain-flow counting. One of the easiest approaches is taking into account only energy discharged from the battery and comparing it with the current energy capacity of the battery (E_{bat}).

$$Cyc_{eq\ number} = \frac{\sum_{i=1}^{n} P_{bat\ out} \cdot t}{E_{bat}} \quad (3.3.)$$

Where:

$Cyc_{eq\ number}$ – equivalent cycles number,
t – single discharge time [h],
$P_{bat\ out}$ – power discharged in time t [W],
E_{bat} – current energy capacity of the battery [Wh].

Advantages of this method is its simplicity and that it can be easily applied in an iterative model. Nevertheless, it does not directly take into account the charge phase and calculation of the cycle depth, which is important factor in the calculation of the capacity cycle fade, is not possible. Hence, more precise method was utilised in the battery model in order to calculate equivalent number of cycles and average cycle depth. The method used rain-flow counting algorithm, which name comes from association of the visualisation of operating algorithm to the rain falling of a pagoda style roof. The algorithm was developed in 1968 by T.Endo and M.Matsuishi is often used in mechanics to estimate the mechanical fatigue or strain put on components. The algorithm finds signal reversals points based on which calculates number of half and full cycles and their depth. Based on its results equivalent number of cycles can be calculated more precisely.

$$Cyc_{eq\ number} = \frac{\sum_{i=1}^{n} Cyc_{number} \cdot Cyc_{depth}}{100} \quad (3.4.)$$

Where:

$Cyc_{eq\ number}$ – equivalent cycles number,
Cyc_{number} – number of cycles of certain depth,
Cyc_{depth} – cycle depth [%].

Calculation of equivalent cycle number in this way includes not only discharging phase but also charging phase. The rain-flow algorithm provides also depth of each full or half cycle, what can be easily used for the average cycle depth calculation, which is required in the lithium-ion lifetime model to calculate cycle fade.

$$Cyc_{avg\ depth} = \frac{\sum_{i=1}^{n} Cyc_{number} \cdot Cyc_{depth}}{\sum_{i=1}^{n} Cyc_{depth}} \quad (3.5.)$$

Where:

$Cyc_{avg\ depth}$ – average cycle depth,
Cyc_{number} – number of cycles of certain depth,
Cyc_{depth} – cycle depth [%].

A comparison between the simple method introduced above and the rain-flow counting algorithm is presented below (Figure 23). The dashed blue lines represent changes that are not directly taken into account in the calculation of equivalent number of cycles used in particular method. As already said the simple method does not take into account all charging phases and the rain-flow counting algorithm does not take into account the first and the last slope of the sequence into consideration.
Table below (Table 2) shows on a simple example (Figure 23) how the equivalent cycles number is calculated utilizing described methods and shows the differences between them.

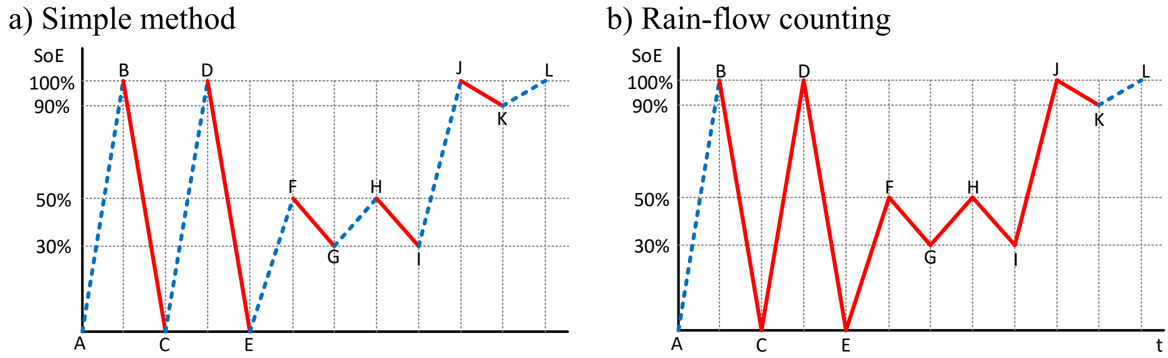


Figure 23 Equivalent cycle number counting methods comparison

Simple method		**Rain-flow counting**			
Slope	*Equivalent cycles number*	*Slope*	*Cycles number*	*Cycle depth*	*Equivalent cycles number*
B-C	1	B-D	1	100%	1
D-E	1	E-F	0,5	50%	0,25
F-G	0,2	F-I	1,5	20%	0,6
H-I	0,2	I-J	0,5	70%	0,35
J-K	0,1	J-K	0,5	10%	0,05
		D-J	1	100%	1
SUM	**2,5**				**3,25**

Table 2 Equivalent cycles number counting methods comparison

Because of higher accuracy and opportunity to easily extract the cycle depth the rain-flow algorithm was applied in the battery model. The particular algorithm was developed by P.Janiszewski in Python environment [34], nevertheless it was used for calculations when whole battery SoE profile is provided beforehand. Because, the cycles number had to be observed at every iteration the algorithm had to be adjusted. It was possible to use the algorithm every iteration without any adjustments, nevertheless while the SoE profile would build up the calculation of first cycles would be repeated in all the further iterations, what was extremely inefficient and unnecessary. Therefore, the adjustment applied allowed to store already calculated cycles and calculate them once as the profile would build up.

When the equivalent cycles number and the average cycle depth is calculated the cycle fade from the lithium-ion battery lifetime model can be estimated. Several cycle fade curves for different average cycle depths are presented below (Figure 24). It can be observed that the degradation loss slows-down along with increasing equivalent cycles number. The average state of energy for all the curves was kept at 40%.

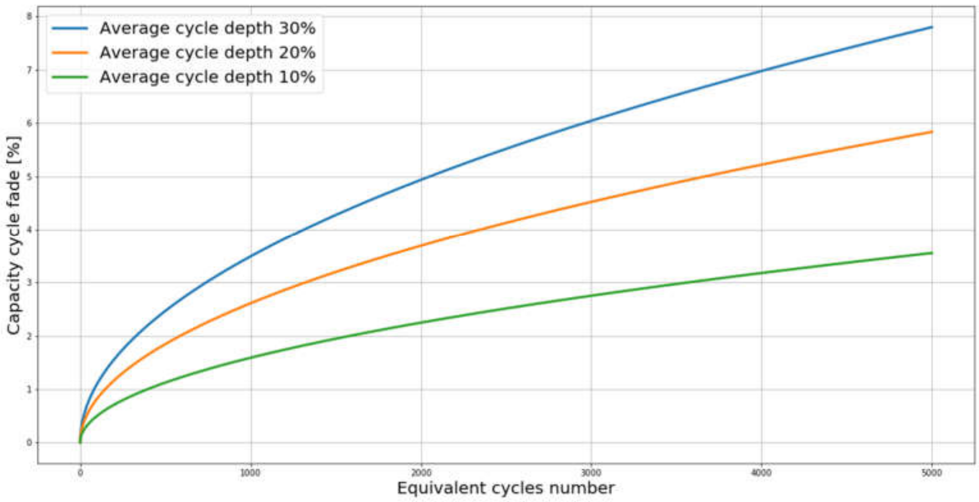


Figure 24 Typical capacity cycle fade curves

The final value of degradation of the battery in the model is a sum of the capacity calendar fade and capacity cycle fade. The degradation represents the percentage of energy capacity lost from the initial capacity of the battery.

$$Deg = E_{fcal} + E_{fcyc} \tag{3.6.}$$

Where:

- Deg – battery degradation [%],
- E_{fcal} – energy capacity calendar fade [%],
- E_{fcyc} – energy capacity cycle fade [%].

After estimating the degradation of the battery it is applied to its capacity. The energy capacity corresponding to the degradation is calculated and subtracted from the initial energy capacity of the battery $E_{bat\ init}$.

3.1.3.2. Self-discharge

The self-discharge reflects the loss of energy from the battery when it is not in use. In the literature rates of self-discharge of different battery technologies are usually given in percentage of energy lost from the SoE achieved after last charge/discharge operation per month. The SoE will be referred to initial self-discharge state of energy $SoE_{init\ sd}$. Sometimes the rate is also provided for the first 24 hours when the process is the fastest. Hence, it is simulated with different rates of discharge in two periods. For the first 24 hours the battery discharge rate can be chosen different than the period after it. The first rate of discharge is provided as percentage loss per 24 hours and the second one, which will be applied indefinitely, is provided as percentage loss per month (per 30 days to be exact).
The calculation of the state of energy achieved after self-discharge is made based on an equation utilised for interest compound calculation.

$$SoE_{sd} = SoE_{init\ sd} \cdot \left(\frac{1 - \frac{r_{sd}}{100}}{\frac{T_{sd}}{t}} \right)^{n} \tag{3.7.}$$

Where:

SoE_{sd}	– state of energy after self-discharge [%],
$SoE_{init\ sd}$	– state of energy before self-discharge [%],
r_{sd}	– rate of self-discharge for certain period [%],
T_{sd}	– self-discharge base period [h],
t	– self-discharge time [h],
n	– number of self-discharge periods of length t [h].

In this way different rates of self-discharge can be easily applied and the initial state of energy has influence on how fast the battery is self-discharged. Several SoE curves with different self-discharge rates are presented below (Figure 25 and Figure 26). Presented curves have identical $SoE_{init\ sd}$, nevertheless the smaller it is the slower self-discharge process will be. It can be observed that with time self-discharge process decelerates.

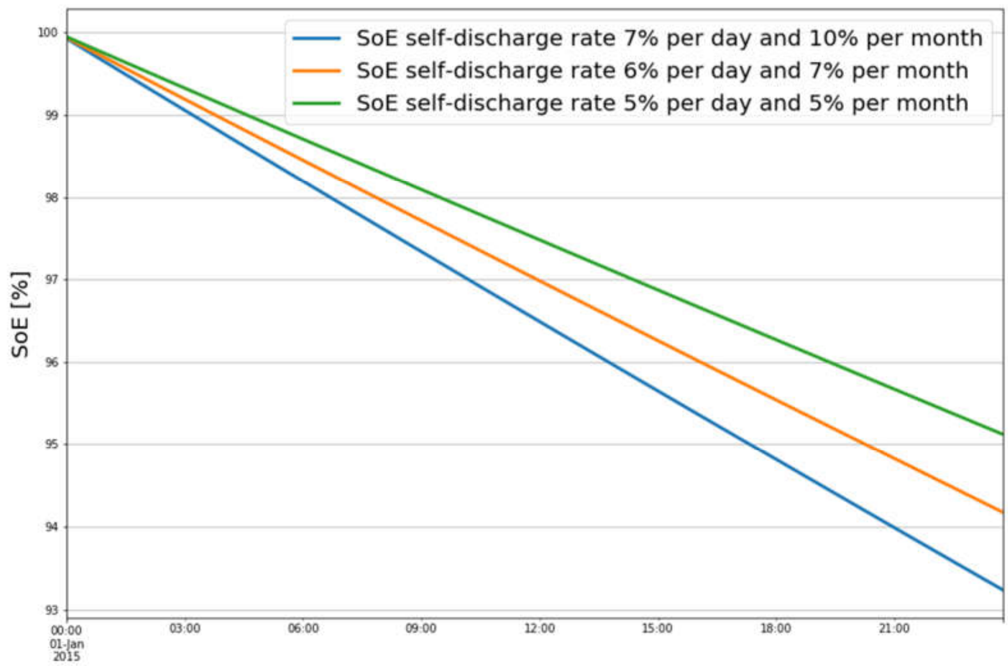


Figure 25 SoE curves showing self-discharge process in first 24 hours

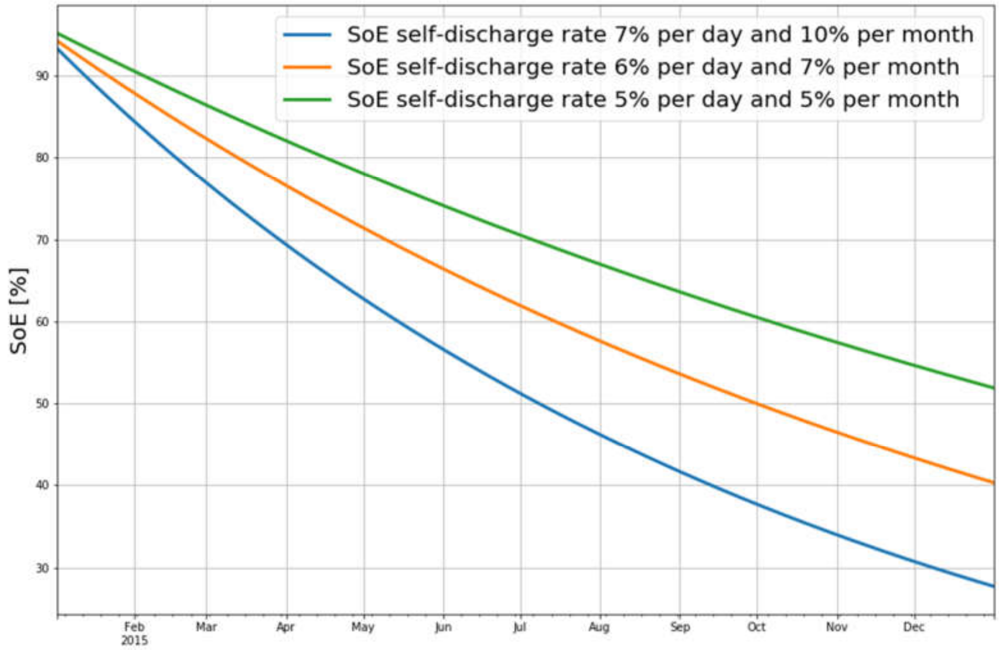


Figure 26 SoE curves showing self-discharge process in a year

3.1.4. Battery converter model

In order to reflect as close as possible the performance of the EES, and therefore whole household, modelling of the battery power converter cannot include only poorly described data from the datasheet of the converter. Some assumptions had to be made to include the most important performance factor of the converter, namely its efficiency. The model to be accurate cannot include only imprecise value of peak efficiency provided by the manufacturer, but it has to know the efficiency in all operation points. As said in the previous chapter the impact of the power converter efficiency, in particular when it is oversized or simply when it is unremarkably loaded most of the time, can be massive.

Therefore, the model allows the user to provide an efficiency curve, which will reflect the performance of the converter and affect the performance of the whole system. There are number of efficiency curves that can be provided to the model including irregularly shaped curves that would simulate performance of parallel converter. Nevertheless, since the converter efficiency curves tend to have a similar shape regardless their topology one unified efficiency curve model was used. Derivative, performance model for grid-connected photovoltaic inverters was developed by Sandia National Laboratories in 2007 [29]. The primary goal was to develop a model, which would be applicable to all commercial PV inverters that would utilize an algorithm that would relate the power input of the inverter, coming from PV panels, with its power output. It is worth mentioning that the model does not take into account the design of the device like its circuit topology or power conditioning algorithms. The model is rather empirical or phenomenological that imitates the characteristics of power inversion process. It uses data provided by PV systems operating for many days with a variety of environmental conditions. The data includes hundreds of measurements at different power levels, from levels higher than the peak loading of the device to zero loading. Below thousands of converter efficiency measurements over 13-day period are shown (Figure 27). [29]

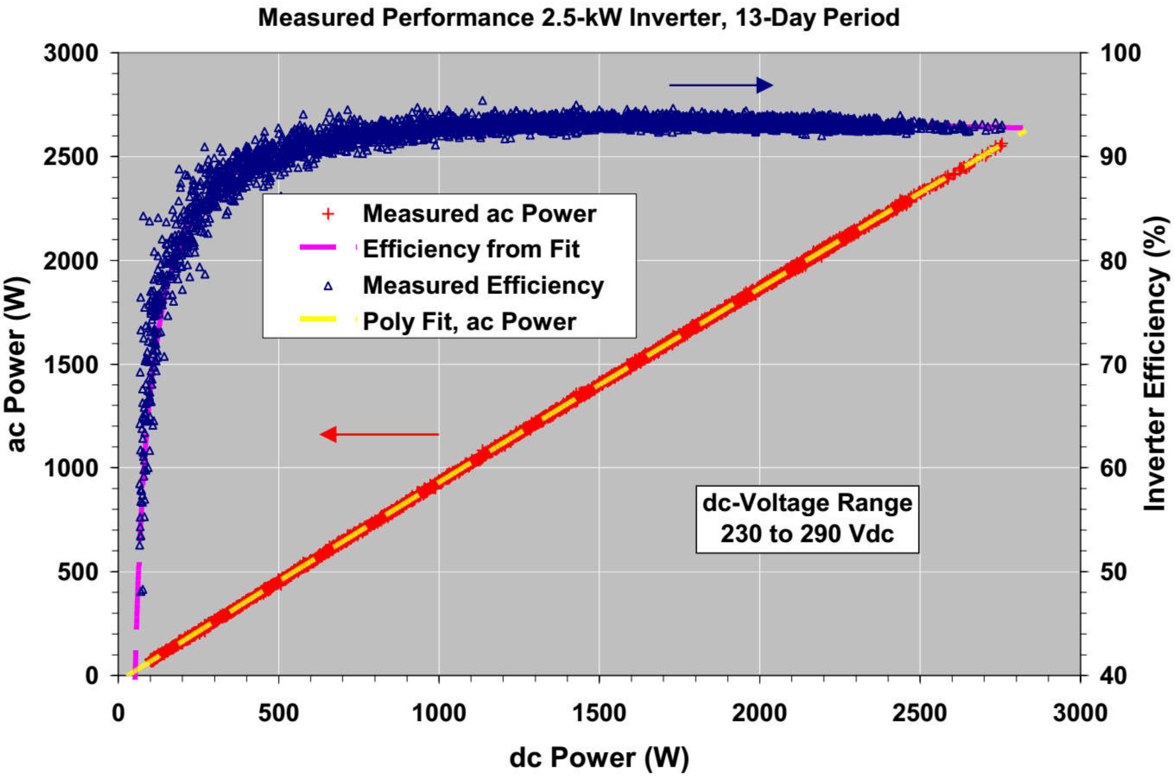


Figure 27 PV inverters performance measurements [29]

It can be observed that relationship between the power input of the inverter and its output is nearly linear. The non-linear behaviour of the efficiency is caused by the power consumed by the inverter itself and the characteristics of its topology at different voltage and power levels. It has to be noted that measurements were conducted in different ambient temperatures. However, the efficiencies of the tested inverters did not have a strong temperature dependence. Hence, it was assumed that if the inverter operates correctly at maximum specified ambient temperature and it is correctly installed the temperature does not have to be taken into consideration in the performance model. [29]
Following equation was used in the converter model to correlate the converter output power and its input power, taking as an input basic data given by the manufacturer in the datasheet. The equation is based on an equation provided for inverters in the performance model described above.

$$P_{conv\ out} = B\left(\frac{P_{conv\max in}}{A} - CA\right) + CB^2 \quad (3.8.)$$

Where:

$$A = P_{conv\max in} - P_{conv\min in} \quad (3.9.)$$

$$B = P_{conv\ in} - P_{conv\min in} \quad (3.10.)$$

$P_{conv\ out}$ – converter power output [W],
$P_{conv\max in}$ – maximum converter power input [W],
$P_{conv\min in}$ – minimum converter power input (required to start conversion process [W],
$P_{conv\ in}$ – converter power input [W],
C – curvature factor.

In order to allow provision of irregular shapes of converter efficiency curves and decrease the simulation time the output power is not calculated every iteration. Instead, during the initialization phase a lookup table is created with accurate efficiency curve (10000 operating points). Because the manufacturer usually provides the peak efficiency of the device the curve is adjusted to match it. Then every time the power output of the converter is required in the simulation the converter power input is matched with the calculated already efficiency at the particular operating point. It is worth adding that the efficiency of the power converter is assumed to be identical in both directions. It means that the same efficiency curve lookup table is used for the charging process and discharging process. Having the efficiency the power output of the converter can be easily calculated.

$$\eta = \frac{P_{conv\ out}}{P_{conv\ in}} \quad (3.11.)$$

Where:

η – converter efficiency [%],
$P_{conv\ out}$ – converter power output [W],
$P_{conv\ in}$ – converter power input [W].

Several efficiency curves developed using abovementioned model are shown below (Figure 28). The curves are presented as a function of converter loading that is to say converter power input presented as percentage of maximum converter power input. In this manner the curves could be applied to any converter regardless to its size.

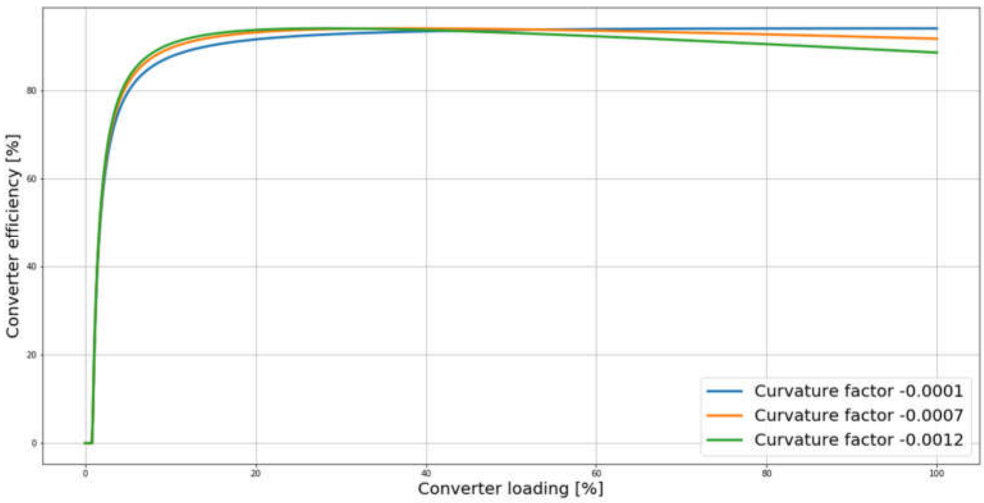


Figure 28 Converter efficiency curves

The converter loading limit is applied to improve the overall EES system efficiency and ensure that the converter is operated at sufficiently high efficiency. It is given in a unit of power and it is associated with certain percentage of loading which can be placed at the converter efficiency curve (Figure 29).

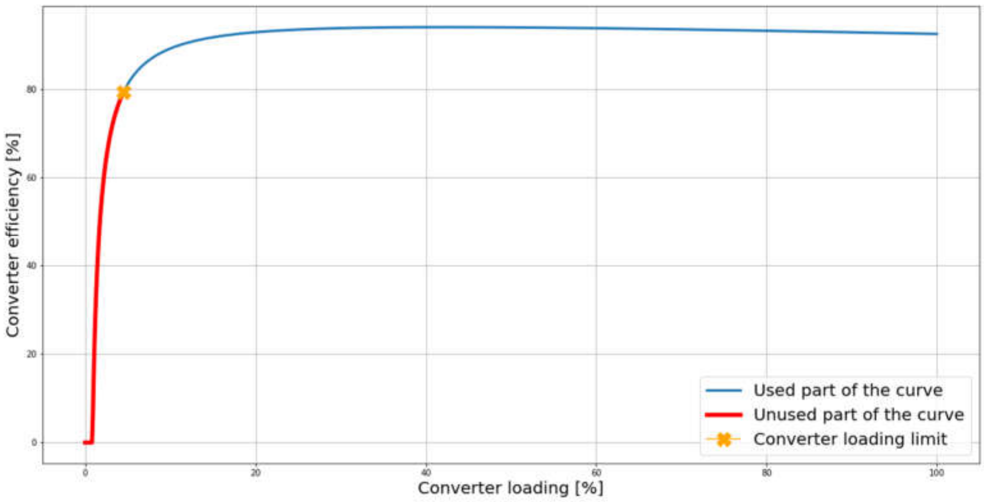


Figure 29 Converter loading limit

The converter loading limit divides the converter efficiency curve on two parts (Figure 29). One part containing operating points below the loading limit will not be used in the conversion process. Simply, when the EES tries to operate the converter with converter input smaller than the converter loading limit the converter control will never allow the charge/discharge process to start. Another part containing operating points above the loading limit will be in use whenever the charge/discharge process is required. In this case the power input of the converter is bigger than the converter loading limit and the conversion process will be allowed by the converter control.

3.1.5. EES management system model

As said in the theoretical background the EES management system is divided into three levels, namely battery management (BMS) ensuring safe operation of the battery, power management (PMS) aiming to operate the battery in most efficient manner as possible and energy management (EMS), which handles the control of the stored energy.

Not all functionalities of the EES management system are applied in the model. Because the temperature, current and voltage are not directly observed in the model the BMS will ensure the safety of the battery based only on the SoE level. As already mentioned the efficiency of the battery is assumed to be 100%, hence the performance of the PMS is simply assumed ideal in terms of providing highest efficiency of the system. The functionality of the PMS implemented in the model is ensuring that the battery is charged or discharged with power within its limits. The highest level management will, based upon peripheral inputs decide on the EES desired behaviour. Since the houses play a role of generating units or controlled loads in a bigger entity, namely VPP, the input to the EMS can also come from the CVPP. The EMS will also receive data about current energy flow in the system and make decisions upon them. Furthermore, because the infrastructure (cabling and/or protection devices) may have not been designed to handle any EES another input had to be given to the EMS, specifically the information about the type of the overcurrent protection.

In order to prevent excessive overcurrents in the cabling of the house, and as a result preventing the overcurrent protection device to trip, the nominal current I_n of the protection device is provided as a limit to the EMS. From the nominal current of the protection device a corresponding power can be calculated and will be referred to nominal power P_n of the device. It is assumed that the current associated with this power will force the overcurrent protection to trip instantly and therefore is applied to the model as a limitation. As introduced in the theoretical background in reality, depending on the current characteristic of the protection device, current higher than the nominal current of the device does not necessarily has to be terminated instantly. The protection device can handle short overcurrents without terminating them. However, for the sake of safety and simplicity of the model this property of the protection device will not be utilised.

The protection device considered in the model, highlighted in red at the example below (Figure 30),is present in the main switchboard of the house. In order to evaluate if the desired behaviour of the battery will force the overcurrent protection to trip the current power balance at each phase bus has to be calculated.

$$P_{bal\ ph} = P_{PV} - P_{load\ ph} \tag{3.12.}$$

Where:

$P_{bal\ ph}$ – power balance at certain phase bus [W],
P_{PV} – power output of the PV inverter [W],
$P_{load\ ph}$ – power demand of the local loads on a certain phase [W].

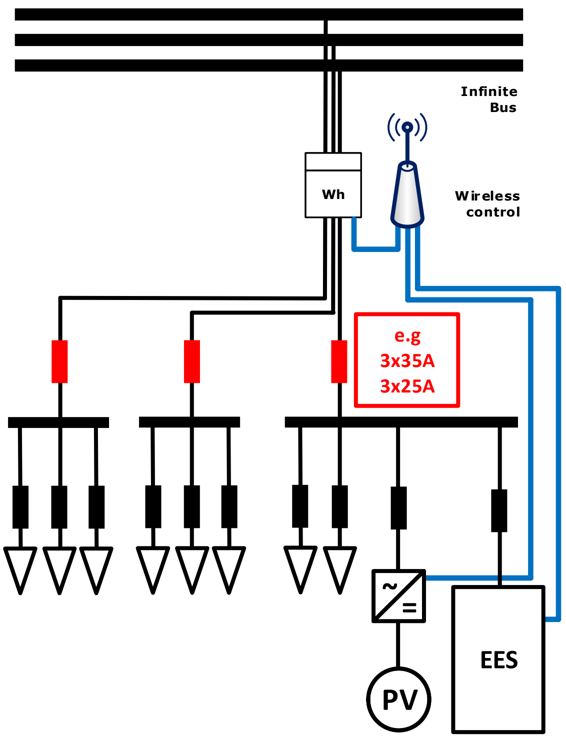


Figure 30 Model limiting overcurrent protection location

Based upon the phase terminals power balance decisions on the battery behaviour can be made. Possibilities of the EES influence on the house load flow are summarised below (Table 3). However, different household topologies will determine different compositions of the phase power balance equation. If certain phase bus does not have PV system connected to it the P_{PV} will simply equal zero at all times and the equation will be reduced. The EES management model was designed to manage the EES behaviour in a way, which would prevent overcurrent protection to trip. Hence, if for instance the PV system power output creates a positive power balance at the phase bus and at the same time the EES connected to the same bus will be asked by CVPP to discharge with power that combined with the positive power balance would force the overcurrent protection device to trip the EMS will act to prevent that. The power output of the EES system asked from the CVPP will be limited to power allowing safe operation of the house circuitry.

	$P_{bal\,ph} > 0$ Battery charging	$P_{bal\,ph} > 0$ Battery discharging	$P_{bal\,ph} \le 0$ Battery charging	$P_{bal\,ph} \le 0$ Battery discharging
	PV system trips the overcurrent protection and the battery eases the final power balance at the bus. $P_{bal\,ph} - P_{conv\,in} \ge P_n$	Battery is discharged with such power that helps the PV system to trip the overcurrent protection. $P_{bal\,ph} + P_{conv\,out} \ge P_n$		The battery is discharged with such high power that it covers the negative power balance and still forces the overcurrent protection to trip. $P_{bal\,ph} + P_{conv\,out} \ge P_n$
P_n				
	The battery charging eases the positive power balance present at the bus. $P_{bal\,ph} - P_{conv\,in} < P_n$	Battery discharge power increases the final power balance, which stays in the limit. $P_{bal\,ph} + P_{conv\,out} < P_n$		The battery is discharged with power allowing to overcome the negative balance on the bus and cause positive final balance. $P_{bal\,ph} + P_{conv\,out} < P_n$
	The battery charges with such power that overcomes the positive power balance present at the bus. $P_{bal\,ph} - P_{conv\,in} > -P_n$		The battery charging power and the demand overcome the PV system output and make the final power balance negative still staying in the limit. $P_{bal\,ph} - P_{conv\,in} > -P_n$	The battery discharge power along with PV system are not able to cover the demand. $P_{bal\,ph} + P_{conv\,out} > -P_n$
$-P_n$				
	The battery charges with such high power that even though the power balance is positive it forces the overcurrent protection to trip $P_{bal\,ph} - P_{conv\,in} \le -P_n$		The power demand along with charging battery overcome power output of the PV system and trip the overcurrent protection. $P_{bal\,ph} - P_{conv\,in} \le -P_n$	The battery discharging eases the negative balance present at the bus nevertheless the demand is still big enough to trip the overcurrent protection. $P_{bal\,ph} + P_{conv\,out} \le -P_n$

Table 3 Influence of the battery on the overcurrent protection

Even though the decisions made on the EES behaviour can be divided logically into systems described above in the model allm are combined into one ultimate EES management system with all required properties.
There are three EES behaviour schemes distinguished in the model:

- power demand driven,
- trading driven,
- power demand and trading driven.

The power demand driven EES behaviour scheme will aim to cover all local demand from either PV panels or from the EES. The battery in this scheme will be always charged from the overproduction of the PV system. Hence, if the power generated by the PV system cannot be consumed by the loads in the house, the battery will start charging. In other words the aim of the scheme will be to create constant "zero on the meter". Nevertheless, from the electrical point of view, depending on the house topology and the profiles, the demand will be rarely covered fully locally. The "zero on the meter" scenario means that the final three-phase power balance is equal to zero. Below the three-phase power balance without EES influence is presented.

$$P_{bal\ 3ph} = P_{PV} - P_{load\ 3ph} \qquad (3.13.)$$

Where:

$P_{bal\ 3ph}$	– three-phase power balance [W],
P_{PV}	– power output of the PV inverter [W],
$P_{load\ 3ph}$	– power demand of the local loads [W].

It is worth mentioning that "zero on the meter" is not equivalent to lack of power exchange with the grid from the electrical point of view. To provide "zero on the meter" the EES connected to one of the phases will have to cover the demand at the three-phase power balance. Hence, the power from the EES will cover fully locally only the load connected to the bus of its own connection and the demand from other two phases will be covered not fully locally. To cover the demand at other two phases in ideal conditions the power from the EES will be injected to one phase of the grid and the same amount of the power will be split into two phases in the neutral point of the transformer to which the feeder is connected to and delivered from there to cover the demand. Because, the power takes path that includes the circuitry beyond the meter the demand is not completely covered locally, at least from the technical point of view. How the system acts to provide "zero on the meter" is presented at the example below (Figure 31).
The trading driven EES behaviour scheme will aim to maximize the amount of power traded at the EIM. The battery will be charged twofold. It can be charged from the overproduction of the PV system just like in the power demand driven scheme or it can be charged when the CVPP decides to get into a short position in the energy market and the trading signal is executed. Even though the intention is not to cover the power demand of the house some portion of it will have to be covered from the battery in the situation when the CVPP decides to get into a long position at the energy market. It may happen that at the same time the three-phase power balance is negative the battery power will have to first cover the current demand of the house and then the remaining power that creates the positive power balance at the three-phase bus can be traded at the energy market. Similar situation applies to the short position and positive three-phase power balance. Below an example of the behaviour of a system working in the trading driven scheme was presented (Figure 32).

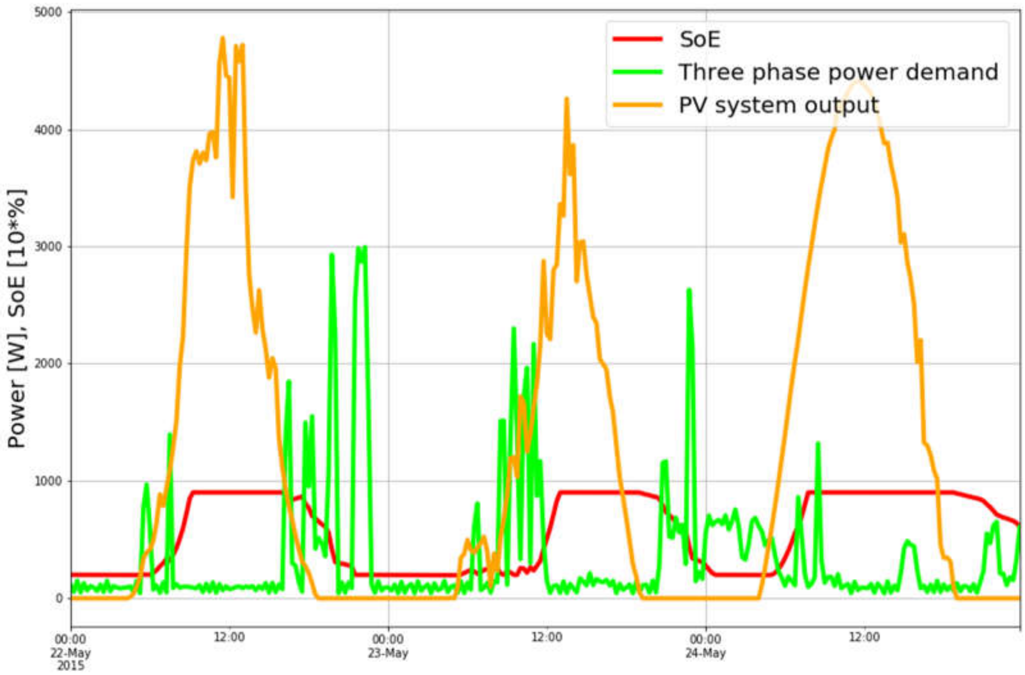


Figure 31 Behaviour of a system working in the power demand driven scheme

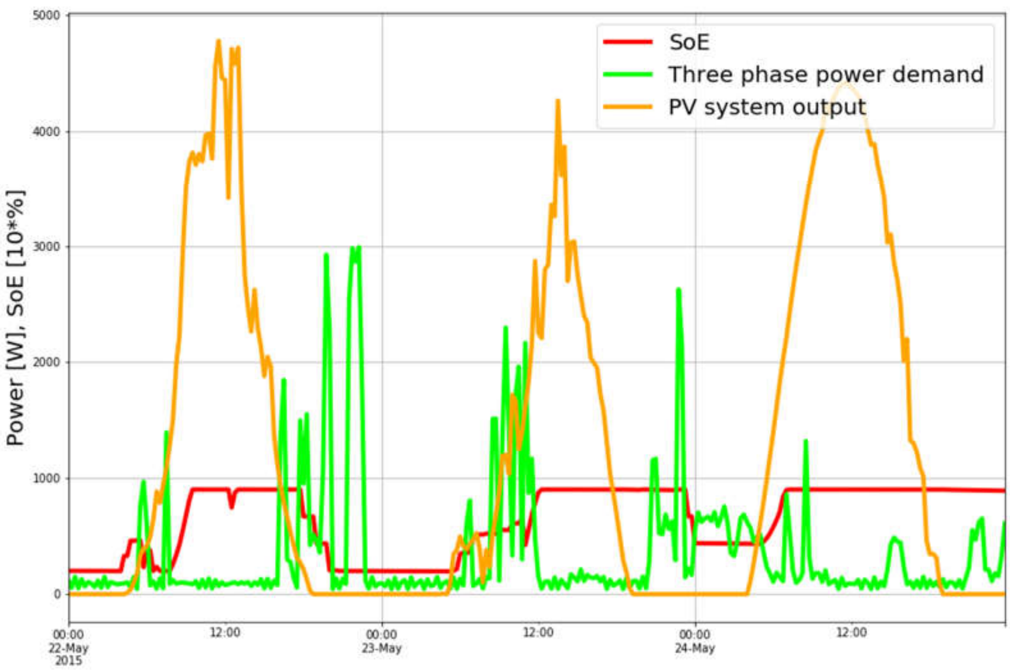


Figure 32 Behaviour of a system operating in the trading driven scheme

The third and last considered in the model battery behaviour scheme is a combination of the two described above. The battery is charged in the same situations as in the trading driven behaviour scheme. However, the signals to discharge coming from EMS will be incentivized by the negative three-phase power balance as well as the CVPP. It can be said that the CVPP signals are major in the mix and every time CVPP sends a trading signal to the EMS it will attempt to carry out the desired CVPP action. Nevertheless, whenever there is no signal given by the CVPP the EMS will manage the battery as it was in the power demand driven behaviour scheme. The behaviour of the system working in the mixed scheme was shown at the example below (Figure 33).

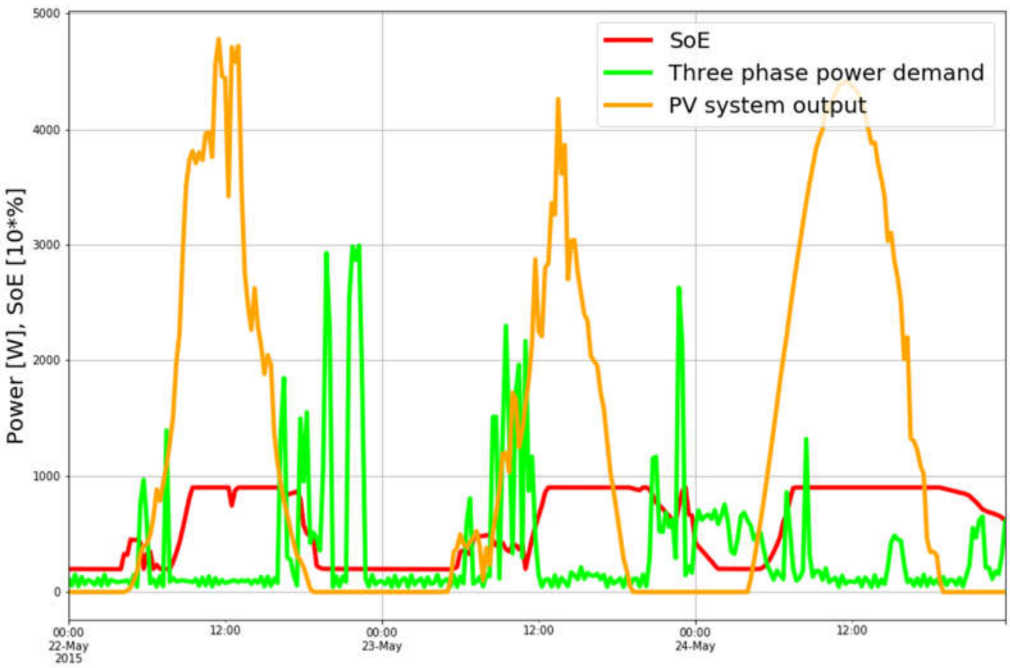


Figure 33 Behaviour of a system operating in the power demand and trading driven scheme

3.1.6. Overall model structure

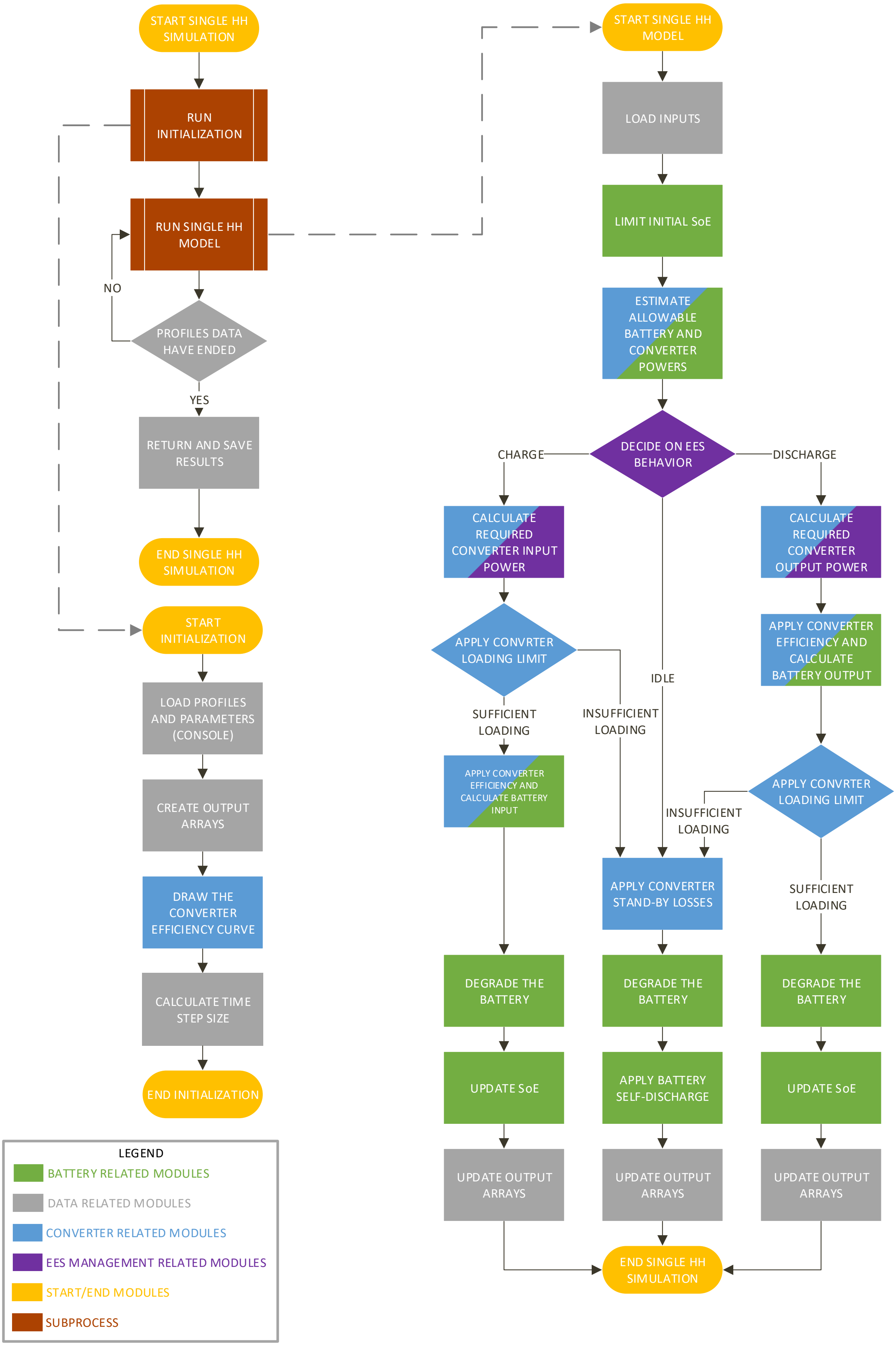


Figure 34 Model structure

The model is composed of modules, which relate to several physical parts of the system and of some related strictly to data processing (Figure 34). The main simulation and sub-processes that it contains start and end with a certain type of module. They symbolise an interface between major parts of the model. Mentioned sub-processes contain major parts of the model. Within the data related modules processes like loading parameters, profiles or global variables and returning and saving results are conducted. The model is also composed of modules related to the phenomena occurring in battery, power converter and EES management system. Below a description of allm is presented.

3.1.7. Simulation process

After introducing all crucial modules of the model the complete sequence of the simulation process can be described. The simulation starts from the initialization, where at first the profiles of the PV system power output and the household power demand are loaded along with all parameters of the system. This process is done in the model console, which was written in jupyter notebook, which is an open-source web browser application, which allows easily create documents, containing live code. System parameters are grouped into five arrays:

- System parameters array,
- Battery parameters array,
- Converter parameters array,
- Trading parameters array,
- Behaviour parameters array.

The complete summary the profiles and parameters loaded in this block can be seen in the table below (Table 4).

Profiles:		**Battery parameters:**	
Time index		Initial energy capacity	[Wh]
PV inverter power output	[W]	Maximum power input	[W]
Power consumption for each phase	[W]	Maximum power output	[W]
Energy market prices	[€/MWh]	Initial SoE	[%]
System connection parameters:		Maximum SoE	[%]
Overcurrent protection nominal current	[A]	Minimum SoE	[%]
Phase number of PV system connection		Self-discharge rate for first 24h	[%]
Phase number of the EES		Self- discharge rate per month	[%]
Converter parameters:		**Trading settings:**	
Minimum power input	[W]	Fixed selling price threshold value	[€/MWh]
Maximum power output	[W]	Fixed buying price threshold value	[€/MWh]
Loading limit	[W]	Minimum SoE reference	[%]
Efficiency limit	[%]	Maximum SoE reference	[%]
Stand-by losses	[W]	Upper selling price threshold limit	[€/MWh]
Switch-off time	Steps no.	Lower selling price threshold limit	[€/MWh]
Behaviour settings:		Upper buying price threshold limit	[€/MWh]
Self-consumption switch		Lower buying price threshold limit	[€/MWh]
Trading switch			
Trading strategy switch			

Table 4 Inputs of the single household simulation

The arrays are further provided to the function which will iterate the single household model. The function along with the single household model is written in Python file (.py) and triggered from the console. At first in the function the arrays for the model outputs are created. The outputs have a form of vectors storing values for each time step of the simulation and are gathered in the table below (Table 5).

System related outputs:		**Battery related outputs:**	
Tripping current indication	[A]	SoE	[Wh]
Converter related outputs:		Power input	[W]
Power input	[W]	Power output	[W]
Power output	[W]	Energy capacity	[Wh]
Efficiency	[%]	Equivalent cycles number	
Tripping current indication	[A]	Average cycle depth	[%]
Trading related outputs:		Cycle fade	[%]
Selling price threshold value	[€/MWh]	Calendar fade	[%]
Buying price threshold value	[€/MWh]	Degradation	[%]

Table 5 Single household simulation output vectors

Then from the power converter specifications the efficiency curve is "drawn" as a lookup table. Further the time step of the simulation is calculated as a part of an hour (e.g. $15\ \text{min} = 0.25\ \text{h}$) and the initialization sub-process is complete and the function can start iteration of the single household model for every time step until the profiles data provided has ended.

At first all inputs to the single household model are loaded from the input arrays. And the first battery related module is executed. To start simulation of the EES behaviour it is required to know the initial SoE (SoE_0) of the battery, which is one of the inputs of the model. As already mentioned the usage of the battery is bounded in terms of its SoE. In default from 0 to 100% and can be bounded liberally within mentioned constraints (e.g. 20 to 90%). The reason behind the bounding SoE is trick that battery manufacturers use to guarantee that their product will withstand certain time in certain operating conditions. The manufacturers usually provide much lower capacity of the battery to the datasheet, which is only operational capacity not real one. In order to reflect as authentically as possible the phenomena occurring in the battery and dependant on energy capacity like degradation and self-discharge the real energy capacity of the battery should be known and applied to the model. Simple way to do it is increasing the operational capacity provided by the manufacturer and bounding the operation of the battery in terms of SoE. Another reason is the desire of the battery owner to bound the battery SoE in order to degrade it less in the long run. In this situation the limits would be provided to the EES management system. The initial SoE (SoE_0) has to be limited at the beginning of the simulation if it is not in the default bounds. In practice if the bounds were liberally chosen it is possible that the SoE_0 of the battery is not the bounds. For instance, if the bounds are 30 to 70% than there is no reason why a newly connected battery SoE cannot be below 30% but after the connection the battery would be operated in a way that would not allow the SoE to drop below 30% or go above 70%. Even though it is possible in practice for the sake of simplicity and because of low influence on final results the SoE_0 is changed to the liberally chosen bounds.

Next module calculates allowable power input and output of the battery and power converter in this particular iteration. In reality all systems of the EES operate in fluent, not gradual time. For the battery it means that the instantaneous power input and output of the battery can be maximal almost at all levels of SoE. However, in the model operating in time steps, when the battery is close to its SoE bound and is discharged with high power it may happen that the calculated afterwards SoE is not in bounds or even is below zero, what physically is not possible. Because of that in all iterations the power output required to discharge the battery to the lower SoE bound and the power input which is required to charge the battery to the higher SoE bound have to be calculated.

$$P_{bat\ in\ SoE_{max}} = \frac{-E_{bat}(SoE_{max} - SoE)}{t_{step\ size}} \tag{3.14.}$$

$$P_{bat\ out\ SoE_{min}} = \frac{E_{bat}(SoE - SoE_{min})}{t_{step\ size}} \tag{3.15.}$$

Where:

$P_{bat\ in\ SoE_{max}}$	–	battery input power required to achieve SoE_{max} in current time step [W],
$P_{bat\ out\ SoE_{min}}$	–	battery output power required to achieve SoE_{min} in current time step [W],
$P_{bat\ \max in\ per\ tst}$	–	maximum allowable battery power input in current time step [W],
$P_{bat\ \max out\ per\ tst}$	–	maximum allowable battery power output in current time step [W],
SoE	–	current SoE [%],
SoE_{max}	–	upper SoE bound [%],
SoE_{min}	–	lower SoE bound [%],
E_{bat}	–	energy capacity of the battery [Wh],
$t_{step\ size}$	–	time step size [h],

After calculating the powers that would charge the battery to the higher SoE bound and discharge the battery to the lower SoE bound in current time step it may happen that the values of calculated powers are higher than the maximum charge or discharge power of the battery provided by the manufacturer. Hence, the calculated values are limited to the maximum power limitations given by the manufacturer. After restraining the values the maximum allowable battery power input ($P_{bat\ \max in\ per\ tst}$) and output ($P_{bat\ \max out\ per\ tst}$) in current time step are calculated.

After calculating the allowable battery power input and output in current time step the allowable converter power input and output in current time step associated with battery powers can be calculated. As already mentioned the converter efficiency linking the converter powers with battery powers is not calculated every iteration, but the efficiency curve is "drawn" as a lookup table in the initialisation sub-process and used further in the single household model. Hence, first the converter efficiency associated with maximum allowable battery powers is assessed and then the maximum allowable converter power input ($P_{conv\ \max in\ per\ tst}$) and output ($P_{conv\ \max out\ per\ tst}$) in current time step are calculated.

After calculating all limiting powers of the battery and power converter the decision on the EES behaviour is made. It happens in the module related to EES management system, which is described above. Based on the system parameters, current power flow, trading signals and the EES behaviour scheme chosen the decision on the behaviour of the EES can be made. It can be made threefold, namely the EES management module can decide to charge, discharge or idle the battery. From now on the sequence is split and depends on made decision.

If the charge or discharge path was chosen in the next module the required converter power input or output is calculated. The required power calculations are based on mentioned above parameters related to: system topology (connection parameters and protection parameters), current power flow (PV system power output and power demand), trading (trading signals), EES behaviour scheme chosen (power demand driven, trading driven or power demand and trading driven) and converter limits (maximum allowable converter power input and output in current time step and converter loading limit). Firstly, the phase power balance and three-phase power balance are calculated. Then taking into account trading signals and the power balances the converter power input or output required to create a state desired by EMS is calculated. The converter powers at this point are already limited to the maximum allowable converter power input or output in current time step. Then the phase power balances are recalculated including the EES system influence. At this point it is possible to evaluate if the behaviour of the EES to achieve state desired by the EMS will trigger the overcurrent protection. As already mentioned the EES management system is designed to counteract this situations. So to say, if the overcurrent protection triggering is expected, the EES behaviour will be adjusted to counteract it. The EES power input or output will be limited according to table presented in the subsection related to EES management system (Table 3).

In the next two modules, if the charging or discharging process was chosen to be executed, based on the power converter parameters and the power input or output power asked from the EES management system module the battery power input or output is calculated. The converter parameters taken into account in those modules are power converter efficiency curve and its loading limit. The steps in case of charging and discharging process is different. When charging was chosen to be executed the converter loading limit can be easily applied because the converter power input is initially known. If the converter power input is lower than the converter loading limit the charging will not be allowed by the converter control. Nevertheless, when the converter power input ($P_{conv\ in}$) is above the limit the lookup table with converter efficiency is utilised and the battery power input ($P_{bat\ in}$) is calculated. The converter power input and the battery power input determined at this point represent final outputs of the model and are stored in separate output arrays. The flowchart representing the charging process is shown below (Figure 35).

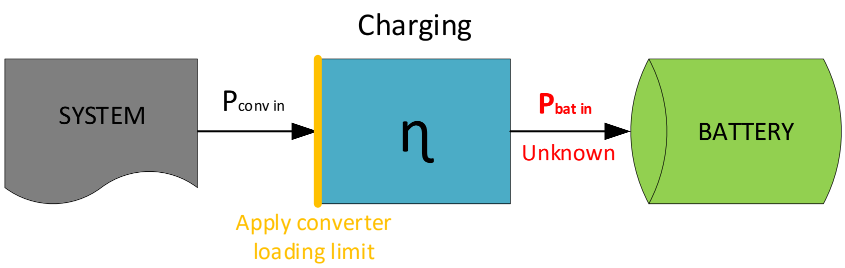


Figure 35 Apply converter efficiency and loading limit - charging

However, while discharging the process is not that straightforward anymore. The EES management system asks for certain power output, nevertheless the converter loading limit is applied regarding to the input of the converter. Hence, to apply the converter loading limit the battery power output required to achieve the converter power output asked by the EES management system has to be known. The battery power output in this case is the converter input power. Therefore, first the lookup table with the converter efficiency curve is used in reverse to estimate the value of battery power output based on converter power output. Then the converter loading limit is applied to it. If the value of the calculated battery power output is lower than the limit the discharge process is not executed and battery is idled. In case when it is bigger the discharge occurs and the converter output power ($P_{conv\ out}$) is equal to the one requested by the EES management system and the battery is discharged with calculated before power ($P_{bat\ out}$). The powers determined at this point are final outputs of the model and will not be changed further in the model. They are stored in separate arrays. Below a flowchart, which presents the discharging process is presented (Figure 36).

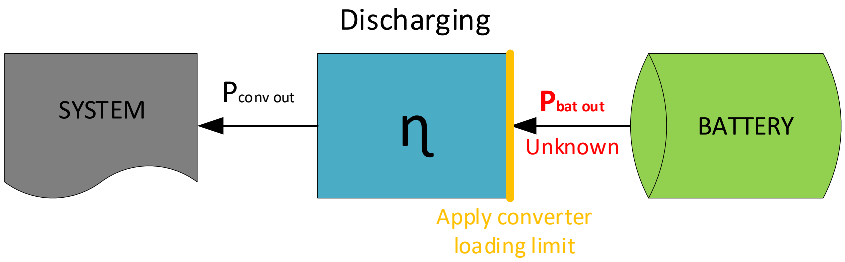


Figure 36 Apply converter efficiency and loading limit - discharging

In case when the EES management system decided to idle the battery or when the charge or discharge process was terminated by the converter limitations the next module used in the sequence is applying the converter stand-by losses. Often the converter is connected through automatic switch, which will disconnect it in case of long enough inaction. Therefore, the model takes as an input number of time steps in which the switch would keep the converter connected. Another input is simply the converter power demand in stand-by mode. If the converter is inactive for the provided amount of time steps the stand-by losses will be added. Stand-by losses are stored in separate output array.

Next module executed is identical for all EES behaviour paths. Since the battery degradation is not only dependent on cycling but also on time it has to be applied in all time steps. Based on SoE_{avg} and number of time iteration the calendar fade is calculated. In the module the equivalent number of cycles and average cycle depth is calculated, based on which the cycle fade is estimated. Because the model is ran in iterations and the degradation model is designed to rely on the data fully provided from the beginning some adjustments had to be made. The average cycle depth calculated in the module can be at the beginning of the simulation unstable. Therefore, the values of the cycle fade calculated at the beginning of the simulation can be sometimes smaller than calculated in iterations before. Because of smaller cycle fade the total value of degradation, which is combination of the calendar and the cycle fade, can be smaller than one calculated in iterations before. The battery degradation process is irreversible and such should be simulated. Therefore, every time when the cycle fade value is smaller than the one calculated in the previous iteration the new value will be adopted with the value of previously calculated cycle fade. This will not allow a reverse degradation to the battery. Based on the value of degradation a new value of battery energy capacity is calculated. This value represents the final output of the single household model and will be stored in a separate array. Furthermore, for an insight into the battery performance also values of both fades, equivalent cycles number and average cycle depth are saved to separate arrays and are the final output of the model.

In the next module if the battery is charged or discharged the SoE of the battery is updated. Based on the power input or output of the battery and the time step size the energy drawn or given to the battery can be calculated, based on which new SoE is established. The current SoE is saved a final output of the single household model in a separate array.

In case when battery is idled the self-discharge of the battery has to be applied to establish new SoE. The battery self-discharge is applied to the current SoE depending on the time of inaction. As already mentioned two different rates of discharge were taken as inputs to the model. One related to the first 24 hours of battery inaction and the second one related to the month of inaction. After applying the self-discharge the new SoE is established and saved in the model output array.

The calculation of new SoE is the last component related step in the single household model. In the next module the results of the current model iteration are returned and the next iteration can start. If the end of input profiles was detected the loop with the single household model ends and all output arrays are returned to the jupyter notebook console, where the results can be displayed.

3.2. Trading as a VPP

An aggregation of small or medium sized power generation units, demand response and storage devices, introduced in the theoretical background as a VPP provides possibility of visibility on different energy markets to the mentioned units, which would not be able to achieve that on their own. In a VPP an entity making decisions on creating and sending trading signals to for execution is a CVPP, which takes into account state of the available units and forecasting data. In real VPP the signals from CVPP are forwarded to TVPP where the influence of the network is taken into account and the final decision on the desired VPP behaviour is made. In the model only functionalities of the CVPP are considered. Furthermore, in real life the connection point of the VPP is at HV level and there the energy traded is measured (Figure 37). In the model though the economical impact of the VPP will be measured as sum of energy measurements made at the points of connection of each household (Figure 37). This situation may be possible in the future with sufficient measurement and control systems technology and suited legislation.

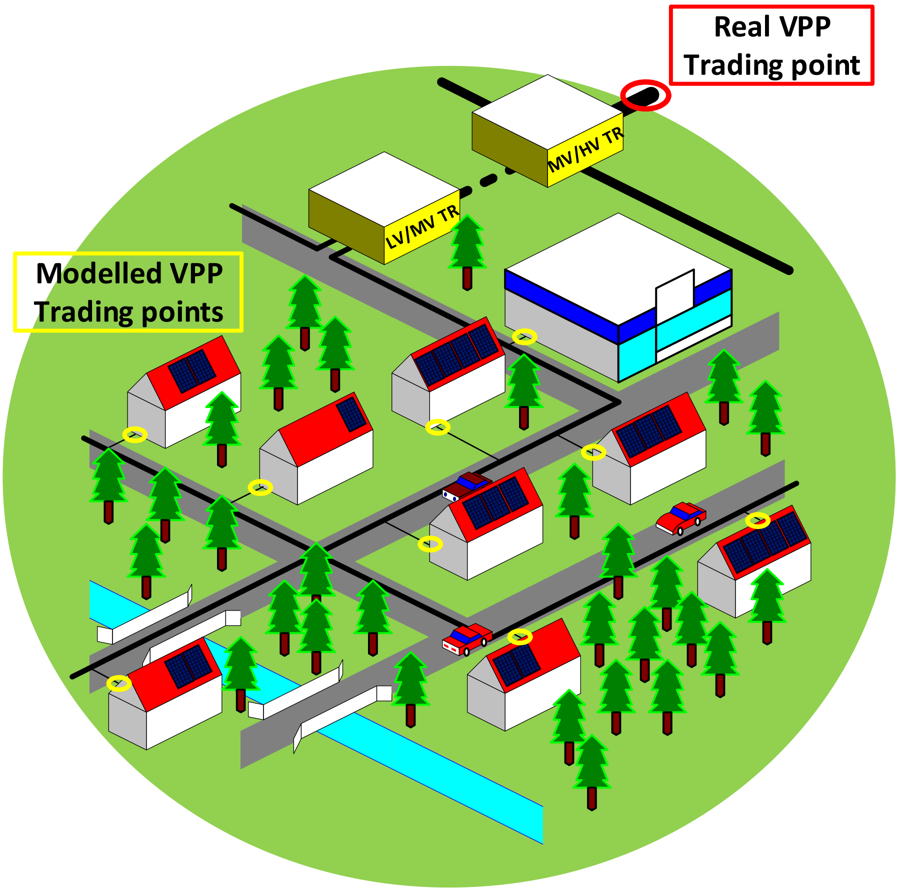


Figure 37 VPP trading points

Furthermore, at the current state of the energy market development an important factor is a minimum size of a bid allowed at the market. Because of it the small and medium capacity entities cannot participate in the energy markets. The VPP concept, as already said allows, by aggregation, participation to those entities, however in the model the minimum bid size was not taken into account. It was assumed that no matter how small the amount of energy the CVPP

decided to trade the transaction will occur. In the future the minimum bid size can be reduced and matching the capacity may be easier.
The model of a CVPP takes as an input profiles of the real market prices and makes decisions based upon them. As already said some markets work in a dual-price system, hence the model receives two profiles of the prices, namely selling and buying price. In case a single-price system has to be modelled the single profile should be provided as a selling and buying price profile. Obviously, in practice the prices are never known to the CVPP, nevertheless there are no contraindications for providing as an input to the CVPP model values, which would be predicted values of the prices. In this way the modelled behaviour of the VPP could be more realistically reflected, and therefore the economical impact could be better evaluated. However, the model even when provided with the price profiles for the length of the simulation does not use the knowledge about future energy prices. It means that the model does not use so called perfect prediction to make decisions. With perfect prediction the model would be able to adjust the behaviour of the system for the future and find an optimal behaviour maximizing the revenues coming from the market investments. The model of the CVPP uses values of the prices present at the market at current time step. The future prices' values do not influence the decisions made for the system behaviour at a current time step. Even though the prices' values are known at certain times a clear decision-making algorithm had to be developed in order to create trading signals. Two trading strategies were developed to model decisions made by the CVPP, namely fixed prices thresholds strategy and SoE changing prices thresholds strategy.

3.2.1. Fixed prices thresholds strategy

The trading strategy was developed harmoniously with a rule buy low, sell high. Two prices thresholds are set and in every time step the prices are compared to the values of the thresholds. If the selling price value is above set selling price threshold the CVPP will generate a long position trading signal. Similar situation applies to the short position trading signal, which is generated when the buying price value is below set buying price threshold. As described in the EES management system description after the trading signal is generated it is sent to the lower levels of the management system and if all technical requirements are met the trading transaction is made. An example how the CVPP generates trading signals is presented below (Figure 38). The Dutch imbalance prices from year 2015 were used. The values of the prices' thresholds were chosen arbitrarily.
In the model the values of the thresholds are loaded at the beginning of the simulation with all other inputs. They are loaded to the trading parameters array and saved after the simulation as a result
An advantage of this strategy is its simplicity. This strategy can be easily applied to a VPP and its settings are not dependant on the state of the system. Hence, the settings are unified for the whole VPP devices. However, the reaction of the system on all prices above the selling price threshold and below the buying price threshold are the same. Therefore, the EES will attempt to charge or discharge with full power as soon as it sees a trading signal no matter what is the price or what is the SoE of the batteries. It means that it may happen that the signals generated by relatively low – just above the selling threshold will cause full discharge of the batteries and an opportunity to utilize coming higher prices will never be taken. Based on this concept another trading strategy was developed, which will react on the current status of a battery.

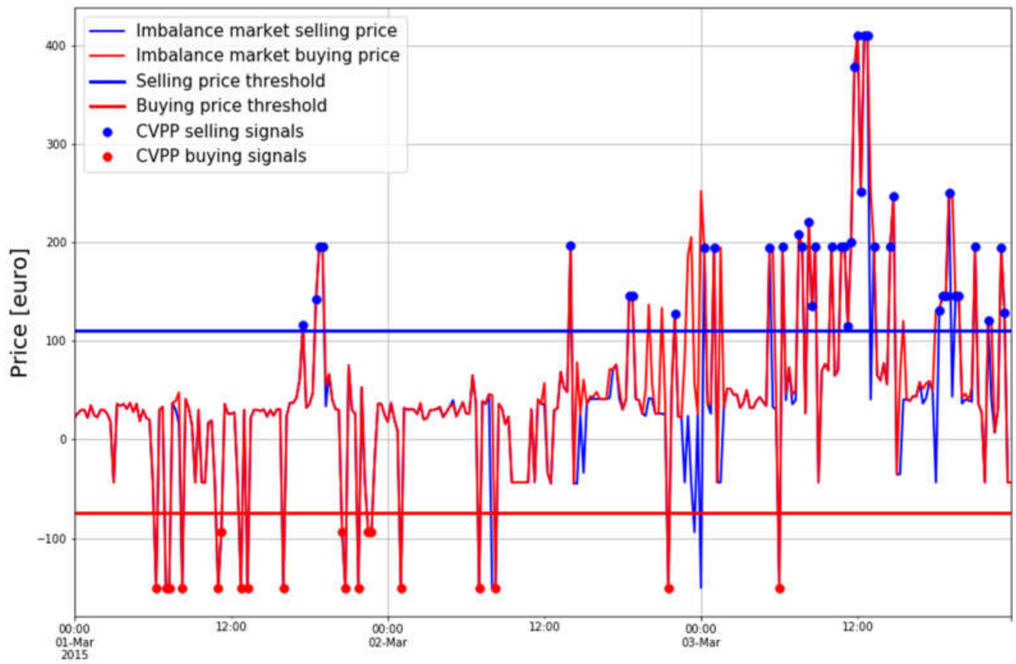


Figure 38 Fixed prices thresholds trading strategy

3.2.2. SoE changing prices thresholds strategy

In this strategy the prices' thresholds from the previous approach are not fixed anymore, but change with the SoE of a battery. In this case the rule is that the closer the SoE is to its limit the CVPP is less eager to accept worse prices. In other words when the SoE of the battery is low the selling price threshold will be increased and the system will be waiting for higher price. We can say that the supply of the energy is decreasing with still unknown demand, hence it is more valuable for the seller. Because of that the selling price threshold is increased and only higher prices will generate trading signals. At the same time noticing low supply the buyer is more eager to accept higher buying price. Therefore, the buying price threshold is increased and CVPP will generate signals to create short position triggered by higher buying price. Similar situation applies to the high battery SoE what means that the supply is high and the seller is more eager to accept lower selling prices. Hence, the CVPP will generate signals to create long position provoked by lower selling price. Accordingly, the buyer will try to find lower buying price and will try to buy the energy for extremely low price. It means that the purchaser will have to accept that the storage unit is full and the part of the flexibility is lost.

The change of the prices' thresholds values can be programmed diversely. However in the model the simplest approach was tested, namely linear change with SoE of a battery. The rate of change can be set independently for the selling and buying price.

To determine the desired rate of change of the prices' thresholds values six inputs are loaded at the beginning of the simulation. First of all those are minimum and maximum SoE where the lines representing the rate of change start and end. They do not necessarily have to match the SoE_{min} and SoE_{max} used for limiting the modelled SoE of a battery. Further inputs are prices limitations for the buying and selling price and for the minimum and maximum SoE mentioned above. From the inputs two line segments are drawn, which represent the rate of change of the prices' thresholds values. An example of the segments can be seen below (Figure 39).

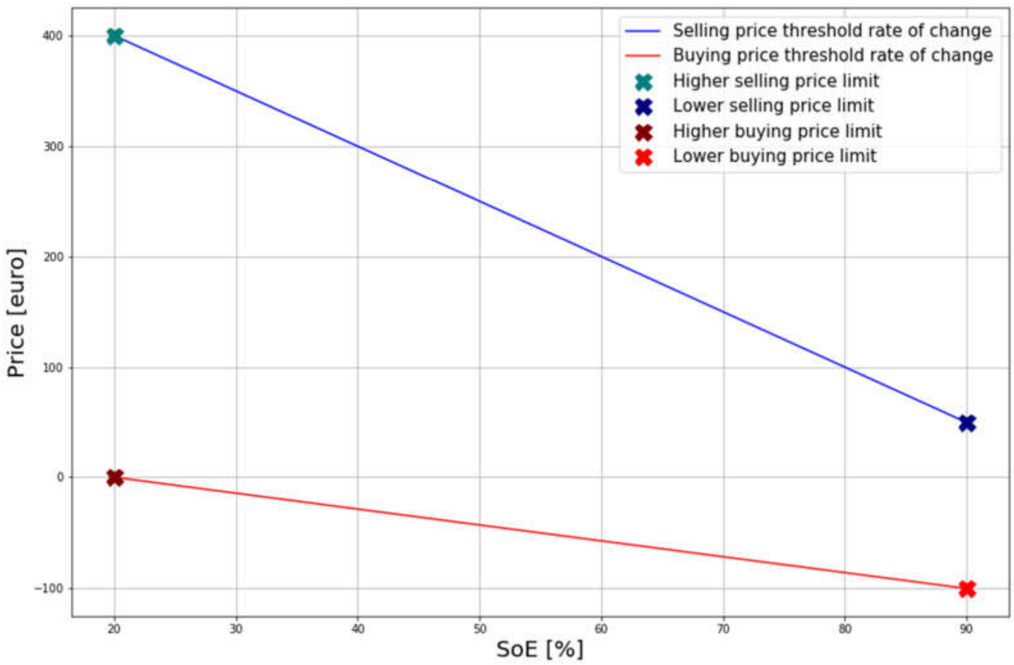


Figure 39 Rate of change of the prices' thresholds values

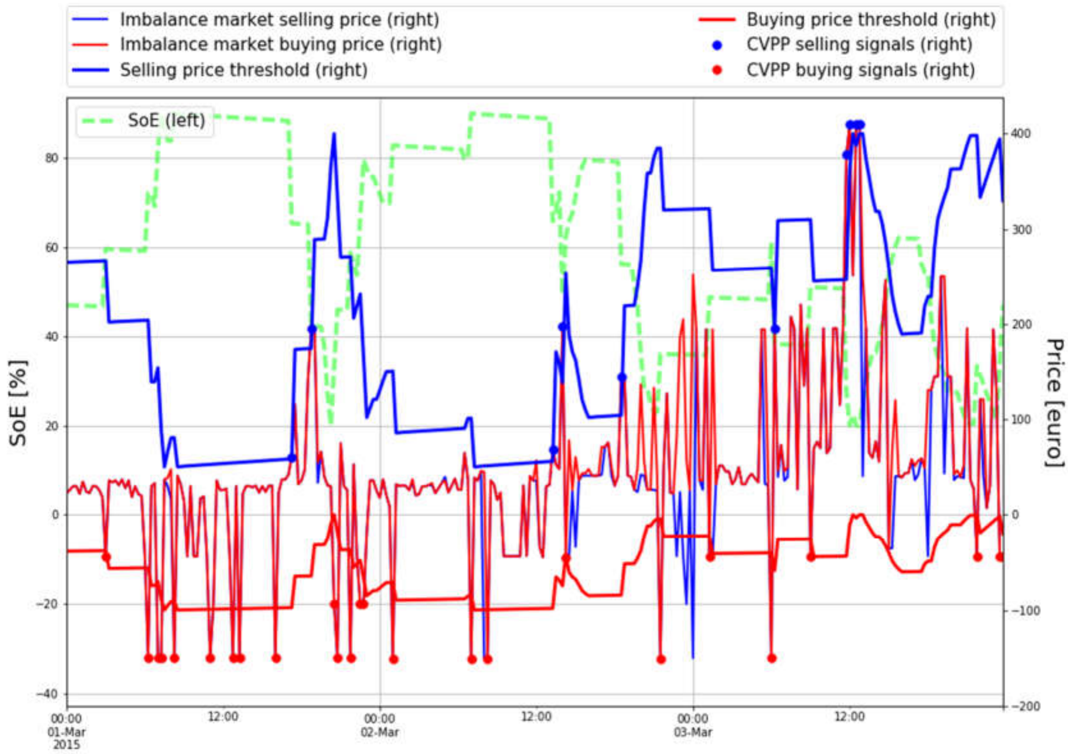


Figure 40 SoE changing prices' thresholds strategy

An example how the CVPP generates trading signals using the described strategy is provided above (Figure 40). The Strategy was applied using the inputs from the example showing the rate of change of the prices' thresholds values. The same period and prices' profiles as in the

description of the previous strategy were used. It can be easily observed how the values of the prices' thresholds change according to the SoE of the battery.
An advantage of this strategy is that the more high value prices trades may occur. However, this might also cause some problems. The strategy may create fairly more trading signals than the previous one, hence causing the battery to extreme cycling and eventually to enhanced degradation. A problem with this strategy is also applicability to the VPP. The CVPP will need SoE based on which it will generate the trading signals. All batteries in the VPP will most probably have different SoE. Therefore one reference battery have to be chosen to generate the prices' thresholds values or more complex approach can be utilized. The CVPP could gather information about the SoE of all batteries in the VPP and calculate from it a reference SoE profile (e.g. average SoE of all batteries) to take as an input.

3.2.3. Retail market

In the retail competition economy model introduced in theoretical background the wholesale and retail markets are completely decoupled. Nevertheless, the modelled VPP combines interactions on the wholesale market and retail market. Even though at some moment the VPP is trading on the energy market each household is still subjected to the economical impact of the transactions with the retailer. The retailers style of selling and buying the energy from its customers or prosumers can vary substantially. Some retailers use tariffs to sell the energy. Energy sold in peak hours is more expensive than the energy sold for instance at night, when the demand is low. Some of retailers ask a base price for each month and on top of that the consumer pays for the energy used with a price from an energy market. Prosumers are able to sell the energy and may be allowed to sell the energy with the same price they pay for the energy, nevertheless until certain limits. There is a number of possibilities how the interaction with retailer can be modelled, however evaluation of the impact of different marketing systems used by the retailers is not in the scope of this project. Because of that it was chosen to model it in a straightforward way, nevertheless if needed other models can be easily applied to the analysis module, which will be described below. The model of the retailer has two prices for selling (rsp) and buying (rbp) the energy. It was assumed that the prices are fixed throughout the time of the simulation. It means that the energy taken from the grid will be always bought with the same price and the energy given back to the grid will be always sold with the same price. There is no limitations put on the amount of energy that is allowed to be given back to the grid.

3.3. Analysis

The outputs of the model can give us a glance of the situation in the system, nevertheless a huge part of the conclusions will be made based on the values coming from the output arrays analysis, which is done in a separate module. Firstly, the power distribution throughout all the simulation period can be made. Based on the determined power profiles an energy corresponding to them can be calculated. Knowing on what the energy was spent during the simulation period the economical impact can be estimated.
Ten different power profiles are determined in the analysis module. Firstly, the power profile showing an interaction with the grid of a household without a battery and of a household without a battery and PV can be calculated. The profiles can be used as a reference to the scenarios with a battery. The corresponding energy will allow calculation of the values of the energy bills for these households. The profiles are calculated from the profile of the PV system power output and the power demand profile.

$$\vec{P}_{bal\ 3ph} = \vec{P}_{PV} - \vec{P}_{load\ 3ph} \tag{3.16.}$$

$$E_{bought\ no\ bat\ no\ PV} = \sum_{i=1}^{s} \vec{P}_{bal\ 3ph}(s) \cdot t_{step\ size}\ \ for\ \vec{P}_{PV} = \vec{0} \tag{3.17.}$$

$$E_{sold\ no\ bat} = \sum_{i=1}^{s} \vec{P}_{bal\ 3ph}(s) \cdot t_{step\ size}\ \ for\ \vec{P}_{bal\ 3ph}(s) > 0 \tag{3.18.}$$

$$E_{bought\ no\ bat} = \sum_{i=1}^{s} \vec{P}_{bal\ 3ph}(s) \cdot t_{step\ size}\ \ for\ \vec{P}_{bal\ 3ph}(s) < 0 \tag{3.19.}$$

$$EB_{no\ bat\ no\ PV} = -E_{bought\ no\ bat\ no\ PV} \cdot rbp \cdot 10^{-3} \tag{3.20.}$$

$$EB_{no\ bat} = -E_{bought\ no\ bat} \cdot rbp \cdot 10^{-3} - E_{sold\ no\ bat} \cdot rsp \cdot 10^{-3} \tag{3.21.}$$

Where:

$\vec{P}_{bal\ 3ph}$	–	three-phase power balance vector [W],
$\vec{P}_{PV}$	–	PV system power output vector [W],
$\vec{P}_{load\ 3ph}$	–	three-phase power consumption vector [W],
$E_{bought\ no\ bat\ no\ PV}$	–	energy bought from the retailer in a house without a battery nor PV [Wh],
$E_{sold\ no\ bat}$	–	energy sold to the retailer in a house without a battery [Wh],
$E_{bought\ no\ bat}$	–	energy bought from the retailer in a house without battery [Wh],
s	–	time step number,
$EB_{no\ bat\ no\ PV}$	–	energy bill of a house without a battery nor PV [€],
$EB_{no\ bat}$	–	energy bill of a house without a battery [€],
rsp	–	retail energy selling price [€/kWh],
rbp	–	retail energy buying price [€/kWh].

Next the power distribution in scenarios including EES system in the household is determined. This will contain power profiles indicating the power taken and returned to the grid, similarly to the power profiles determined above. Furthermore, in these scenarios the power demand is covered from three sources, namely from PV system, EES system and the grid. The power demand covered from PV system and EES system is self-consumed and the amount of these powers is calculated. Moreover, the amount power sold and bought at the energy market is determined. Energies corresponding to the power profiles will allow us to calculate the energy bill and the part of the trading revenue that particular household contributed to.

The power profile indicating interaction of the house with the grid has changed and three power profiles were added, namely converter power input and output and its standby losses. Based on the final power balance the corresponding energies are calculated and the value of energy bill can be determined.

$$\vec{P}_{final\ bal\ 3ph} = \vec{P}_{bal\ 3ph} + \vec{P}_{conv\ out} + \vec{P}_{conv\ in} - \vec{P}_{conv\ sb\ loss} \tag{3.22.}$$

$$E_{sold} = \sum_{i=1}^{s} \vec{P}_{final\ bal\ 3ph}(s) \cdot t_{step\ size} \quad for\ \vec{P}_{final\ bal\ 3ph}(s) > 0 \tag{3.23.}$$

$$E_{bought} = \sum_{i=1}^{s} \vec{P}_{final\ bal\ 3ph}(s) \cdot t_{step\ size} \quad for\ \vec{P}_{final\ bal\ 3ph}(s) < 0 \tag{3.24.}$$

$$EB = -E_{bought} \cdot rbp \cdot 10^{-3} - E_{sold} \cdot rsp \cdot 10^{-3} \tag{3.25.}$$

Where:

$\vec{P}_{final\ bal\ 3ph}$ – three-phase power balance vector in a house with EES [W],
E_{sold} – energy sold to the retailer in a house with EES [Wh],
E_{bought} – energy bought from the retailer in a house with EES [Wh],
EB – energy bill of a house with EES [€].

The power self-consumed from the PV system has a priority over the power self-consumed from the EES system. Hence, if the power coming from the PV system is enough to cover the demand it will compensate it. Even if the power is not enough the demand will be fulfilled partially. The power self-consumed from PV system is calculated and the corresponding energy, based on which the avoided costs by PV system can be calculated.

$$\vec{P}_{sc\ PV}(s) = \begin{cases} \vec{P}_{load\ 3ph}(s)\ for\ \vec{P}_{PV}(s) > \vec{P}_{load\ 3ph}(s) \\ \vec{P}_{PV}(s)\ for\ \vec{P}_{PV}(s) \le \vec{P}_{load\ 3ph}(s) \end{cases} \tag{3.26.}$$

$$E_{sc\ PV} = \sum_{i=1}^{s} \vec{P}_{sc\ PV}(s) \cdot t_{step\ size} \tag{3.27.}$$

$$AC_{sc\ PV} = E_{sc\ PV} \cdot rbp \cdot 10^{-3} \tag{3.28.}$$

Where:

$\vec{P}_{sc\ PV}$ – power self-consumed from PV system vector [W],
$E_{sc\ PV}$ – energy self-consumed from PV system [Wh],
$AC_{sc\ PV}$ – avoided costs by PV self-consumption [€].

The secondary source of the self-consumption is EES system, nevertheless the calculation of the power self-consumed from it has more constraints and depends on the system behaviour. Crucial is knowledge if the EES is currently fulfilling commands of the CVPP to trade. Therefore, a trading signal vector is created. Each element of the vector can equal to three constants indicating the behaviour of the system. Zero will indicate no trading situation, one will mean selling signal and minus one buying signal. Further the equations used for calculation of power, energy and avoided costs from the EES system are similar to those above.

$$\overrightarrow{TS}(s) = \begin{cases} 1\ for\ selling\ signal \\ 0\ for\ no\ trading \\ -1\ for\ buying\ signal \end{cases} \quad (3.29.)$$

$$\vec{P}_{sc\ bat}(s) = \begin{cases} \vec{P}_{conv\ out}(s) - \vec{P}_{PV}(s)\ for\ \overrightarrow{TS}(s) = 1\ and\ \vec{P}_{PV}(s) \leq \vec{P}_{load\ 3ph}(s) \\ \vec{P}_{conv\ out}(s)\ for\ \overrightarrow{TS}(s) = 0 \end{cases} \quad (3.30.)$$

$$E_{sc\ bat} = \sum_{i=1}^{s} \vec{P}_{sc\ bat}(s) \cdot t_{step\ size} \quad (3.31.)$$

$$AC_{sc\ bat} = E_{sc\ bat} \cdot rbp \cdot 10^{-3} \quad (3.32.)$$

Where:

$\overrightarrow{TS}$ – trading signals vector

$\vec{P}_{sc\ bat}$ – power self-consumed from EES system vector [W],

$E_{sc\ bat}$ – energy self-consumed from EES system [Wh],

$AC_{sc\ bat}$ – avoided costs by EES self-consumption [€].

To complete the power distribution of the household the power that that contributes to the VPP trading from the particular house is needed. This amount of power is the final three-phase power balance in particular time step, when the trading occurs what complies with the modelled trading points described in the VPP trading section. The profile of the traded power, the corresponding energy and energy market prices' profiles will allow calculation of the contribution of the household to the VPP energy market revenues.

$$\vec{P}_{sold\ EM}(s) = \vec{P}_{final\ bal\ 3ph}\ for\ \overrightarrow{TS}(s) = 1\ and\ \vec{P}_{final\ bal\ 3ph}(s) > 0 \quad (3.33.)$$

$$\vec{P}_{bought\ EM}(s) = \vec{P}_{final\ bal\ 3ph}(s)\ for\ \overrightarrow{TS}(s) = -1\ and\ \vec{P}_{final\ bal\ 3ph}(s) < 0 \quad (3.34.)$$

$$\vec{E}_{sold\ EM} = \vec{P}_{sold\ EM} \cdot t_{step\ size} \quad (3.35.)$$

$$\vec{E}_{bought\ EM} = \vec{P}_{bought\ EM} \cdot t_{step\ size} \quad (3.36.)$$

$$R_{sold\ EM} = \sum_{i=1}^{s} \vec{E}_{sold\ EM}(s) \cdot \overrightarrow{emsp}(s) \cdot 10^{-6} \quad (3.37.)$$

$$R_{bought\ EM} = \sum_{i=1}^{s} \vec{E}_{bought\ EM}(s) \cdot \overrightarrow{embp}(s) \cdot 10^{-6} \quad (3.38.)$$

Where:

$\vec{P}_{sold\ EM}$ – power sold on energy market vector [W]

$\vec{P}_{bought\ EM}$ – power bought on energy market vector [W]

$\vec{E}_{sold\ EM}$ – energy sold on energy market vector [Wh],

$\vec{E}_{bought\ EM}$ – energy bought on energy market vector [Wh],

$\overrightarrow{emsp}$ – energy market selling price vector [€/MWh],
$\overrightarrow{embp}$ – energy market buying price vector [€/MWh],
$R_{sold\ EM}$ – total contribution of the household to the VPP revenue from selling transactions at the energy market [€],
$R_{bought\ EM}$ – total contribution of the household to the VPP revenue from selling transactions at the energy market [€].

After determining the energy bill of the house and its contribution to the VPP operator revenues it is possible to calculate fragment of so called cumulative cash-flow of the VPP. Cash-flow is defined as "the net amount of cash or cash-equivalents moving into and out of a business" [35], which for our VPP will be combination of the VPP operator revenues at the energy market and summarized energy bill of the households. The analysis module is designed to work with the single household simulation results and the contribution to the VPP energy market revenues along with the household owner energy bill are calculated in it. Hence, as mentioned above, only a fragment of the cumulative cash-flow of the VPP will be determined in the module. The cumulative cash-flow will be an output of the VPP simulation and will be a base for the economical impact evaluation.

$$CF = R_{sold\ EM} + R_{bought\ EM} - EB \qquad (3.39.)$$

Where:
CF – fragmentary cash-flow representing the contribution of particular household to the cumulative cash-flow of the VPP [€].

The biggest part of the energy lost in the EES system is lost in the power converter. During the operation the efficiency curve of the converter plays a role of efficiency indicator and after the operation the converter uses energy to maintain stand-by mode. The amount of power lost during the operation and in stand-by mode and corresponding energy can be calculated using the simulation output data. Based on the value of lost energy it can be determined what is its financial worth.

$$\vec{P}_{conv\ eff\ loss}\,(s) = \begin{cases} \vec{P}_{bat\ in}(s) - \vec{P}_{conv\ in}(s)\ for\ \vec{P}_{bat\ in}(s) < 0 \\ \vec{P}_{bat\ out}(s) - \vec{P}_{conv\ out}(s)\ for\ \vec{P}_{bat\ out}(s) > 0 \end{cases} \qquad (3.40.)$$

$$E_{conv\ eff\ loss} = \sum_{i=1}^{s} \vec{P}_{conv\ eff\ loss}\,(s) \cdot t_{step\ size} \qquad (3.41.)$$

$$L_{conv\ eff\ loss} = E_{conv\ eff\ loss} \cdot rsp \cdot 10^{-3} \qquad (3.42.)$$

Where:
$\vec{P}_{conv\ eff\ loss}$ – power lost in the converter during its operation vector [W]
$\vec{P}_{bat\ in}$ – power battery input vector [W]
$\vec{P}_{bat\ out}$ – power battery output vector [W]
$E_{conv\ eff\ loss}$ – energy lost in the converter during its operation [Wh],
$L_{conv\ eff\ loss}$ – revenue lost due to energy lost in the converter during its operation [€].

In the model stand-by losses of the converter are stored in separate array and are returned after the simulation as a result. Therefore the power profile does not have to be determined like for previous profiles and the corresponding energy can be calculated directly. Based on the energy the revenue lost can be estimated.

$$E_{conv\ sb\ loss} = \sum_{i=1}^{s} \vec{P}_{conv\ sb\ loss}\ (s) \cdot t_{step\ size} \tag{3.43.}$$

$$L_{conv\ sb\ loss} = E_{conv\ sb\ loss} \cdot rsp \cdot 10^{-3} \tag{3.44.}$$

Where:

$\vec{P}_{conv\ sb\ loss}$	–	power lost in the converter during stand-by mode vector [W]
$E_{conv\ eff\ loss}$	–	energy lost in the converter during stand-by mode [Wh],
$L_{conv\ eff\ loss}$	–	revenue lost due to energy lost in the converter during stand-by mode [€].

Another interesting revenue loss that could be calculated is loss of the return due to power curtailment caused the insufficient nominal current of the overcurrent protection device to which the charge or discharge power is matched. As already mentioned one of the physical limitations of the house is the overcurrent protection. Even though the VPP operator desires to operate the EES system at the limit sometimes the nominal current of the overcurrent protection can be smaller than the current that would flow in the cables during the operation at the limit. Therefore, EES management system curtails the power and charges or discharges the battery at lower rate. For the VPP operator it means that a part of its potential revenue from trading transaction is lost. One of the simulation outputs is an indicator of overcurrent protection device triggering ($\vec{I}_{OCP\ triggered}$). It stores the value of the current that without EES behaviour would flow through cables and most probably trip the device. Based on the indicator the calculation of the curtailed power will be conducted.

$$\vec{P}_{OCP\ curt}(s) = \begin{cases} P_{bat\ in\ max} \cdot \vec{\eta}_{conv}(P_{bat\ in\ max}) + \vec{P}_{conv\ in}(s)\ for\ \vec{I}_{OCP\ triggered}(s) < 0 \\ P_{bat\ out\ max} \cdot \vec{\eta}_{conv}(P_{bat\ out\ max}) - \vec{P}_{conv\ out}(s)\ for\ \vec{I}_{OCP\ triggered}(s) > 0 \end{cases} \tag{3.45.}$$

$$\vec{E}_{OCP\ curt} = \vec{P}_{OCP\ curt}(s) \cdot t_{step\ size} \tag{3.46.}$$

$$L_{OCP\ curt\ sell} = \sum_{i=1}^{s} \vec{E}_{OCP\ curt}(s) \cdot \overrightarrow{emsp}(s) \cdot 10^{-6}\ for\ \vec{I}_{OCP\ triggered}(s) < 0 \tag{3.47.}$$

$$L_{OCP\ curt\ buy} = \sum_{i=1}^{s} \vec{E}_{OCP\ curt}(s) \cdot \overrightarrow{embp}(s) \cdot 10^{-6}\ for\ \vec{I}_{OCP\ triggered}(s) > 0 \tag{3.48.}$$

Where:

$\vec{P}_{OCP\ curt}$	–	power curtailed due to overcurrent protection limitations vector [W],
$\vec{\eta}_{conv}$	–	converter efficiency curve vector [%],
$\vec{I}_{OCP\ triggered}$	–	overcurrent protection triggering indication vector [A],
$\vec{E}_{OCP\ curt}$	–	energy curtailed due to overcurrent protection limitations vector [Wh],
$L_{OCP\ curt\ sell}$	–	revenue lost due to the energy curtailment during selling transactions at the energy market [€],
$L_{OCP\ curt\ buy}$	–	revenue lost due to the energy curtailment during buying transactions at the energy market [€].

3.4. VPP models

As already described a VPP is an entity that aggregates small to medium sized energy sources, EES systems and/or demand response units. In this work the VPP is perceived as an aggregation of households with PV and EES systems, which separate model was described above. Now the VPP model consisting of the households will be introduced.
The evaluation of the VPP impact is divided into two subjects, namely evaluation of the economical impact of the VPP for the prosumers involved in the VPP and for the VPP owner. Further evaluation of physical impact exerted on the local distribution grid which is of the DSO concern will be done. The assessment focused on two mentioned subjects will be made using two models. The model used for the economical evaluation is kept only in Python environment and includes iteration of the single households simulations and mostly economical processing of the results. Another model used for the physical impact assessment in some manner will use the model used for the economical evaluation. Furthermore, it utilises some functionalities of the power system analysis software called PowerFactory (PF). The software is a very powerful tool, nevertheless it will be used only for load-flow calculations. The results of those will be retrieved to Python environment where they will be processed.

3.4.1. Economical impact evaluation

The concept of a VPP modelled in this work is relatively new, hence the economical performance of such an investment is unknown. Since the VPP will couple interests of several parties the correlations have to be determined. The model created in this work is capable of providing results which after an analysis will lead to the economical impact evaluation of the VPP.

3.4.1.1. Model and the simulation process

The VPP model used for the evaluation of the economical impact of the VPP is kept only in Python environment. Focusing only on the financial aspects of the VPP allows us to run the VPP simulation as a sequence of single household simulations. Provided that the CVPP trading signals are unified over each of the single household simulations it can be assumed that the responses of each VPP entities are simultaneous even though the simulation is conducted with a different progression.
Just like the single household simulation the VPP simulation can be also represented as a set of modules. The modules by interacting with each other create a model presented as a flowchart, which can be observed below (Figure 41).
The inputs of the VPP model are loaded during the VPP initialization sub-process and can be divided into two groups, namely arrays with changing parameters and unified parameters. The arrays with changing parameters represent specifications of the components of each household type, like:

- area of the PV panels,
- PV connection manner,
- EES connection manner,
- the nominal current of the overcurrent protection device,
- VPP extension.

In order to virtually extend the size of the VPP in the model an VPP extension vector was created. As already said other arrays not necessarily store specifications of each household but each household type. A number of each household type can be multiplied in the VPP and extend its size virtually. The VPP extension vector simply stores numbers of different household types contributing to the VPP final results. This measure allows simulation of a few household types and creating from them a VPP with great number of households.

Each of the arrays consists of parameters for multiple household types. The position in the vector represents the number of the household type. The PV and EES systems connection manner vectors store simply the number of phase of connection or indication that the system is three-phase connected. The overcurrent protection vector simply stores the nominal current of the protection device installed in households of certain type.

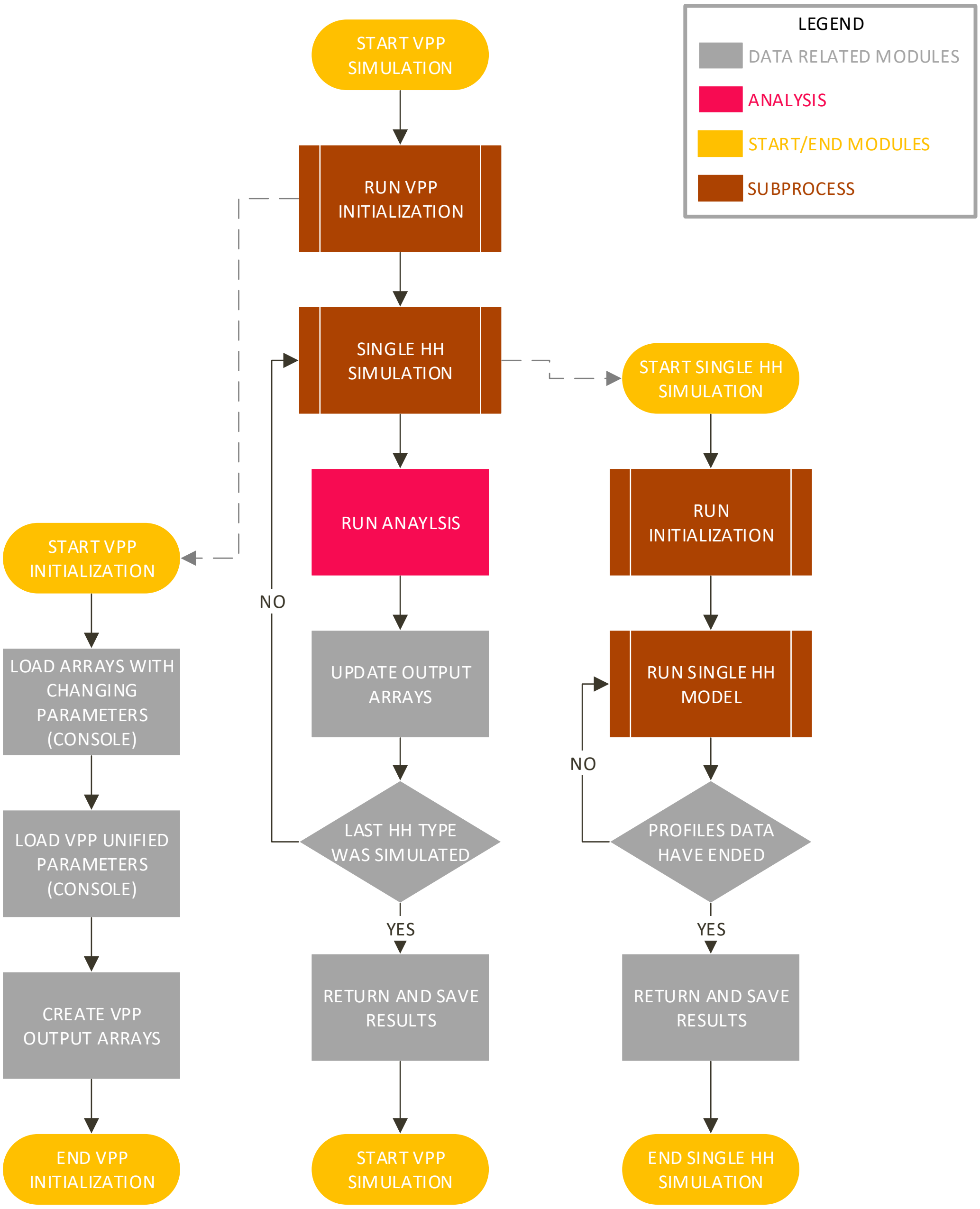


Figure 41 Economical impact VPP model structure

In order to model houses with different sizes of PV panels and do not use different PV system power output profiles a unified profile for all houses can be provided. The profile should represent the PV system power output per 1 m^2 of the PV panel. In this manner profiles of multiple PV systems in a neighbourhood can be reflected realistically enough. Providing different PV system power output profiles is also possible. If so the values of the panels size should be all equal one.

Another type of inputs provided to the VPP are unified for all components in the VPP. It was assumed that all parameters of the EES systems are unified over the VPP. It means that the EES would be all installed as they had the same parameters and they would be started simultaneously. The inputs are summarized in the table below (Table 6).

Profiles:		**Battery parameters:**	
Time index		Initial energy capacity	[Wh]
Energy market prices	[€/MWh]	Maximum power input	[W]
Converter parameters:		Maximum power output	[W]
Minimum power input	[W]	Initial SoE	[%]
Maximum power output	[W]	Maximum SoE	[%]
Loading limit	[W]	Minimum SoE	[%]
Efficiency limit	[%]	Self-discharge rate for first 24h	[%]
Stand-by losses	[W]	Self- discharge rate per month	[%]
Switch-off time	Steps no.	**Trading settings:**	
Behaviour settings:		Fixed selling price threshold value	[€/MWh]
Self-consumption switch		Fixed buying price threshold value	[€/MWh]
Trading switch		Minimum SoE reference	[%]
Trading strategy switch		Maximum SoE reference	[%]
		Upper selling price threshold limit	[€/MWh]
		Lower selling price threshold limit	[€/MWh]
		Upper buying price threshold limit	[€/MWh]
		Lower buying price threshold limit	[€/MWh]

Table 6 VPP unified inputs

Further in the initialization process of the VPP simulation arrays for outputs are created. Each iteration of the VPP simulation includes the single household simulation and provides the output of this simulation to the analysis module described above. Hence, most of the outputs of the VPP simulation will not store the outputs of the single household simulation but results of their analysis, which are crucial when evaluating the economical impact of the VPP. Each output has a form of a vector which size is equal to the number of modelled household types. The VPP simulation output vectors are shown in the table below (Table 7).

After creating the output arrays the initialization process of the VPP simulation is finished. The next sub-process ran in the core of the VPP simulation is single household simulation, which along with analysis and output array update modules are iterated through all household types. The single household simulation process was already described in depth above. However, there are slight differences in the initialization sub-process of the single household simulation sub-process used in the VPP simulation. As already said the parameters and profiles of each household type are different. The profiles are loaded in the initialization sub-process of the single household simulation used in the VPP model directly from the Excel Workbook in Python. In the single household simulation which is not a part of the VPP model they were loaded in the jupyter notebook console. The household parameters stored in the VPP changing parameters arrays described above are also loaded in the initialization sub-process. Further the single household simulation is conducted and the outputs of the simulation are provided to the analysis module. The analysis module description is provided above. In every iteration the outputs arrays are updated before the next one starts. After all the household types were simulated the outputs of the VPP simulation are returned and saved for sake of visualization and further processing. As this process is finished the VPP simulation comes to an end.

Battery condition:	
Equivalent number of cycles	
Average cycle depth	[%]
Degradation	[%]
Converter performance:	
Power, energy and revenue lost during operation	[W, Wh, €]
Power, energy and revenue lost during stand-by mode	[W, Wh, €]
Total power, energy and revenue and energy lost	[W, Wh, €]
Power, energy and revenues lost due to lost due to the energy curtailment transactions at the energy market	[W, Wh, €]
Power distribution:	
Energy and revenue from PV if there was no battery	[Wh, €]
Energy balance and energy bill of the household if there was no battery	[Wh, €]
Energy and avoided costs from battery self-consumption	[Wh, €]
Energy and avoided costs from PV self-consumption	[Wh, €]
Energy and revenue from PV	[Wh, €]
Total energy and revenue from selling energy to retailer	[Wh, €]
Total energy balance and energy bill of the household	[Wh, €]
Trading:	
Number of selling transactions	
Number of buying transactions	
Number of all transactions	
Number of selling transactions used	
Number of buying transactions used	
Energy sold and revenues from selling transactions at the energy market	[Wh, €]
Energy bought and revenues from buying transactions at the energy market	[Wh, €]
Total energy traded and revenues from transactions at the energy market	[Wh, €]
Economical impact:	
Fragmentary cash-flow	[€]

Table 7 VPP simulation output vectors

3.4.1.2. Approach

The economical impact of the VPP will be evaluated using basic cost-benefit analysis measures like Net Present Value (NPV), PayBack Period (PBP) and Internal Rate of Return (IRR) for a scenario.

The NPV is defined as “a difference between the present value of cash inflows and the present value of cash outflows” [35]. It is used for the evaluation of profitability of a project investment. In general the positive NPV indicates that revenues of a project are bigger than anticipated costs. It means that an investment with positive NPV will be cost-effective and with negative NPV will bring losses. The NPV is calculated as follows.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \qquad (3.49.)$$

Where:

NPV	–	Net Present Value,
t	–	number of time periods,
C_t	–	net cash inflow during the period t [€],
C_0	–	total initial investment costs [€],
r	–	discount rate [%].

The PBP is an indication of the time required to reclaim the costs of an investment. It is also an important measure for the evaluation if a project should be undertaken or not. The IRR measures the profitability of potential investment. It is defined as "a discount rate that makes the NPV of all cash flows from particular project equal zero" [35]. In general the investment will be profitable if the value of IRR is greater than the value of discount rate from the NPV calculation. The IRR is calculated from the equation below.

$$\sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 = 0$$

Where:

IRR – Internal Rate of Return [%].

Described above measures will be applied to the VPP cumulative cash-flow and the initial VPP investment costs. The initial costs will be combined costs of the EES systems in the VPP. The economical evaluation will be applied to a certain project presented in as a study case.

3.4.2. Physical impact evaluation

As said in the theoretical background the development of renewable penetration in the network will force it to be operated in bidirectional power flow conditions. This situation may force the DSOs to costly grid upgrades. The notion of a VPP described in this work includes trading on energy markets. The VPP operator will therefore try to maximize his revenues by making highest energy bids with best prices as often as possible. Therefore, already difficult situation with high penetration of PV systems may be enhanced by the VPP operation. This may mean for DSOs even more expensive upgrades required to provide security and reliability of the network. The power flow caused by the VPP operation in the local distribution grid on top of the PV systems power output may deeply influence the performance of the components operated at their power limits. In this work a model, which allows analysis of a part of distribution network subjected to operation of a VPP was created.

3.4.2.1. Model and the simulation process

As already said the model uses a power system analysis software called PowerFactory (PF), where Quasi-Dynamic Simulations are made. The Quasi-Dynamic Simulation (QDS) is a sequence of power flow simulations with dynamically changing parameters. The power-flow or load-flow calculations allow analysis of the power system condition during its steady-state operation. The QDS creates an impression of time changing conditions in the system. In this work parameters changing from power flow calculation to another will be values of an active power in the loads. The PF model of a single household consists of loads elements (*.ElmLod,) representing three systems, namely EES system (BAT_HH), PV system (GEN_HH) and household power demand (CONS_HH) (Figure 42). PV systems and EES systems do not only draw energy from the grid but also produce and they are still modelled as loads. The negative value of an active power in a load is simply perceived as ideal source of power. In the VPP economical impact model described above only calculations of active power were done, hence the reactive power in the systems modelled as a VPP will be equal to zero. The PF single household models have to be linked through a distribution network, which model can be arbitrarily created in the software.

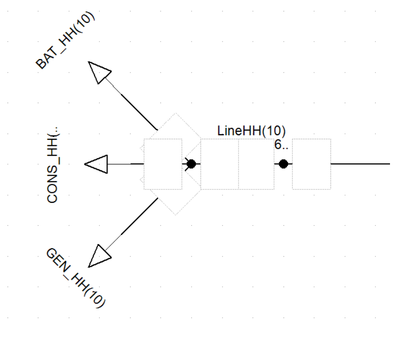


Figure 42 PF single household model structure

From the results of the VPP economical impact simulation described above power profiles of all EES systems in the VPP can be determined. Based on those profiles along with PV systems power output and power demand profiles QDSs will be conducted. At the figure below a structure of the physical impact VPP model is presented (Figure 43). The first step of the VPP impact simulation is creation of the file with all mentioned above profiles. This sub-process is based on the VPP simulation, nevertheless our interest this time is only to retrieve the power profiles not to analyse any of the results. The single household simulation is iterated to create power profiles for all possible combinations of EES behaviour schemes and EES connection manners for all household types included in the VPP. Along with the EES power profiles the demand and PV system output profiles are saved to the file.

Next sub-process triggered in the core of the VPP physical impact simulation is initialisation where at first the connection between PF and the Python console is established. When the connection is made desired PF project and grid layout can be activated. Afterwards the VPP physical impact simulation parameters are loaded. The summary of the parameters can be seen below (Table 8).

Profiles:	
Time index	
PV inverter power output for all household types	[W]
Power demand for all household types	[W]
EES system power for all connection manners and behaviour schemes for all household types	[W]
Assigning profiles to loads:	
Household number array	
VPP extension array	
PV system connection manner array	
EES system connection manner array	
EES behaviour scheme settings	
Quasi-Dynamic Simulation parameters:	
Start of the simulation	[YYYY-MM-DD hh:mm:ss]
End of the simulation	[YYYY-MM-DD hh:mm:ss]
Number of households disconnection steps	
Loading curves processing:	
Overloading limit	[%]

Table 8 VPP physical impact simulation inputs

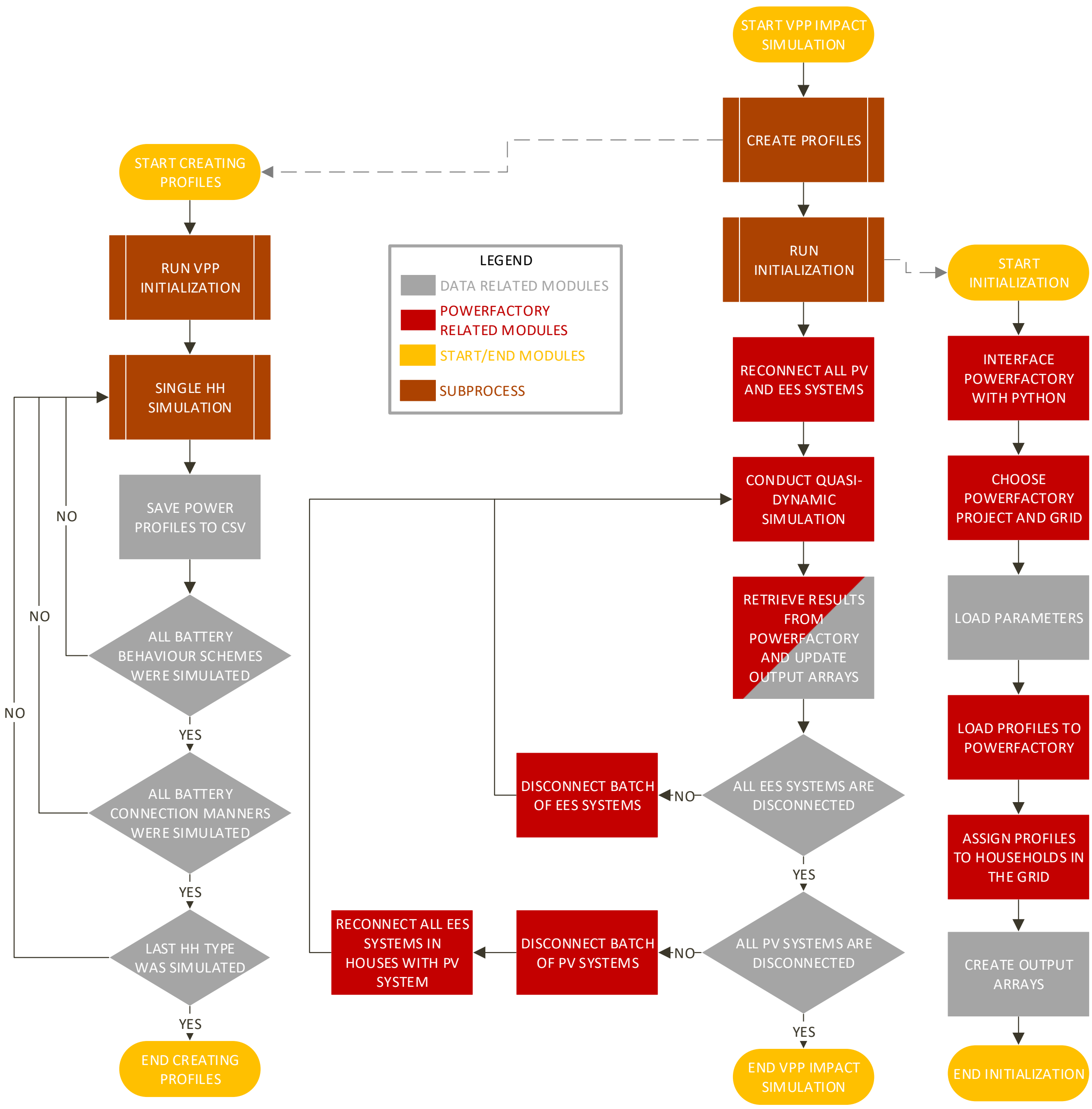


Figure 43 Physical VPP impact model

The next module in the initialization process loads all created previously profiles to PF. In this software it is done by creating characteristics objects (*.ChaTime), which take the active power profiles directly from the file. Further those objects are assigned to the loads representing systems of a household. One of the parameters loaded is household number array, which determines in what order the power profiles are matched with the household types. After assigning the profiles to respective load elements the output arrays are created and the initialization sub-process ends. The outputs retrieved from PF can be chosen arbitrarily. All voltage magnitudes, angles, currents, frequencies, powers or other parameters in every part of the grid can be retrieved saved and analysed. Nevertheless, in this work the main interest will be put on the power transformer loading, what will be described more closely in the next paragraph.

In the model QDSs are made with different penetration of PV systems and EES systems in the network. In PF this will mean that the load elements representing those systems will be disconnected (set out of service) as the penetration decreases. This disconnections will happen in batches of households. The batch size is determined by the number of households disconnection steps loaded as a parameter during the initialization. The first QDS is made with full penetration of PV systems and EES systems in the network. Hence, the reconnection of all load elements is ran as a first module after the initialization. Then the QDS is conducted and the desired result of the simulation is retrieved and saved to the output array. After full penetration a batch of EES systems is disconnected and the QDS is re-conducted. After all EES systems were disconnected and QDS with none EES systems in the grid was done a batch of PV systems is disconnected. After this process the penetration of EES systems in the grid is increased to the fullest. However, in the VPP model described in this work the EES system is fully dependant on the PV system. The battery is simply not allowed to charge from any other source than PV system. Because of that the penetration of EES systems in the grid will never be higher than the penetration of PV systems. After QDS conducted with zero penetration of both systems the VPP physical impact simulation has ended and the results stored in the output arrays can be presented and processed.

3.4.2.2. Approach

The physical impact exerted on the local distribution network by an operating VPP can be evaluated variously. As already said mass of different parameters can be observed as a result of QDS. The most common approach is observation of voltage changes in the grid. Two main limitations put on voltage levels in the distribution grid is its magnitude and unbalance. According to the an European standard EN 50160 – Voltage characteristics of electricity supplied by public electricity networks. Those are the limits that should not be exceeded:

- Undervoltage/Overvoltage:
  „Under normal operating conditions excluding the periods with interruptions, supply voltage variations should not exceed ± 10 % of the nominal voltage *U*n."
- Voltage difference between phases:
  „Under normal operating conditions, during each period of one week, 95 % of the 10 min mean r.m.s. values of the negative phase sequence component (fundamental) of the supply voltage shall be within the range 0 % to 2 % of the positive phase sequence component (fundamental)."

Usually the voltage problems indicate coming problems with transformer overloading. Even though it is preceded with voltage problems the complications with loading of the power transformer will be a focus in this work. One of the reasons behind this is that in order to evaluate the impact of the operating VPP on voltage in the network more global approach is needed. It is not exactly known at which terminals the biggest voltage violations will occur. We can expect the biggest violations to occur at the end of long lines, in most common conditions, nevertheless with bidirectional power flow the situation is not that simple anymore. Even though one of the functionalities of the VPP physical impact model, which was not described above is visualization of the voltage changes on the grid layout and presenting the results after each QDS, to properly process the results voltage profiles from all the terminals would have to be retrieved what is more complex. Furthermore, the VPP physical impact simulation is done in unbalanced conditions, thus the number of voltage profiles to be processed is multiplied by three phases. Because all of that the observation of much lower number of power transformer loading profiles was undertaken.
Depending on the power transformer type the overloading can be more or less acceptable. The cheaper versions of transformers – oil filled transformers much better tolerate short overloads, nevertheless they are more dangerous because of the oil. More expensive, but safer and recently more often used in highly populated urban areas, especially in developed countries dry-type transformers suffer more from overloads. According to IEEE standard C57.96-2013 - IEEE Guide for Loading Dry-Type Distribution and Power Transformers:

- „The permissible load on dry-type transformers may be increased above rated load for short times by the multipliers derived from the equations of Clause 5 and the computer program in Annex B.1, provided that:
  - The short-time peak load occurs not more than once in any 24-h period.
  - The short-time peak load follows and is followed by either a constant load or an equivalent constant load.
  - The limitations of 6.6 and the basic conditions of 6.1 are met."
- „Permissible loading is a function of the initial load, the peak load and their durations."

In order to evaluate the impact of operating VPP on the loading of a transformer the parameter that will be retrieved from PF after QDS and further processed is transformer loading profile. The processing of the profiles can be done directly after each QDS in the core of the simulation using an overloading module developed or the module can be applied to the output array after the full simulation. The overloading module takes two inputs. One of them is power transformer loading profiles and the second is overloading limit. The limit indicates operation above what power transformer loading percentage is perceived as an overloading. This value usually will be set to 100% nevertheless it can be set arbitrarily. The outputs of the overloading module are summarized below (Table 9). Based on them the evaluation of the operating VPP impact will be done.

Single overloading data:	
Start time stamp of each overloading	[YYYY-MM-DD hh:mm:ss]
End time stamp of each overloading	[YYYY-MM-DD hh:mm:ss]
Maximum transformer loading during each overloading	[%]
Minimum transformer loading during each overloading	[%]
Average transformer loading during each overloading	[%]
Global overloads data:	
Number of overloads during the simulated period	
Average number of overloads per day during the simulated period	
Average overloading depth during the simulated period	[%]
Average overloading length per day during the simulated period	[min]
Average transformer loading during the simulated period	[%]

Table 9 Overloading module outputs

The overloads array stores vectors with data of all detected overloads. Each overloading vector contains time index of an overloading start and end, its maximum, minimum and average value. Further the numbers of overloads in the whole simulation period and per day are calculated. The severity of the overloading is a very important factor, hence the average depth of overloads is calculated along with the average loading of the transformer. Another factor which indicates a severity of an overloading is its length, thus the average length of on overloading is determined.

The overloading module is applied to all power transformer loading curves resulted from QDSs. When the outputs of each overloading module simulation are gathered it is possible to determine how the overloads parameters change throughout the gradual development of the grid. The influence of the operating VPP on the power transformer loading is therefore evaluated. The aim of this evaluation is determination of thresholds in the penetration of PV and EES systems in the network after which the overloads start to occur or are more severe than allowed. It is also important to evaluate how severe is operation of VPP without any limitations at higher level of EES systems penetration in the network. Furthermore, it should be observed in what periods the DSO is subjected to power transformer overloads the most. On top of that the VPP behaviour schemes can have different influence on the local distribution grid. It can also happen that some of them may be even encouraged by the DSO, because of easing the power transformer loading at certain periods. Therefore, the focus will also be put on VPP behaviour schemes in the evaluation.

3.5. Optimisation modules

In order to reflect realistically operation the VPP the values taken as inputs for the aforementioned simulations should be chosen properly. As far as technical data that can be found in the data sheets is simply copied as inputs the parameters which decide on the behaviour and economical performance of the VPP are unknown. Because of that certain focus was put on optimization of the VPP behaviour parameters. Therefore, by choosing the optimal parameters it is believed that the behaviour of the VPP will be close to the behaviour triggered in reality by a VPP operator. Such an operator would most certainly be focused on its revenues, nevertheless as already said prosumers with their energy bills are also involved in the final economical calculations. Therefore, the values of parameters will be chosen to keep the cumulative cash-flow, which was described as a part of the analysis module above, as high as possible. Cumulative cash-flow is a combination of the household owners' energy bills and the revenue of the VPP owner. The value of energy bill is highly dependant on the retail energy prices and this fact will be taken account. Even though none of the parties involved in the VPP have influence on the retail prices it is valuable to know what approach should be taken as they are changed.

The VPP owner revenue is dependant on cost-effectiveness of the transactions made on the energy market. While the profitability of the transactions depend on the trading strategy. Two different trading strategies were developed in this work. The fixed prices thresholds trading strategy and SoE changing prices trading strategy. After some preliminary simulations the performance of the SoE changing prices trading strategy was not much better than the fixed prices thresholds trading strategy, nevertheless it more severely degraded the batteries. Therefore, the focus is put more on fixed prices thresholds strategy and choosing values of the thresholds to keep the cumulative cash-flow as high as possible.

Another factor to be studied do not influence the cumulative cash-flow directly nor the energy bills and the revenue from energy market. This factor is energy loss, which biggest part is due to power converter. In the model description it was already said that the power converter has a setting, which prevents operation of the converter at the operating points located at the lower part of the efficiency curve. The converter loading limit therefore prevents EES system of loosing excessively energy in the converter. Hence this parameter will be chosen to keep the cumulative cash-flow as high as possible.

3.5.1. Converter loading limit

The module developed to determine optimal value of the converter loading limit conducts a sequence of VPP simulations. Each VPP simulation runs through all household types included in the VPP, like the VPP extension vector would consist only ones. The VPP simulations are iterated through different values of the converter loading limit. After each simulation the fragmentary cash-flow of each household type is saved. The values of the fragmentary cash-flow can be afterwards plotted as a function of the converter loading limit. From the plots it is possible to choose the converter loading limit, which applied to the EES systems converter will maximize the cumulative cash-flow. The determination of an optimal setting can be done for different values of retailer prices or EES behaviour schemes.

3.5.2. Fixed prices thresholds values

The prices thresholds values are found similarly to the converter loading limit. The difference is that the revenues of the VPP owner using fixed thresholds trading strategy depend on two thresholds, essentially on the combination of the thresholds values. Furthermore, the size of energy bill is also influenced by the activity on the energy market, hence the combination of correlations is relatively complex. The module developed for determination of the optimal trading settings for the strategy conducts a sequence of VPP simulations. In this case the ratios of different household types are very important, hence the VPP extension vector is kept the same as during the economical evaluation VPP simulation. The VPP simulations are iterated with different combinations of fixed prices thresholds values. Because of two factors to be chosen the presentation of the results is extended by another dimension, compared to the converter loading limit optimization. The output of the optimization module is an array storing cumulative cash-flow for different settings of fixed prices trading thresholds. The results therefore are presented in form of area plots.

A single VPP simulation in not time-consuming, nevertheless to determine precisely the thresholds values a big number of VPP simulations have to be made. Especially when the number of household types is increased the determination of the thresholds can become sluggish. However, certain maneuver was used to decrease the optimization time. A number of optimization processes are performed with the same thresholds values combinations, nevertheless with increasing resolution. At first the optimization process is done in a wide range of prices' thresholds values. Next the output array storing the cumulative cash-flow is processed and the borders of an area with the highest cash-flow become inputs for the next optimization process. This can be repeated several times until desired resolution is achieved. This maneuver can be simply compared to zooming in a photograph and increasing the resolution of the zoomed area. An example was shown below (Figure 44). The optimization process should be applied for different values of retailers energy prices and EES behaviour schemes.

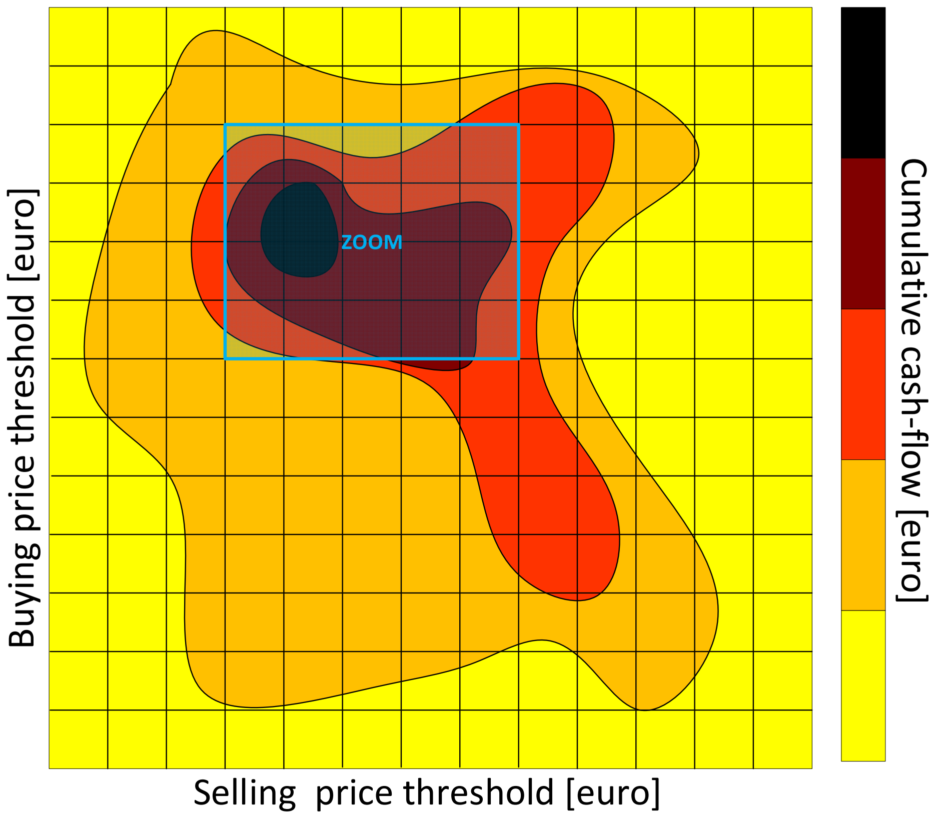


Figure 44 Fixed prices thresholds values optimization performance enhancing maneuver

4 Case Study

This work is done based on the VPP concept originating from the City-Zen project ongoing currently in one of the districts of the Dutch capital - Amsterdam. There are four partners involved in the deployment and evaluation of the VPP concept. Firstly, Alliander is one of the DSOs present in the Netherlands and operating the part of the network where the project is deployed. Another partner - Greenspread is an aggregator, which gathers power capacity and has an access to Dutch energy markets. Energy eXchange Enablers (EXE) also involved in the project is a software developer deploying programs enabling connection of the flexible power assets with energy markets. And finally DNV GL Energy, which is responsible for the theoretical impact analysis of the VPP concept. Current work was done in association with DNV GL Energy in form of a 9-month internship. Because of that, even though the functionalities of the model can be applied to any project of this or similar characteristics, the results will be presented based on the specific case of City-Zen project.
As a result of close collaboration with abovementioned project partners most of the inputs provided to the model are real and were acquired by either interviews with household owners, datasheets of the installed devices or from the single line diagram of the network provided by one of the partners. The realism of the project is of an enormous value and will allow in the future confrontation of the modelling results with the field data.
In this chapter the inputs used for the simulations, which results are presented in the next chapter, will be chosen. At first all information required to run economical impact simulation will be provided. The data about the VPP on the macroscale will contain number of households compositions of the VPP. Further the selection of an energy market will be made. On the microscale the data about the types of connection, households profiles and EES systems will be given. Further the inputs required to conduct physical impact simulation will be presented. Each PF household model needs three profiles, which will be assigned to its elements in a way described below. Also, the parameters of the QDS simulation will be chosen.

4.1. Economical impact simulation inputs

As already introduced in the model description following inputs are required to successfully conduct an economical VPP impact simulation:

1. Excel Workbook with profiles:
   - Power demand per phase
   - PV inverter power output per 1m^2 of PV panels
   - Energy market prices
2. Arrays with changing parameters:
   - area of the PV panels,
   - PV connection manner,
   - EES connection manner,
   - the nominal current of the overcurrent protection device,
   - VPP extension.
3. VPP unified parameters:
   - Behaviour settings
   - Converter parameters
   - Battery parameters
   - Trading settings

While gathering participants of the VPP in Amsterdam Nieuw-West data about the households were gathered. Four parameters were of high importance for current work, namely the indication of energy consumption, size of PV system, nominal current of the overcurrent protection device and type of the household connection to the grid. The data gathered is presented below (Table 10).

	Annual energy consumption [kWh]	PV system peak power output [W]	Nominal current of the overcurrent protection device [A]	Household connection manner [no. of phases]
Household 1	3000	2250	25	3
Household 2	3000	1500	25	3
Household 3	4000	4000	35	3
Household 4	3000	1760	35	3
Household 5	5000	5015	35	3
Household 6	3000	3600	35	3
Household 7	2000	1500	25	3
Household 8	1000	8640	25	3
Household 9	5000	9880	35	3
Household 10	5000	4125	25	3
Household 11	1000	2860	25	3
Household 12	3000	2650	25	3
Household 13	4000	2500	25	3
Household 14	3000	3000	25	1
Household 15	3000	2500	35	1
Household 16	5000	2400	35	3
Household 17	5000	2700	25	3
Household 18	5000	7020	35	3
Household 19	3000	4750	35	3
Household 20	3000	2500	25	3
Household 21	4000	2475	25	3
Household 22	5000	3780	35	3
Household 23	5000	2760	25	3
Household 24	3000	4320	25	3
Household 25	4000	1600	25	3
Household 26	3000	2200	35	3

Table 10 City-Zen participants households data

The data from above was used as an exemplar of the household mix to be reflected in the VPP model. The power demand and PV system size was divided into three groups. Furthermore, besides the composition of households taken from the data presented above two fictional compositions were prepared with the same number of households. First of them contains mostly households with low annual energy consumption and big PV system. While the second one contains mostly households with big annual energy consumption and small PV systems. Those compositions should present the extreme situations that may happen in a distribution network. The summary of the compositions was made below (Table 11).

Consumption\PV [no. of households]	Small (below 2000 Wp)	Medium (between 2000 and 5000 Wp)	Big (above 5000 Wp)	SUM	DATA
Realistic composition					
Small (below 1000 kWh)		1	1	2	
Medium (between 1000 and 4000 kWh)	4	12		12	
Big (above 4000 kWh)		5	3	8	
SUM	4	18	4	26	
Small power demand big PV power input					
Small (below 1000 kWh)			20	20	
Medium (between 1000 and 4000 kWh)		4		4	
Big (above 4000 kWh)	2			2	
SUM	2	4	20	26	
Big power demand small PV power input					
Small (below 1000 kWh)			2	2	
Medium (between 1000 and 4000 kWh)		4		4	
Big (above 4000 kWh)	20			20	
SUM	20	4	2	26	

Table 11 VPP composition proportions

As said in the model description the modelled VPP does not necessarily contain all unique household models. It is build from a number of household types combined in certain ratio given in the VPP extension array. Each VPP composition for purposes of the economical impact evaluation and further for physical impact evaluation presented in this study case will be created from ten unique household types. The types were chosen in a way that would maximize the diversity of the types not exactly reflect the ratios of the types seen above. The summary of different household types was presented below (Table 12).

Consumption\PV [no. of households]	Small (below 2000 Wp)	Medium (between 2000 and 5000 Wp)	Big (above 5000 Wp)	SUM	HOUSEHOLDS TYPES
Realistic composition					
Small (below 1000 kWh)		1	1	2	
Medium (between 1000 and 4000 kWh)	2	3		5	
Big (above 4000 kWh)		2	1	3	
SUM	2	6	2	10	
Small power demand big PV power input					
Small (below 1000 kWh)			7	7	
Medium (between 1000 and 4000 kWh)		2		2	
Big (above 4000 kWh)	1			1	
SUM	1	2	7	10	
Big power demand small PV power input					
Small (below 1000 kWh)			1	1	
Medium (between 1000 and 4000 kWh)		2		2	
Big (above 4000 kWh)	7			7	
SUM	7	2	1	10	

Table 12 Variety of household types used for the case study

4.1.1. PV system power output and power demand profiles

As already said profile of the PV systems power output is in some way unified for all households in the VPP. The profile given in the Excel Workbook, which is an input to the simulation is given for one square meter of a solar panel. Then the same profile is simply multiplied by the area of PV panels, which can be different for each household type. Those areas are stored in one of the changing parameters arrays. The PV system power output profile comes from Royal Netherlands Meteorological Institute (KNMI). The profile had sampling time of 10 minutes and it was processed by averaging some values to acquire 15-minute time step. The processing was required to match the step size of all the other profiles. Three different areas of PV panels were used in the simulation, which are in line with the division made above. The small sized PV system has 15 m^2 of PV panels, medium and big have 30 and 60 respectively. All profiles can be observed below (Figure 45).

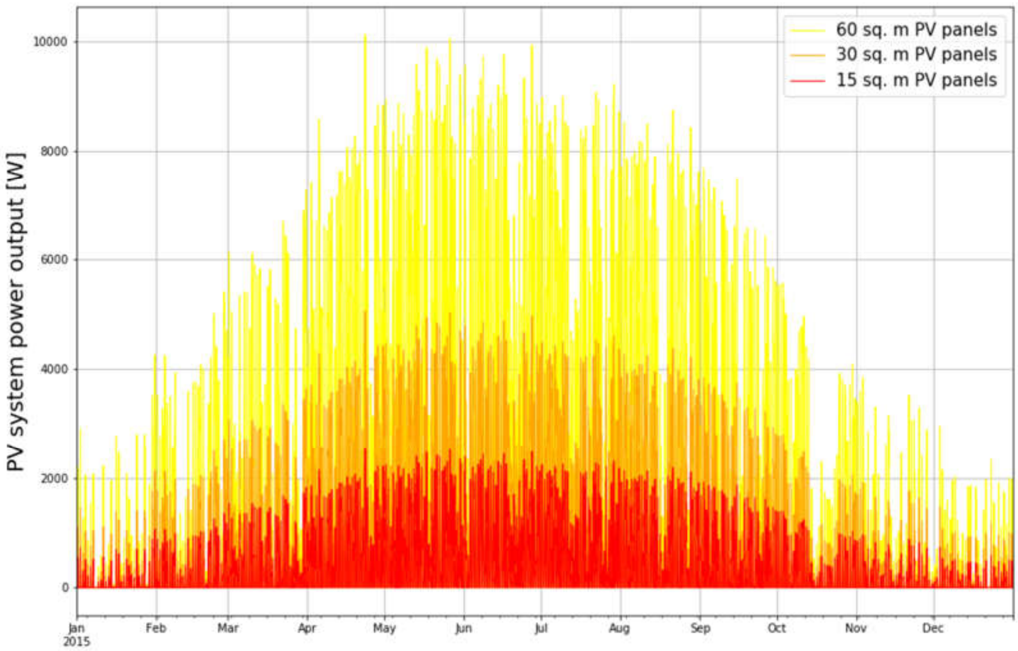


Figure 45 Power output of PV systems used in the simulation

As far as the PV inverter power output profile of each household type is different only by the PV panels size factor the power demand profiles need to be fully unique. It was possible to use real power demand profiles measured on site. DNV GL has at its disposal a set of such power demand profiles, however the profiles were given in a form of a three-phase power balance. To reflect realistically the situation and be able to observe the influence of different connection manners and influence of overcurrent protection devices limitations three different profiles of the power balance on each phase were required. The measured data could still be utilised and simply divided by three therefore creating constantly balanced loading in the household, nevertheless this situation is not realistic. During the design of the wiring of a household and division into sub-circuits in the switchgear cabinet a technician divides the loads evenly throughout the sub-circuits. It means that when all appliances in the household are operational at the same time the loading on three phases should be roughly equal. Because all appliances in a household are rarely on simultaneously unbalanced loading is usually present. The division is usually done by electricians based on physical structure of the household, namely using division into particular rooms of the house and lightning and electrical sockets' sub-circuits. Below an example of such division is presented (Figure 46).

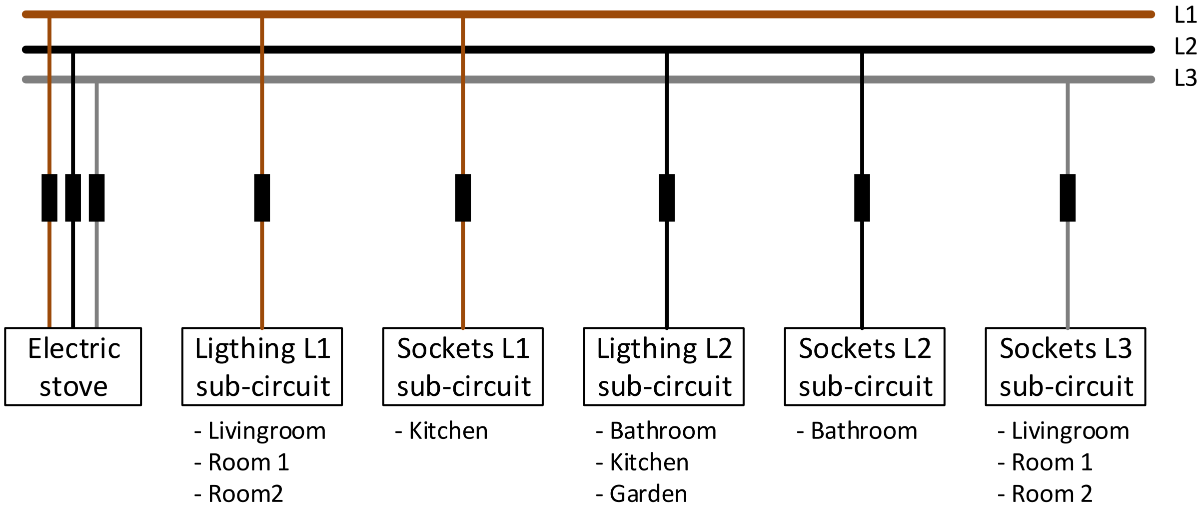


Figure 46 Division of household appliances into sub-circuits example

Because of the importance of reflecting the unbalanced power loading in the model a tool for power demand profile generation was utilized. LoadProfileGenerator (LPG) [36] is a tool which based on the customizable simulator of humans behaviour is capable of electricity, gas hot and cold water profiles generation. It means that LPG creates a virtual life with its own habits, desires and needs. All of this is transferred to the usage of electricity, gas and water. In the software a unique household profile can be created with customization of houses types, geographic locations, ambient temperature profiles, energy usage intensity and residents behaviour or age. The electrical profiles generated by LPG are provided separately for all appliances in the virtual household. LPG also provides information about the location of each appliance in the house. This feature allows discretionary division of the devices into sub-circuits. Exactly how it is done in reality, therefore creating real life power demand conditions. In the profiles provided to the model as an input all divisions were made in line with the example given above (Figure 46).

4.1.2. Changing parameters

As the unique one-phase power demand profiles for each household type were created we can extrapolate the VPP compositions given above to create the modelled VPPs. The number of households in the VPPs will be extended to 50. Below the exact composition of each VPP is presented (Table 13). If the VPP size is to be extended the it is also recommended to extend the number of the household types.

Further, all remaining changing parameters can be chosen. The data of the VPPs models based on which the economical impact evaluation will be done is presented below (Table 14). All household types can be distributed throughout the VPP. This distribution is simply creation of the VPP extension array which will multiply certain household types in the VPP. As can be seen in the households data of the City-Zen participants almost all houses have three-phase connection and this shall be reflected in the model input arrays. The PV connection manner depends simply on the peak power. All systems with peak power above 8 kW will be connected with three-phase inverter which is indicated as 4 below. All EES systems in the City-Zen project are single phase systems. Other parameters of the EES systems will be introduced in depth later. The number of the connection phase of the EES systems was chosen arbitrarily. The most of the overcurrent protection devices from the data had relatively small nominal current rating. The protection devices in the modelled VPP are changed to withstand bigger currents. The correlation with the power demand profile was made. Simply households with higher energy consumption and possibly higher peak power demand will use overcurrent protection devices with bigger nominal current.

Consumption\PV [no. of households]	Small (below 2000 Wp)	Medium (between 2000 and 5000 Wp)	Big (above 5000 Wp)	SUM
Realistic composition				
Small (below 1000 kWh)		2	2	4
Medium (between 1000 and 4000 kWh)	6	25		31
Big (above 4000 kWh)		10	5	15
SUM	6	37	7	**50**
Small power demand big PV power input				
Small (below 1000 kWh)			35	35
Medium (between 1000 and 4000 kWh)		10		10
Big (above 4000 kWh)	5			5
SUM	5	10	35	**50**
Big power demand small PV power input				
Small (below 1000 kWh)			5	5
Medium (between 1000 and 4000 kWh)		10		10
Big (above 4000 kWh)	35			35
SUM	35	10	5	**50**

VPP EXTENDED

Table 13 VPP compositions used in the economical impact evaluation

4.1.3. Energy market prices profiles

The last of the profiles that have to be chosen are the energy market process profiles. Two Dutch energy markets were considered as options for the economical impact evaluation, namely Amsterdam Power Exchange (APX) and TenneTs Energy Imbalance Market (EIM), which were already introduced in the theoretical background. As already said in the model description the prices of the energy market are known in every time step and are available for the CVPP for the trading signals generation. Even though the perfect prediction is not used in the model it was assumed that an energy market with bigger prices fluctuation will be more suitable for the simulation. In those circumstances it is simply expected that an energy market with more changing prices will generate bigger revenues for the VPP owner. Therefore, from the considered options EIM was assumed to be more suitable. EIM operates in the dual-price system, hence two prices profiles are provided as inputs to the model. The prices profiles were already presented as examples in the model description (Figure 20 and Figure 21). The profiles come from the official website of TenneT and are from year 2015.

HH type	PV system		Consumption [kWh]				Electric stove	Nominal current of the protection [A]	HH connection [no. of phases]	PV connection [phase no.]	EES connection [phase no.]	VPP extend [no. of HHs]
	Area [m sq.]	P max [W]	L1	L2	L3	SUM						
VPP with realistic composition												
1	30	5063	491	67	292	850	+	25	3	1	1	2
2	60	10126	625	48	286	959	+	25	3	4	2	2
3	15	2531	1393	100	482	1975	+	25	3	1	3	3
4	30	5063	1077	255	978	2310	+	35	3	1	2	8
5	30	5063	1204	207	1282	2693	+	35	3	1	2	9
6	15	2531	1437	373	989	2799	-	35	3	1	3	3
7	30	5063	3177	0	0	3177	+	35	1	1	1	8
8	30	5063	2010	1280	716	4006	+	35	3	1	3	5
9	30	5063	2372	575	1070	4017	+	35	3	1	2	5
10	60	10126	4895	1491	2985	9371	+	35	3	4	1	5
VPP with small power demand and big PV power output												
1	60	10126	294	85	391	770	+	25	3	4	1	5
2	60	10126	491	67	292	850	+	35	3	4	2	5
3	60	10126	288	368	250	906	+	25	3	4	2	5
4	60	10126	554	32	368	954	+	35	3	4	1	5
5	60	10126	625	48	286	959	-	25	3	4	2	5
6	60	10126	326	302	405	1033	+	35	3	4	3	5
7	60	10126	681	207	358	1246	-	35	3	4	1	5
8	30	5063	1204	207	1282	2693	+	35	3	3	1	5
9	30	5063	3177	0	0	3177	+	35	1	3	3	5
10	15	2531	4895	1491	2985	9371	+	35	3	3	1	5
VPP with big power demand and small PV power output												
1	60	10126	554	32	368	954	+	25	3	4	1	5
2	30	5063	1077	255	978	2310	+	25	3	1	2	5
3	30	5063	1437	373	989	2799	-	35	3	1	3	5
4	15	2531	2010	1280	716	4006	+	35	3	3	1	5
5	15	2531	2372	575	1070	4017	+	35	3	3	2	5
6	15	2531	0	0	4024	4024	+	35	1	3	3	5
7	15	2531	974	784	2401	4159	-	35	3	3	1	5
8	15	2531	0	4883	0	4883	+	35	1	2	2	5
9	15	2531	1909	1406	1882	5197	+	35	3	3	3	5
10	15	2531	4895	1491	2985	9371	+	35	3	3	1	5

Table 14 Economical impact evaluation VPP inputs

4.1.4. Unified VPP parameters

The EES systems installed in the participants households (Figure 47) is fully assembled from Victron Energy components. It is composed of two C-$LiFePO_4$ batteries and multifunctional power converter. The performance of the battery technology was described already in the theoretical background, nevertheless the precise data from the datasheets of the batteries could be used. The voltage of lithium-iron-phosphate cells is 3,2 V and the voltage of one battery is 12,8 V what means that 4 cells are connected in series. The recommended charge voltage of the batteries is equal to 14,5 V. The batteries are also connected in series what gives 25,6 V. The maximum charge and discharge current of the battery is 50 0A and recommended continuous values are 100 A and 200 A respectively. From the values of the voltage and current the battery power limitations were calculated. The nominal capacity of each battery is 200 Ah in temperature of 25 °C. The nominal energy capacity, is equal to 2560 Wh for each battery. It will be increased by 10 % in the VPP model and the battery cycling bandwidth will be decreased, because of the error usually given in the datasheets by the producers. The battery cycle life is 5000 cycles. The battery parameters taken as an input for the VPP simulation are gathered below (Table 15 - Table 18). [37]

The power rated DC voltage is equal 24 V and AC voltage 230 V. The maximum continuous power output at 25 °C is 6,5 kW. Further, the power required to start the conversion process regardless the power flow direction was assumed to be equal 55 W. The converter power consumption in the stand-by

Figure 47 City-Zen EES system

Battery parameters:	
Initial energy capacity	$E_{bat\ init} = 5632\ Wh$
Maximum power input	$P_{bat\ \max in} = 2900\ W$
Maximum power output	$P_{bat\ \max out} = 5120\ W$
Initial SoE	$SoE_{init} = 50\ \%$
Maximum SoE	$SoE_{max} = 90\ \%$
Minimum SoE	$SoE_{min} = 20\ \%$
Self-discharge rate for first 24h	$r_{sd\ 24h} = 5\ \%$
Self- discharge rate per month	$r_{sd\ month} = 5\ \%$

Table 15 Economical impact evaluation battery parameters

mode is equal to 30 W. In the EES system a switch was installed, which disconnects the converter after certain time if not used. The time was assumed to be equal 15 minutes, what means one time step. The maximum efficiency provided by the manufacturer in the datasheet is 94 %. [38] The loading at which the maximum efficiency occurs is determined by the curvature factor of the SNL model described above. The curvature factor used for the simulation was chosen to be equal -0,005. As already said in order to optimize the value of the average efficiency the converter is subjected to loading limit. The value of the loading limit is determined based on the converter loading limit optimization module described above. The results of the simulations are one of the results and will be given in the next section. However, all other economical impact simulation inputs regarding EES power converter are provided below (Table 16).

Converter parameters:	
Minimum power input	$P_{conv\,\min in} = 55\,W$
Maximum power output	$P_{conv\,\max out} = 6500\,W$
Loading limit	$to\ be\ determined$
Efficiency limit	$0\,\%$
Stand-by losses	$P_{conv\,sb\,loss} = 30\,W$
Switch-off time	$1\ step$

Table 16 Economical impact evaluation converter parameters

As already mentioned the economical VPP impact simulations will be conducted for all EES behaviour schemes, therefore the behaviour parameters will change from simulation to simulation. The summary of the parameters is presented below (Table 17).

Behaviour settings:	
Self-consumption switch	$changing\ with\ different\ scenarios$
Trading switch	$changing\ with\ different\ scenarios$
Trading strategy switch	$changing\ with\ different\ scenarios$

Table 17 Economical impact evaluation behaviour settings

The last set of the parameters are required to generate trading signals. Those parameters, just like converter loading limit, are subjects of an optimization. They will be determined for all EES behaviour schemes and retailer approaches. The module described already above will be used and the results of the simulations will be presented in the next chapter. As already said the fixed prices thresholds trading strategy will be utilized, hence the settings required for the SoE changing prices thresholds trading strategy are not needed. The summary of the parameters is presented below (Table 18).

Trading settings:	
Fixed selling price threshold value	$to\ be\ determined$
Fixed buying price threshold value	$to\ be\ determined$
Minimum SoE reference	$irrelevant\ for\ chosen\ strategy$
Maximum SoE reference	$irrelevant\ for\ chosen\ strategy$
Upper selling price threshold limit	$irrelevant\ for\ chosen\ strategy$
Lower selling price threshold limit	$irrelevant\ for\ chosen\ strategy$
Upper buying price threshold limit	$irrelevant\ for\ chosen\ strategy$
Lower buying price threshold limit	$irrelevant\ for\ chosen\ strategy$

Table 18 Economical impact evaluation trading parameters

4.3. Physical impact simulation inputs

In order to successfully conduct the physical impact simulation following inputs are required:

1. Grid layout in PF
2. Excel Workbook with profiles:
    - Time index
    - PV inverter power output per $1m^2$ of PV panels
    - Power demand for all the household types
    - EES system power response for all connection manners and behaviour schemes for all household types
3. Assigning profiles to PF household models:
    - Household number array
    - VPP extension array
    - PV system connection manner array
    - EES system connection manner array
    - EES behaviour settings
4. QDS parameters:
    - Start of the simulation
    - End of the simulation
    - Number of households disconnection steps
5. Loading curves processing:
    - Overloading limit

Further information about the inputs used for the physical impact simulation are confidential because of the agreements binding City-Zen project partners shall not be shared publicly.

5 Results

This chapter is devoted to the results of the VPP impact evaluation. The results some of the other chapters were divided into two sections. The first section will introduce the results of the economical impact evaluation in which it was determined in what of the considered scenarios the business case for the modelled VPP exists. After the economical evaluation the results of the physical impact evaluation will be presented. The results allowed determination if the levels of batteries degradation with different ways of its usage will be problematic for the VPP owner. Furthermore, the impact that was exerted by VPPs in different scenarios on the part of distribution grid where it was located was determined and its evaluation showed at what PV systems and EES systems penetration in the network the DSO may expect transformer overloads.

5.1. Economical impact evaluation

In this section the results of the economical impact evaluation will be presented. At first the results of determining the parameters required for conducting the VPP simulations will be shown. The converter loading limits will be assigned for different scenarios as first. Then the fixed prices thresholds values required to model realistic involvement of the VPP on the EIM will be assigned for different scenarios. After determining the parameters the results of the VPP simulations could be presented. In order to understand fully how those results are created the results of the single household simulation are provided at the beginning and followed by the results for different VPPs. After demonstrating the results the economical analysis can be performed aiming in evaluation of cost-effectiveness of investments in different VPPs.

5.1.1. Converter loading limit

The limits will be chosen for all EES behaviour schemes and two retailer prices sets. One of the setups represents to some extent the circumstances currently present in the Netherlands, namely the price of the energy taken from the distribution grid is the same as the price of the sold energy. Therefore, both selling and buying prices are equal 0,2 €/kWh. The second setup represents the subjected future retailer prices values. The prices values are not the same anymore. The buying price remained at 0,2 €/kWh and the selling price is decreased to 0,05 €/kWh. Firstly, the results for the power demand driven behaviour scheme will be presented (Figure 50).

It can be deduced that prices given by the retailer decide whether the dedication of the EES system to self-consumption is payable or not. When the energy selling and buying price are equal the energy bill for the consumer is minimized when the battery is not used at all. Storing the energy simply does not make sense from the economical point of view. The excess of energy from PV panels can be instantly sold to the retailer, avoiding costs from the future consumption. Usage of the battery simply wastes the energy on the EES system losses and sells stored energy later for the same price. Therefore, there is no business case for the ESSs working in self-consumption mode at the moment. However, the power demand driven behaviour scheme in current retailer pricing circumstances will be still a subject of the economical evaluation. It was chosen that in this scenario the converter will not be subjected to any limitations, even though it is noneconomic.

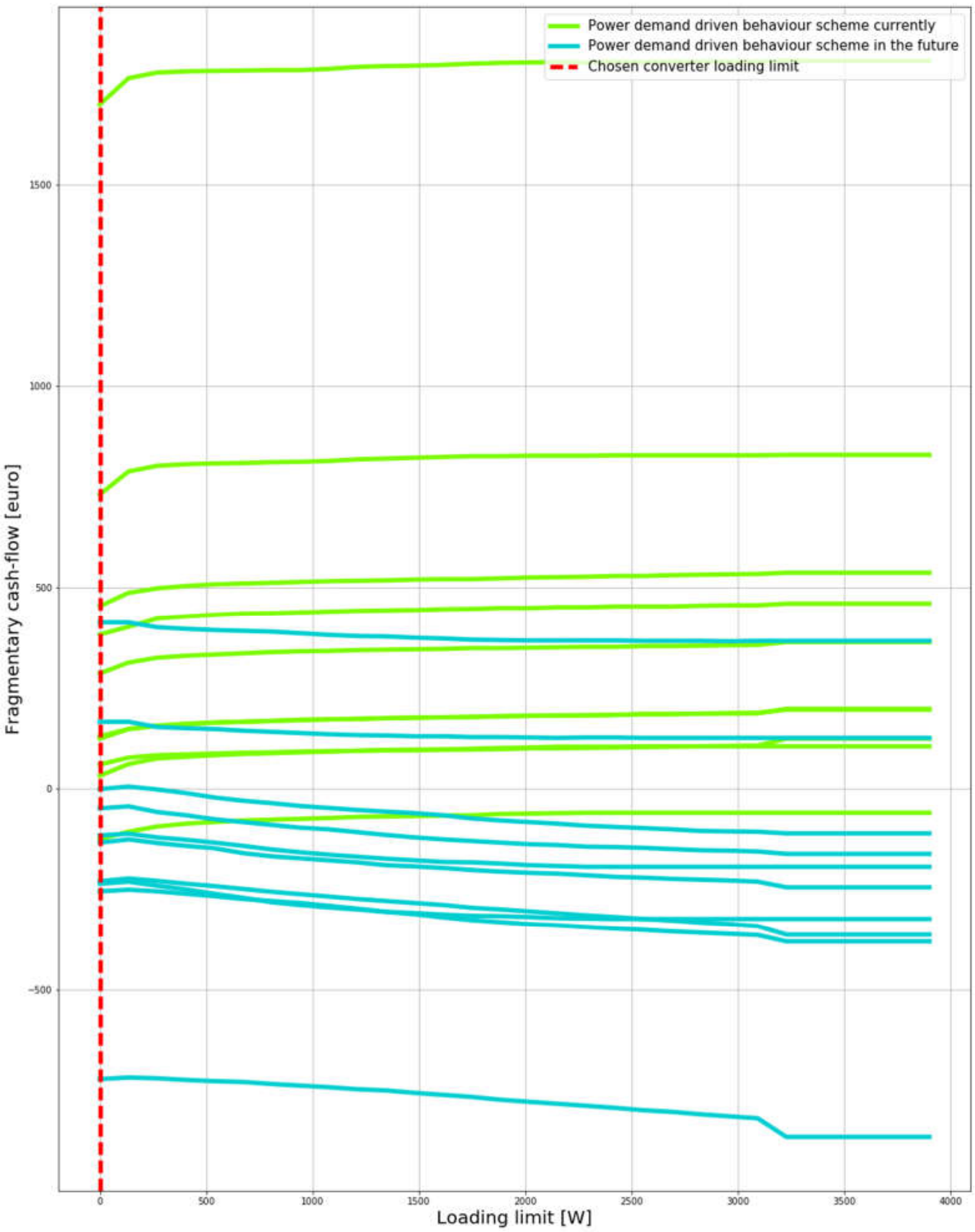


Figure 50 Determination of converter loading limit for power demand driven behaviour scheme in different retail market situations

The flat end of every curves is related to the power limitations of the battery. The battery maximum charging power is limited, hence if the loading limit of the converter is set to a value, which after conversion gives a value above maximum charging power of the battery it will never charge. In this situation the battery will discharge from its initial SoE to the lowest allowable SoE and continue to self-discharge. The value of fragmentary cash-flow achieved after the drop is almost equal to energy bill of a household operating without a battery. Transition to subjected future prices is much more optimistic for the enthusiasts of home energy storage systems. The price of the energy generated by the household is subjected to be much lower than the price of the energy drawn from the grid. Therefore, selling the overproduction of the energy instantly is less cost-efficient than storing it and avoiding costs by supplying the demand when the power balance becomes negative. The simulation conducted with resolution of 30 steps showed that the energy bill for the consumer will be minimized with the converter loading limit set very low. In this case it was decided not to put any limitations on the converter.

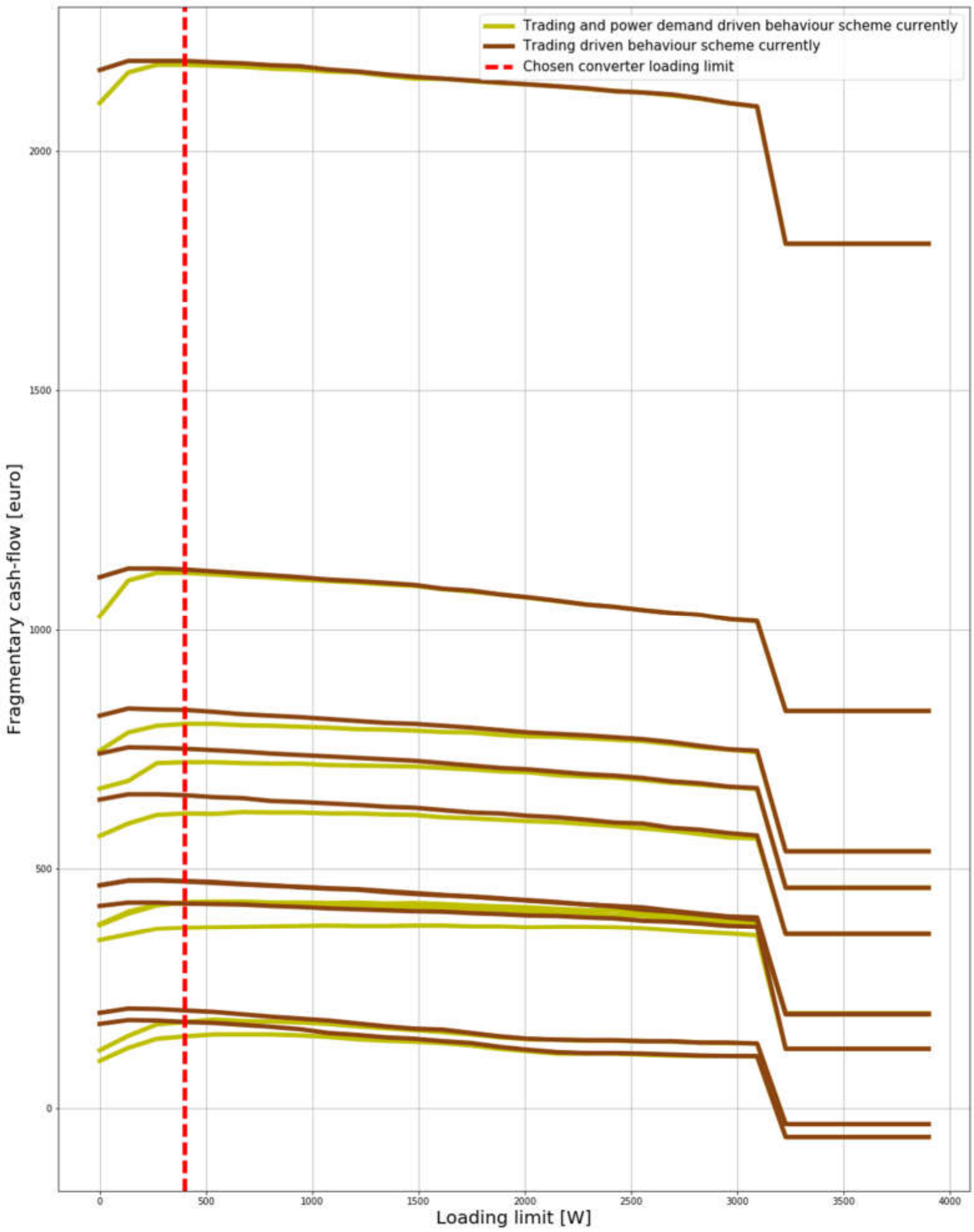


Figure 51 Determination of converter loading limit for behaviour schemes involving trading in current retail market situation

In the case of two other battery dedication schemes (Figure 51 and Figure 52) less extreme loading limit setting gives high values of fragmentary cash-flow for different household types. The difference in the optimal setting for particular household types is relatively small hence unified value of the limit for entire VPP is expected to give high cumulative cash-flow. Furthermore, because of that the same values of the converter loading limits are chosen for the other VPP household compositions. After the conclusions driven from results of the power demand driven behaviour scheme simulations it could be expected that the projected future retailer prices will force the optimal setting to decrease. Even the trading driven behaviour schemes, because of inseparability of the EIM market from the retail market in this VPP concept, are subjected to big influence of the retailer pricing. Values of the converter loading limit used in the economical VPP impact simulations are gathered below (Table 20).

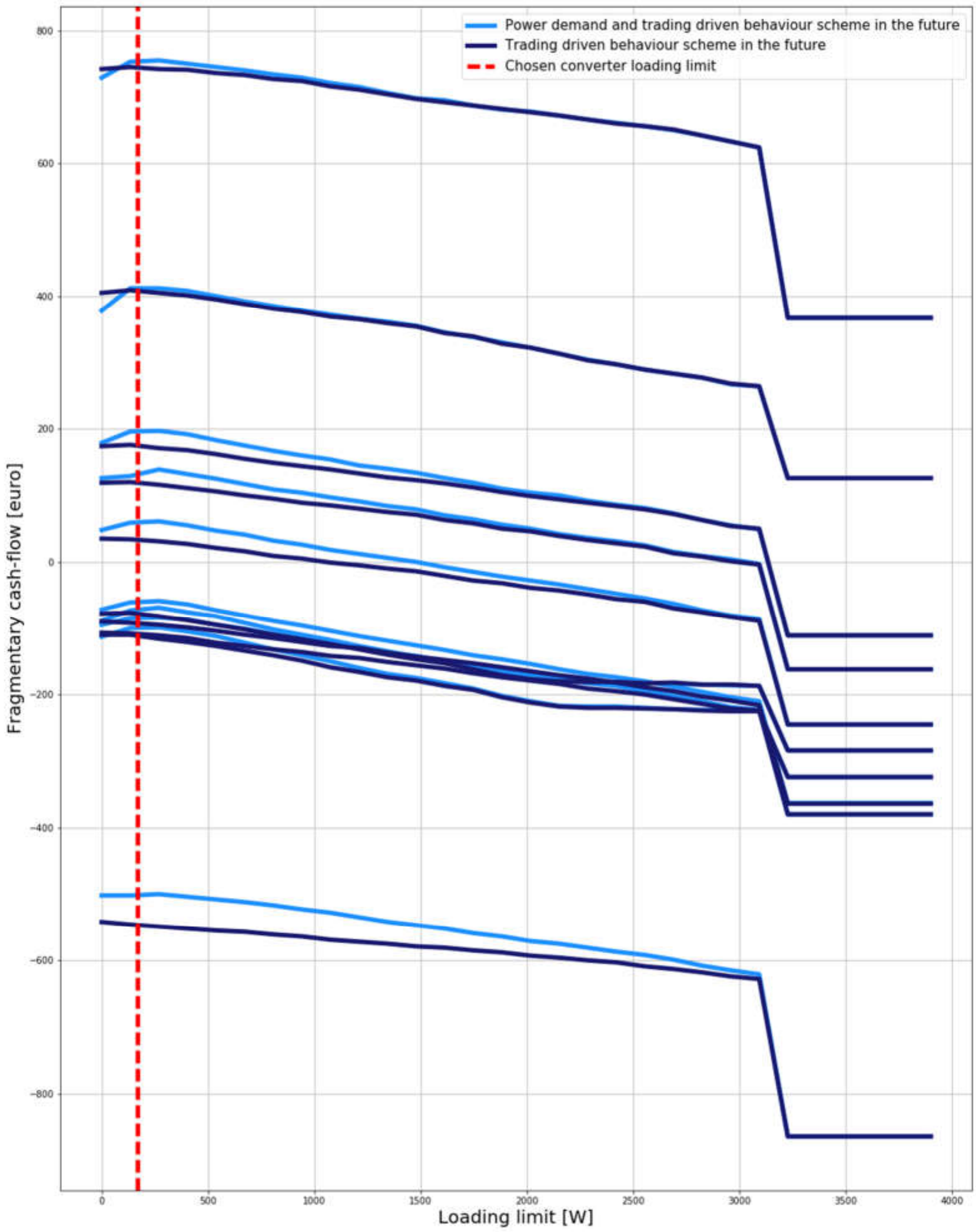


Figure 52 Determination of converter loading limit for behaviour schemes involving trading in future retail market situation

	$rsp = 0{,}20\ €/kWh$ $rbp = 0{,}20\ €/kWh$	$rsp = 0{,}05\ €/kWh$ $rbp = 0{,}20\ €/kWh$
Power demand driven behaviour scheme	Logical setting: $\boldsymbol{Battery\ not\ used}\ (P_{conv\,\max\,out})$ Actual setting: $\boldsymbol{No\ limit}\ (\mathbf{0}\ \boldsymbol{W})$	$\boldsymbol{No\ limit}$ $(\mathbf{0}\ \boldsymbol{W})$
Trading driven behaviour scheme	4 00W	1 7 0W
Power demand and trading driven behaviour scheme	4 00W	1 7 0W

Table 20 Economical impact evaluation converter loading limit settings

5.1.2. Fixed prices thresholds values

As already said the module used for the determination of the thresholds values works in steps. Firstly, a wide range of prices is chosen and after the first step an area of interest is "zoomed" to achieve higher resolution. In this case the process is performed two times after the first simulation. Each simulation consists of 100 VPP simulations with 100 different combinations of fixed prices thresholds values. At first simulation the buying prices thresholds values are changed in ten steps from -200 to 0 €/MWh and selling prices thresholds from 50 to 500 €/MWh. Below the results of the determination of thresholds for the realistic VPP composition operated with power demand and trading driven EES behaviour scheme and current retailer prices ($rsp = 0{,}20\ €/kWh$ and $rbp = 0{,}20\ €/kWh$) are presented.

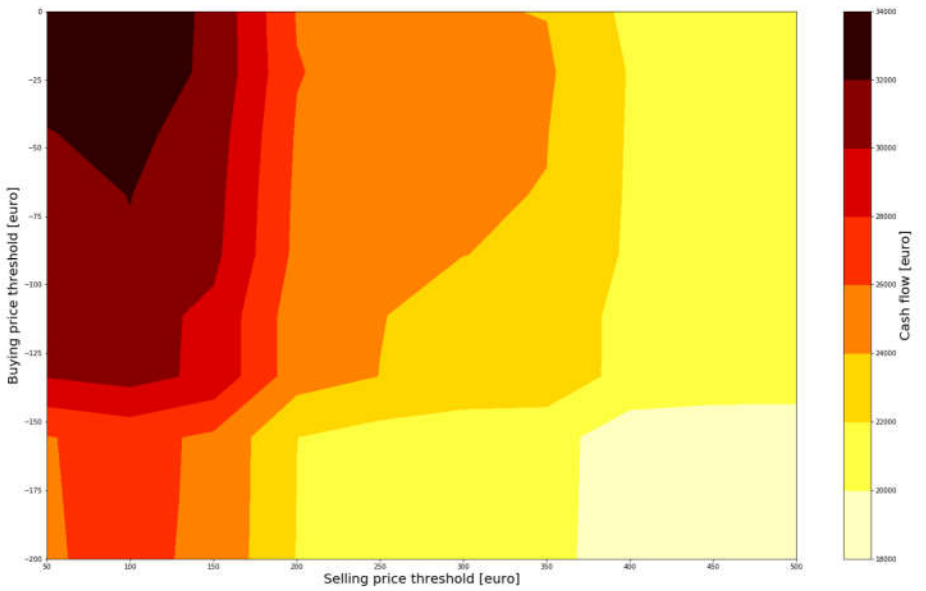


Figure 53 First step of the simulation determining fixed prices thresholds values for the realistic VPP composition operated with power demand and trading driven EES behaviour scheme and current retailer prices

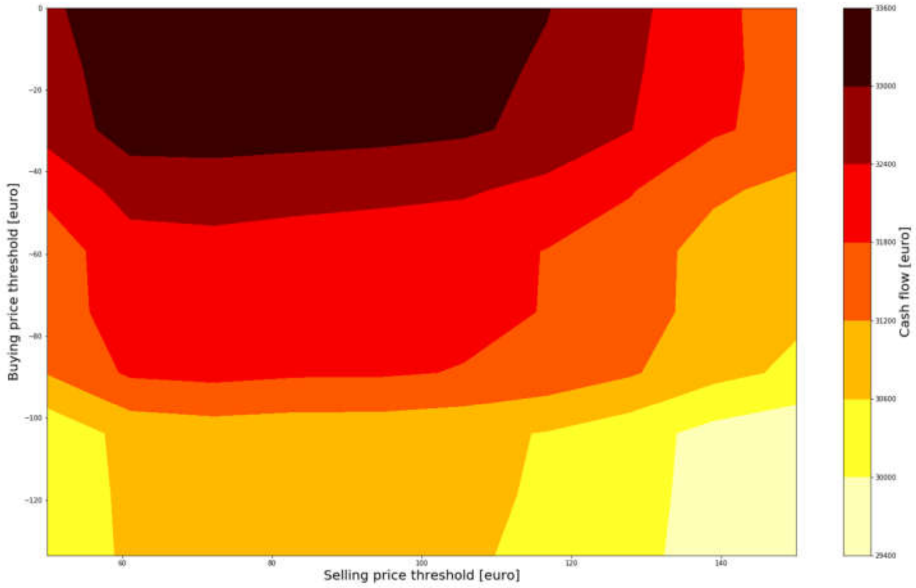


Figure 54 Second step (zoom 1) of the simulation determining fixed prices thresholds values for the realistic VPP composition operated with power demand and trading driven EES behaviour scheme and current retailer prices

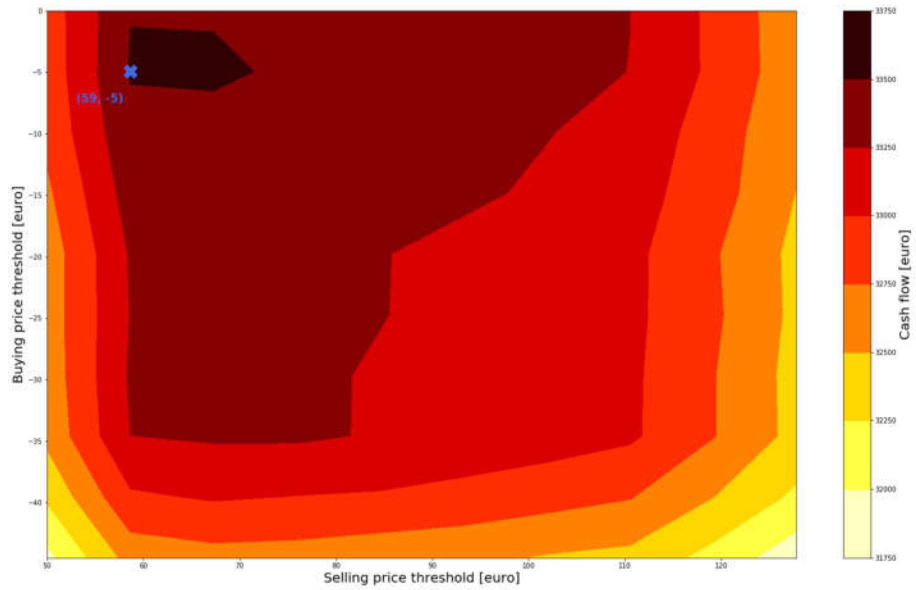


Figure 55 Third and final step (zoom 2) of the simulation determining fixed prices thresholds values for the realistic VPP composition operated with power demand and trading driven EES behaviour scheme and current retailer prices

From the results of the simulation last step (Figure 55) fixed prices thresholds values with which the highest cumulative cash-flow was generated are chosen as optimal combination. At the last area plot the combination is highlighted with the values of the thresholds. Similar simulations are made for other scenarios. The values of the thresholds for the remaining scenarios are summarized below (Table 21).

		VPP with realistic composition		VPP with small power demand and big PV output		VPP with big power demand and small PV output	
		Fixed selling price thresholds value [€/MWh]	Fixed buying price thresholds value [€/MWh]	Fixed selling price thresholds value [€/MWh]	Fixed buying price thresholds value [€/MWh]	Fixed selling price thresholds value [€/MWh]	Fixed buying price thresholds value [€/MWh]
$rsp = 0{,}20\ €/kWh$ $rbp = 0{,}20\ €/kWh$	Trading driven EES behaviour scheme	**+98**	**0**	**+69**	**0**	**+104**	**-5**
	Power demand and trading driven EES behaviour scheme	**+59**	**-5**	**+65**	**0**	**+67**	**-5**
$rsp = 0{,}05\ €/kWh$ $rbp = 0{,}20\ €/kWh$	Trading driven EES behaviour scheme	**+81**	**-74**	**+76**	**-84**	**+120**	**-74**
	Power demand and trading driven EES behaviour scheme	**+110**	**-74**	**+76**	**-72**	**+113**	**-48**

Table 21 Fixed prices thresholds determination results

5.1.3. Single household economical impact evaluation

After determining the optimal settings of the VPP the economical performance of each VPP household composition in different scenarios can be evaluated. As already said the evaluation will be based on the cumulative cash-flow, which is a sum of fragmentary cash-flows of each household. Therefore, at first the results of a single household simulation for one household of the VPP operated with optimal conditions described above will be presented. As an example household type number five from the realistic composition was chosen. The operation of the system in different EES behaviour scheme will be presented on a three-day span during summer and winter.

The first EES behaviour scheme presented is power demand driven. It can be seen that during summer (Figure 56) after the battery is charged during the day almost all power demand at night can be covered from the EES system. Furthermore, during the day almost all consumption is covered from PV and massive amount of PV overproduction is given back to the grid and sold to the retailer. During winter (Figure 57) the situation is worse the time window when the PV system power output is present is much shorter, hence less consumption is covered from PV and the overproduction almost does not exist. Even though the battery is once charged to its limit it is discharged during the afternoon demand peak. In this EES behaviour scheme no trading actions are taken, what can be seen in the results summary (Table 22). The battery is only dedicated to self-consumption, hence the avoided costs from EES in those scenarios are the highest. As already said the cost-effectiveness of this scheme with equal selling and buying retailer prices is none what is reflected in the results summary. It can be observed that installation of the battery and running it in this scheme will create losses of around 80 euro per year. However, with projected future retailer prices self-consumption becomes cost effective and creates profit of around 100 euro per year. It can be seen that the value of the energy lost in the converter in this scheme is the highest. The reason behind this is converter loading limit set to zero and allowing operation at low efficiency. It can be also observed that the switching of the converter in this scheme was much lower compared to other schemes. It can be inferred from the value of the energy lost in the stand-by mode.

The behaviour of the system operated in trading driven behaviour mode was shown next (Figure 58 and Figure 59). The vertical axis on the right shows EIM prices levels and on the diagram the prices values can be followed. The blue colour is related with selling and red with buying. Two horizontal lines in mentioned colours represent the fixed prices thresholds values chosen for different scenarios using methodology described above. All signals generated by the CVPP are presented as dots. If the VPP was able to establish position on the EIM then on the diagram it is indicated with a cross, with which an area representing amount of traded energy is associated. The selling transactions are shown with positive values of power and buying transactions with negative values of power, reversely to other areas representing energy, however matching the EIM prices convention. During summer much more long trading positions are established due to the fact that the SoE of the battery is more likely to be high. Reverse situation can be observed during winter, when more short positions are established. In the results summary (Table 22) it can be observed that the revenues from buying energy on EIM are much lower than the revenues from selling. There is number of reasons behind it. Firstly, the characteristics of the any energy market is that negative prices with which the CVPP generates buying signals are simply rare. Secondly, the characteristics of the household is that during selling transactions the EES system output is stacked and sold with output of the PV system. The output of the PV system is often much bigger than the consumption, which stacked with EES input do not generate that much revenue. Finally, the battery power capabilities favour profitability of selling transactions simply because of higher maximum discharge than

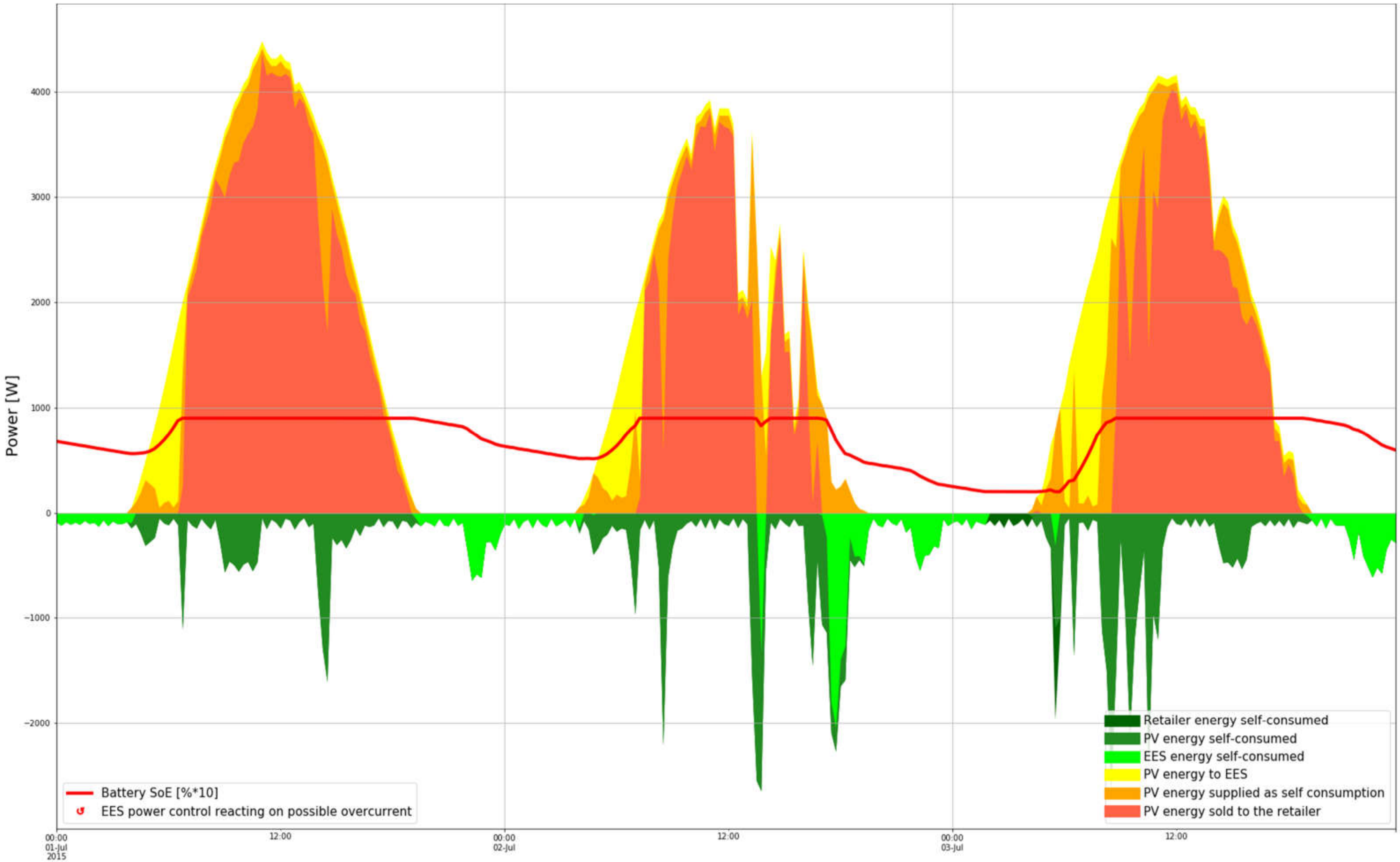


Figure 56 Household system behaviour with power demand driven EES behaviour scheme during summer

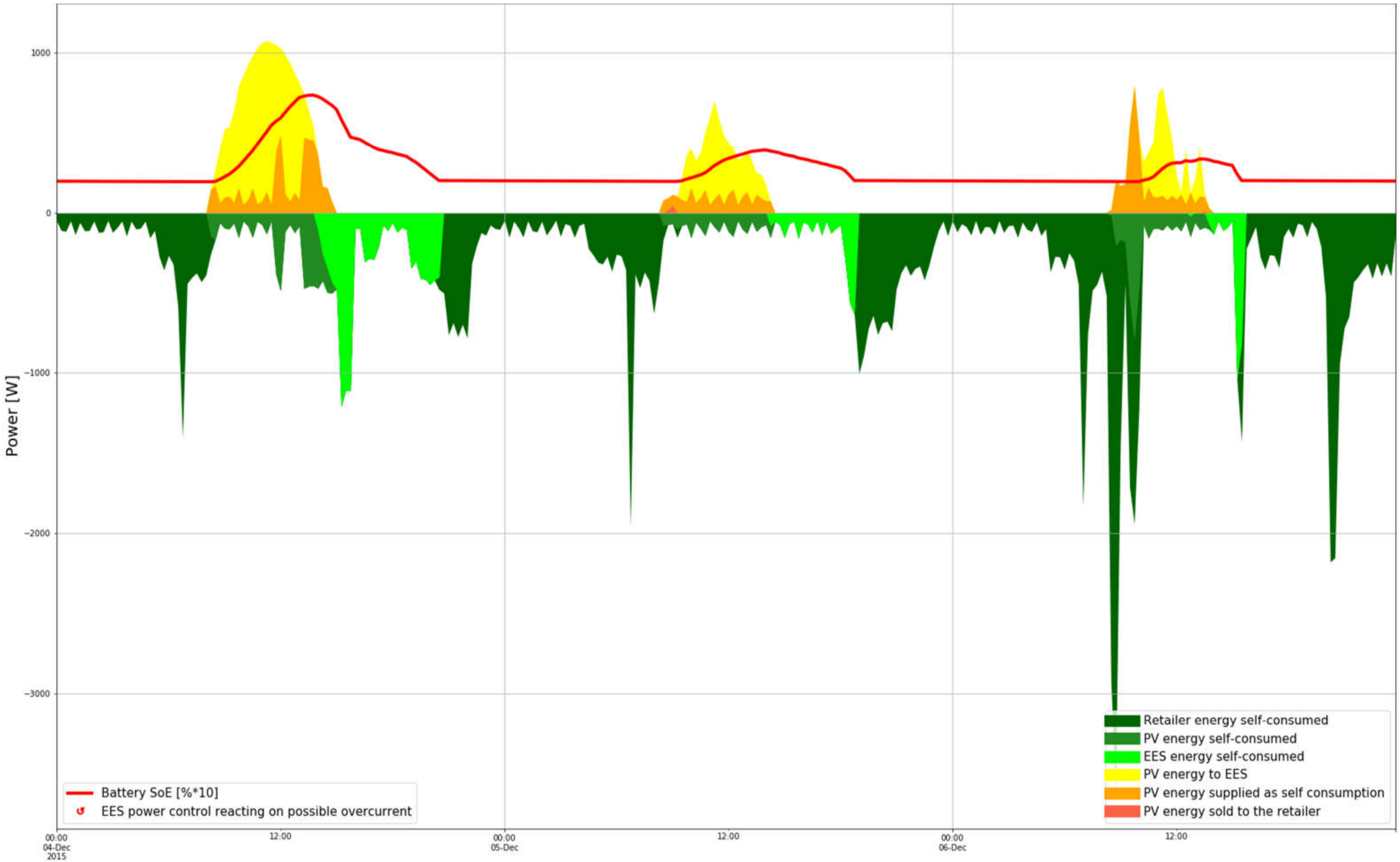


Figure 57 Household system behaviour with power demand driven EES behaviour scheme during winter

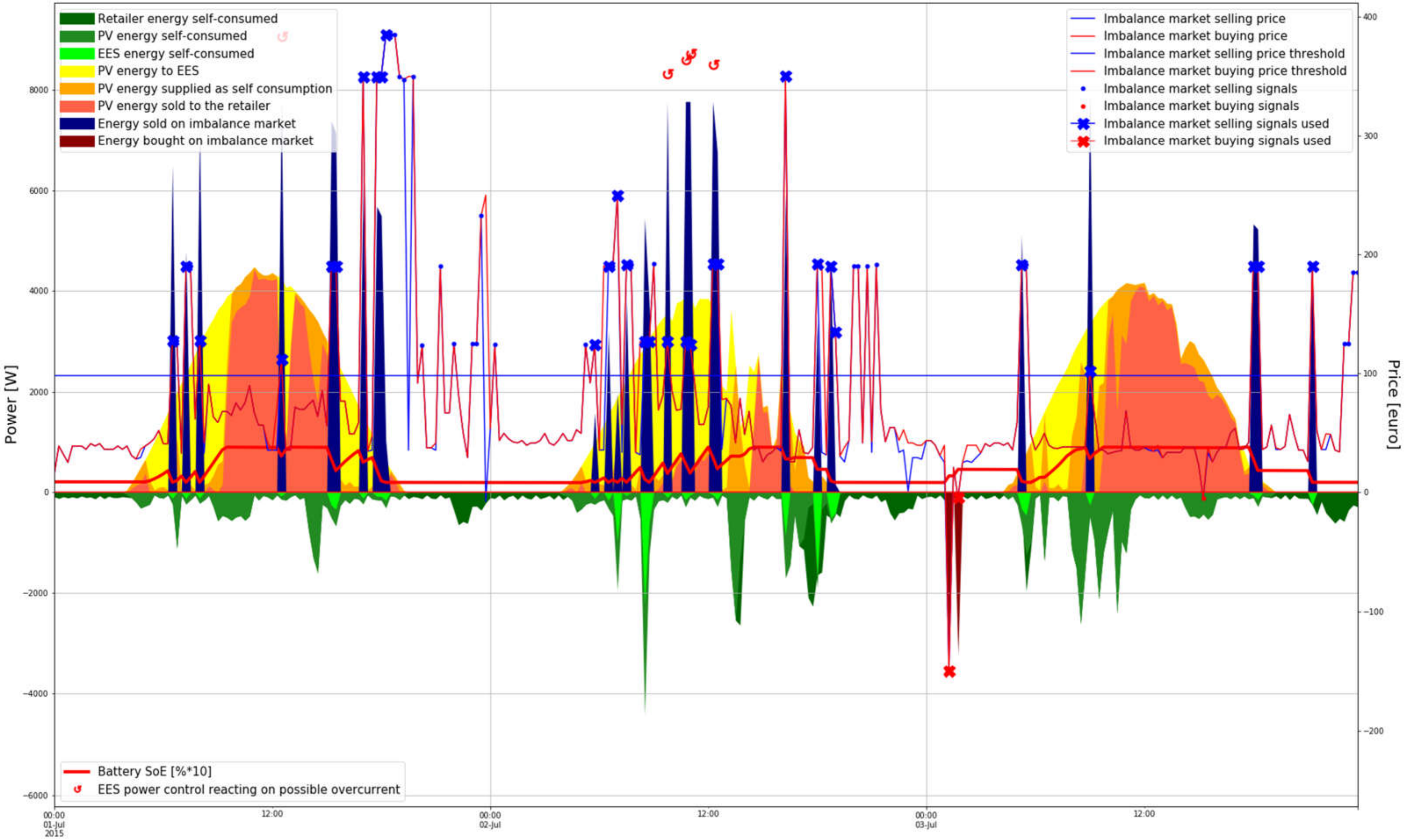


Figure 58 Household system behaviour with trading driven EES behaviour scheme during summer

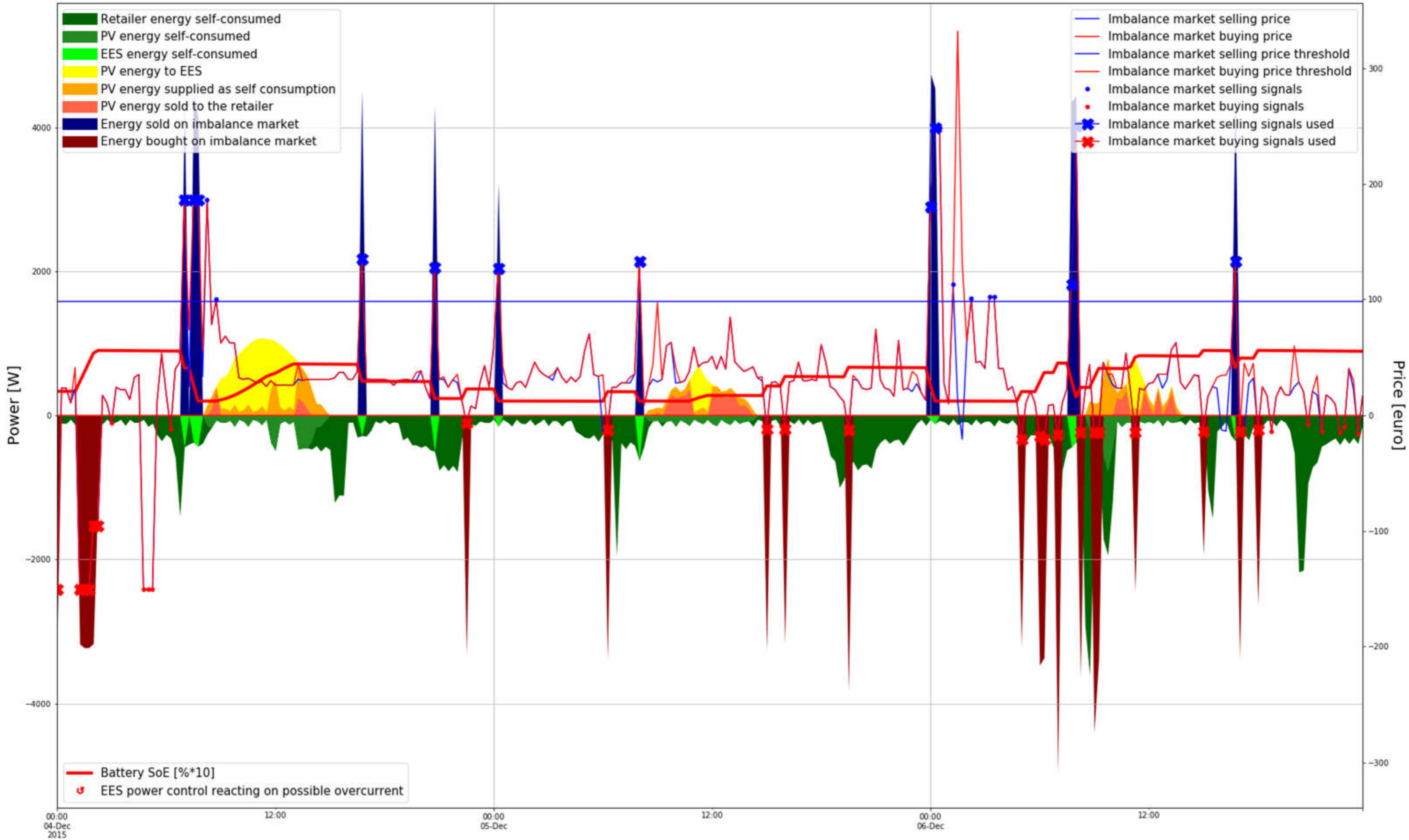


Figure 59 Household system behaviour with trading driven EES behaviour scheme during winter

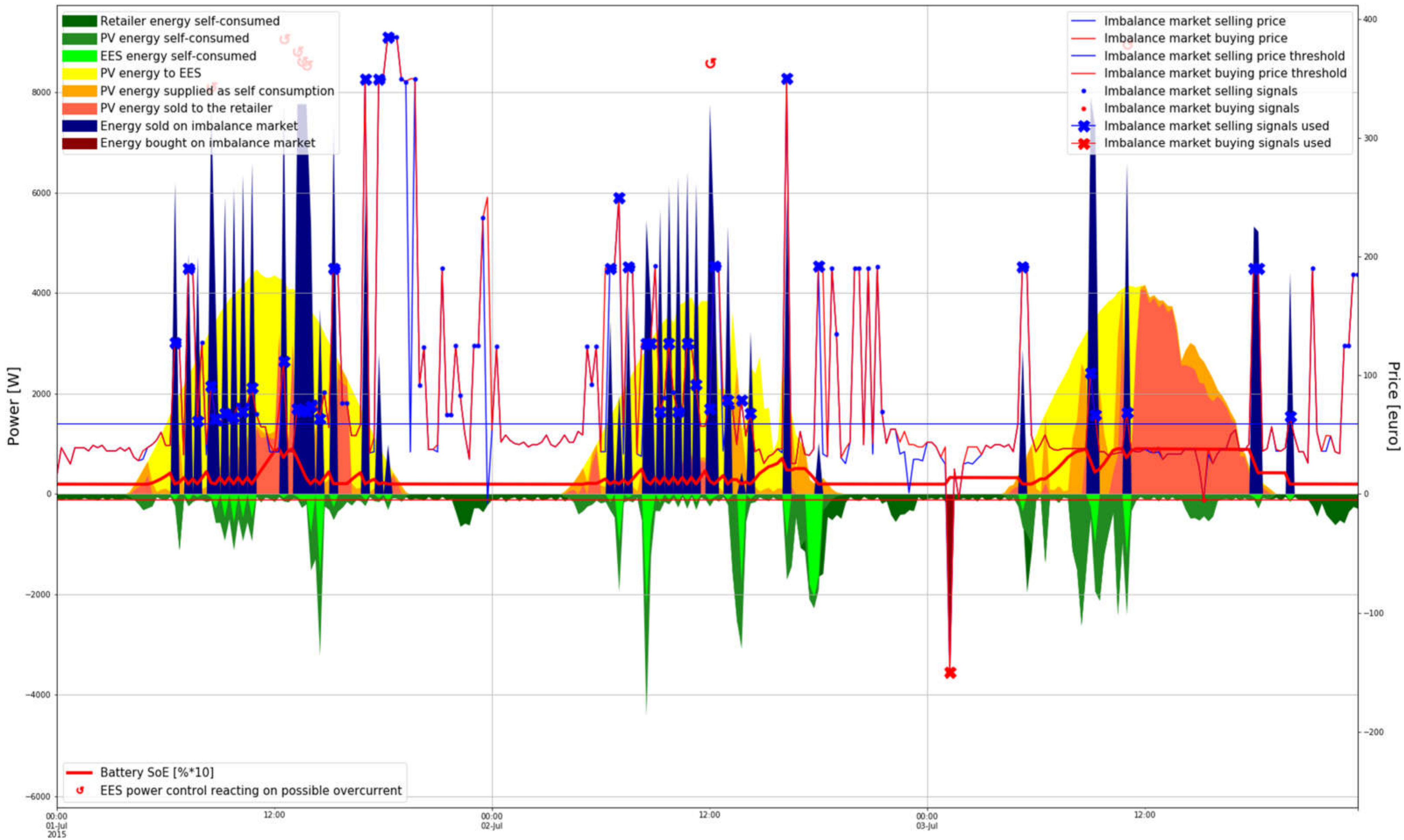


Figure 60 Household system behaviour with power demand and trading driven EES behaviour scheme during summer

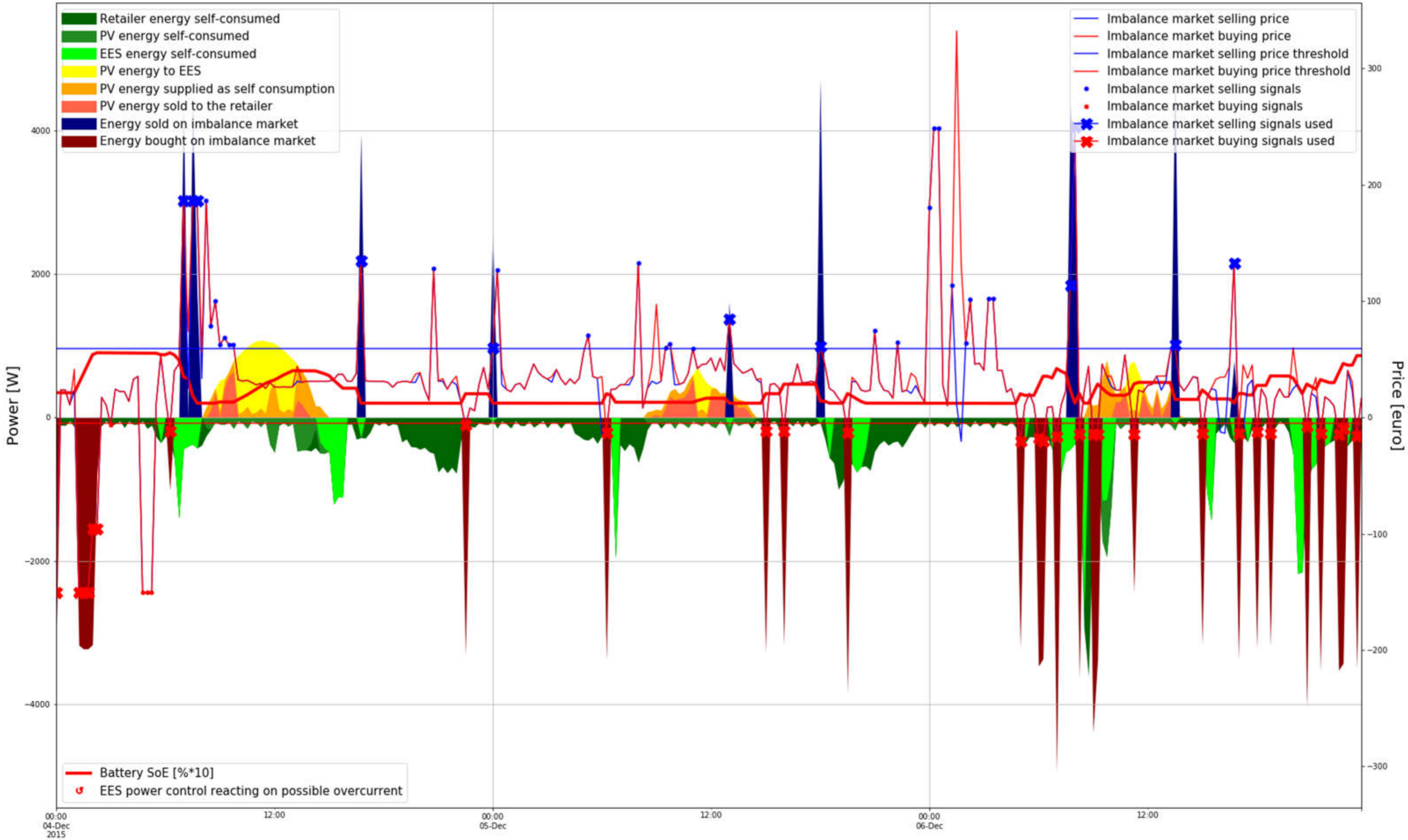


Figure 61 Household system behaviour with power demand and trading driven EES behaviour scheme during winter

Analysis module outputs		$rsp = 0{,}20\ €/kWh$ $rbp = 0{,}20\ €/kWh$			$rsp = 0{,}05\ €/kWh$ $rbp = 0{,}20\ €/kWh$		
		EES behaviour schemes			EES behaviour schemes		
		Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven
$EB_{no\ bat\ no\ PV}$	energy bill of a house without a battery nor PV [€],	**560**	**560**	**560**	**560**	**560**	**560**
$EB_{no\ bat}$	energy bill of a house without a battery [€],	**-440**	**-440**	**-440**	**169**	**169**	**169**
EB	energy bill of a house with EES [€].	**-357**	**-368**	**-347**	**71**	**250**	**195**
$AC_{sc\ PV}$	avoided costs by PV self-consumption [€].	**187**	**187**	**187**	**187**	**187**	**187**
$AC_{sc\ bat}$	avoided costs by EES self-consumption [€].	**164**	**19**	**106**	**164**	**15**	**120**
$R_{sold\ EM}$	total contribution of the household to the VPP revenue from selling transactions at the energy market [€],	**0**	**324**	**286**	**0**	**299**	**242**
$R_{bought\ EM}$	total contribution of the household to the VPP revenue from selling transactions at the energy market [€].	**0**	**71**	**98**	**0**	**70**	**88**
CF	fragmentary cash-flow representing the contribution of particular household to the cumulative cash-flow of the VPP [€].	**357**	**763**	**731**	**-71**	**119**	**135**
$L_{conv\ eff\ loss}$	revenue lost due to energy lost in the converter during its operation [€].	**86**	**55**	**79**	**86**	**56**	**74**
$L_{conv\ sb\ loss}$	revenue lost due to energy lost in the converter during stand-by mode [€].	**1**	**4**	**4**	**1**	**4**	**5**
$L_{OCP\ curt\ sell}$	revenue lost due to the energy curtailment during selling transactions at the energy market [€],	**0**	**4**	**7**	**0**	**3**	**2**
$L_{OCP\ curt\ buy}$	revenue lost due to the energy curtailment during buying transactions at the energy market [€].	**0**	**0**	**0**	**0**	**0**	**0**
	Profit [€]	**-83**	**323**	**291**	**98**	**288**	**304**

Table 22 Single household simulation results analysis summary

charge power. This characteristic of the EES system also influences the moments when the output of the system is controlled to avoid overcurrents in the household cabling. The moments when this control occurs are indicated with red circular arrows. Those situations occur only with big PV power output and establishing long position on the market, what is associated with discharging the battery with maximum possible power. The vertical position of the arrow indicates the power that would be present on the bus and could trigger the overcurrent protection devices to trip. It can be observed that the biggest losses are present in the trading driven EES behaviour scheme. The reason is aggressiveness of the scheme and the amount of trading transactions established, which is higher compared to the power demand and trading driven scheme. Further it can be seen that the EIM prices values determine fully the behaviour of the system and that the demand is covered with energy from the EES system only when trading occurs. It is reflected in the summary, where this scheme generates the lowest amount of EES avoided costs from all schemes.
The last of considered EES behaviour schemes is presented further (Figure 60 and Figure 61). It is a combination of the schemes discussed above. In this scheme the battery is dedicated to self-consumption and trading with primary position of trading. It can be seen at the diagrams that even though the EES system is involved in trading actions at the end of the day it covers the household power demand if needed. This fact is reflected in the summary (Table 22) as the avoided costs from EES are somewhere between two other schemes. The value of the energy lost in the converter during its operation in this scheme is also somewhere in between. The reason is covering the demand of the household and because of that often using the converter with lower efficiency. In the trading driven scheme the discharge actions are always conducted with full possible power and only charging with low power will force the converter to operate with low efficiency. In this scheme the low efficiency may occur during charging or discharging even though the 400 W converter limit is present. Finally, the revenues from EIM selling transactions are slightly lower compared to the previous scheme and from buying transactions are slightly higher. The reason is again the characteristic of the scheme in which the SoE is more likely to be lower because of the self-consumption factor. Because of the retailer pricing the trading driven behaviour scheme will be better option for currently present circumstances generating around 320 euro of profit per year, around 30 euro more than the scheme also involving self-consumption from EES. However, with future projected prices the situation is reversed and the power demand and trading driven scheme will be more cost-effective, generating around 305 euro of profit per year, almost 20 euro more than the trading driven scheme.

5.1.4. VPP economical impact evaluation

After introducing the results of the single household simulations analysis it is possible to present the results of the VPP simulations with different households compositions and evaluate them under the economical angle. The results of the VPP simulations will have similar outputs as the output of the analysis module applied to the single household simulation, however the values are combined values for the entire VPP.
Firstly, the results obtained with current retailer pricing are presented (Table 23). Comparing different VPP household compositions gives interesting results. The VPP with realistic composition and small consumption and big PV systems power output in terms of the EES avoided costs follow the pattern from the single household simulation, namely the value of energy self-consumed from EES system along with the value of energy lost in the converter during its operation in power demand driven behaviour scheme is the highest. The trading behaviour scheme generates the lowest values and the scheme combining functionalities of the previous ones generates values somewhere in between. However, the VPP with big consumption and small PV systems power output shows a different pattern.

Σ [k€]	$rsp = 0{,}20\ €/kWh \quad rbp = 0{,}20\ €/kWh$								
	Realistic			Small consumption big PV			Big consumption small PV		
	EES behaviour schemes			EES behaviour schemes			EES behaviour schemes		
	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven
$EB_{no\ bat\ no\ PV}$	**34.6**	**34.6**	**34.6**	**21.9**	**21.9**	**21.9**	**41.7**	**41.7**	**41.7**
$EB_{no\ bat}$	**-19.3**	**-19.3**	**-19.3**	**-60.5**	**-60.5**	**-60.5**	**4.3**	**4.3**	**4.3**
EB	**-14.9**	**-16.1**	**-15.4**	**-55.2**	**-56.7**	**-56.5**	**7.8**	**7.1**	**7.6**
$AC_{sc\ PV}$	**10.9**	**10.9**	**10.9**	**6.3**	**6.3**	**6.3**	**10.4**	**10.4**	**10.4**
$AC_{sc\ bat}$	**8.3**	**1.1**	**6.1**	**5.6**	**0.7**	**3.5**	**6.6**	**1.2**	**7.4**
$R_{sold\ EM}$	**0.0**	**15.4**	**12.9**	**0.0**	**18.9**	**17.9**	**0.0**	**12.8**	**9.9**
$R_{bought\ EM}$	**0.0**	**3.6**	**5.1**	**0.0**	**3.5**	**4.2**	**0.0**	**4.2**	**5.7**
CF	**14.9**	**35.1**	**33.5**	**55.2**	**79.2**	**78.5**	**-7.8**	**9.8**	**8.0**
$L_{conv\ eff\ loss}$	**4.0**	**2.7**	**3.6**	**4.7**	**3.3**	**3.6**	**3.2**	**2.4**	**3.1**
$L_{conv\ sb\ loss}$	**0.1**	**0.2**	**0.2**	**0.1**	**0.2**	**0.2**	**0.1**	**0.2**	**0.2**
$L_{OCP\ curt\ sell}$	**0.0**	**0.2**	**0.3**	**0.0**	**0.5**	**0.5**	**0.0**	**0.1**	**0.1**
$L_{OCP\ curt\ buy}$	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Profit	**-4.4**	**15.8**	**14.2**	**-5.3**	**18.6**	**18.1**	**-3.6**	**14.1**	**12.3**

Table 23 Economical impact VPP simulation results for different households compositions with current retailer pricing

Σ [k€]	$rsp = 0{,}05\ €/kWh \quad rbp = 0{,}20\ €/kWh$								
	Realistic			Small consumption big PV			Big consumption small PV		
	EES behaviour schemes			EES behaviour schemes			EES behaviour schemes		
	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven
$EB_{no\ bat\ no\ PV}$	**34.6**	**34.6**	**34.6**	**21.9**	**21.9**	**21.9**	**41.7**	**41.7**	**41.7**
$EB_{no\ bat}$	**12.9**	**12.9**	**12.9**	**-3.4**	**-3.4**	**-3.4**	**24.5**	**24.5**	**24.5**
EB	**7.8**	**16.5**	**13.1**	**-6.2**	**0.4**	**-1.1**	**20.5**	**28.2**	**25.6**
$AC_{sc\ PV}$	**10.9**	**10.9**	**10.9**	**6.3**	**6.3**	**6.3**	**10.4**	**10.4**	**10.4**
$AC_{sc\ bat}$	**8.3**	**1.0**	**6.8**	**5.6**	**0.5**	**3.5**	**6.7**	**0.9**	**7.1**
$R_{sold\ EM}$	**0.0**	**14.0**	**11.0**	**0.0**	**17.5**	**16.2**	**0.0**	**11.3**	**8.3**
$R_{bought\ EM}$	**0.0**	**3.5**	**4.5**	**0.0**	**3.2**	**3.9**	**0.0**	**3.8**	**5.3**
CF	**-7.8**	**1.0**	**2.4**	**6.2**	**20.4**	**21.2**	**-20.5**	**-13.1**	**-12.0**
$L_{conv\ eff\ loss}$	**4.0**	**2.7**	**3.1**	**4.7**	**2.9**	**3.3**	**3.2**	**2.1**	**2.9**
$L_{conv\ sb\ loss}$	**0.1**	**0.2**	**0.2**	**0.1**	**0.2**	**0.2**	**0.1**	**0.2**	**0.2**
$L_{OCP\ curt\ sell}$	**0.0**	**0.1**	**0.1**	**0.0**	**0.2**	**0.3**	**0.0**	**0.1**	**0.1**
$L_{OCP\ curt\ buy}$	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Profit	**5.1**	**13.9**	**15.3**	**2.9**	**17.0**	**17.8**	**4.0**	**11.5**	**12.5**

Table 24 Economical impact VPP simulation results for different households compositions with projected future retailer pricing

The avoided costs from the EES self-consumption is the highest when the VPP is operated in the power demand and trading driven EES behaviour scheme. The power demand driven is somewhere in the middle and the trading driven scheme generates the lowest EES self-consumption avoided costs. The reason behind it is simply the characteristics of the households composition and the behaviour schemes. With big consumption and small PV systems with the power demand driven scheme the batteries will be charged less often compared to the scheme involving trading. Simply short positions established on the imbalance market allow charging the batteries and therefore the SoE of the batteries can more likely be high in this conditions what may transfers to possibility of outperforming the power demand driven scheme in self-consumption. It can be seen that the VPP with bigger PV output generates in both EES behaviour schemes bigger revenues from selling transactions made on EIM compared to the VPP with small PV power output operated in the same schemes. Reverse situation can be observed in case of the buying transactions made on EIM. The reason behind it is simply stacking of the powers. The transactions on EIM are made with the households three-phase bus power balance as said in the model description. Therefore, when short positions on EIM are established the current consumption of the household will generate higher revenue from this position. When the long position is being established the PV power output will add to the revenue of the transaction. This fact is transferred to the to the optimal trading settings chosen earlier. Even though the value of energy bill and revenues from trading are always coupled a clear pattern in the trading settings for different VPPs operated in trading driven scheme can be seen. The VPP with more PV and low consumption will be able to gain more from selling transactions and less from buying therefore the price thresholds will be set lower. Reverse situation can be seen for the VPP with high consumption and small PV where the selling thresholds will be ideally set higher. This pattern is interfered in current retailer pricing but can be clearly seen in the results for the projected future retail pricing. As expected the power demand driven schemes generate losses and other schemes generate profits. The highest profits are generated by the composition with small consumption and big PV systems power output and the lowest by the one with big consumption and small PV. It can be seen that in all compositions the highest profits are generated by the trading driven behaviour schemes.
The results for the projected future retailer prices are presented further (Table 24). Similar pattern in terms of the value of energy self-consumed from the EES systems and value of the energy lost in the operating converter could be observed with future retailer pricing as with current retailer pricing. Furthermore, the same differences are present when comparing the compositions in terms of revenues of EIM transactions. However, it can be seen that trading in the future becomes less profitable most probably because it has to share its cost-effectiveness with self-consumption which started to make sense. This can be also seen in the results of the optimal trading settings. Almost all selling thresholds were lifted what means that less trading signals will be created and less trading transactions will be executed. Also, the thresholds values for buying prices dropped sharply what may mean that buying energy by such a VPP on EIM has no future with such retail pricing. What is more it can be observed that in all compositions the favourable behaviour scheme moved from trading driven to mixed one. However, the most profitable composition remained the same, namely with small consumption and big PV systems power output, generating almost 18 thousand euro of profit per year.
Further the profits of all the scenarios were analysed in terms of investment profitability in time span of 15 years. The results of the analysis are presented below (Table 25). Currently the cost of the entire EES system is around 9 thousand euro, hence the current $CAPEX$ is equal 450 thousand euro. It was assumed that the price of the EES system in the future will be significantly lower and equal to 4 thousand euro and $CAPEX$ would in this scenario equal 200 thousand euro. As introduced in the VPP economical impact approach three measures were calculated based on values of the yearly profit determined by the VPP model. The NPV levels were calculated

without any discount rate. It is also worth mentioning that the calculations were made without addition of any losses due to operation and maintenance of the systems, which in real life would most probably be applied.

$rsp = 0{,}20\ €/kWh \quad rbp = 0{,}20\ €/kWh$ $CAPEX = 450\ k€$									
Measures	Realistic			Small consumption big PV			Big consumption small PV		
	EES behaviour schemes			EES behaviour schemes			EES behaviour schemes		
	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven
Profit [€/year]	**-4.4**	**15.8**	**14.2**	**-5.3**	**18.6**	**18.1**	**-3.6**	**14.1**	**12.3**
NPV	**-516**	**-213**	**-179**	**-530**	**-171**	**-179**	**-504**	**-239**	**-265**
IRR [%]	**-**	**-7.12**	**-5.74**	**-**	**-5.46**	**-5.74**	**-**	**-8.23**	**-9.52**
PBP [year]	**-**	**15+**	**15+**	**-**	**15+**	**15+**	**-**	**15+**	**15+**
$rsp = 0{,}05\ €/kWh \quad rbp = 0{,}20\ €/kWh$ $CAPEX = 200\ k€$									
Measures	Realistic			Small consumption big PV			Big consumption small PV		
	EES behaviour schemes			EES behaviour schemes			EES behaviour schemes		
	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven
Profit [€/year]	**5.1**	**13.9**	**15.3**	**2.9**	**17.0**	**17.8**	**4.0**	**11.5**	**12.5**
NPV	**-124**	**9**	**30**	**-167**	**55**	**67**	**-140**	**-28**	**-13**
IRR [%]	**-10.15**	**0.52**	**1.77**	**-14.92**	**3.20**	**3.85**	**-12.28**	**-1.79**	**-0.80**
PBP [year]	**15+**	**15**	**14**	**15+**	**12**	**12**	**15+**	**15+**	**15+**

Table 25 Economical impact analysis results

As the VPPs operated in power demand driven scheme with current retailer pricing generated losses the IRR and PBP measures are not calculated and the value of NPV is more negative

than $CAPEX$. All other scenarios with this pricing did not meet the economical expectations and generated negative values of NPV and IRR in the considered period. The payback periods of all other scenarios were found higher than fifteen years.
The results of the economical impact analysis applied to the scenarios with projected future retailer pricing were more optimistic. However even though the power demand driven schemes generated profits it was not enough to generate positive values of NPV and IRR and make the investment worth accomplishing. Similar results are generated by remaining behaviour schemes of the VPP with big consumption and small PV systems power output. The values generated are negative and the PBP is beyond fifteen years. Nevertheless, the values are relatively close to zero and most probably by extending the investment period by one or two years would make the VPP operation profitable. Two VPPs, both operated in trading driven and mixed behaviour schemes, generated positive NPV and IRR what makes them cost-effective investments. The VPP placed in the realistic households composition and operated in mixed behaviour scheme would generate 30 thousand euro of profit after fifteen years of operation. The investment would pay itself back in fourteen years. However better opportunity for profit is given by composition of households with small consumption and big PV systems. The trading driven and mixed behaviour schemes in the composition outperformed the others generating 55 and 67 thousand euro profit respectively after fifteen years of operation. Both investments would pay themselves back in twelve years.

5.2. Physical impact evaluation

This section is devoted to the results of the evaluation of physical impact that the VPP exerts on the surrounding environment, namely part of the distribution grid where it is located. Furthermore, the impact that the operation as a part of a VPP exerts on the batteries will be also evaluated in this section. As first the results related to the battery cycling and their degradation will be presented first for a single battery and further for the entire VPP. Next the results of the impact made on the distribution network will be presented. The parameter that was observed and based on which the evaluation is done is transformer loading. At first some examples of transformer loading curves in different scenarios and for different levels of EES and PV systems penetration will be shown. Next the complete results for different scenarios are presented and discussed. This will be followed by a summary showing the penetration thresholds after which the overloads of the transformer were detected and which should not be exceeded.

5.2.1. Battery degradation

Similarly, to the economical evaluation results firstly the results of single household simulation regarding degradation will be presented and further average values for entire VPPs will be shown. The level of each battery pack degradation is estimated in the single household simulation. The values of the equivalent number of cycles, cycle fade, calendar fade and the total degradation are estimated every time step. In this way it is possible to see in what part of the year batteries are cycled and degraded with the highest rate. Below the curves representing the equivalent number of cycles for a single household with EES operated in different behaviour schemes in current retailer pricing conditions are presented (Figure 62). It can be observed that in all scenarios the battery cycling is enhanced in the middle of the year. The reason behind it is simply bigger PV systems power output in this period what means more opportunities to charge.

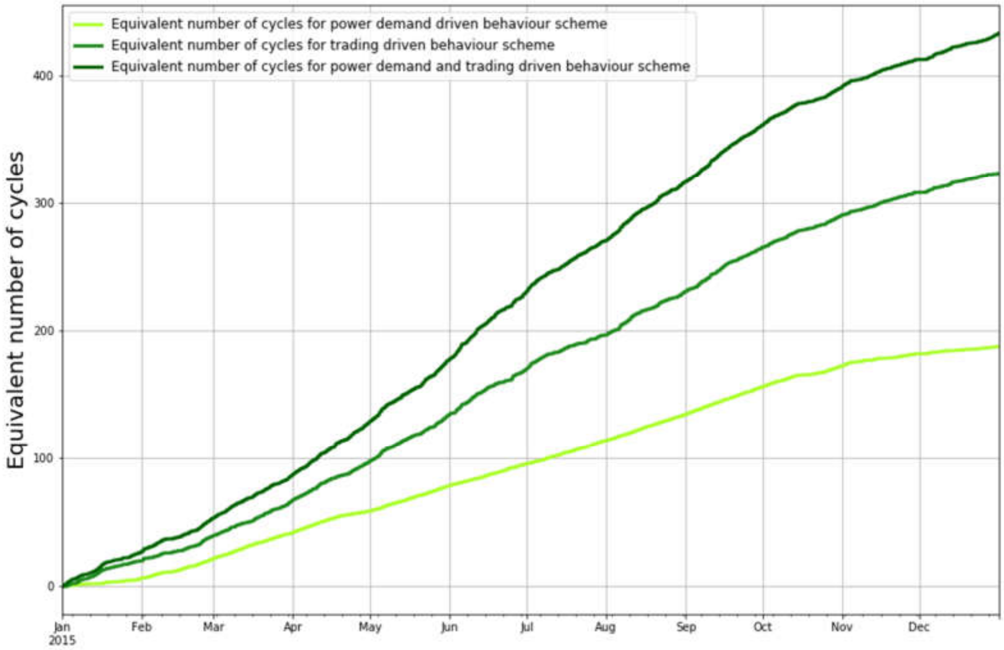


Figure 62 Equivalent number of cycles for different EES behaviour schemes

The least cycled battery was operated in the power demand driven behaviour scheme and reached around 190 equivalent cycles during the year. The most cycled battery was used for in the mixed behaviour scheme and reached more than twice of that number, namely around 430 equivalent cycles. In the middle the battery used for trading only reached around 320 equivalent cycles.

The equivalent number of cycles along with the average battery SoE and average cycle depth have a direct influence on the cycle fade. The cycle fade of batteries in each of the mentioned scenarios are indicated below in the shades of green (Figure 63). It can be observed that the highest value of cycle fade is achieved by the battery which was cycled the most, what is not surprising. However, the final values of the cycle fades for remaining scenarios are almost identical even though the final equivalent number of cycles for them were much different. The reason behind it is the value of average SoE and average cycle depth mentioned above. The higher the values of the average SoE and average cycle depth the higher value of the capacity cycle fade.

The calendar capacity fade value as already said in the theoretical background depends on the time and the average SoE and was indicated in the shades of blue below (Figure 63). The rates of change of calendar fades are similar for all scenarios, however after a year there are some differences in the final values. The battery operated in the trading behaviour scheme had the highest level of average SoE from the beginning what can be justified with its characteristics – the battery is charged with PV nevertheless discharges only when a trading signal is present. The battery used for self-consumption only at the beginning of the year had the lowest calendar capacity fade rate of change what means the lowest average SoE, however in the middle of the year battery with operated in mixed scheme must have been rarely full, because the calendar fade decreased even lower than in the case of the battery operated in the power demand driven behaviour mode.

Even though different patterns in cycle and calendar fades can be observed the total degradation, which was indicated above in shades of red (Figure 63), is in line with the battery cycling. The battery used for self-consumption and trading was at the end of the year degraded the most losing more than 3 % of its initial capacity. Then the battery used to trading only was degraded slightly more than the one used only for self-consumption.

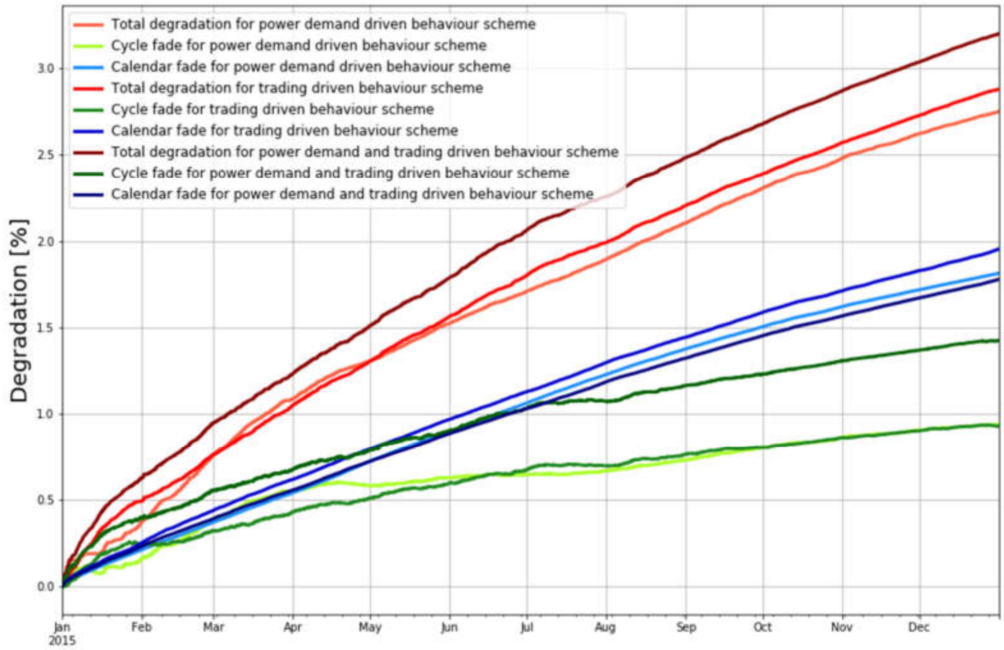


Figure 63 Battery degradation for different EES behaviour schemes

The summary of the batteries degradation results used in different VPPs are presented below (Table 26). Similar patterns can be observed in the results of entire VPPs as in the single household simulation results. Even though the batteries used for self-consumption only are cycled less the degradation is still similar or even higher compared to batteries operated in the batteries behaviour schemes more aggressively cycling them. It can be seen that the batteries are used in the same way for self-consumption only with future and current retailer pricing. In general the degradation of the batteries used in schemes involving trading in current retailer pricing conditions is higher compared to those used in projected future. The highest degradation percentage was achieved by the VPP with realistic composition operated in power demand and trading driven EES behaviour scheme with current retailer prices. The smallest value of degradation was achieved by batteries used only for self-consumption in households composition with big consumption and small PV systems power output with future projected retailer pricing.

$rsp = 0{,}20\ €/kWh \quad rbp = 0{,}20\ €/kWh$									
Measures	Realistic			Small consumption big PV			Big consumption small PV		
	EES behaviour schemes			EES behaviour schemes			EES behaviour schemes		
	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven
Avg. eq. number of cycles	**186**	**318**	**428**	**150**	**386**	**426**	**144**	**278**	**362**
Avg. degradation [%]	**2.81**	**2.89**	**3.26**	**2.72**	**3.06**	**3.19**	**2,49**	**2.77**	**3.07**

$rsp = 0{,}05\ €/kWh \quad rbp = 0{,}20\ €/kWh$									
Measures	Realistic			Small consumption big PV			Big consumption small PV		
	EES behaviour schemes			EES behaviour schemes			EES behaviour schemes		
	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven
Avg. eq. number of cycles	**186**	**292**	**326**	**150**	**328**	**356**	**144**	**224**	**290**
Avg. degradation [%]	**2.81**	**2.75**	**2.92**	**2.72**	**2.83**	**2.95**	**2.49**	**2.54**	**2.81**

Table 26 Batteries degradation in VPPs

5.2.2. VPP impact on distribution network

As already said in the section devoted to the physical impact evaluation approach the point at which the influence of the VPP will be measured is transformer. In this particular case it is carrying all load of the neighbourhood. The loading of the transformer was measured with different penetration of PV systems and EES systems in the network. The results are presented as three dimensional bar plots showing number of overloads, average number of overloads per day, average overloading depth, average overloading length per day and average transformer loading during the simulated period. Each cuboid represents one QDS and based on the transformer curves obtained after the simulation abovementioned measures are determined. Some examples of the loading curves for the VPP with realistic households composition are given below (Figure 64 to Figure 67). The EES systems in the model are charged mostly from PV system, hence operation of an EES without PV system present is almost impossible. Therefore, the penetration of the EES systems can never be greater than the penetration of the PV systems. As a result the triangular shape of the data is obtained. Green colour means no overloads detected and red indicates presence of some. Because of unknown future grid layout and difficulty in reflecting one the physical impact that is exerted on the part of the distribution network will be evaluated only for the current retailer pricing conditions.

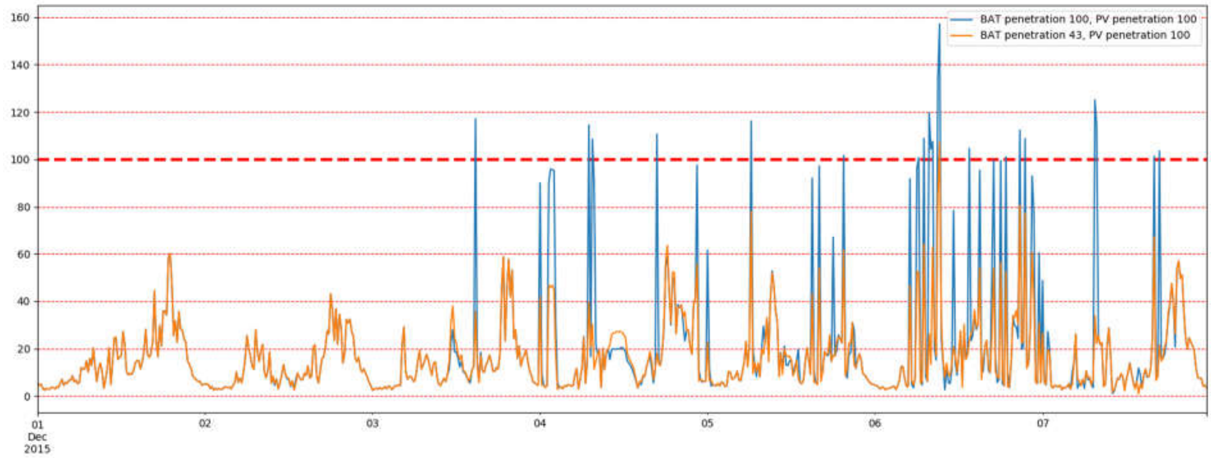


Figure 64 Power transformer loading for power demand and trading behaviour scheme in December

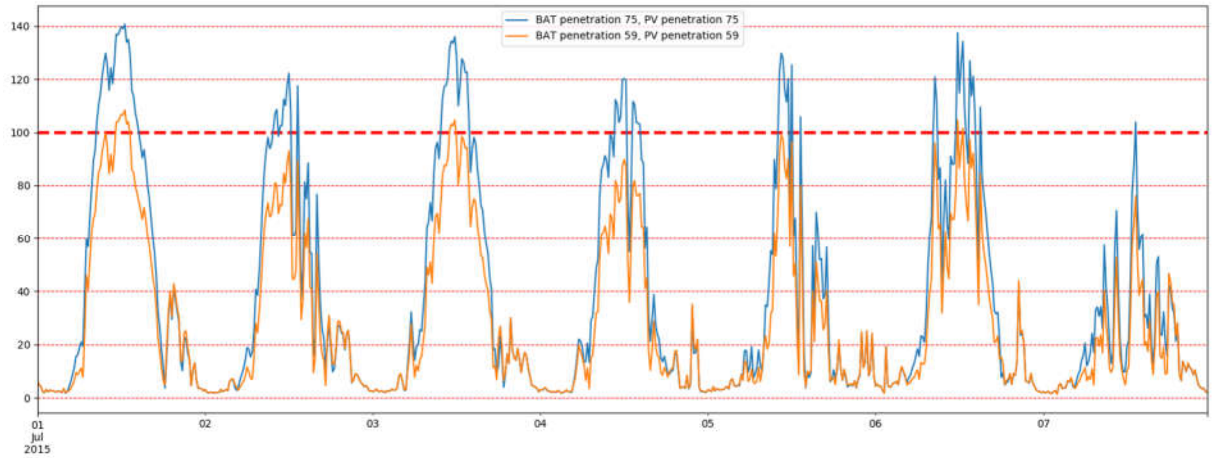


Figure 65 Power transformer loading for power demand behaviour scheme in July

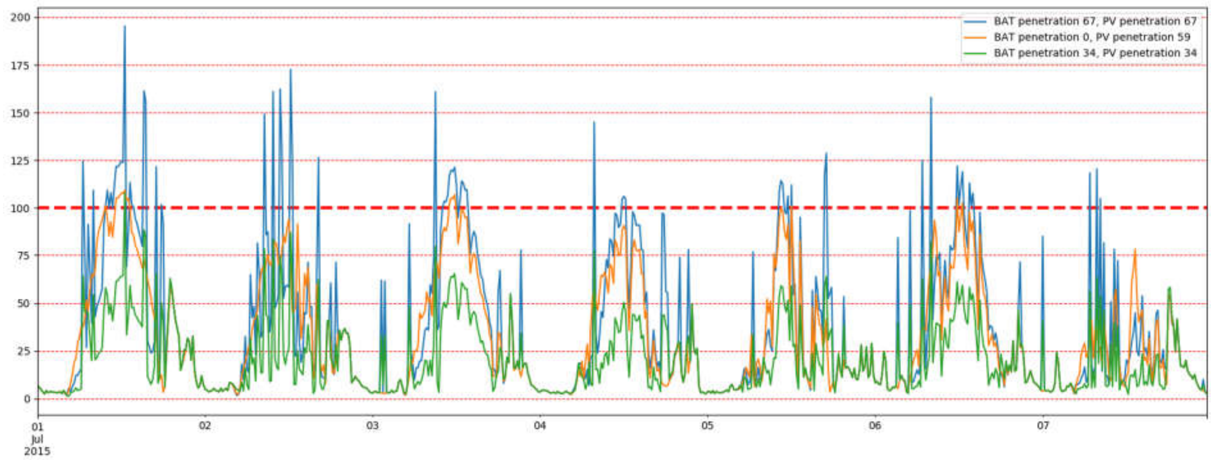


Figure 66 Power transformer loading for trading driven behaviour scheme in July

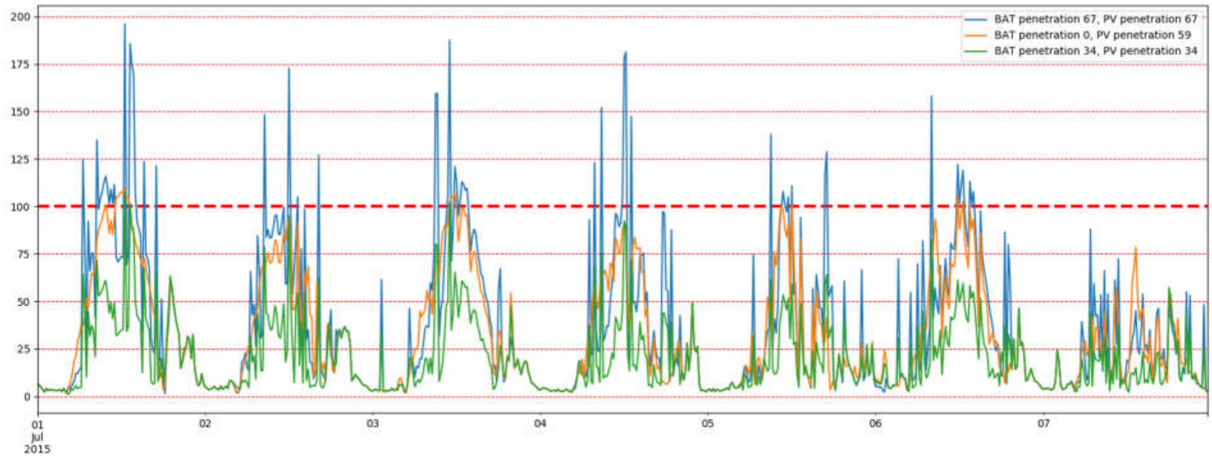


Figure 67 Power transformer loading for power demand and trading behaviour scheme in July

As first results of the realistic VPP households composition in the first week of December and for different behaviour schemes are presented (Table 27). It can be clearly seen that no overloads occur during this period when the EES systems are operated in the power demand driven behaviour scheme. When the VPPs are operated in schemes involving trading some overloads are detected. First overloads occur with 34 % of the PV and EES penetration. Then when the penetration of PV systems is increased the number of overloads drops to zero. Reason behind it is simply characteristic of trading in periods with less PV power output. As already said during elaboration on the single household simulation results during those periods much more trading actions are buying energy from EIM, hence the transformer in those periods may be more overloaded with power drawn from the grid not by overproduction of PV. This means that increased PV penetration actually eases the transformer loading. This effect can be observed at the diagram showing average transformer loading, which value drops with increasing penetration of EES systems in the network. In the scenarios in which the batteries are used for trading a small amount of overloads is present until 75 % of PV and EES penetration. The depth of the overloads until 50 % penetration is similar for both schemes involving trading. However, after that point the VPP operated in trading driven scheme generates deeper overloads on average. Similar pattern can be seen while observing the average length of the overloads.

Further the results of simulations for the first week of July are presented (Table 28). The dramatic difference can be seen in the results. The VPP operated in power demand driven behaviour scheme starts generating overloads from 59 % of PV systems penetration. It can be seen that correlation with the penetration of EES systems and overloads in this behaviour scheme is almost none. It may mean that mostly PV systems overproduction is causing the transformer to overload. With high penetrations of PV the part of the distribution network may act like a small PV power plant. As already said some big loads in the network were replaced with normal households and the balance between the production and demand may have been upset. Again, it can be observed that that higher penetration of EES systems operated with a power demand driven behaviour scheme slightly decreases the transformer loading. Completely reverse situation is observed in two remaining behaviour schemes. The length of the periods in which the transformer is overloaded in the summertime is maximized with the full penetration of PV systems and none EES systems. Further the results for the VPP households composition with small consumption and big PV systems power output is presented (Table 30 and Table 31). Again in the scenario with power demand driven behaviour scheme no overloads are generated in the simulated winter period. The VPPs trading on the EIM with this household composition would start overloading the transformer with much higher penetration of EES systems in the network than in the realistic one. The reason is the characteristics of the trading

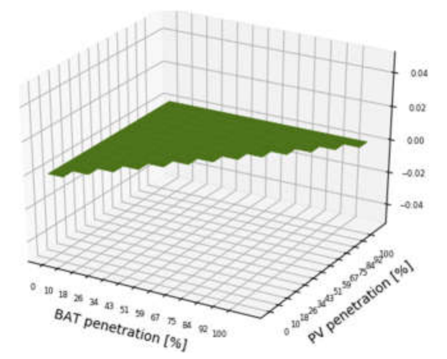
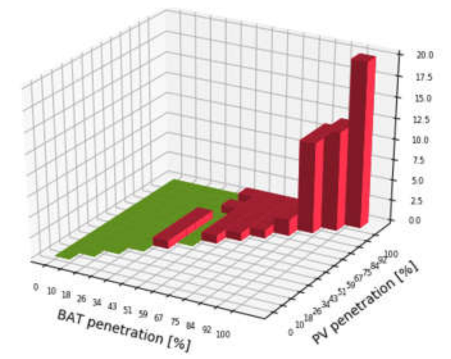
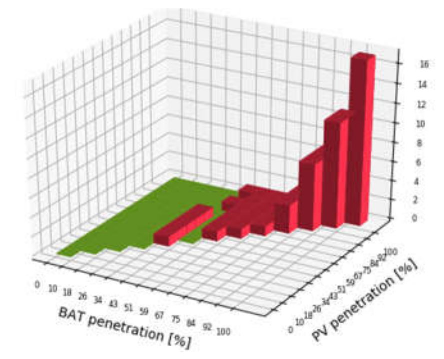
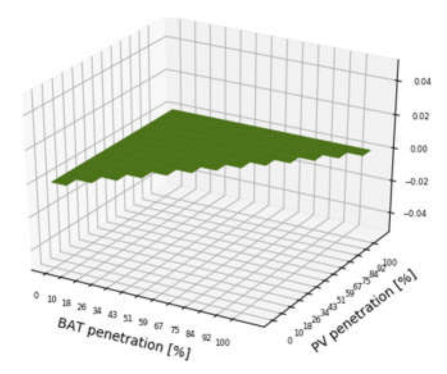
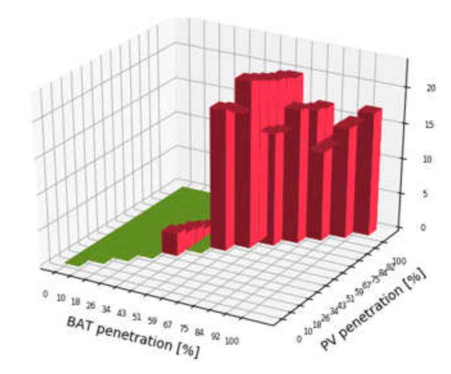
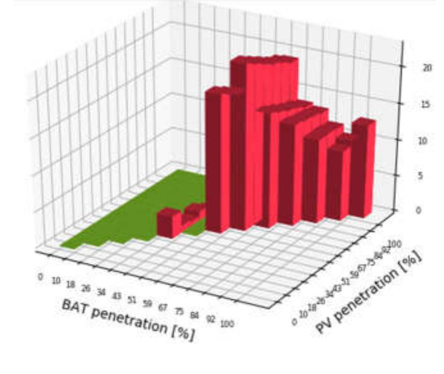
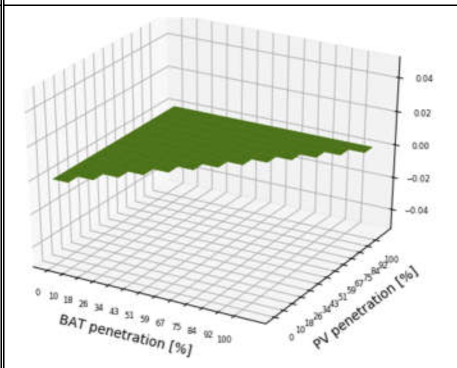
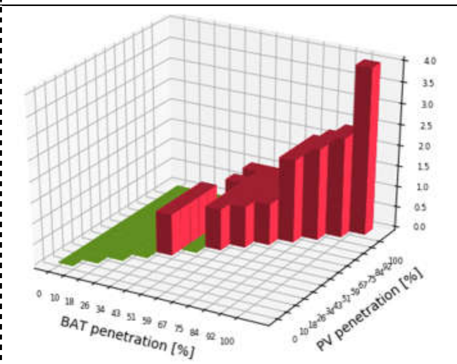
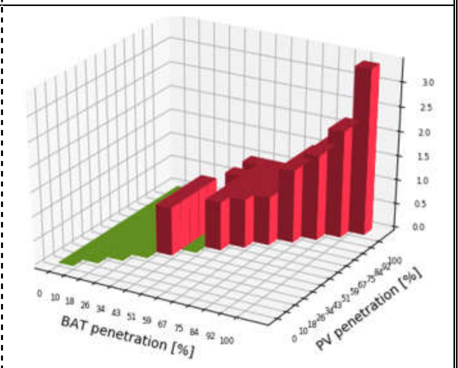
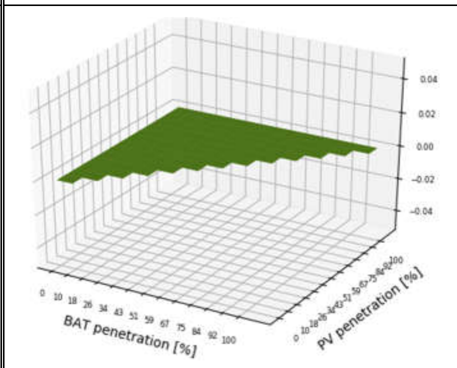
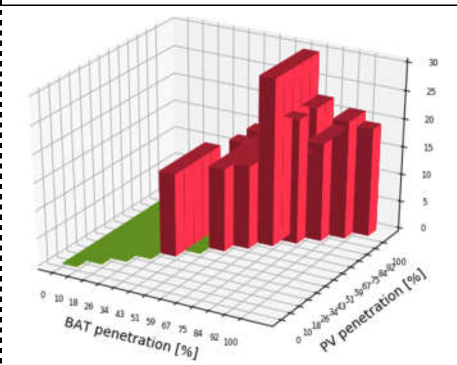
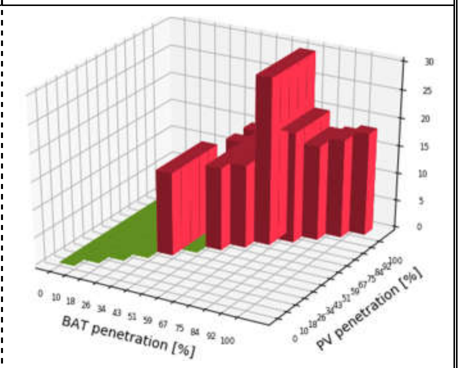
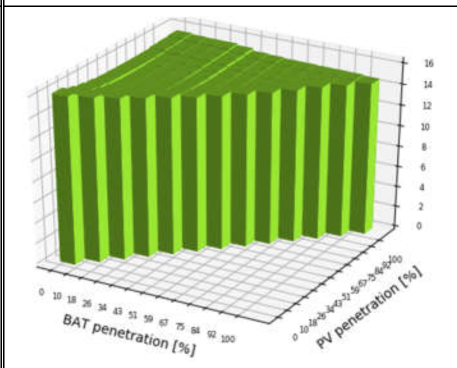
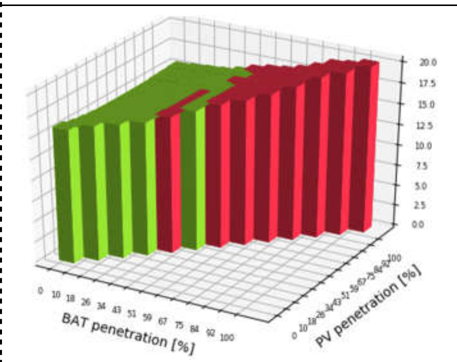
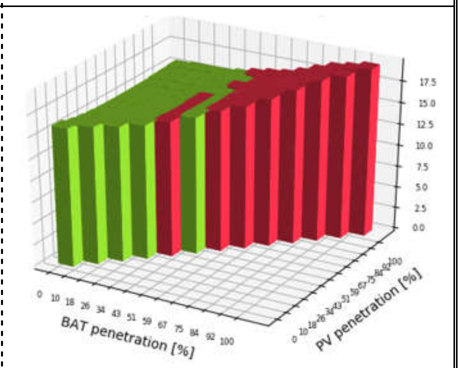
	Realistic in December		
	Power demand driven	Trading driven	Power demand and trading driven
Number			
Avg. depth [%]			
Avg. number per day			
Avg. length per day [minutes]			
Avg. loading [%]			

Table 27 Transformer overloads for realistic VPP composition in December

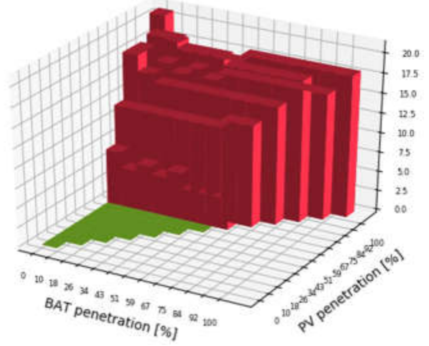
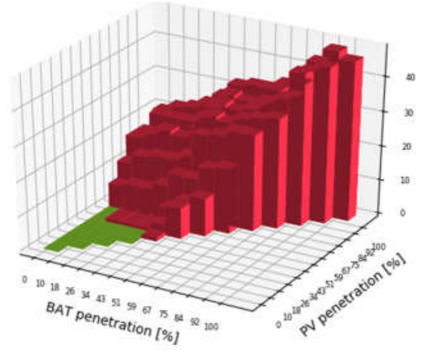
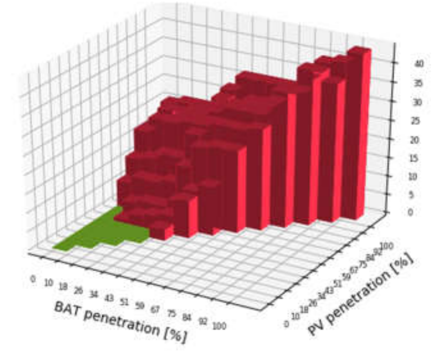
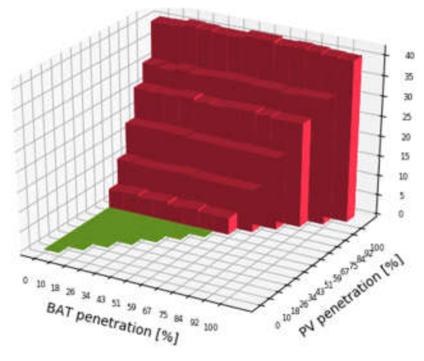
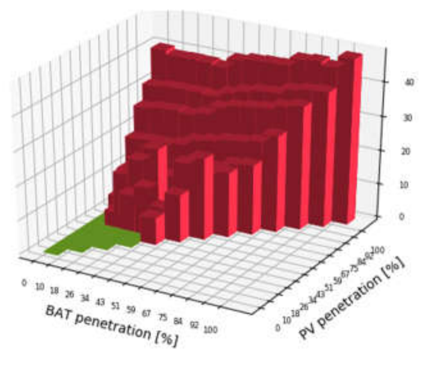
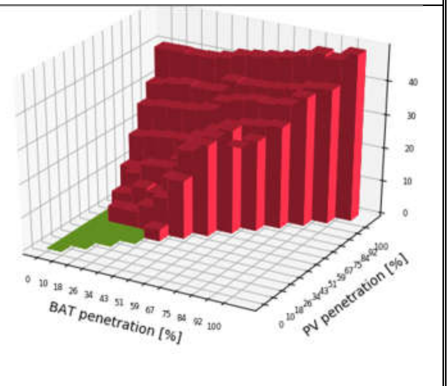
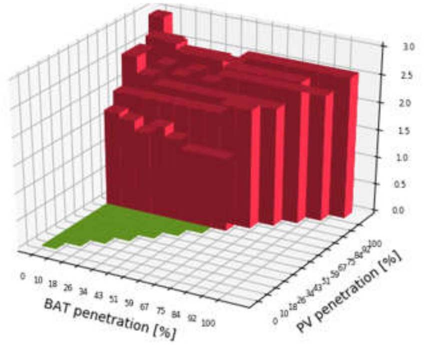
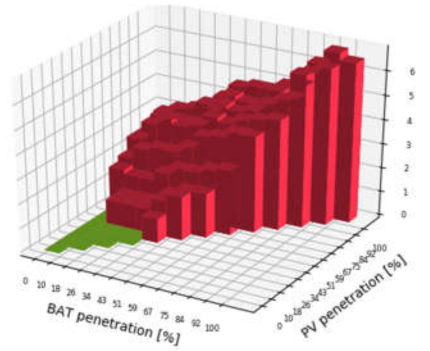
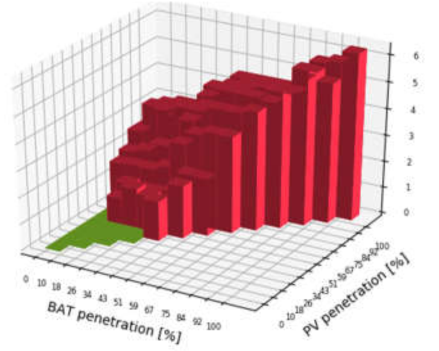
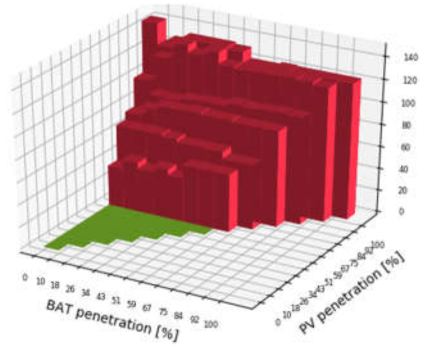
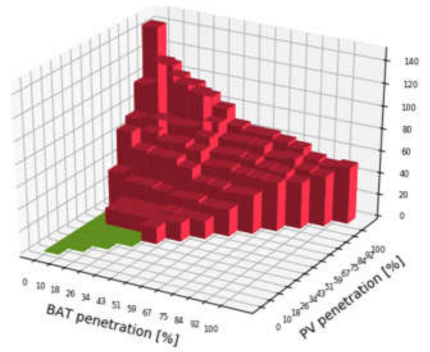
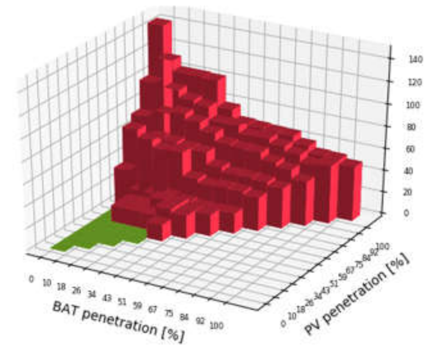
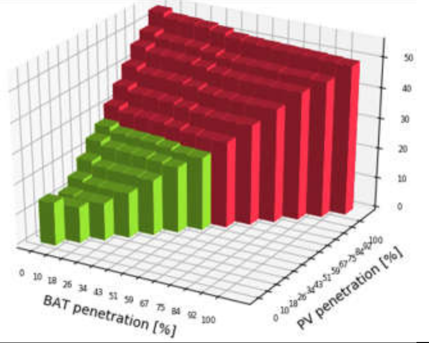
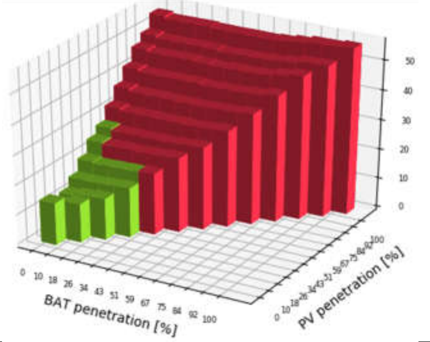
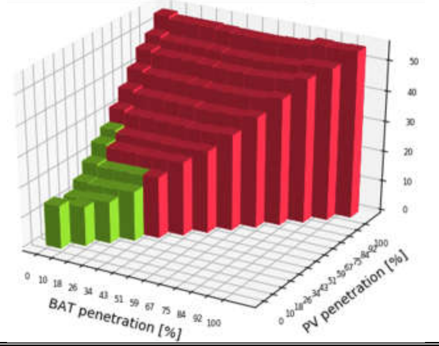
	Realistic in July		
	Power demand driven	Trading driven	Power demand and trading driven
Number			
Avg. depth [%]			
Avg. number per day			
Avg. length per day [minutes]			
Avg. loading [%]			

Table 28 Transformer overloads for realistic VPP composition in July

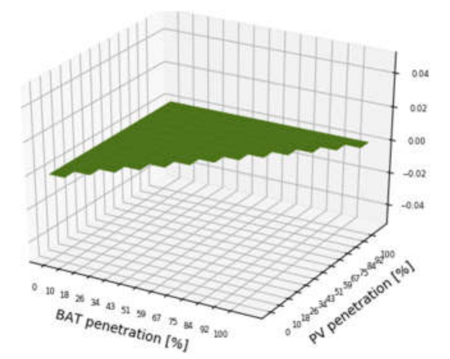
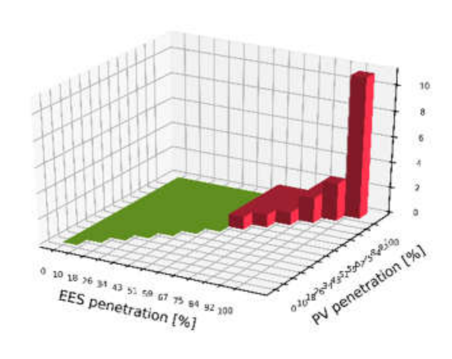
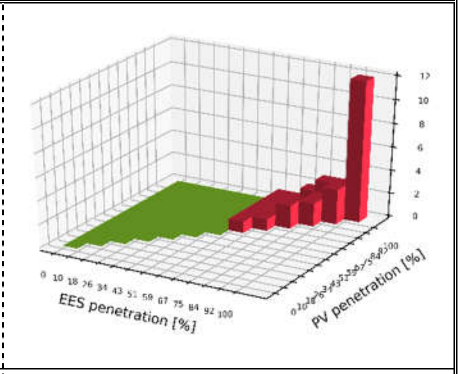
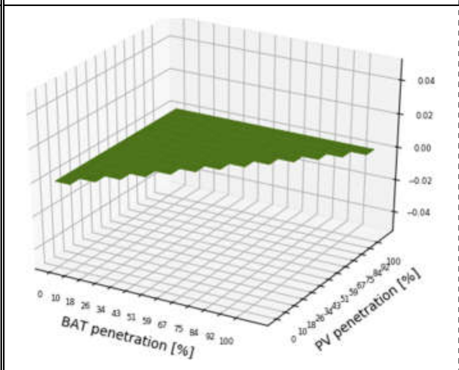
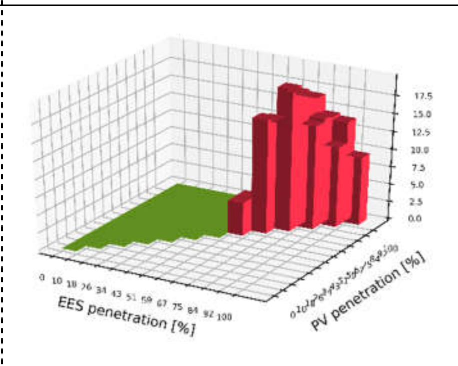
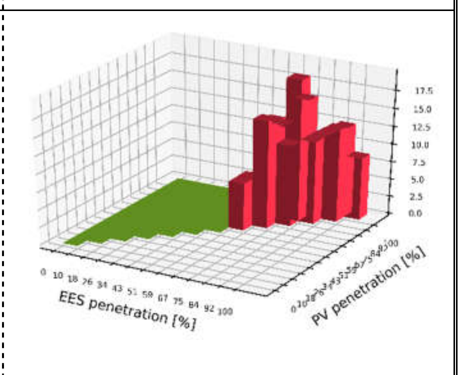
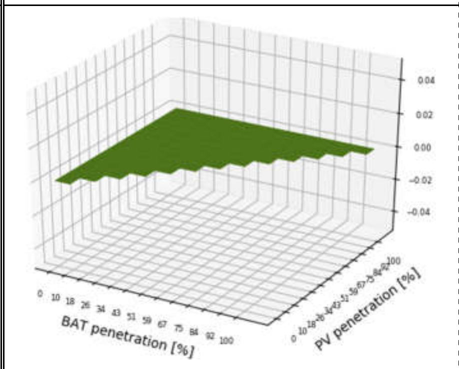
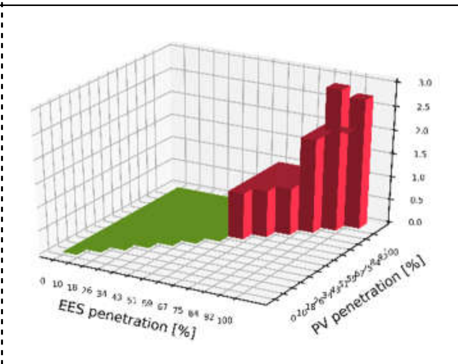
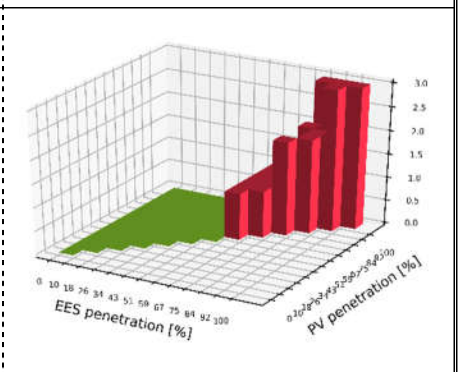
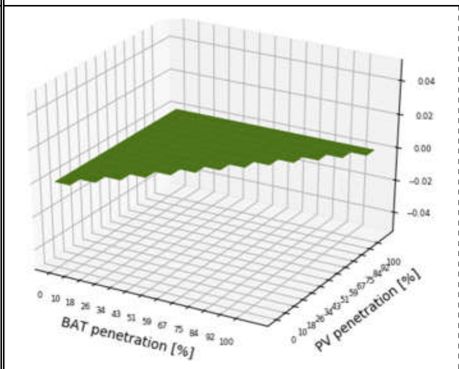
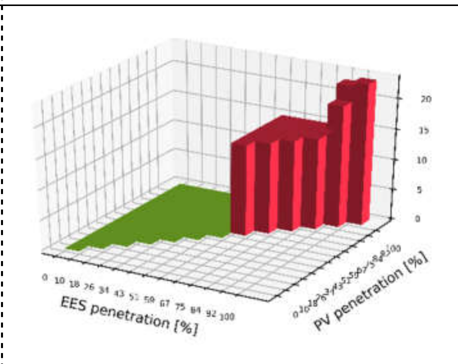
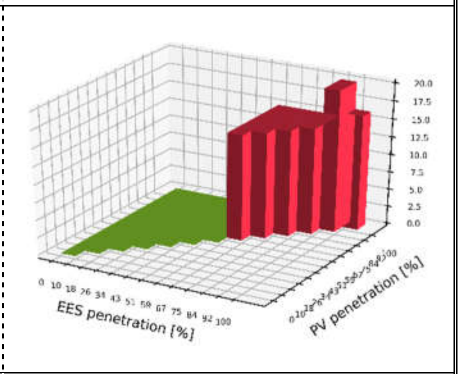
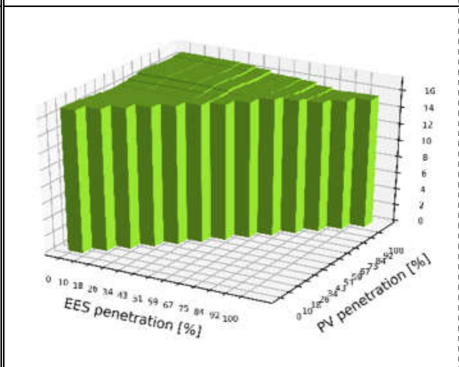
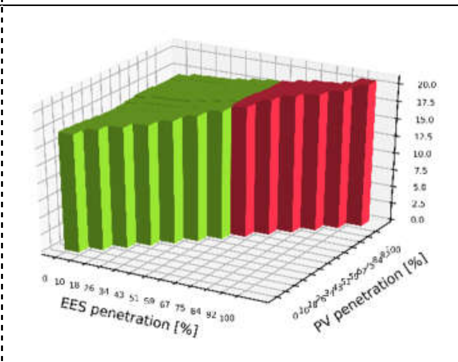
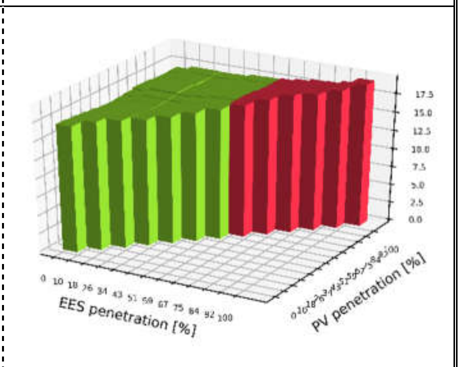
	Small consumption big PV in December		
	Power demand driven	Trading driven	Power demand and trading driven
Number			
Avg. depth [%]			
Avg. number per day			
Avg. length per day [minutes]			
Avg. loading [%]			

Table 29 Transformer overloads for VPP composition with small consumption and big PV in December

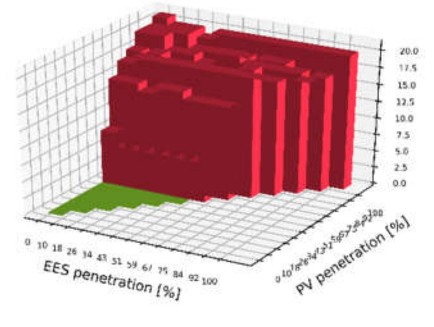
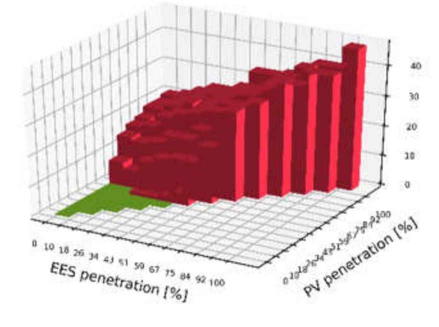
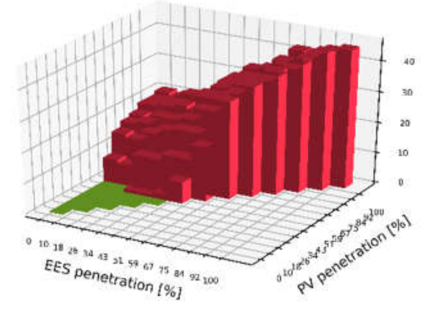
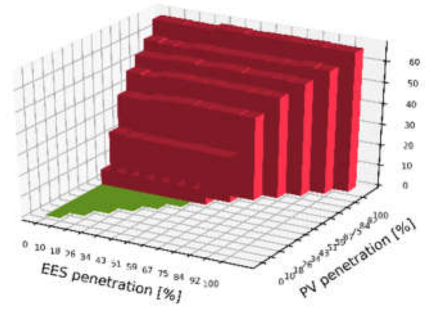
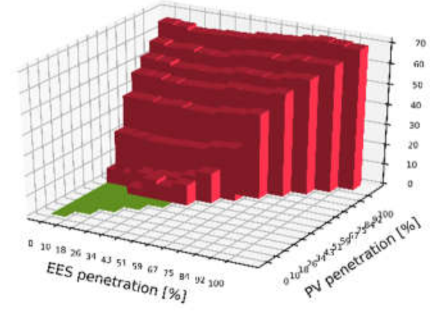
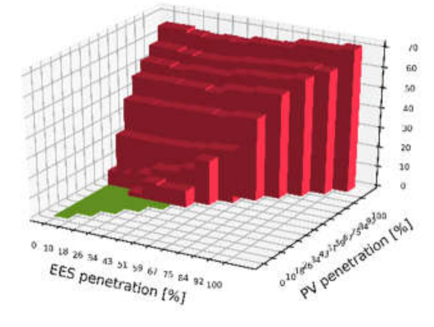
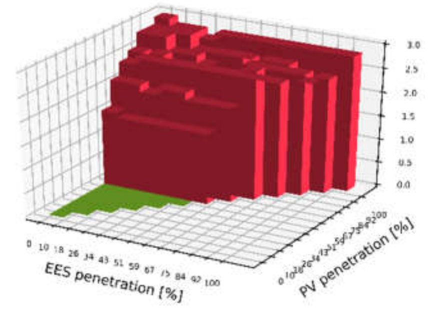
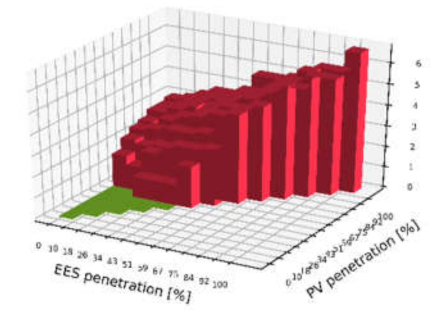
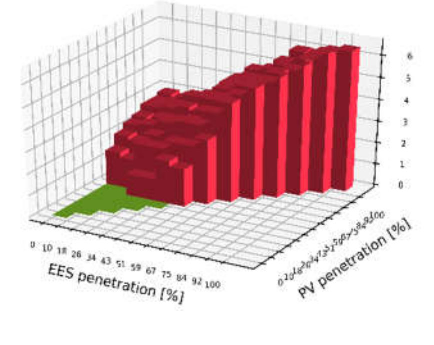
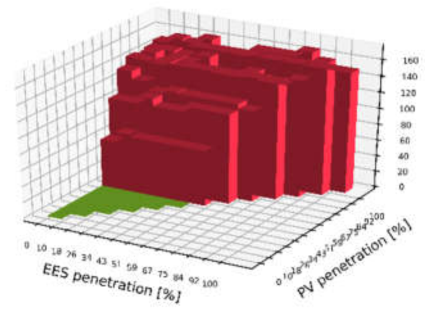
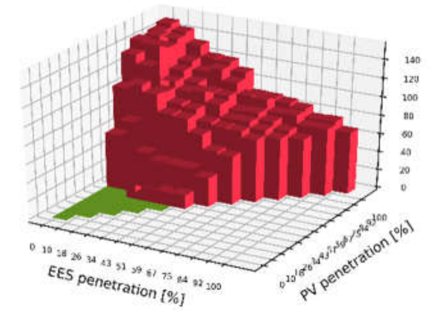
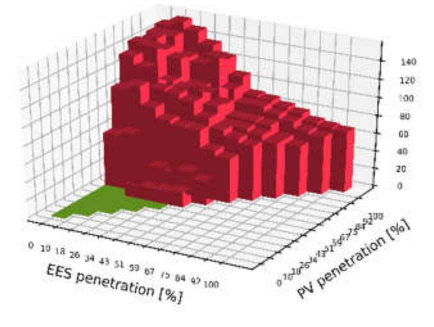
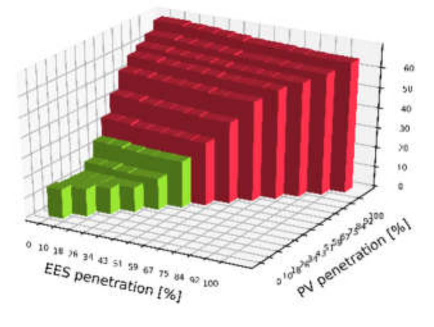
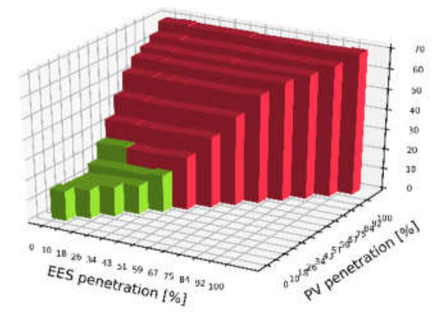
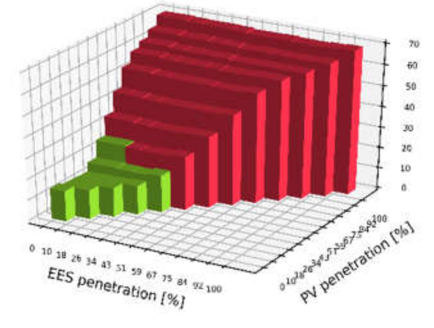
	Small consumption big PV in July		
	Power demand driven	Trading driven	Power demand and trading driven
Number			
Avg. depth [%]			
Avg. number per day			
Avg. length per day [minutes]			
Avg. loading [%]			

Table 30 Transformer overloads for VPP composition with small consumption and big PV in July

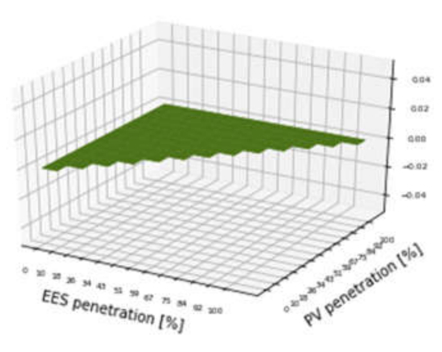
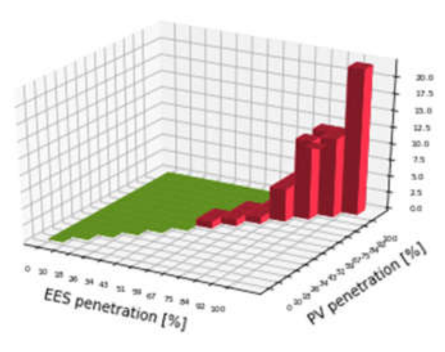
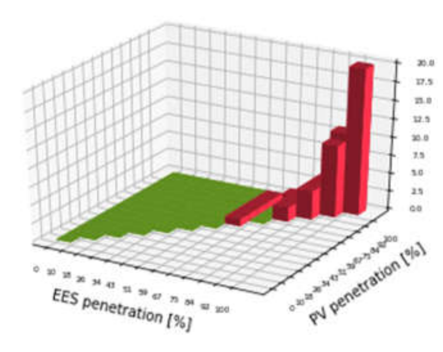
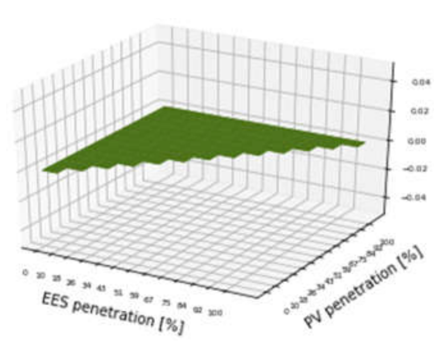
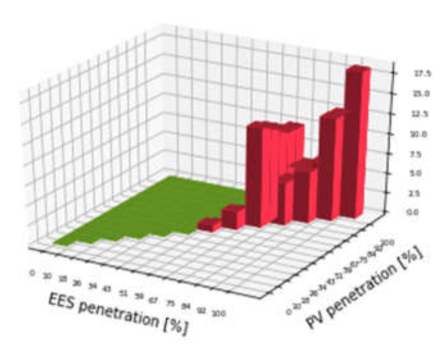
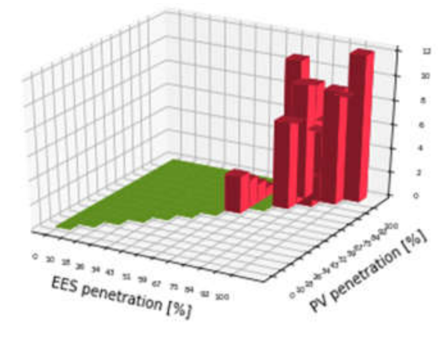
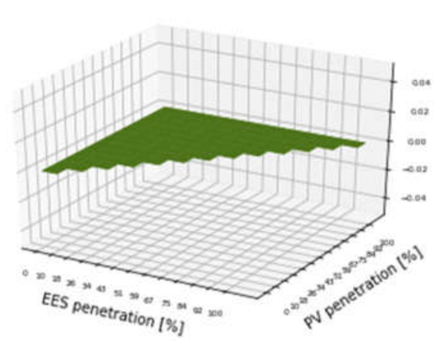
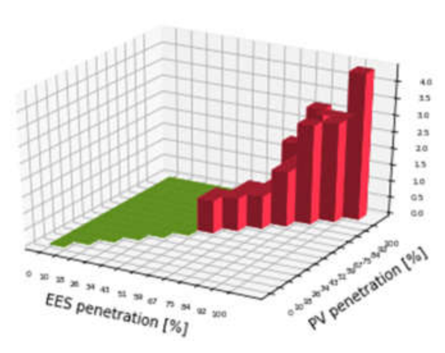
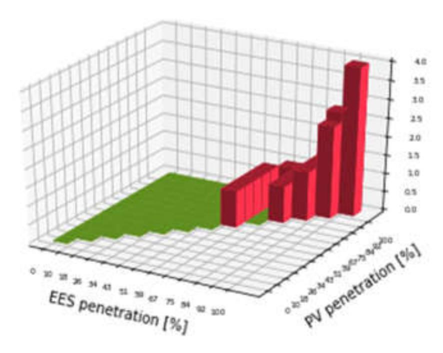
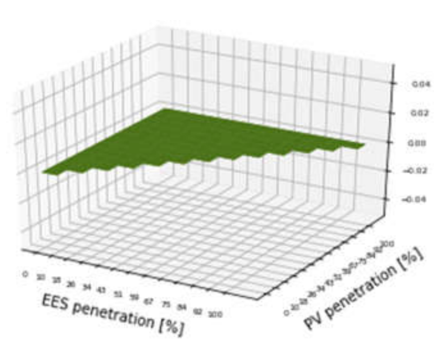
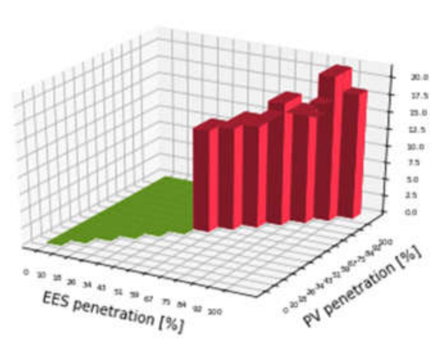
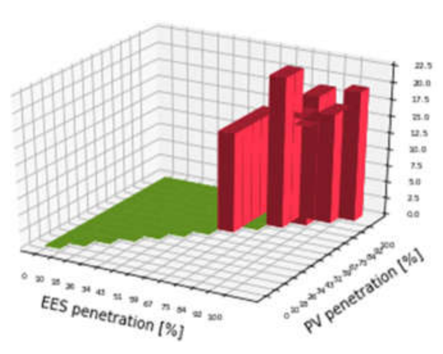
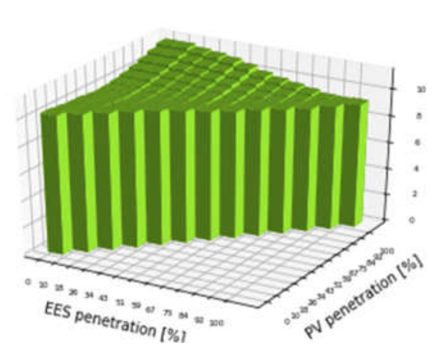
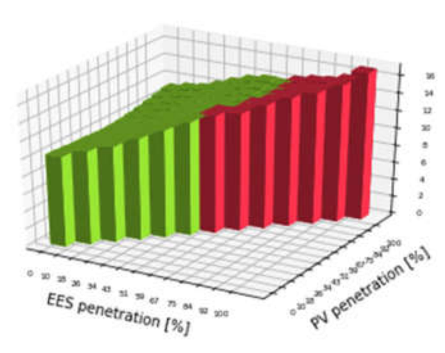
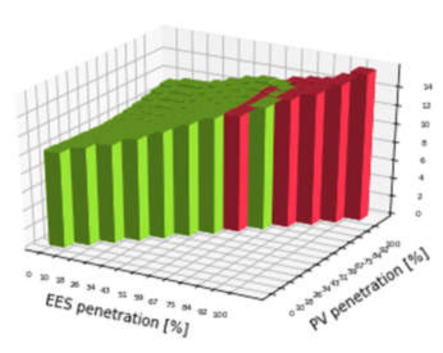
	Big consumption small PV in December		
	Power demand driven	Trading driven	Power demand and trading driven
Number			
Avg. depth [%]			
Avg. number per day			
Avg. length per day [minutes]			
Avg. loading [%]			

Table 31 Transformer overloads for VPP composition with big consumption and small PV in December

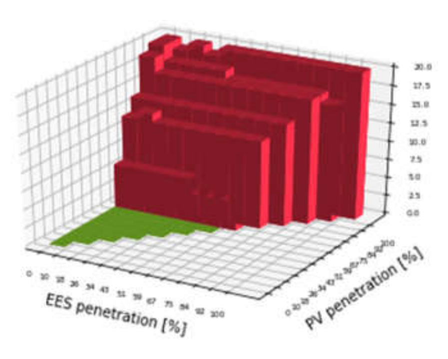
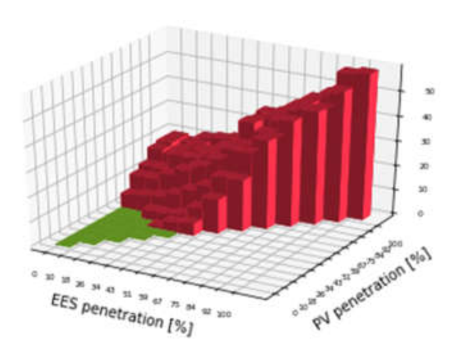
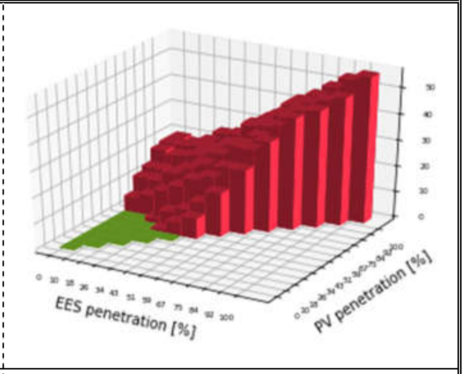
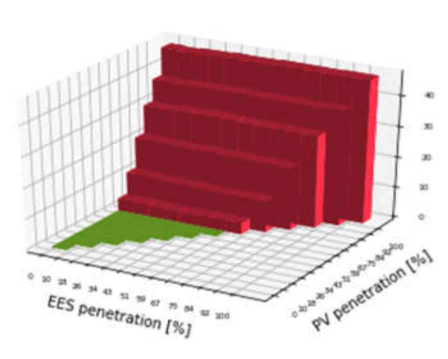
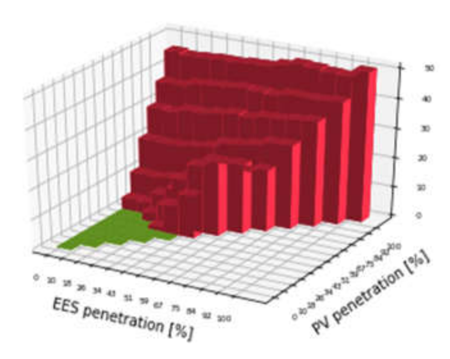
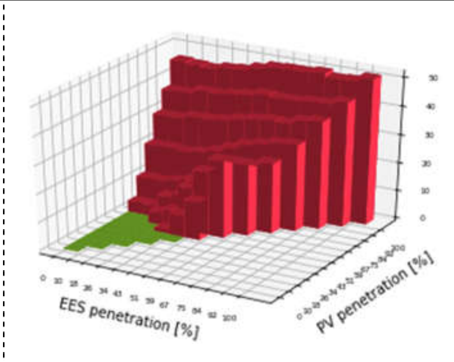
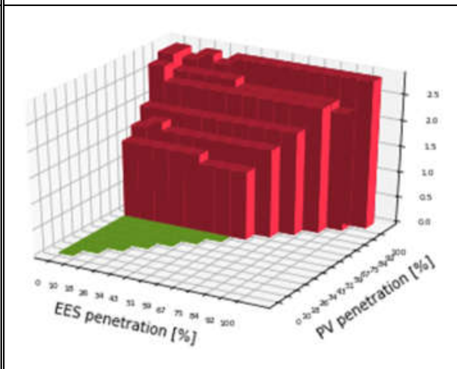
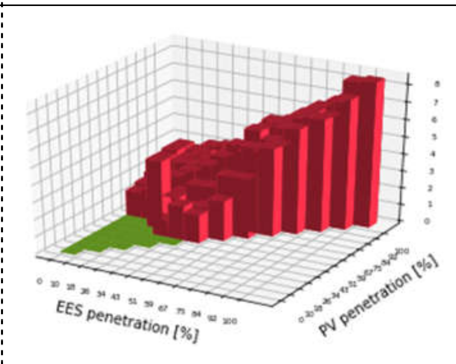
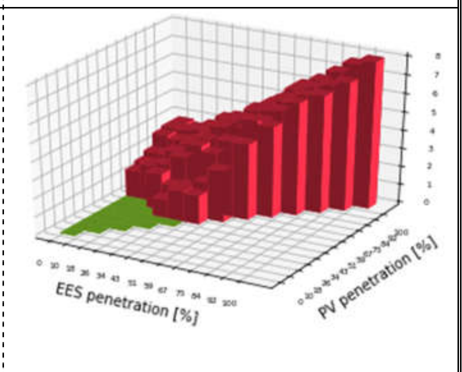
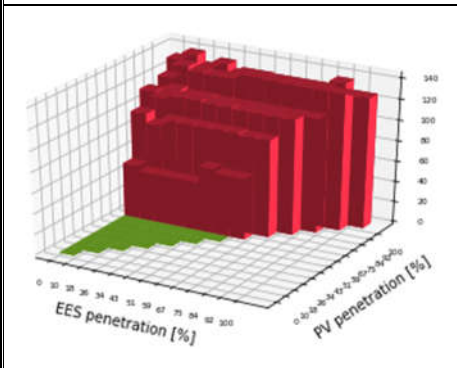
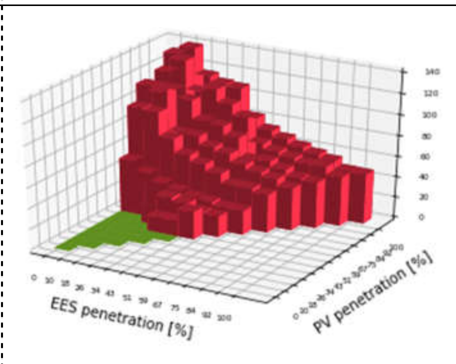
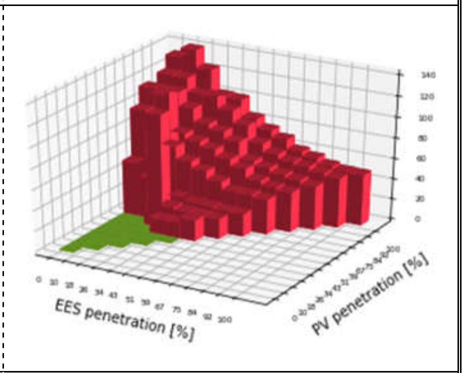
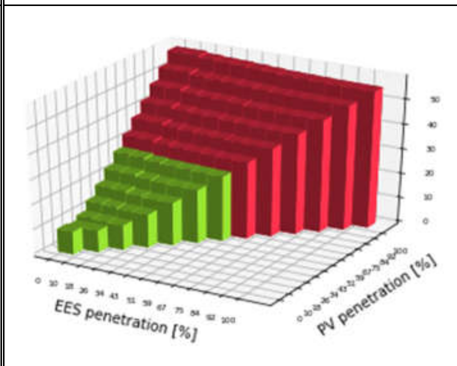
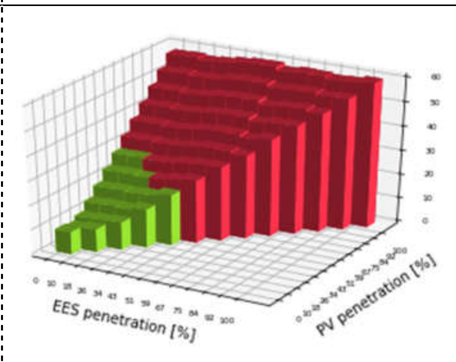
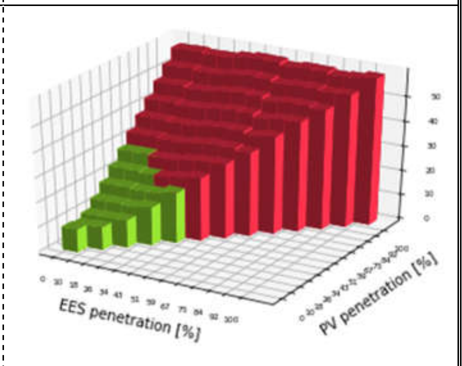
	Big consumption small PV in July		
	Power demand driven	Trading driven	Power demand and trading driven
Number			
Avg. depth [%]			
Avg. number per day			
Avg. length per day [minutes]			
Avg. loading [%]			

Table 32 Transformer overloads for VPP composition with big consumption and small PV in July

in the winter and lower amount of power demand. The trading actions in this periods are mostly buying transactions. When the power demand is lower charged batteries less often cause overloads with the power drawn from the MV part of the network. The reverse situation is observed in the summer period when lower PV systems penetration generates overloads earlier compared to the VPP with realistic households composition.
The results for the VPP composition with big consumption and small PV systems power output are presented next (Table 32 and Table 33). During winter the households in the composition with big power demand and small PV systems power output using EES systems only for self-consumption did not generate any overloads. The overloads in this composition are generated relatively in the winter. The penetration is the same as in the VPP with realistic scenario however the average depth of those overloads is much bigger. The reason is high power demand and big amount of short positions established by VPP during winter period. Reverse situation can be seen in July. The penetration at which the overloads start to occur is the same as with realistic composition however the average depth is smaller.
It is worth adding that the average values of depth and length of overloads may for the behaviour schemes involving trading lead to similar conclusions for extremely different household compositions. The reason is aggressiveness of the trading strategy and as a result spiky profile of the power transformer loading. For instance very few deep overloads may happen at the same time as many short and shallow overloads what will not affect the average values, but the severity of such situation will be much bigger for the transformer.

In December									
Thresholds PV/EES [%]/[%]	Realistic			Small consumption big PV			Big consumption small PV		
	EES behaviour schemes			EES behaviour schemes			EES behaviour schemes		
	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven
Max PV	**100/100**	**100/34**	**100/34**	**100/100**	**51/51**	**51/51**	**100/100**	**100/59**	**51/51**
Max EES	**100/100**	**43/43**	**43/43**	**100/100**	**51/51**	**51/51**	**100/100**	**43/43**	**51/51**

In July									
Thresholds PV/EES [%]/[%]	Realistic			Small consumption big PV			Big consumption small PV		
	EES behaviour schemes			EES behaviour schemes			EES behaviour schemes		
	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven	Power demand driven	Trading driven	Power demand and trading driven
Max PV	**51/51**	**51/0**	**51/0**	**43/43**	**51/10**	**51/10**	**51/51**	**43/10**	**43/10**
Max EES	**51/51**	**43/43**	**43/43**	**43/43**	**34/34**	**34/34**	**51/51**	**34/34**	**34/34**

Table 33 Maximum penetration thresholds not generating overloads at the transformer

The summary of the penetration thresholds above which the overloads are generated is presented above (Table 33). Two different types of penetration combinations were chosen. One of them shows what is the maximum PV systems penetration achievable without overloading the transformer. If the overloads were not present with fixed penetration of PV systems and with different penetration of EES systems the highest possible EES systems penetration was chosen. The next combination shows what is the maximal possible penetration of the EES systems in the network without causing overloads. Again, if possible maximum PV systems penetration will be chosen to the combination if the EES penetration is the same.
It can be seen that no patterns can be observed even though the characteristics of households compositions considered are extremely different. The observation of the transformer loading direction would possibly make the results more clear and more conclusions could be drawn. However, because of the power demand driven behaviour scheme simplicity the differences can be seen in the summer period. The composition with big PV systems output generate the overloads with lower penetration of PV and EES systems.

6 Conclusions

The conclusions of the work will give answers to the research questions posed in the introduction of this work. It is worth saying that the conclusions are drawn based on results made for particular study case, namely for City-Zen project and should not be perceived as general. However the model developed in this work is fully capable of modelling similar case studies which results may lead to completely opposite conclusions as those presented below.

1.

It was found that in the conditions reflecting current market situation no business case exist for neither of the EES operation schemes or household compositions. Furthermore, it was inferred that with assumed current retailer pricing the home storage used for self-consumption purposes will bring losses. The excess of the energy from PV panels can be instantly sold to the retailer, avoiding costs from the future consumption. Usage of the battery simply wastes the energy on the EES system losses and sells stored energy later for the same price. VPPs operated in other two behaviour schemes generated profits however the projected payback period in ideal conditions with zero operation and maintenance costs still went beyond 15 years which may be an end of lifetime for such an EES system.

It was found that some business cases are present in assumed future circumstances. The change of retailer pricing made self-consumption of stored energy cost-effective. Selling the overproduction of the energy instantly is simply less cost-efficient than storing it and avoiding costs by supplying the demand when the power balance becomes negative. Even though the power demand driven scenarios generated profits the payback period exceeded 15 years. Because of decrease of initial investment costs the two VPPs with realistic household composition and with low power demand and big PV operated in EES behaviour scheme involving trading generated a positive value of NPV what proves an existence of business case for this VPP in assumed conditions.

The fixed prices trading thresholds chosen for maximization of the revenues as one of the trading strategies settings showed that in the future because of cost-effectiveness of self-consumption the role of trading in the mix will be smaller. The thresholds used in the future will be more spread. It was found that with used strategy more buying transactions are made in the winter periods and more selling transactions is made during summer periods. This may suggest using different thresholds for different periods of the year. Because of the difference in retail prices in the future usage of the power converter with lower efficiencies may transfer to lower energy bills.

In general more economically correct households composition was the one with low power demand and big PV. The reason behind it is revenues stacking. It was found that much more revenues are gained in general from selling transactions. Because of the big power output of PV systems, which was stacked with the power from EES systems bigger revenue could be generated. Regarding EES behaviour schemes in assumed current market conditions more cost-effective was trading driven scheme. The reason behind it is the contribution of the trading to the revenues mix and lack of self-consumption cost-effectiveness. Whereas in assumed future market conditions more profitable is operation in power demand and trading driven behaviour scheme, the reason is enhanced cost-effectiveness of self-consumption and reduced importance of trading in the mix.

The results showed that the limitations implied to the system by the overcurrent protection devices did not influence significantly the business case. The association of the power consumption profile with the overcurrent protection nominal current was made. In reality the protection devices may be rated with lower currents what will influence the business case more.

2.

Both EES behaviour schemes which involved energy market trading cycled the batteries more, however it did not transfer to much higher degradation of the battery. Batteries used only for self-consumption were almost equally degraded because of high value of the average state of energy which was enhanced during summer period. The batteries in general were cycled more with current retailer pricing because of higher cost-effectiveness of trading. None of the batteries reached 500 cycles what according to the manufacturer will allow operation for more than 10 years. Furthermore, taking into account decelerating characteristics of the degradation process life of such batteries may possibly reach even 15 years.

The impact exerted by an operating VPP on the is negative from the transformer loading point of view. VPPs with all household compositions and operated in behaviour schemes involving trading always generated transformer overloads with lower penetration of EES systems and PV systems than the households in which EES systems were operated in the power demand driven scheme. The DSO may have to limit the number of households participating in the project, upgrade the transformer or collaborate with the VPP owner to create behaviour scheme which would not generate overloads.

It was found that the big number of shallow or short overloads may overlap with small number of deep and long overloads making the results insensitive to the severity reflection. However, the total number of overloads and the average transformer loading did provide some insight to evaluate if the influence of the VPP is harmful.

Bidirectional characteristics of phenomena occurring in the grid especially in the scenarios involving trading made the established penetration thresholds similar in value for extremely different household compositions.

7 Recommendations

The recommendations as some parts of the work are divided into more economical and technical. Some of them go beyond the boundaries of the case study and the City-Zen project and some of them are more to it related. In general the possibilities of expansion of the model are enormously broad, interesting and promising.

1.

The VPP can be modelled with bigger number of households, however to an extension of the households types population is recommended. The portfolio of the construction types can be extended by offices, malls or other buildings. The model can be extended with other physical storage devices technologies, especially cheaper technologies could create more business cases for the VPP concept. Moreover, the size of the battery for particular case study may be optimized.

The collaboration scheme between the VPP and the DSO can be developed. Such collaboration scheme could allow the DSO to avoid costly grid upgrade which would be necessary if the VPP would act without any limitations. This may mean lost revenues for the VPP owner, which may be smaller than the grid upgrade. This economical flexibility creates base for collaboration between the parties. This goal is especially reachable, because a VPP model which runs load flow calculations on the time step basis and is capable of reacting on the situations occurring in the grid was already created but was not used in the current work.

The complexity of the interactions between the household owner and the retailer can be increased. The retailer may use tariffs or some fixed pay rate on top of the energy market prices. This extension would lead to more realistic reflection of the economical situation of the VPP and may create more business cases.

After preliminary simulations the fixed prices' thresholds strategy turned out to be more effective for the Dutch Energy Imbalance Market, however more simulations can be made to evaluate the changing state of energy trading strategy more accurately. Furthermore, other more sophisticated trading strategies may be developed. Another energy markets may be added to the model in order to facilitate more complex revenues stacking.

In order to make the economical evaluation more precise more factors can be added. The cycles costs can be estimated and based on them the CVPP could decide if particular action is cost-effective. Furthermore, the operation and maintenance costs should be added. The forecasting functionalities would also make the CVPP decision making processes more realistic.

2.

In order to improve the physical impact evaluation different measures of the transformer overloading severity have to be utilised. Furthermore, the bidirectional observation of the transformer loading is recommended in order to have a full insight in the phenomenon. What is more other network parameters should be observed especially the voltage levels and voltage imbalance. In this case the influence of different EES systems connections' configurations on the voltage imbalance can be measured.

In the model no TVPP functionalities were included. The TVPP functionalities would allow taking into account the influence of the distribution grid like losses or other distribution grid limitations on the business case.

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