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Renewable energy communities

Analysis of the technical impacts on the low-voltage grid

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Abstract

As a result of the energy transition, the low-voltage distribution networks are penetrated more and more by technologies such as solar panels, electric vehicles and heat pumps. However, the current grid was not initially designed to support such loads and their development raises more and more issues. In this context, the regulation of voltage fluctuations, unbalance levels and of the overloading of the components is now more crucial than ever.

The aim of this master's thesis is to analyse how the emerging concept of renewable energy communities could help alleviate technical constraints, resulting from the penetration of photovoltaic panels, electric vehicles and heat pumps in the low-voltage distribution network. To achieve this, a model was designed to represent a Belgian rural street composed of twenty houses.

Based on time-series simulations in *PandaPower*, the results from multiple asymmetric three-phase power flows compare the implementation of community-shared storage units to the development of privately-owned batteries, while considering different penetration levels for the studied technologies. The main findings include that, depending on the scenario and the penetration level, the implementation of private batteries outperforms the concept of community-shared storage. While the first option decreases the maximum unbalance levels by up to 55%, the second one only reaches 14%. However, the implementation of shared storage units still results in a greater reduction of the average load factors across the community, due to the smaller amount of energy that is fed back into the higher voltage grid.

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Acronyms

COP Coefficient Of Performance

CWaPE Wallonian Energy Commission

DHW Domestic Hot Water

EU European Union

EV electric vehicles

HP heat pumps

P2P Peer-to-Peer

PV photovoltaic

RE Renewable Energy

REC renewable energy communities

SGEN static generator

SH Space Heating

SOC State Of Charge

Chapter 1

Introduction

The European power grid is a continuously evolving environment: new technologies emerge regularly and policies never stop changing. In Belgium, many recent decisions have shaken the energy system: uncertain future for nuclear energy, ban on diesel cars in big cities, prosumer tariff for owners of photovoltaic (PV) panels. The energetic transition is here, and the Belgian energy system is undergoing a major revolution. As a result, solar panels, electric vehicles (EV) and heat pumps (HP) are expected to become widespread in low-voltage distribution networks in the coming years[1; 2; 3]. However, the current distribution network was not originally designed to account for such big loads and decentralised generators. Therefore, the infrastructure does not optimally manage the excess energy fed back into it. Voltage fluctuations and unbalance levels are higher than ever, regularly causing the disconnection of PV systems, preventing re-injection and resulting in a direct loss of produced energy and money.

To prevent this, the Flemish government gives out funds so that the owners of PV panels can equip their houses with private batteries. However, the emerging concept of renewable energy communities could potentially better address the problem thanks to shared means of storage. Their ways of operating diverge: in the first option, the isolation of the decentralised producers from the local grid is promoted. In the other, the nuisances are used to procure an advantage to an entire community.

This master's thesis aims at comparing how these two solutions perform at reducing unbalance levels and voltage fluctuations in local distribution networks where PV panels, electric cars and heat pumps are common. To do so, two research questions are addressed:

- What is the impact of the implementation of private vs. shared means of storage, in a futuristic low-voltage distribution network ?

- What is the impact of the penetration levels of PV panels, electric vehicles and heat pumps on the proposed solutions ?

The early development stage of renewable energy communities shows the innovative aspect of this work. Indeed, even though some foreign countries, such as Germany or Denmark, already have long-term experiences with renewable energy communities[4], the concept is only present in Belgium through a few pilot projects. Therefore, the general context around such communities and the current state of the Belgian legal framework is first developed in Chapter 2; alongside with a few technical reminders designed to help the readers get acquainted with the tools and concepts used throughout this work. Subsequently, Chapter 3 delves into the different methods used regarding the implementation of the studied model and the simulated scenarios. The results are then presented and analysed in Chapter 4.

Chapter 2

State of the art

First and foremost, it is interesting to delve into the general context around this work and to remember some of the key concepts that are necessary for the good understanding of this thesis.

2.1 General context & legal framework

The recast of the Renewable Energy Directive (2018/2001/EU), also known as RED II, entered into force in December 2018, as part of the Clean energy for all Europeans package. This directive aimed at keeping the European Union (EU) a global leader in renewables and, more broadly, helping it to meet its emissions reduction commitments under the Paris Agreement.[5] The article 22 of RED II focuses on the emerging concept of renewable energy communities (REC). Particularly, it states that the citizens of the Member States are entitled to take part in RECs without being subject to either unjustified or discriminatory conditions or procedures which would prevent their participation. Furthermore, such communities have the right to:

- produce, consume, store and sell energy from renewable sources, including through renewable power purchase agreements;
- share, within the renewable energy community, the renewable energy that is produced by the production units owned by the renewable energy community;
- access, in a non-discriminatory manner, all suitable energy markets both directly or through aggregation.[6]

Also, the Member States are required to provide, by the end of June 2021, an enabling framework for RECs, which shall notably ensure: the availability of tools designed to facilitate access to finance and information; that the relevant distribution system operator cooperates with the communities or that unjustified regulatory and administrative barriers are removed.

Besides the RED II, other directives support the concept of RECs. For example, the Directive on common rules for the internal electricity market (2019/944/EU) includes new rules that enable active consumer participation, individually or through citizen energy communities, either by generating, consuming, sharing or selling electricity, or by providing flexibility services through demand-response and storage. Just like the RED II, this directive aims to boost and facilitate the development of energy communities and make it easier for citizens to integrate efficiently the energy system, as active participants. A desired impact of these decrees is to empower RECs as they will help improve energy efficiency in households, support the use of renewable energy and, at the same time, contribute to fighting poverty through reduced energy consumption and lower supply tariffs.[7]

In Belgium, the implementation of the EU Directives varies between the three regions, since they have different legal transpositions. Hereafter, multiple aspects of the regulatory frameworks of each region are presented.[8]

- **Brussels Capital Region:**
  The Brussels Capital Region transposed the EU framework on energy communities and energy sharing with the ordinance of 17 March 2022. The decree defines «Local Energy Communities». For these, production, consumption, storage, and sharing should take place within the energy community, and is limited to renewable energy. In this region, the energy consumption within a community is not considered as collective self-consumption but as a supply of energy. Thus, supplier licences are required. Brugel, the regulator, is mandated to supply these licences and to regulate the tariffs of the energy exchanges. Also, in the two years leading up to the adoption of the ordinance, Brugel and the Brussels government have introduced exceptions for a few pilot projects.[9]

- **Flanders:**
  Here again, the regulator decides of the tarification of the exchanges. Additionally, the members of the energy community who inject energy in it, are not allowed to sell energy to other members anymore, unless they apply for a supplier licence. The complexity of the legislation does not encourage market actors to develop dedicated products and services. Hence, there is no actual market development and the phenomenon currently remains marginal in this region.

- **Wallonia:**
  The framework adopted by the Wallonian government defines RECs as communities that produce, consume, store and sell renewable electricity for the benefit of participants at the local level using the public network or a private grid. The decree also defines the notion of a «local perimeter», which is determined by the government after having consulted the Wallonian Energy Commission (CWaPE) and the network operators.

Hopefully, the previous information successfully demonstrated that, even though RECs are still in their early age, there is already a real political engagement around them. However, all the notions and regulations are very complex, especially in Belgium because of its complicated political structure. A literature review, aimed at identifying the existing barriers and potential benefits f renewable energy communities, was carried out. Since the review does not strictly fit the scope of this thesis, it was added in Appendix A.

Finally, it interesting to note that pilot projects already exist in Belgium. For example, HospiGREEN[10] was launched in November 2020. This project is promising as the members have already observed a reduction of up to 10% of their energy-related costs.[11] The MéryGrid microgrid is also a pilot project for the development of RECs; and many other communities are being studied, like in Hannut, where the city plans to build an energy community to reduce the energy bill of 800 households.[12]

2.2 Technical background

2.2.1 Power quality in low-voltage distribution networks

Solar voltage rise

The solar voltage rise is a relatively new issue linked to the penetration of photovoltaic systems in the power grid. Even though the phenomenon is observable for every PV installation, it is only becoming more and more problematic in low-voltage distribution networks, as this part of the network was not designed for excessive power generation. This issue can be illustrated thanks to simple electrical notions. The current flows from the higher voltages to the lower ones. So, when the PV system of a house is producing more than it can consume, the inverter that connects the PV installation to the grid has to increase the voltage of the generated electricity, so that it can flow back into the grid. This results in a voltage rise on the inverter side, but also in a more moderate one in the grid. The effect of a single PV farm is not harmful for the network. However, when there is too much solar generation in a same area of the grid, these small increments add up: the voltage keeps rising, and the PV inverters need to increase the voltage even more. This can result in a significant increase of the voltage magnitude of the grid. At some point, this effect can become dangerous for network components and appliances. For example, the inverter turns off once the voltage reaches a certain threshold. When the inverter is disconnected, the excess energy is not fed back into the grid, causing a direct loss of energy, and thus money, for the owner of the installation. Also, the disconnection of the inverter results in a decrease of the grid voltage, which can then stabilise again under the disconnection threshold of the inverters, which will then turn on again... until the voltage rises too much. This is known as inverter cycling, which can result in decreased lifetime of the component.[13]

Voltage Unbalance

Nowadays, the majority of the households are connected to a single phase of the distribution network. If these single-phase loads are unevenly distributed among the three available phases, then significant voltage unbalances can occur as this phenomenon is nothing more than a variation of the voltage magnitudes and/or phase angles between phases.[14] Therefore this power quality issue only affects poly-phase systems, such as the three-phase distribution network. Voltage unbalance can have harmful impacts if they are not addressed properly, as they can travel upstream and damage induction machines for example. This undesired phenomenon can indeed result in much higher current unbalances which will cause various power system components to overheat. Another fact to consider is that voltage unbalances are increased by the voltage drop encountered in distribution networks as one moves away from the supply source. This explains how the loads located at the end of distribution lines are more subject to voltage unbalances than the ones located closer to the feeder. This needs to be avoided since excessive levels of unbalance can also damage households appliances.

In order to evaluate the levels of voltage unbalance, one needs to first calculate the symmetrical components of the voltage thanks to the Fortescue transformation. Then, the unbalance levels are defined as the ratio between the negative-sequence or the zero-sequence components, and the positive-sequence component. This yields the negative-sequence or the zero-sequence voltage unbalance, respectively, as defined by the IEEE.[15]

Overloading of components

A last aspect to take into consideration is the loading factor of the multiple components of the network (transformers, lines, etc). Indeed, the current distribution network is quite old, and was not originally designed to account for massive loads such as electric cars or heat pumps; nor was it designed to take care of the massive decentralized generation caused by domestic solar panels. Eventually, the current network will not be able to support what is required of it: the cables will not support the massive currents anymore, the transformers will not be powerful enough anymore or they will overheat. This is a crucial aspect that needs to be taken into account when (re)designing power systems. To evaluate the constraints imposed on the components, the load factor is a simple, useful notion. Basically, each component is designed to work within a specific range of values for different variables: cables have a limited maximal current they can support, for example. Their loading factor is thus defined as the current that is actually flowing through them, divided by the maximal current supported. Therefore, a loading factor that is very low translates an oversized cable, while a value over 100% highlights an overloaded line. Above that percentage, the component is exposed to technical failures and accelerated wear, both can result in important damage of the network and the connected loads.

Norms

Many of the aspects presented previously are strictly regulated, notably by the EN 50-160 standard. This norm sets low-, medium-, and high-voltage supply characteristics. In the context of this work, it is interesting to look at the regulations surrounding the low-voltage network.

First off, it is stated that the standard nominal voltage U_n for public low voltage is $U_n = 230$ V, either between phase and neutral, or between phases, for four-wire and three-wire three phase systems respectively. Under normal operating conditions (excluding the periods with interruptions), supply voltage variations should not exceed ± 10% of the nominal voltage U_n. On top of that, the negative-sequence unbalance levels should not exceed the value of 2%, for more than 5% of the time.[16]

The standard also regulates other aspects such as the changes in frequency, flicker severity or harmonics; but these are not considered in this work.

2.2.2 Three-phase power flow analysis & time series simulations on *PandaPower*

Let us now present the tool used for the many simulations of this work. This section provides a few insights on how *PandaPower* runs time series simulations and asymmetric three-phase power-flow analyses. The following information is based on the *PandaPower* documentation, available online.[17]

Power flow analyses are a powerful tool used in power systems. They are a numerical analysis of the flow of electric power in an electrical system. A load flow study is also an assessment of the steady-state conditions of the electrical system, whose goal aims at evaluating the flow of real and reactive power, current and voltage under any load conditions. These analyses are necessary during the design phase of a new project or when evaluating changes and additions to existing electrical systems. That way, one can ensure that the system voltages and currents remain within safe limits, for example.[18]

In *PandaPower*, three-phase load flows are solved using a sequence frame solver, based on the Newton-Raphson method. First, the system's components are replaced by equivalent circuits. Lines are modelled using the π-equivalent model, and transformers can be modelled by T-equivalent or by π-equivalent circuits. Loads and generators are modelled as PQ-buses, i.e. buses for which both active and reactive power are specified. The analysed network is thus converted in the symmetrical components frame. However, the resolution of the load flow requires the definition of certain parameters inside the model. The zero-sequence impedance parameters need to be added to the model of lines, and the transformers require the addition of their zero-sequence relative short-circuit voltage as well as the zero-sequence short circuit impedance of their high-voltage side. For this project, these values have been picked from similar work available on the *PandaPower* GitHub. The evaluation of these values is a real challenge and this data was difficult to obtain. This constitutes one of the limitations of the presented work.

For this project, load flows were simulated every fifteen minutes, for an entire month. This represents 2976 load flow analyses and the use of time series simulation was required. In *PandaPower*, when a time series simulation is started, a loop is started. That loop iterates over every time step. During each step, a control loop is started for each controller. Within the control loop, the controlled variables (power consumption and production in this case) are updated by the controllers. Figure 2.1 shows the time series loop used in this type of simulation. It highlights how the time series loop is the master loop while the control loop is the slave loop. Also, it clearly shows that inside the slave loop, the power flow analysis is called right after the controlled variables are updated.

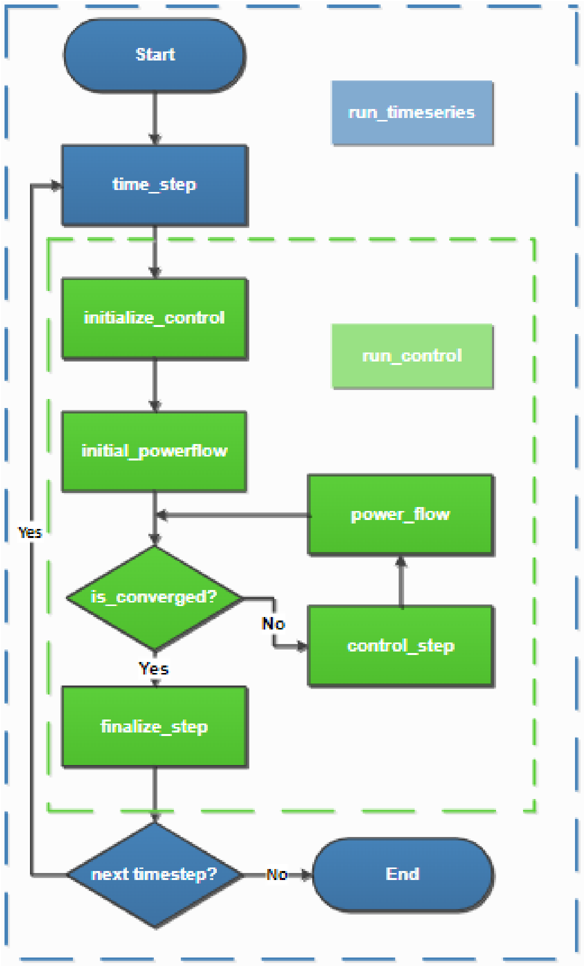


Figure 2.1: *Block diagram of a PandaPower time series simulation. The run_timeseries loop is the master loop and iterates over each time step. The run_control is the slave loop. It is used for updating the values of the controlled variables and then for running a load flow analysis.[17]*

The three-phase power flows give out a massive amount of data such as: the voltages at the different buses, the active and reactive power consumed/generated by each load/generator, the power extracted from the grid, the loading percent of each component and their power losses. All the data obtained through this work is analysed in Chapter 4; but before jumping into that, Chapter 3 will detail the methods used in this work.

Chapter 3

Methods

In this work, the concept of energy communities is analysed in a Belgian low-voltage network. Different consumer profiles and different technologies can be found in the community, such as PV panels, EVs and HPs. Multiple scenarios and cases have been analysed. Depending on those, the penetration levels of the previous technologies are adapted. This leads to a large collection of data, which is then used for the different simulations that were run.

The first section (3.1) explains in more details how the separation into cases and scenarios works. After that, Section 3.2 thoroughly describes the modelled network. In Section 3.3, the different technologies are presented one-by-one and in detail: for each, assumptions and load profiles are provided before being discussed. Finally, Section 3.4 describes thoroughly the different scenarios and cases.

3.1 Description of the setup

This section describes in more details how the separation into scenarios and cases works. It provides a first insight on how this project is divided. The explanations are thus purposely fairly general. More complete explanations are provided for each scenario in Section 3.4

First, the different scenarios determine the penetration level of the various technologies implemented in the community.

- **Scenario 1** models a common street, where none of the different energy technologies are implemented, i.e. there are no PV panels, no EV and no HP. Such streets can still be found nowadays even though these systems and appliances become more and more common in developed countries.

- **Scenario 2** models the same street in 2050, resulting in the implementation of new technologies in the community. Their different penetration levels have been determined based on multiple sources, which will be discussed in Section 3.4.2.

- In **Scenario 3**, the houses either have none of technologies implemented (like in scenario 1) or they are fully-equipped, i.e. they have all of them. The penetration level of the fully-equipped houses varies in order to study how renewable energy communities are impacted by the penetration level of the studied technologies.

On the other hand, the cases determine the way storage options are used in the community, as follows:

- **Case A:** There are no storage options implemented in the community. The energy needed is always drawn from the grid, and the excess production (from solar panels) is fed back into it.

- **Case B:** Some storage options are implemented, at an individual level. The only houses that can benefit from these storage options are those equipped with PV panels. This storage unit is modelled by a battery, which can thus store part of the solar production of the house it is connected to, and release the energy stored when the demand of that house is high.

- **Case C:** As for case B, a storage unit is implemented in the community, but this one is shared by all individuals from the REC. The excess energy, produced by all PV installation, is stored in a shared battery. This energy can be fed back into the grid when the total demand of the community is high. This way of storing energy is really representative of energy communities: in this work, the concept of REC is studied thanks to the analysis of case C.

Note that in this work, the studied means of storage are modelled via the implementation of batteries, in order to cope with the solution proposed by the Flemish region. However, the results shown later in this work can be translated to other means of storage, which could be more eco-friendly. This would for sure imply a slight modification of the results because of other technical constraints such as efficiency for example, but the impact of the shared storage unit would remain identical.

Note also that for scenario 1, only case A is simulated as there are no PV panels and thus no batteries. For scenarios 2 and 3, all three cases are simulated.

A last segmentation is found in scenarios 1 and 2. They both simulate and compare the two most extreme months of the year, January and July. In January, the heating demand is high, and the solar production is very low. On the contrary, the PV panels produce a lot of energy during July, and the heating demand is almost nonexistent. Scenario 3 only focuses on the month of July as the PV production is much higher than compared to January.

3.2 Modelled network

The studied network is a low-voltage residential grid, which is connected to the main grid via a transformer. The community uses 12 electric lines, which are used to connect the external grid, the transformer, the loads and generators together. The multiple loads represent the 20 houses that the street is made of. On top of that, the PV installations are modelled as generation units. All loads and generators are connected to the network at specific connection points, the buses. There are 14 of them. A graphic representation of the entire system is depicted in Figure 3.1.

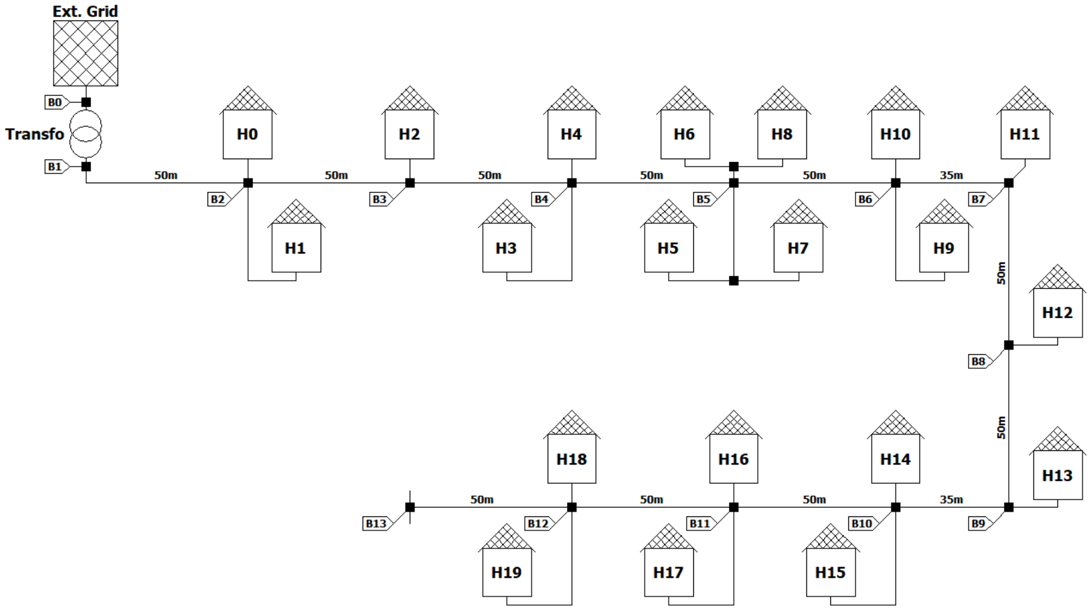


Figure 3.1: *Schematic representation of the modelled community. Houses are numbered "Hx" with* $x \in [0:19]$*. The same logic is used for all 14 buses, which are named "Bx" with* $x \in [0:13]$*.*

The habitations are divided into three different categories: "Retired" (just a couple of retired people) , "Family" (big family of five) and "Workers" (young couple with no kids). The 20 houses are separated into these three categories according to the following distribution:

- 5 houses belong to the "Retired" group,
- 8 houses belong to the "Family" group,
- 7 houses belong to the "Workers" group.

The repartition into these groups has been made pseudo-randomly. Depending on the scenario, the houses have different loads, and thus different load profiles which are further developed in Section 3.4.

3.2.1 Practical implementation of the model in *PandaPower*

This section dives deeper in the modeling of the studied community, detailing the characteristic values of each elements as well as some other aspects of the model in the *PandaPower* python package.

External grid

The external grid is a vital component of the network. It serves as slack node, i.e. it is used to balance the active and reactive power of the community while performing power flow analysis. In the studied REC, the external grid is connected to the bus "B0". The external grid represents the higher level power grid, which is why the nominal voltage of the bus "B0" is $U_{n,B0} = 20\text{kV}$.

Transformer

The transformer ensures the connection between the bus "B0" on the high voltage side and the bus "B1" on the low voltage side. Thanks to the transformer, the nominal voltage of is stepped down to $U_{n,B1} = 400\text{V}$. Table 3.1 summarises these values as well as the apparent power, S, and the iron losses of the transformer.

HV Bus	$U_{n,HV}$ [kV]	LV Bus	$U_{n,LV}$ [kW]	Apparent Power [kVA]	Iron Losses [kW]
B0	20	B1	0.4	630	1.65

Table 3.1: *Characteristic values of the transformer.*

Buses and lines

The community is composed 14 buses. Except for the bus "B0", all buses have a nominal voltage of $U_n = 400\text{V}$. The electric lines used to connect all the buses with each other are designed after the "94-AL1/15-ST1A 0.4" standard type, found in the *PandaPower* library, which provides the values for the cable section, maximum admissible current, as well as impedance values per length unit. Table 3.2 summarises these different values. The lines are 50m or 35m long.

R [Ω/km]	X [Ω/km]	C [nf/km]	∅ [mm^2]	I_{max} [A]
0.306	0.35	10	94	350

Table 3.2: *Characteristic values of the electric lines. In order: resistance, reactance, capacitance, cross-section, maximum admissible current.[19]*

Loads & generators

In *PandaPower*, the houses are represented by asymmetric loads (mono-phased). If in a certain scenario, a house is equipped with a PV system, then it is incorporated in the code as an asymmetric static generator (SGEN).

So the habitations are all mono-phased and are thus connected between a certain phase and the neutral. The phase they are connected to alternates after each house: the first house is connected to phase A, the second to phase B, the third to phase C, then the fourth is connected to phase A again, and so on. This is done in most residential areas. The PV installations are also mono-phased and are connected to the same phase as the house they belong to.

Storage

Depending on the simulated case, some storage units are added into the community. The component modelled in *PandaPower* is only designed for balanced three-phase systems, and is thus not suitable for the asymmetric system that the community is. To overcome that challenge, storage units are modelled by the implementation of an asymmetric load and an asymmetric SGEN in parallel. The load models the storage of the energy while the generator takes care of the energy that is released from the storage unit, modelled by a battery. In the case of a community-shared battery bank, it is assumed that the technology allows to absorb power from all phases and feed it back into different phases as well.

Controllers

Controllers are crucial components of the model. These modules allow to set and update the value of a certain parameter. In this project, many controllers are used to impose the power consumption and generation for all loads and PV units as this projects simulates the energy exchanges of the community over a month. Controllers are also responsible for managing the charge and discharge of the batteries. All values are updated every fifteen minutes. Without the controllers, these month-long time series simulations would not be possible.

3.3 Implementation of the different technologies

3.3.1 Photovoltaic panels

Photovoltaic panels have been around for many years, and they will most likely still be around by 2050. In fact, the Walloon Region still provided monetary incentives for the installation of PV panels in 2022.[20]

In the community, all PV installation have the same size of 4kWp. This is a fairly average size for a residential application, and it corresponds to the upper limit for the monetary incentive of 300€/kWp, granted by the Walloon Region. Above that value, the incentive is degressive. Above 6kWp, no more grants are accorded.[20]

After the penetration level and the size of the installations, the power production curve still needs to be established. Multiple sources have been reviewed (Elia[21], NASAPower[22]) and the final choice fell on *Renewables.ninja*, which provided a complete set of data for the solar irradiance at a precise location (Louvain-La-Neuve, Belgium) for the year 2019, as well as the corresponding electricity output based on the PV system characteristics. The weather data is supported by NASA MERRA reanalysis[23] and CM-SAF's SARAH dataset.[24; 25] The solar irradiance data is converted into power output using the GSEE model (Global Solar Energy Estimator), written by Stefan Pfenninger.[26]

Figure 3.2 shows the power generation curves of one of the 4kWp PV installations modelled in the scenarios. It compares the daily production of January, 3^{rd} with that of July, 3^{rd}. These curves are quite representative of the general aspect of the generation curves of the PV systems.

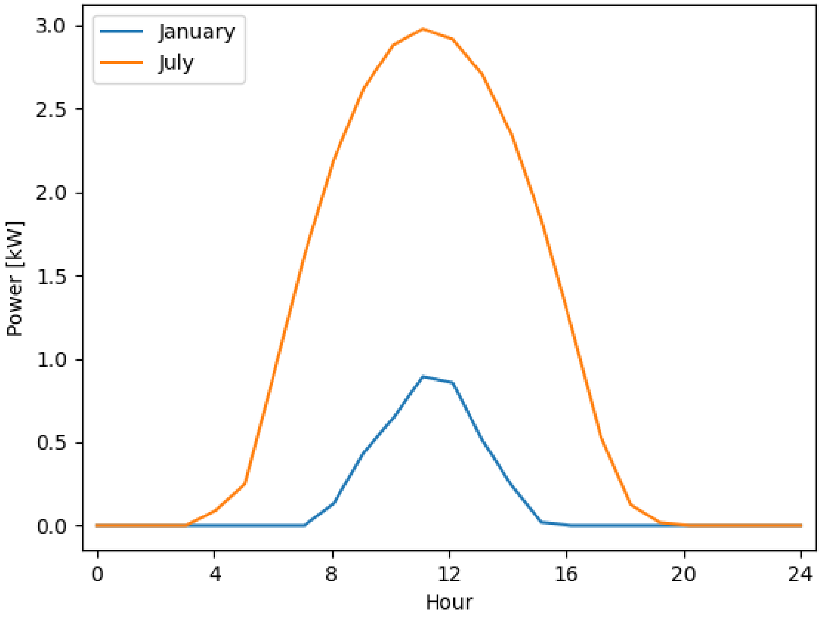


Figure 3.2: *Daily power generation curves of photovoltaic panels for January and July 3^{rd}, 2019.*

3.3.2 Electric vehicles

Nowadays, electric vehicles occupy about 0.6% of the private cars fleet in Belgium.[27] By 2050, the U.S. Energy Information Administration projects that EV fleet shares will reach 34% in OECD (Organization for Economic Cooperation and Development) countries, which includes Belgium.[3]

The load profile resulting from EV charging is based on multiple factors such as the traveled distance, the consumption of the vehicle or the time of the day at which the user plugs his car in order to charge it. Figure 3.3 shows a normalised curve for the charging of an electric vehicle. This specific curve charges a total of 1kWh between 4PM and 4AM on the next day. This profile is a simplified model from those observed in other articles.[28; 29]

Here is how this normalised curve is adapted to the different profiles of the households:

- **"Retired":** This type of household has a reduced need for transportation which justifies that only one car is at disposition. As for the need in electricity, it is assumed that the traveled distance does not vary between weekdays and weekends. This category is expected to travel 35km everyday on average, which falls merely above average according to Statista[30]. The average consumption of EV being 200Wh/km[31], the actual load curve is easily obtained by scaling the normalised curve of Figure 3.3 to an overnight charge of 7kWh.

- **"Workers":** Houses of this group are in most cases in possession of two cars. Also, the distance traveled by each car on weekdays is defined by the average commute to work of 23km in Belgium[32]. Based on that, it is assumed that this group travels 50km daily with each car. This value covers travels to and back from work as well as a few extra kilometers to do some shopping or other activities. On weekends however, workers usually travel a bit less as they are more prone to stay at home for chores, as it was assumed in Section 3.4.1. On weekends, the expected distance traveled is thus scaled back down to the average value of 35km per car, provided by [33]. The load curve is then obtained following the same methodology as previously.

- **"Family":** As for the "Workers", this group is assumed to possess two cars. The distance traveled on weekdays is also assumed to be only based on the commute to work. We thus obtain the same value of 50km during weekdays per car. However, during weekends, this category is more prone to have more distance to cover as kids usually have extra-curricular activities. Based on this, the cars of this group are expected to travel 50km on weekends as well. The daily load curves are obtained with the same methodology as for the other categories.

A last factor weighs in the load curve of EV charging. Indeed, variability is added in the model as all cars do not start charging up at the same time. The different vehicles start loading up at different times between 4:00PM and 6:30PM.

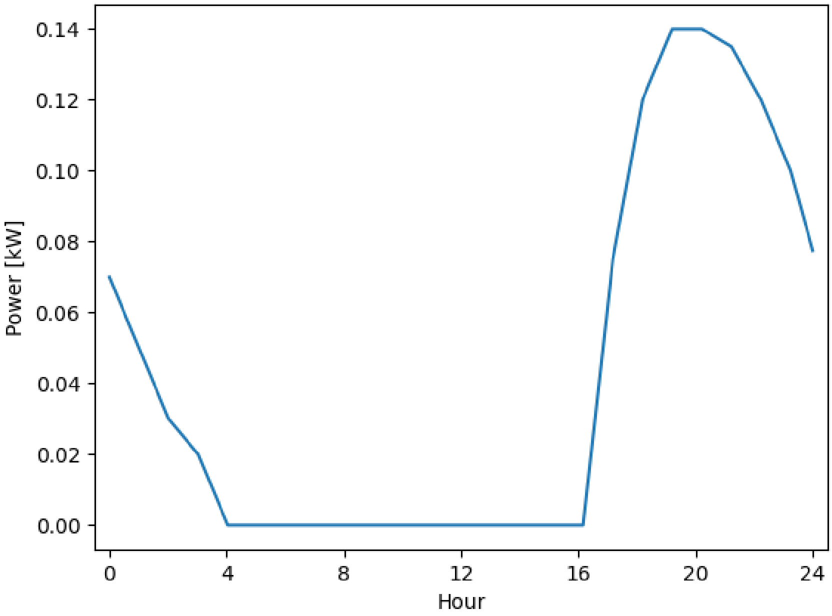


Figure 3.3: *Normalised EV charging curve, starting at 4PM. Normalised to a 1kWh charge overnight.*

3.3.3 Heat pumps

Thanks to this technology, the inhabitants of the community are provided with an alternative to standard heating systems that are usually powered by oil or gas. With the energy transition plan for 2050, fuel oil boilers are expected to be banned from sales as of 2035, as stated in the Belgian federal and regional energy agreement. Heat pumps are thus becoming more and more popular, as they are a very interesting alternative to conventional heating systems.[34] They also pair well with PV installations.

The implemented heat pump model is based on a method previously used in many works.[35; 36] The user demand for heat is based on data provided by the Open Energy Information[37] which provides hourly heat and electricity data per dwellings in cities across the US. Thanks to *Codeminders*[38], which compares meteorological data collected for over a century, the climatic equivalent for Brussels is found in Olympia, with a 99% overlap. Based on this, it is assumed that the demand in heating is comparable between the two cities. Hence, the demand curve from Olympia is used for our model.

Since the consumption profile of a dwelling does not only depend on the weather but also on the behaviour of its inhabitants (comfort temperature, heating habits, etc), the previously obtained curve is scaled down to the actual average demand in heating for Belgian dwellings. This value is provided by the Odyssee-Mure project[39], and the demand curves for Space Heating (SH) and Domestic Hot Water (DHW) are finally obtained for the community.

In order to translate the demand in heating to a demand in electricity, a standard model of an air source heat pump was selected: Viessmann Vitocal201-A06. Thanks to the provided datasheet[40], the Coefficient Of Performance (COP) curves as a function of the air intake temperature and the output temperature were retrieved. These curves are shown in Figure 3.4.

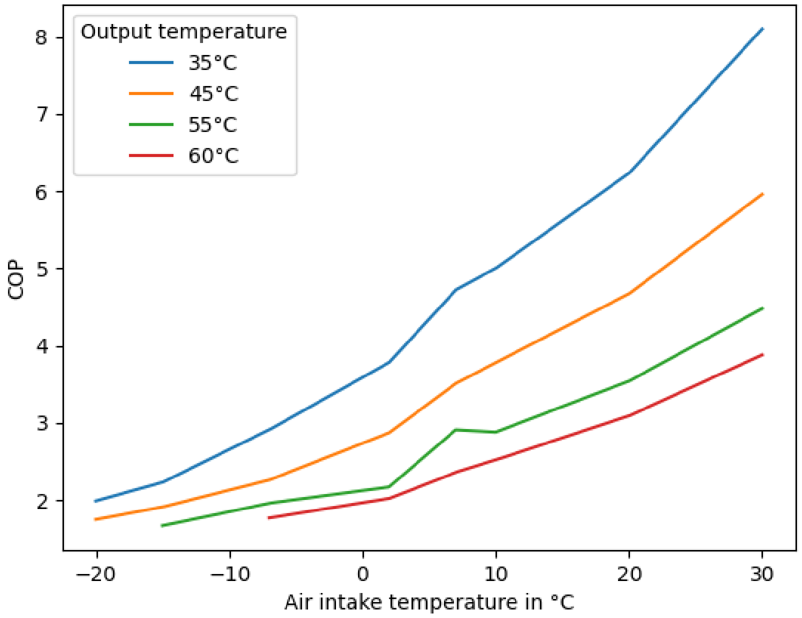


Figure 3.4: *Influence of the air intake temperature on the coefficient of performance of the Vitocal201-A06 heat pump, for different output temperatures (35°C, 45°C, 55°C, 60°C).[40]*

To finalise the HP model, desired temperatures of 45°C and 60°C were selected for space heating and domestic hot water, respectively. Thanks to the temperature data obtained by *Renewables.ninja* and the Viessmann COP curves, the total demand in heating (SH and DHW) can be translated into a demand in electricity.

Throughout the year, the average COP values for SH and DHW are 3.9 and 2.6, respectively. The annual electric consumption per dwelling required for heating purposes equals 5650kWh annually, with domestic hot water only accounting for 4% of that value. Also, the difference between January and July is enormous: per dwelling, a heat pump consumes 15.2% of the annual consumption during the month of January, compared to 1.7% during the month of July.

Figure 3.5 shows the daily load curve of the modelled heat pumps for a day of January and July. These curves are quite representative of the general aspect of the heat pump load curves. They allow to visualise the significant difference in power consumption between the two months. Also, one could notice that the HPs work at constant power for periods of one hour in January. This is actually due to the demand for space heating. The model of HPs, which are based on temperature thresholds, consume constant power over the period between set-points updates.

For space heating, these updates happen on an hourly basis. The curve representing the demand in domestic hot water is smoother. The «July» curve from Figure 3.5 does not show constant power consumption over periods of one hour, because the demand in space heating for that month is greatly reduced, and the total demand is thus governed by the need for domestic hot water.

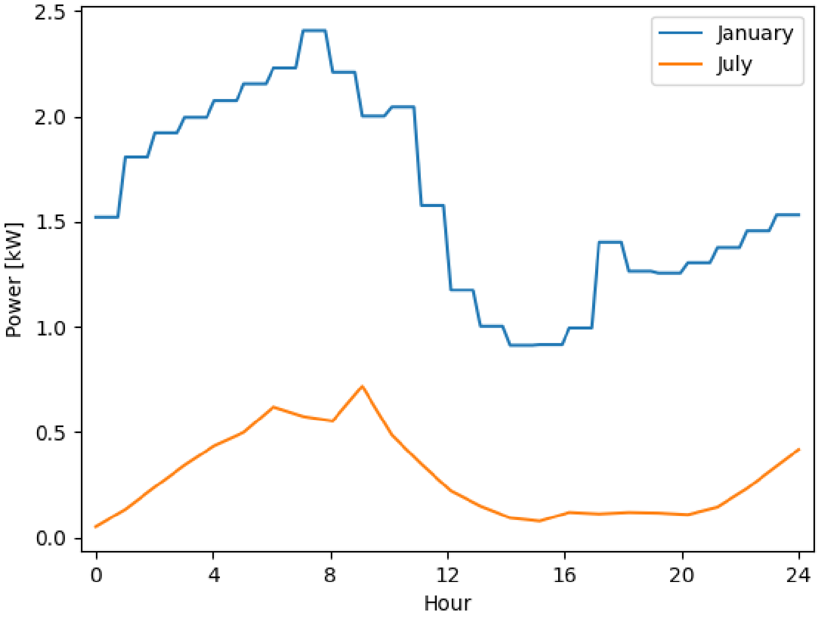


Figure 3.5: *Daily load curve of a heat pump for January and July* 1^{st}*, 2019.*

3.3.4 Discussion

Even though variation and realism have been incorporated in the models, they still have their limitations. The creation of technologies that truly reflect reality is only possible if the simulation uses actual measured data which is not the case here. Assumptions have been made, and variations have been introduced in the load profiles up to a certain degree. This raises the question whether the models are realistic enough or with enough variability. Some of the limitations of this work are:

- All PV installations are of the same size and are assumed to have the same orientation and thus, production. This does not reflect reality as multiple PV systems would have different orientation angles, some would have more shadow, some would be old and others would be new, some would be dusty while others would be clean. All these factors impact the final production of a PV unit which would introduce variations in the different energy fluxes across the community.
- All inhabitants of the community are assumed to have the same behaviour regarding space heating, hot water consumption and transportation, leading to identical demand curves. This is not perfectly accurate as each individual is different. For example, a certain temperature could be comfortable for some while it could be too hot or too cold for others. Another factor that influences heat demand is the level of insulation of the houses, and this has not been taken into account. Finally, it is obvious that the assumption that all houses of a certain type travel the same distance everyday does not reflect reality. Also, the need for transportation also depend much on work-related decisions such as work-from-home policies, which could change significantly in the coming years.
- Finally, the need for cooling has not been taken into account in this work, as it is not yet common in Belgium. However, it is possible that, because of climate change, the demand in cooling becomes important, and should thus be considered in future works.

A common message comes out of these different points: when it comes to consumption, each individual is different and will consume in his own way. This is also true for PV systems or for households: each have their specificity, which is not represented in this work.

3.4 Scenarios

In this section, the three scenarios are detailed. The multiple load profiles that come into play are also explained thoroughly. Note that throughout this work, the loads are considered as fatal. In order to evaluate the proposed solution, the consumption and the production of energy is known in advance for the months that are simulated. However, a certain level of variability has been incorporated in the different load profiles, as described hereafter.

3.4.1 Scenario 1

As previously mentioned, scenario 1 is very basic: none of the considered technologies are implemented. Thus, the consumer's load profiles are fairly simple. They are entirely based on an average load curve per house, in Belgium. This data was obtained via the *HomerGrid*[41] tool, which has a large collection of data. The profiles obviously differ between January and July. The average load curve obtained was then adapted to the three types of habitations.

Table 3.3 displays the different values of daily consumption for the different house types, for January and July. These are based on the desired annual consumption, which is also shown in the table. This annual consumption value represents how much a house would consume per year if all days were identical, e.g. if all days were weekdays. Based on this, the daily values are computed given the following equation:

$$\text{Daily consumption} = \frac{\text{Annual consumption}}{365}$$

The daily consumption values in January are 50% higher than in July, due to the higher demand for lighting and because of some electric heating appliances. This is taken into account in the computation of the annual consumption.

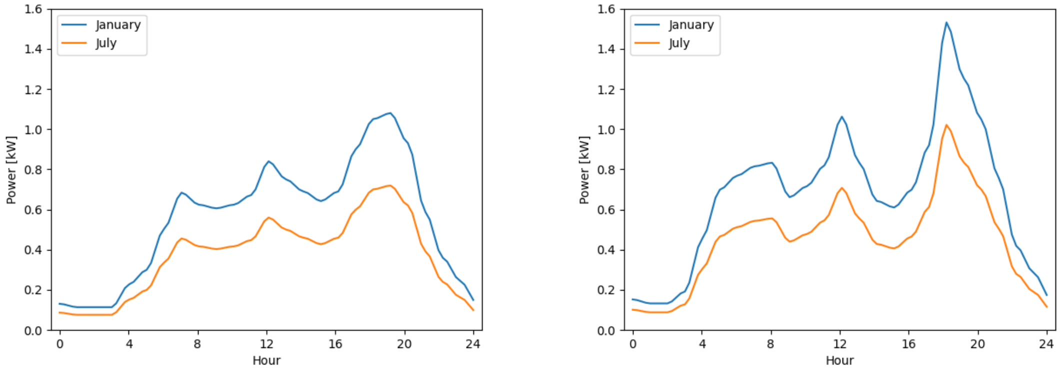
		Daily cons. [kWh] January	Daily cons. [kWh] July	Annual cons. [kWh]
Retired	Everyday	13.48	8.99	4100
Family	Weekdays	14.80	9.86	4500
	Weekends	16.44	10.96	5000
Workers	Weekdays	13.15	8.77	4000
	Weekends	16.44	10.96	5000

Table 3.3: *Daily and annual consumption values for the different house types (Retired, Family, Workers), depending on the month of the year and the day of the week.*

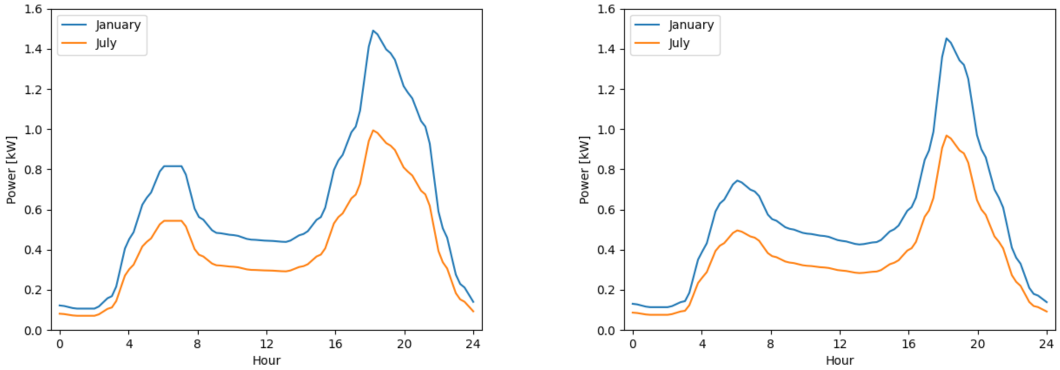
The "Retired" model has an annual consumption of 4100kWh, which is average. There are no differences between weekdays and weekends as these people do not work anymore and spend most of their time at home. The daily profiles for January and July are shown in Figure 3.6a. Three consumption peaks can be observed, around each meal time.

The daily consumption values of the two other groups are based on the annual consumption of the "Retired" profile. However, their daily consumption values vary depending on the day of the week. During weekdays, the house is left empty because children are at school and parents are at work. However, during the weekends, the consumption rises as most people are at home and take care of the various chores a household requires (washing clothes, clean the house etc). Also, Belgian households that have a certain electric meter benefit from reduced energy prices during weekends.[42] This encourages people to run their energy-intensive appliances during weekends, and not during weekdays. Therefore, "Family" and "Workers" types of houses both consume more during weekends, and their daily consumption is based on a 5000kWh annual consumption. Their identical daily load curves for January and July are shown in Figure 3.6b. Here also, three consumption peaks are noticeable around meal times.

During the week, the consumption profiles of "Family" and "Workers" houses differ, as the presence of kids obviously translates in a higher demand in energy: more rooms need to be lit up, more appliances are powered (computers, television), etc. Therefore, the daily consumption of a "Family" during the week is based on an annual consumption of 4500kWh. On the other side, a "Worker" type of house is expected to have a lower energy demand. That is why their daily consumption during the week is based on an annual consumption of 4000kWh. Both daily load curves can be observed in Figure 3.6c and 3.6d. The absence of occupants in the house during work and school hours is clearly noticeable due to the lower energy consumption and the absence of consumption peak around noon.



(a) *Retired - Everyday* **(b)** *Family & Workers - Weekends*



(c) *Family - Weekdays* **(d)** *Workers - Weekdays*

Figure 3.6: *Scenario 1 - Daily load curves for January and July for (a) the "Retired" group where there are no differences between weekdays and weekends, (b) the groups "Family" and "Workers" which both have the same consumption profile during weekends, (c) the "Family" group during weekdays, (d) the "Workers" group during weekdays. For all profiles, the daily consumption in January is 50% higher than in July.*

Finally, since there are no PV installations and no batteries, scenario 1 does not compare multiple cases as mentioned in Section 3.1.

3.4.2 Scenario 2

The second scenario models the same community as previously, but in 2050. By then, technologies such as PV panels, EVs and HPs are expected to be much more developed than they are now. They are all included in this scenario. The following paragraphs describe how their respective penetration levels have been determined.

- **PV:** The penetration level of this technology is hard to determine. While many numbers can be found in the literature, there is no clear scientific agreement. For this scenario, the choice fell on a penetration level of 40%, which seems reasonable. This is supported by the fact that the modelled community is made of single-family houses. The houses are all detached and have no adjoining neighbours. On top of that, rural areas are more likely to have a higher PV penetration level than urban areas.[43] Note that other penetration levels are also evaluated in scenario 3.

- **EV:** The modelled REC comprises a total of 35 cars. Considering the previously established penetration level of 34%[3], this scenario considers a total of 12 EVs, spread throughout the different houses of the community.

- **HP:** According to the AFPAC, heat pumps are expected to reach a penetration level of 50% by 2050.[2] In this scenario, this translates into ten houses being equipped with such heating systems.

Given these penetration levels, the community will host 12 electric cars, 8 PV systems and 10 heat pumps. Since these systems pair well with each other, they are spread in the community in the following way: all the houses that are equipped with PV panels also have a heat pump and an electric vehicle. This thus concerns eight houses. On top of that, two other houses benefit from a heat pump and an EV. Finally, two more houses only have an electric car. The rest of the houses remain identical to the first scenario, i.e. they have no added technologies and they thus have the same load curve as in scenario 1. The distribution of the different technologies across the community is illustrated in Figure 3.7.

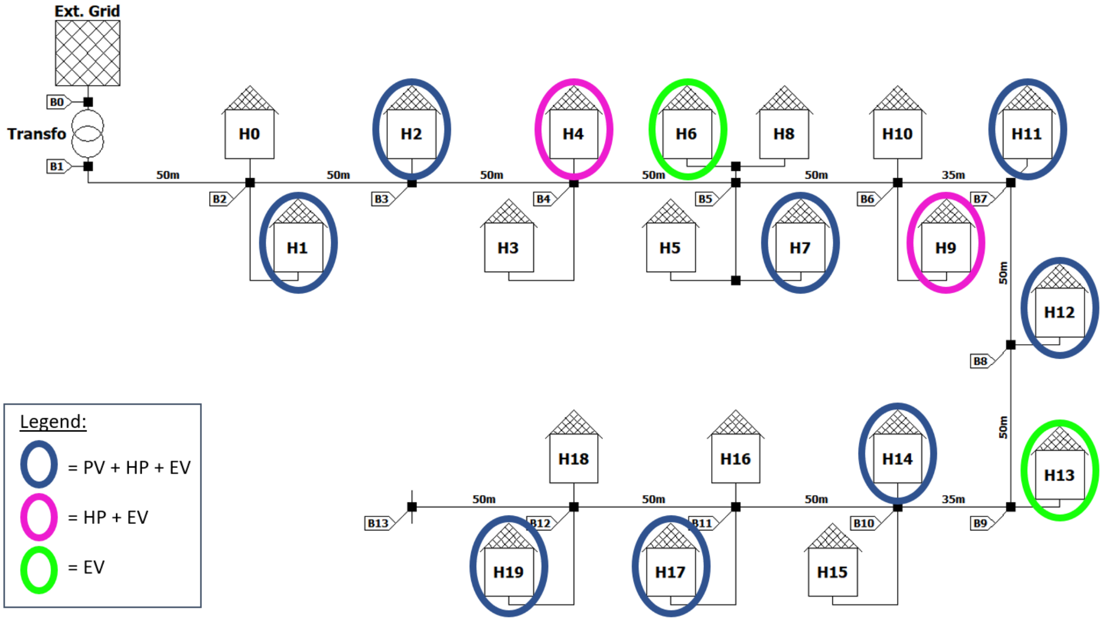
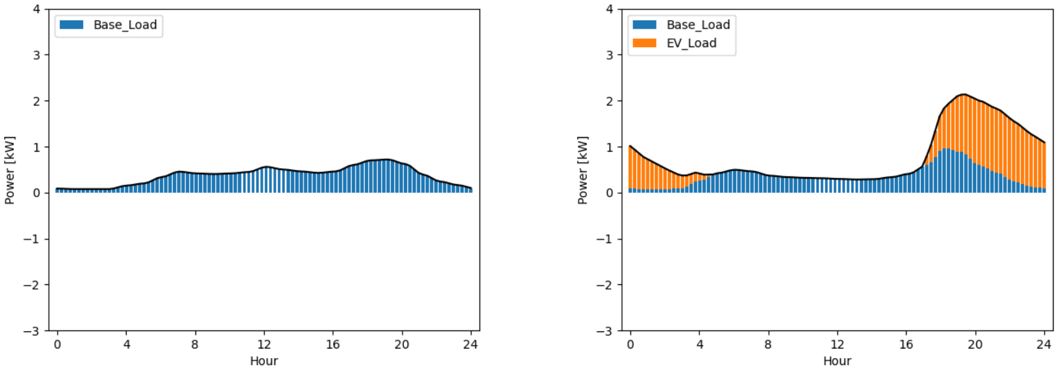
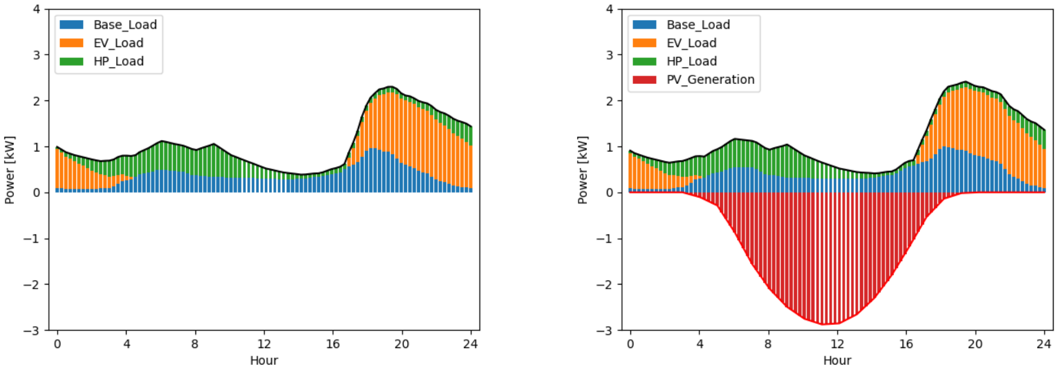


Figure 3.7: *Distribution of the different technologies in the modelled community. Houses marked by a green circle only possess an electric car. Those circled in pink have a heat pump and an electric car. The houses circled in blue have all three technologies: a PV installation, an electric car and a heat pump. The houses that are not circled do not have any additional technology compared to scenario 1.*

The load profile of each household is based on the base-load curve from scenario 1. That means that, at first, the consumption profile without any technology is considered. When a technology is added to a house, its corresponding load profile is superposed to the base-load curve. This can be done multiple times if a house possesses multiple technologies. In the end, the total load curves are obtained. This process is illustrated in Figure 3.8. House 0 does not have any technology added, so its load curve is the basic curve from the first scenario. House 6 has an electric car so the load profile from the EV charging is added onto the total demand curve. House 4 benefits from a heat pump and an EV, so both load curves are added into the model. Finally, House 2 has all of the technologies implemented. The generation from its PV panels is thus incorporated into the profile, as well as the curves for the heat pump and the electric vehicles. Note that the generation from the PV panels has negative values so that the convention is respected in the consumer point of view: positive values for consumed energy and negative values for produced energy.



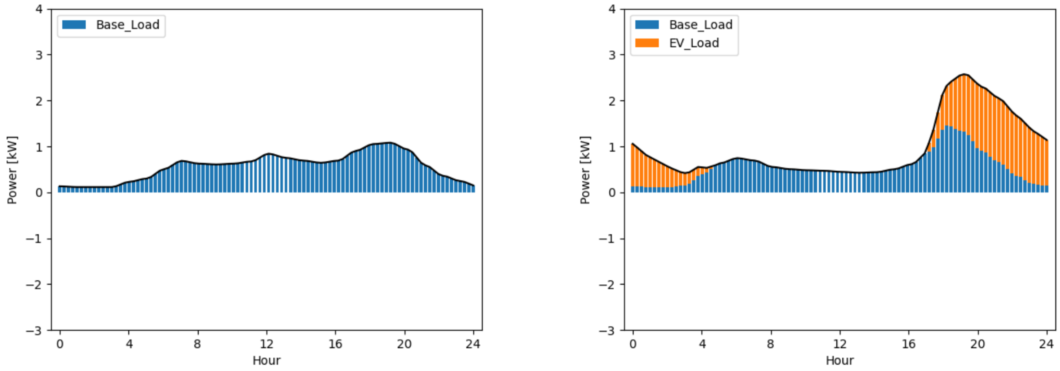
(a) *House 0* **(b)** *House 6*



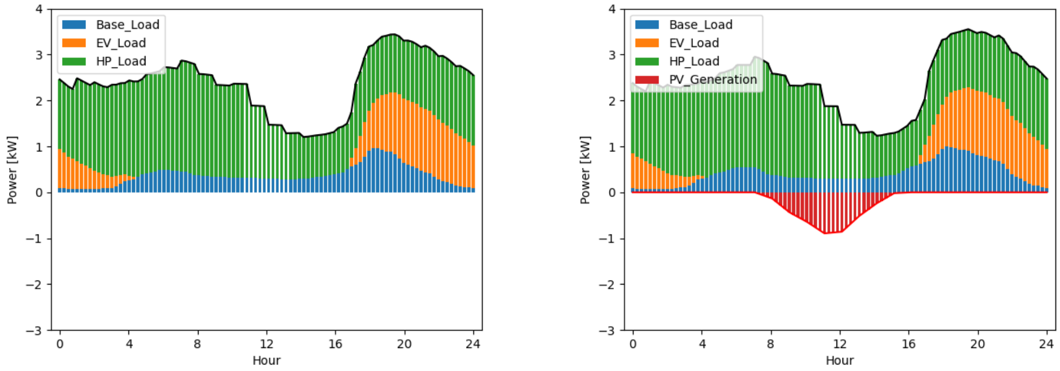
(c) *House 4* **(d)** *House 2*

Figure 3.8: *Total daily load curves of houses with different technologies for the month of* ***July*** *- Scenario 2. In (a), house 0 has no technology implemented. In (b), house 6 possesses an EV. In (c), house 4 has an EV and a HP. In (d), house 2 possesses all technologies.*

The same methodology is applied for the load profiles of January. Figure 3.9 shows the curves obtained for the same four houses in the winter month. Two points stand out: the reduced solar production and the massive increase in power consumption from heat pumps.



(a) *House 0* **(b)** *House 6*



(c) *House 4* **(d)** *House 2*

Figure 3.9: *Total daily load curves of houses with different technologies for the month of* ***January*** *- Scenario 2. In (a), house 0 has no technology implemented. In (b), house 6 possesses an EV. In (c), house 4 has an EV and a HP. In (d), house 2 possesses all technologies (EV,HP,PV). The generation from the PV panels has negative values so that the convention is respected: positive values for consumed energy and negative values for produced energy.*

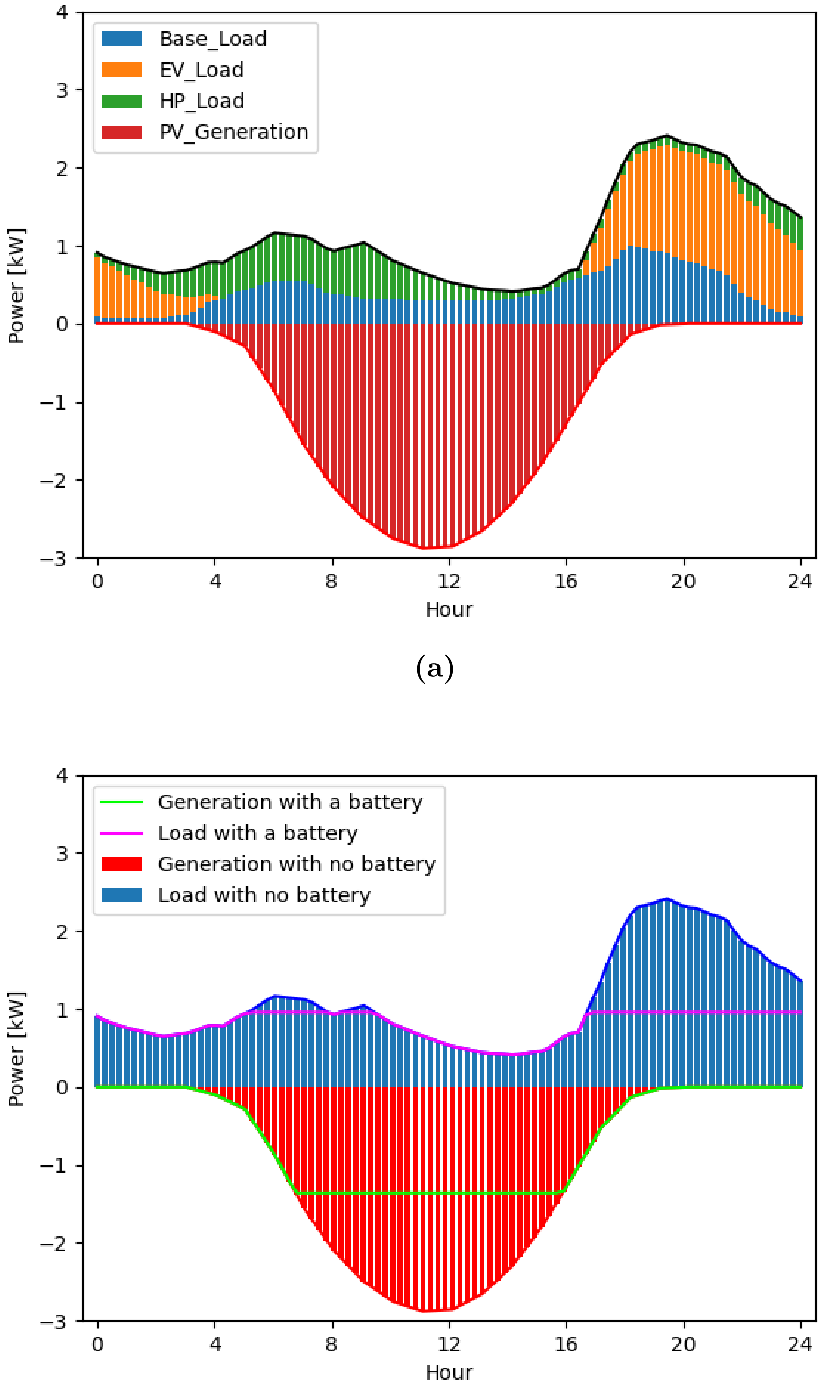
As previously mentioned, three different cases are simulated in this scenario.

- **Case A:** This case does not provide any energy storage option. The load profiles remain identical to those illustrated in the Figures 3.8 and 3.9.

- **Case B:** In this case, the houses equipped with PV panels are now equipped with batteries. All batteries have the same capacity of 9kWh. This value is based on the maximal monetary incentive found in Flanders which covers installations of up to 9kWh of capacity.[44; 45] Also, this value seems quite normal for such installations: in [46], Engie compares domestic batteries installations with a capacity ranging from 2.9kWh up to 30kWh.

The batteries have a 24-hour long cycle: they charge as much as possible thanks to the PV production, and provide the stored energy during peak consumption hours, in the evening. The batteries are not designed to draw power directly from the grid. If there is enough energy produced daily to fully charge the battery, the excess production is then balanced with the demand of the house. If some energy still remains after that, it is fed back into the grid. This leads to a modification of the load profiles as seen from the house's point of view. Part of the production is absorbed by the battery which later covers part of the demand. Figure 3.10 shows how the load profile of these houses are modified. The action of the battery is easily noticed : part of the PV production is stored by the battery, thus the houses perceive a production that is shaved, as represented by the green curve. The same observation is made regarding the demand curve, as part of it is covered by the energy released by the battery.

- **Case C:** The difference between this case and case B lies in the way the stored energy is used. In this case, the street has the same storing capacity of 9kWh per PV installation, but instead of being a private storage unit, it is at the disposal of the entire community. This represents a big battery bank of 72kWh, which is connected to the bus "B2". This way of storing energy is inherent to energy communities: in this work, the concept of energy communities is studied thanks to the analysis of case C.



(a)

(b)

Figure 3.10: *Modification of the load profile of a house due to the installation of a private domestic battery. In (a), the house is not equipped with a battery (Case A). In (b), a storage unit is implemented. The generation curve perceived by the house is shaved as part of the production is stored in the battery. The peaking load demand is also shaved as the energy stored in the battery covers partially the energy demand of the house.*

The battery bank also has a 24-hour long cycle, charging as much as possible thanks to the excess PV production from the entire community. This differs from previously because in case B, the PV production is used in priority to charge the private batteries. In case C however, the energy has to circulate through the grid. Thus, only the excess PV production can be used to charge the battery. Once it has accumulated a maximum of energy, the battery bank empties itself when the demand is high, feeding its energy back into the community so that that amount of energy does not have to be provided by the external grid.

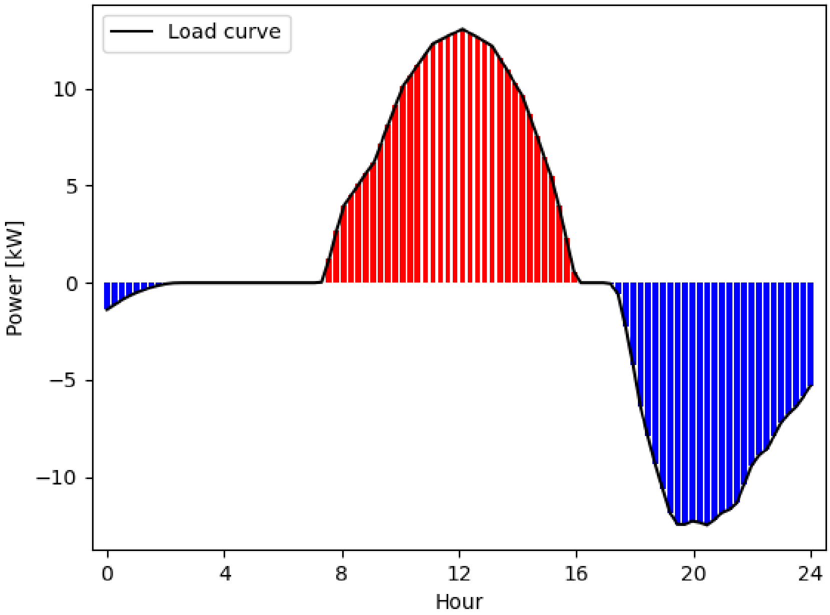


Figure 3.11: *Load curve of the shared battery for a typical day of July. The graph clearly shows how the battery absorbs power during high-production hours, i.e. around noon, and how it feeds it back during peak consumption hours, at night.*

This case does not modify any of the load curves of the households. Instead, it adds a controllable unit which can exchange energy with the grid by absorbing or restoring it. The net amount of energy exchanged daily is null as the battery only stores energy and does not produce any. The amount of energy stored is thus equal to the amount of energy fed back into the community. The load curve of the battery for a typical day of July, is shown in Figure 3.11, which clearly shows how the battery stores most of its energy around noon, and feeds it back during the evening and the night. The State Of Charge (SOC) of the battery is depicted in Figure 3.12. On this particular day, the battery was able to fully charge.

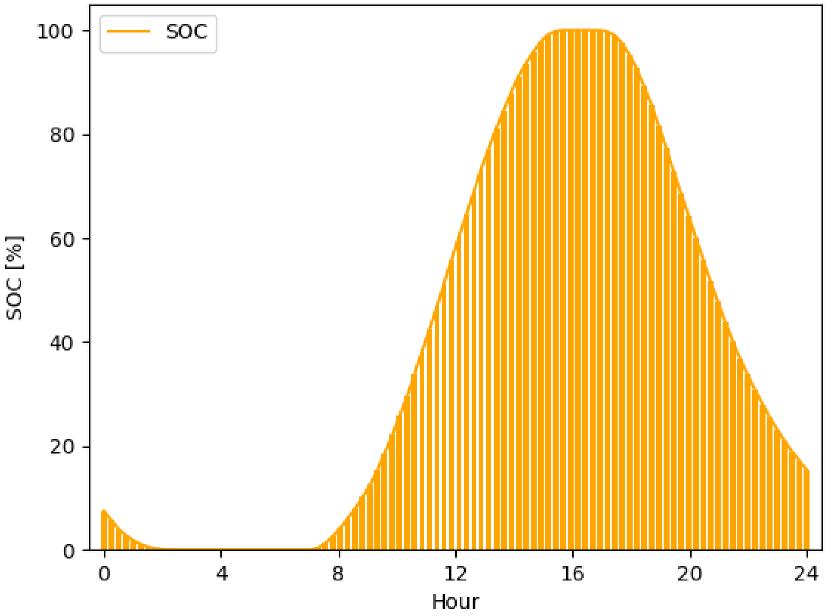
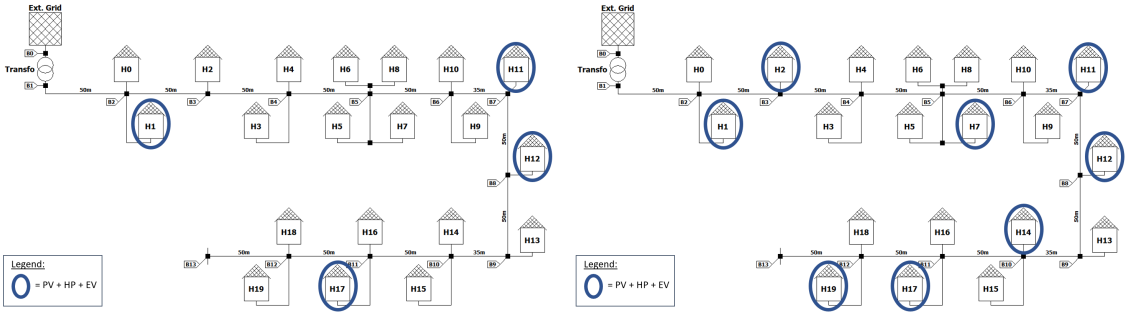


Figure 3.12: *State of charge of the shared battery for a typical day of July. The daily cycle of the battery is highlighted by the fact that the SOC of the battery reaches 0% around 2AM, illustrating the end of the precedent cycle and the beginning of a new one. The battery then reaches its full capacity around 4PM.*

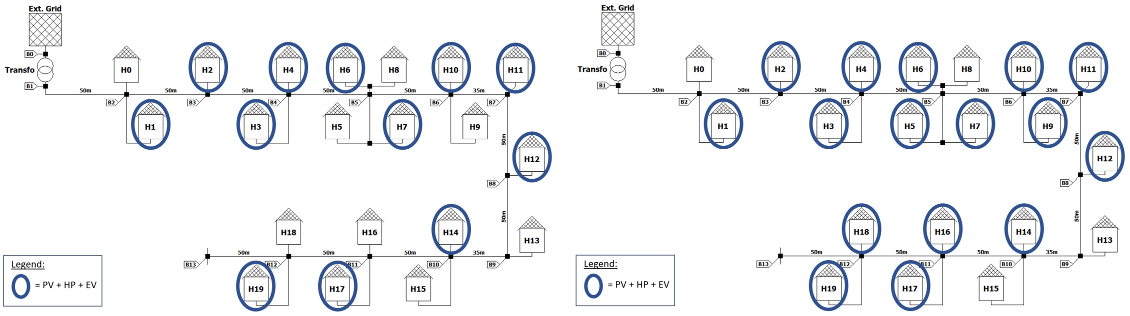
3.4.3 Scenario 3

The third scenario is used to perform a parametric analysis. All previously established penetration levels are discarded. For this setup, the houses either have no technologies, or they have all three of them. The penetration level of these fully equipped houses is increased from 0% up to 100%, by 20% increments. As for the second scenario, all three cases are simulated for scenario 3: case A studies the penetration of fully-equipped houses into the community without any mean of storage; case B considers that the fully-equipped houses all benefit from private batteries; and case C implements a shared storage unit which serves the entire community. Because the methodology is the same as for scenario 2, the different impacts of the different cases on the load curves are not detailed any further for this scenario.

Figure 3.13 shows the distribution of the fully equipped house for each penetration level. The houses that benefit from all three technologies are circled in blue. The houses that are not circled do not have any technology implemented. Note that a penetration level of 0%, i.e. no technologies are implemented in the community, models the same network as scenario 1, see Section 3.4.1. Also, the following figure does not show the penetration level of 100% as then, all houses have all three technologies implemented.



(a) *20%* **(b)** *40%*



(c) *60%* **(d)** *80%*

Figure 3.13: *Distribution of the fully equipped houses throughout the community for the different penetration levels. Houses marked by a blue circle are fully equipped: they possess of a PV installation, an EV and a HP.*

3.4.4 Limitations of the scenarios

Despite the effort that was put in to make the scenarios as realistic as possible, they still have several limitations.

In scenario 1, it is assumed that the inhabitants are divided in there categories and that all households from a certain category have the same load curve. This does not reflect reality as the uniqueness of each individual, family, household is not represented. This adds on to the limitations of the implement technologies from Section 3.3.4.

Another aspect of these models which can be discussed are the various penetration levels that are considered for scenario 2. Many different numbers can be found in the literature and sometimes, consensus can be observed. But whether it is observed or not, these predictions regarding the penetration levels of technologies for the year 2050 remain hypothetical. But in the end, these numbers do not matter that much for such a small project. Indeed, even in 2050, there will still be some street that do not have any PV systems installed, while others could have all of their houses equipped with it.

Finally, it is clear that the management of the batteries are not optimised, as it is not the objective of this work. This matter has been massively researched in the past few years. However, an optimisation of battery management algorithms, especially designed for energy communities, could be a very interesting approach to complete this work. Additionally, other concepts such as the promising «vehicle-to-grid» technology could greatly contribute to the present work, and would drastically modify the model used for the electric vehicles.

Chapter 4

Results

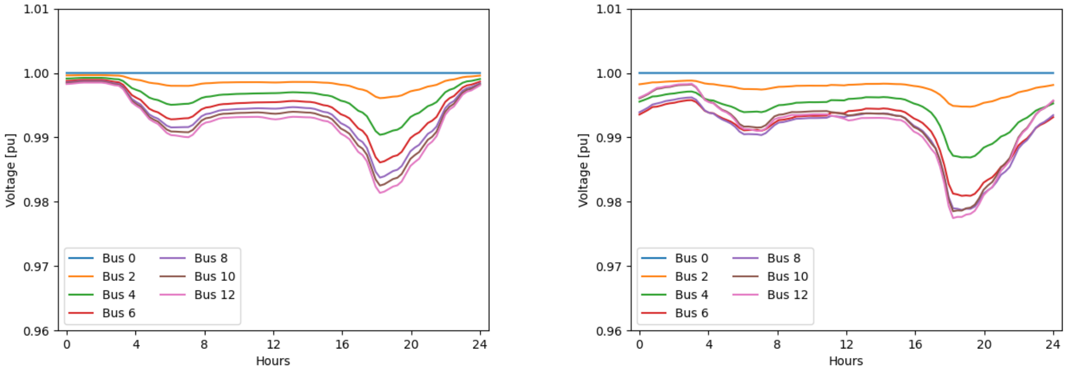
This section covers the two different research questions relative to this work. The first question studies the impact of the sharing of storage units inside the community, as opposed to communities without any storage or with private batteries. To do so, scenarios 1 and 2 are compared in order to firstly assess the impact of the penetration of PV panels, EVs and HPs in low-voltage grids. Then the different cases simulating the presence of private or shared storage units (cases B and C) are compared in order to evaluate how the management of these batteries influences the local grid.

The second question analyses the impact of different penetration levels of fully-equipped houses, i.e. houses that have all technologies implemented. The houses with only one technology implemented out of the three available are thus not considered anymore. To do so, the results from the different configurations of scenario 3 are examined in order to assess how the constraints on the grid evolve depending on the penetration level. Once again, cases A, B and C are compared.

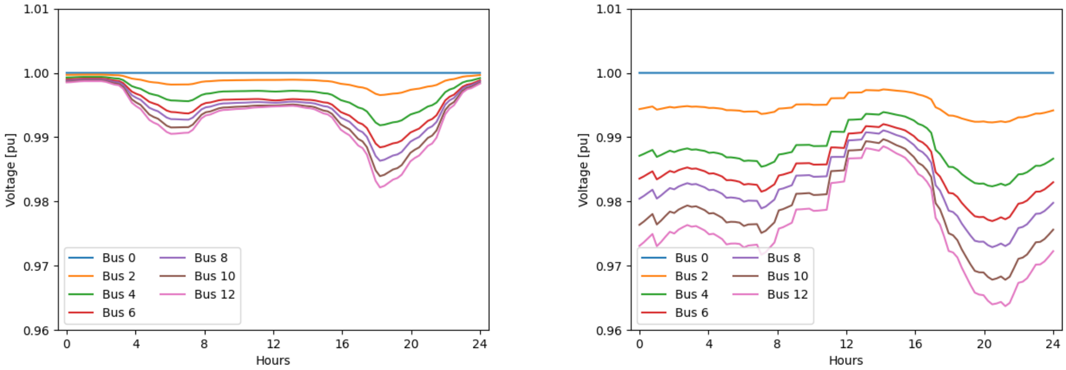
4.1 Technical impact of the implementation of community-owned versus private batteries

4.1.1 Impact of PV panels, EVs and HPs on the local grid voltage: a comparison of scenarios 1 and 2

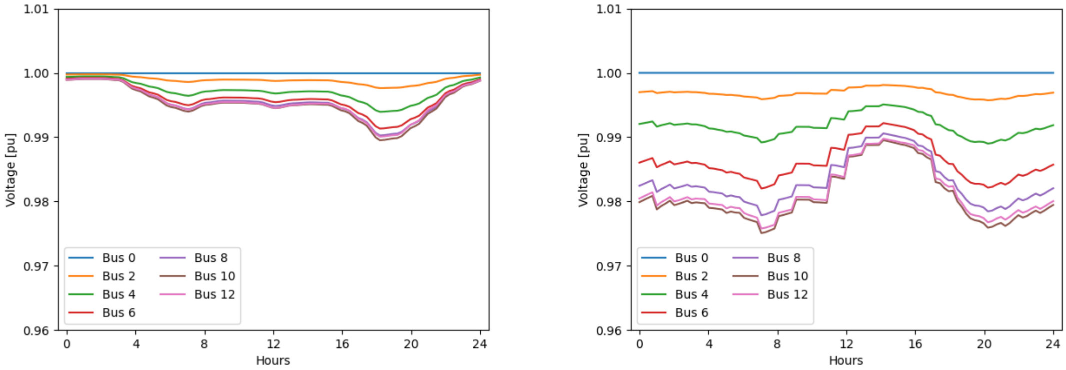
In order to assess how the implementation of the various technologies affects the low-voltage network, the hourly evolution of the voltage magnitude has been simulated for both scenarios, for the months of January and July. Figures 4.1 and 4.2 compare the results between the scenarios for all three phases, for the months of January and July, respectively.



(a) *Scenario 1 - Phase A* **(b)** *Scenario 2 - Phase A*

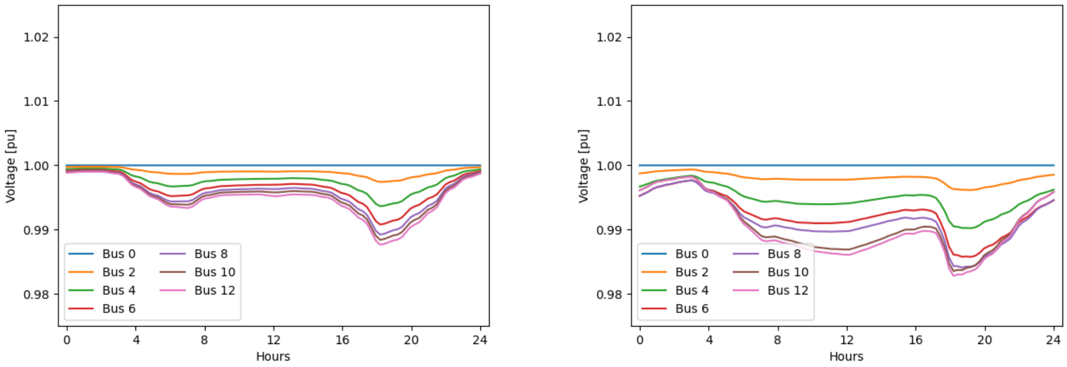


(c) *Scenario 1 - Phase B* **(d)** *Scenario 2 - Phase B*

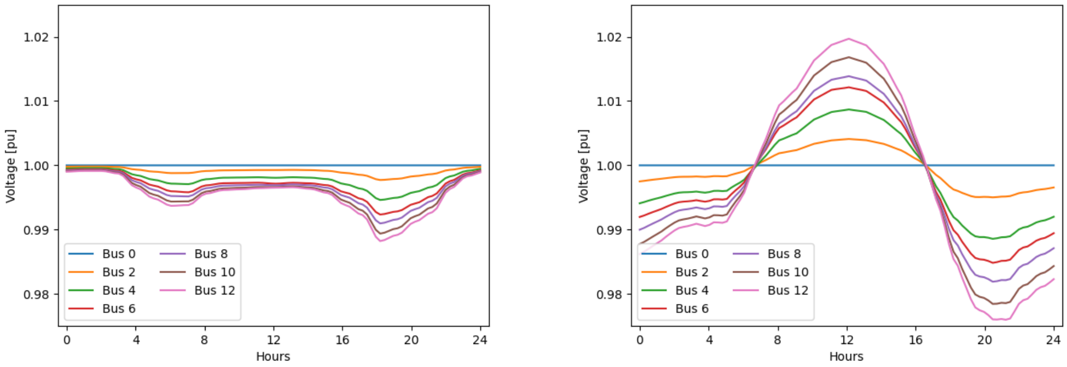


(e) *Scenario 1 - Phase C* **(f)** *Scenario 2 - Phase C*

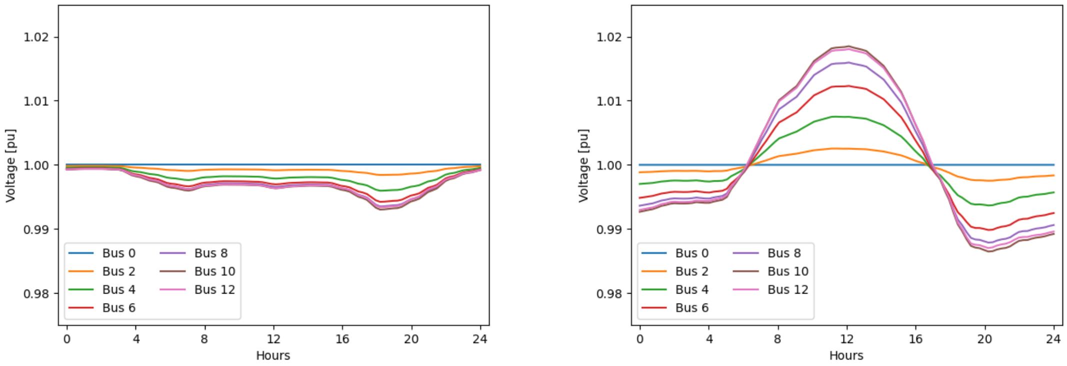
Figure 4.1: *Comparison of the voltage magnitude across the community between scenario 1 and scenario 2, for the month of* ***January****. The curves represent the voltage magnitude for a typical day of the month for the pair-numbered buses. On the left, the voltage evolution from scenario 1 is displayed in (a), (c) and (e), for phases A, B and C respectively. On the right, the voltage evolution from scenario 2 is shown in (b), (d) and (f), for phases A, B and C, respectively. The voltage magnitude is represented in the per-unit [pu] system.*



(a) *Scenario 1 - Phase A* **(b)** *Scenario 2 - Phase A*



(c) *Scenario 1 - Phase B* **(d)** *Scenario 2 - Phase B*



(e) *Scenario 1 - Phase C* **(f)** *Scenario 2 - Phase C*

Figure 4.2: *Comparison of the voltage magnitude across the community between scenario 1 and scenario 2, for the month of* ***July****. The curves represent the voltage magnitude for a typical day of the month for the pair-numbered buses. On the left, the voltages from scenario 1 are displayed in (a), (c) and (e), for phases A, B and C respectively. On the right, the voltages from scenario 2 are shown in (b), (d) and (f), for phases A, B and C, respectively.*

Throughout both months, phase A is the phase that is the less affected by the change of scenario. This can be explained by the fact that the technologies are not distributed evenly across all phases throughout the community. Indeed, only 3EVs, 2 HPs and 1 PV unit are assigned to phase A. On the other hand, 5EVs, 4 HPs and 3 PV are added on phase B while phase C takes care of the 4EVs, 4 HPs and 4 PV units remaining. It is thus expected that phase A would be less affected by the penetration of the technologies. Accordingly, higher perturbations are foreseen on phases B and C, with B being the most disturbed phase. Indeed, voltage drops are directly related to the load so that an increased load results in a higher voltage drop. Solar power generation, which often leads to power being fed back into the grid, shows the opposite phenomenon: the voltage rise. Figures 4.1 and 4.2 confirm that phases B and C are more disturbed than phase A. Three points stand out:

- The voltage drop related to the evening consumption peak (around 6PM) is bigger and wider in Scenario 2. This can be associated to the demand for EV charging, which reaches a peak around that time.

- On top of that, the demand in electricity for powering heat pumps should be responsible for a higher load overall, resulting in a bigger voltage drop. This is especially true for the month of January, as the demand in heating is reduced during summer. The effect of heat pumps is not easily noticed for phase A, but phases B and C are clearly impacted by the four heat pumps connected to them. The heat pumps are also responsible for the multiple dents in the curves of January. As explained in Section 3.3.3, their power consumption is regulated on an hourly basis and is constant between each adaptation, resulting in a rough demand curve.

- Finally, the multiple PV units are responsible for the reduction in voltage drop around noon for phase A, and for the massive over-voltage for phases B and C. This is caused by the massive production of the panels, injecting power back into the grid, which results in a voltage rise. Because of the reduced PV production in January, this phenomenon is especially noticeable in July.

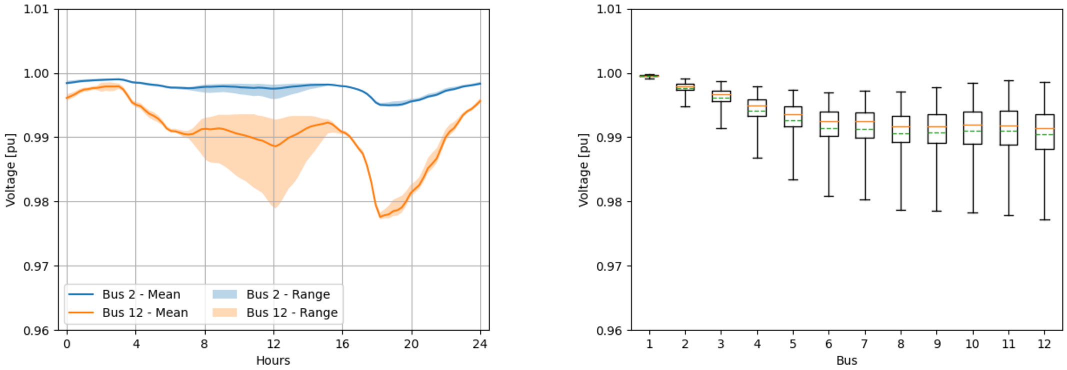
4.1.2 Comparison of the voltage fluctuations for cases A, B and C, in January

Let's now see how the voltage fluctuates in between the different cases of scenario 2. As a reminder, case A simulates the community without any option for storing electricity: all excess production is fed back into the grid. Case B considers that the owners of PV panels own private batteries, which load up thanks to the solar production, in order to be used later during high consumption hours. In case C, shared storage units are added in the community. The battery bank is managed to load up when the production of the various PV systems is high. The shared storage unit then empties itself when the demand is high, during the evening.

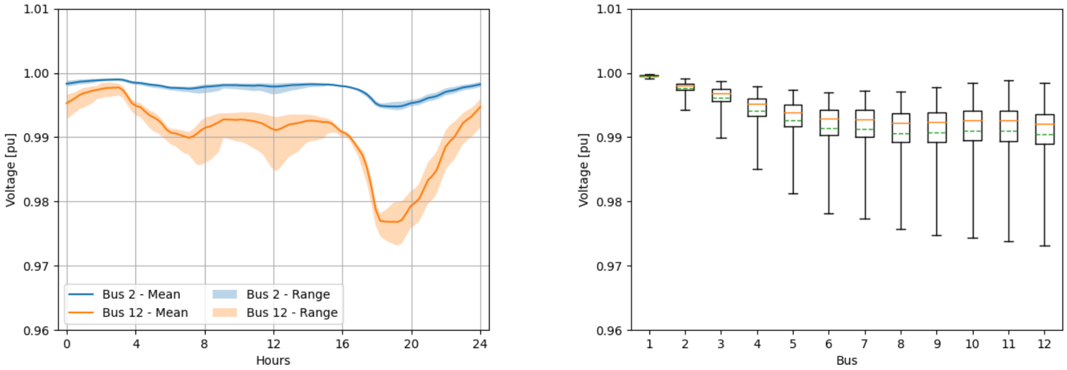
Figure 4.3 displays in two different ways the voltage fluctuations inherent to the phase A in January. All three cases are compared. This figure only showcases the data from the buses "B2" and "B12", as they are the two extremities of the line. The bus "B2" is thus less subject to voltage unbalances than any other bus of the street. At the other end of the line, the bus "B12" is the most subject to unbalances. On the left side of the figure, according to the daily evolution of case C, the implementation of shared batteries does not appear to have any impact. This can be explained by the fact that the PV production is too weak and so, it is not able to feed energy back into the grid. Cases A and C are thus exactly identical. On the other hand, the private batteries do show a slight impact on the evening consumption peak, explaining the wider range of values around 6PM.

On the right side of the figure, the same data is exposed for all buses, thanks to boxplots. It is now clearly noticeable that the buses "B2" and "B12" are respectively less and more subject to voltage unbalance than the other buses. Indeed, the data distribution at each bus highlights how the voltage drop is increased as we move away from the supply point at the bus "B0". Also, by comparing the boxplots with the corresponding curves plotted on the left side of the figure, it is noticeable that the upper and lower whiskers of the boxplots extend to the maximum and minimum values of the data. The boxplots show a similar distribution for all cases, even though case B is a little less spread out around the mean, due to the effect of the private battery.

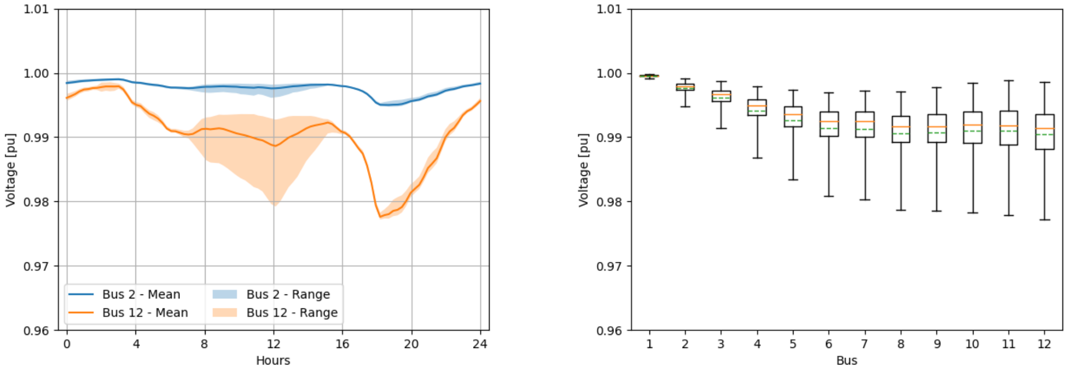
For phases B and C, analysed in Figures 4.4 and 4.5 respectively, the penetration levels of PV systems are higher and their impact is more easily noticed. Indeed, the implementation of private batteries leads to a significant shaving of the voltage rise happening around noon because of the reduced amount of energy fed back into the grid. Moreover, the boxplots show that case B also results in smaller interquartile ranges (Q3-Q1), meaning that the data is less spread out around the median and thus, more constant, as demonstrated by the daily evolution curve. On the other hand, the impact of the shared-battery leads to a slight decrease of the over-voltage peak around noon. The effect of the power re-injection around 6PM is barely visible.



(a) *Daily evolution - Case A* **(b)** *Monthly distribution - Case A*

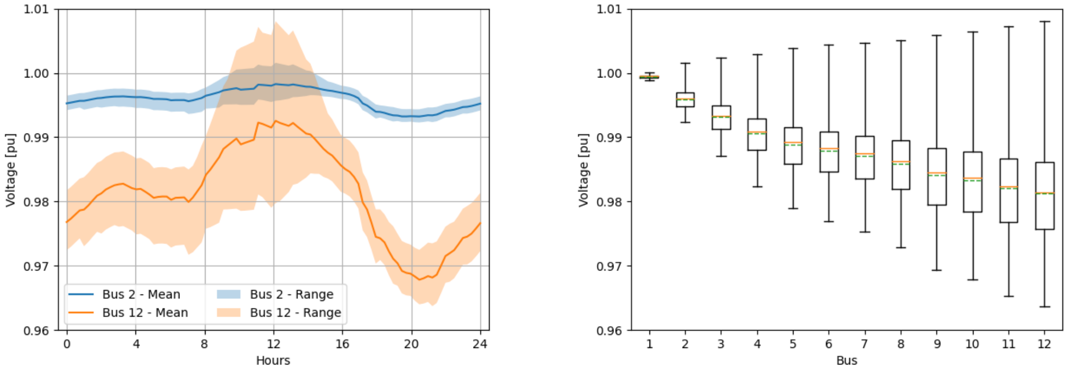


(c) *Daily evolution - Case B* **(d)** *Monthly distribution - Case B*

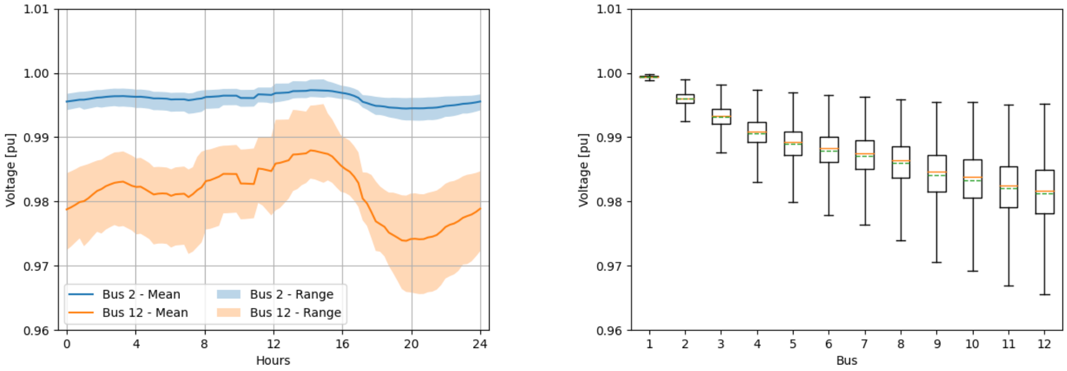


(e) *Daily evolution - Case C* **(f)** *Monthly distribution - Case C*

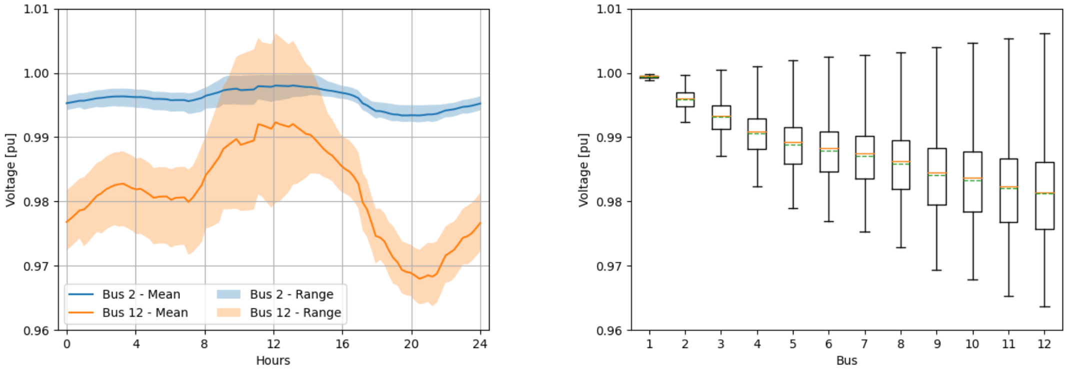
Figure 4.3: ***January - Phase A.*** *On the left, evolution of the voltage magnitude at the buses "B2" and "B12" throughout the day; for case A (a), case B (c) and case C (e). The solid lines show the evolution of the average voltage magnitude. The shaded areas represent the total range of obtained values. On the right, monthly distribution of the voltage magnitude at each bus; for case A (b), case B (d) and case C (f). The lower and upper whiskers extend to the minimum and maximum values, respectively. The black boxes determine the first and third quartiles. The solid orange lines show the median values of the data while the dashed green lines show the mean values.*



(a) *Daily evolution - Case A* **(b)** *Monthly distribution - Case A*

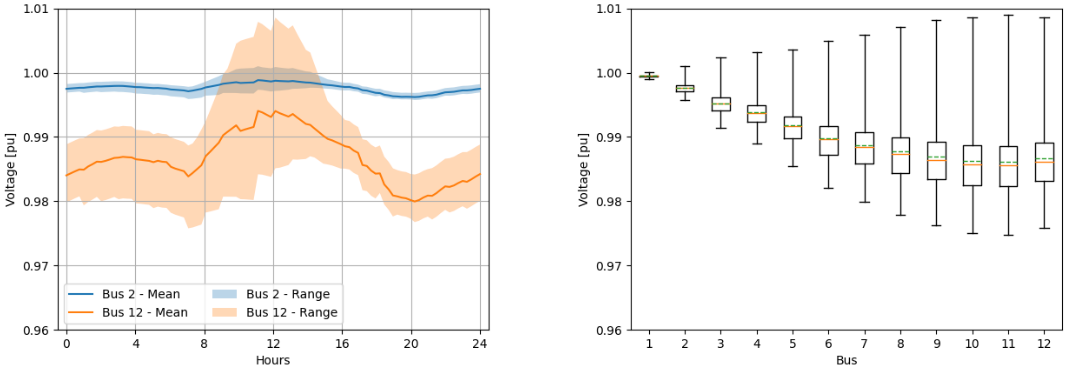


(c) *Daily evolution - Case B* **(d)** *Monthly distribution - Case B*

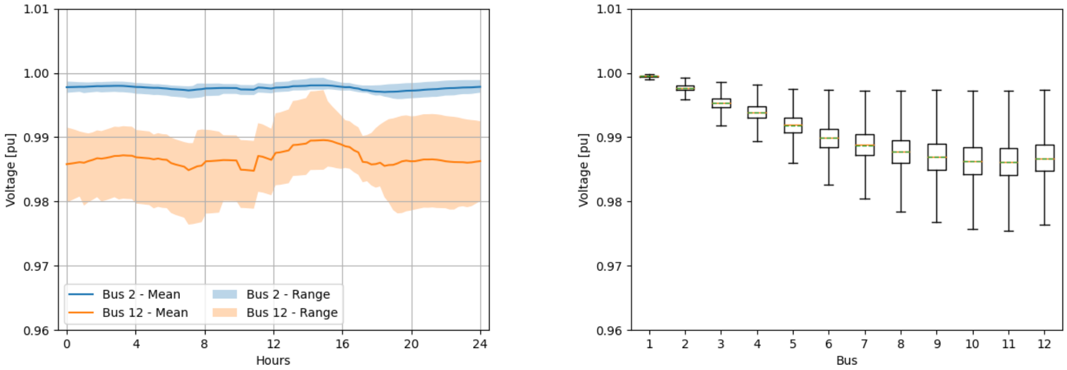


(e) *Daily evolution - Case C* **(f)** *Monthly distribution - Case C*

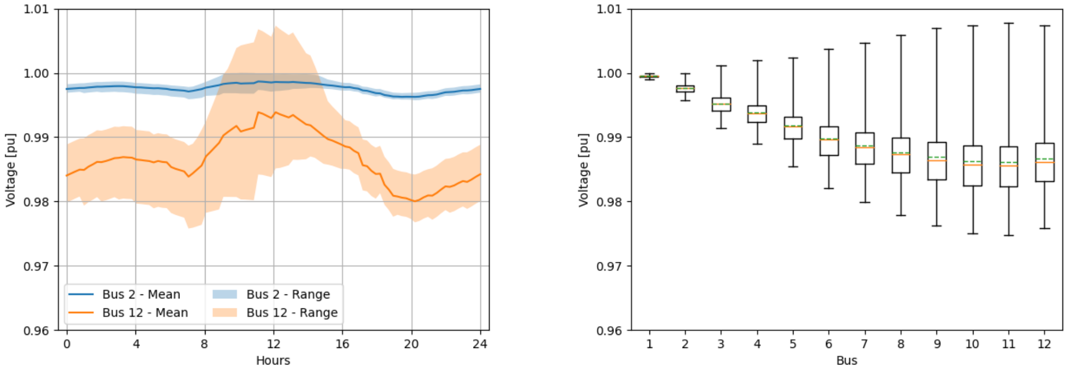
Figure 4.4: ***January - Phase B.*** *On the left, evolution of the voltage magnitude at the buses "B2" and "B12" throughout the day; for case A (a), case B (c) and case C (e). On the right, monthly distribution of the voltage magnitude at each bus; for case A (b), case B (d) and case C (f). The same explanations as for Figure 4.3 apply.*



(a) *Daily evolution - Case A* **(b)** *Monthly distribution - Case A*



(c) *Daily evolution - Case B* **(d)** *Monthly distribution - Case B*



(e) *Daily evolution - Case C* **(f)** *Monthly distribution - Case C*

Figure 4.5: ***January - Phase C.*** *On the left, evolution of the voltage magnitude at the buses "B2" and "B12" throughout the day; for case A (a), case B (c) and case C (e). On the right, monthly distribution of the voltage magnitude at each bus; for case A (b), case B (d) and case C (f). The same explanations as for Figure 4.3 apply.*

The analysis for the month of July yields similar results and interpretation as for January. The figures and a few comments are available in Appendix B.

Finally, for both months, all the variations observed stayed inside the required range of $[U_n + -10\%]$, imposed by the EN 50-160 standard, which regulates the quality of the supplied power for low-, medium- and high-voltage networks.[16] Thus, in this network, the implementation of either of the solutions does not cause intolerable voltage fluctuations.

4.1.3 Evaluation of the voltage unbalance

Limiting voltage fluctuations is an important aspect of power quality. Voltage drops have been discussed in the previous section; however, asymmetric fluctuations of the voltage lead to another power quality issue: voltage unbalances. The EN 50-160 standard states that: «*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 of the supply voltage shall be within the range 0% to 2% of the positive phase sequence component.*»[16]

Figures 4.6 and 4.7 depict the unbalance levels present in the network in January and July, respectively. The data is presented in the same way as for voltage fluctuations.

In January, similarly to voltage fluctuations, the implementation of private batteries seems to have a bigger influence, as shown by the evolution of the average unbalance level throughout the day and the monthly distribution of the data across all buses. Indeed, the voltage rise around noon is completely shaved, and thus, the voltage levels across the different phases are more similar to each other. Also, during the evening, the unbalance levels are once again decreased thanks to the action of the batteries. In contrast, the implementation of shared batteries has a significantly reduced impact. Indeed, the voltage rise is less affected by this solution, and thus greater disparities arise throughout the community. Notably, this can be illustrated by the comparison of the Figures 4.5e and 4.3e.

The first thing to notice about the month of July is that unbalance levels are increased by about 30% on average when compared with the results from January, because of the higher solar power generation. Besides that, cases B and C show two different impacts:

- Case B results in a lower unbalance level for most of the day, but causes an increase of the latter around 7PM, due to some loads being entirely covered by the battery while others are feeding from the grid. As a battery is providing energy to a house, the load of that house, as seen from the grid, is significantly reduced. On top of that, other houses which do not benefit from batteries reach their evening consumption peak. These disparities cause the unbalance level to rise substantially. However, the height of this peak does not exceed by much the unbalance levels experienced throughout the rest of the day. This results in a more compact distribution as illustrated by the boxplots. The significant reduction of the unbalance levels around noon contribute to the drop (24%) of the average unbalance levels.

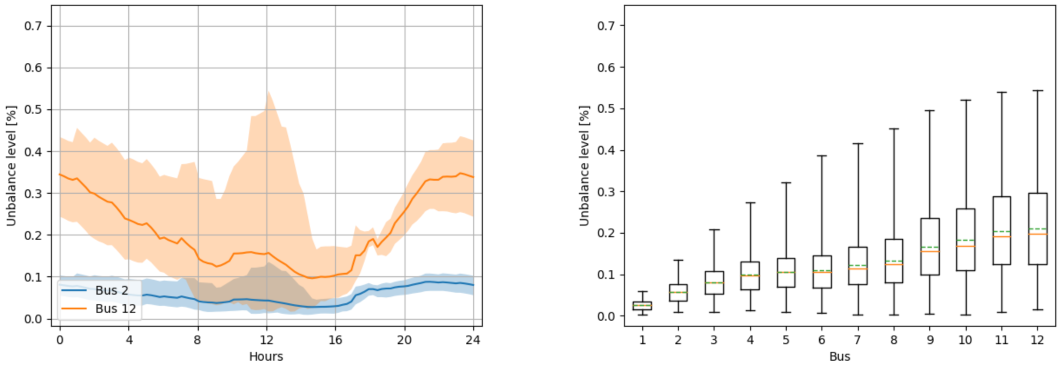
- Case C results in a significant reduction of the unbalance levels of the buses "B2" and "B12" around noon. Also, the levels encountered during the evening are improved, in comparison to cases A and B.

Table 4.1 displays the values for the mean and maximum unbalance levels at the bus "B12" in July, for each case. It highlights how the two solutions result in a decrease of both mean and maximum unbalance levels. In addition, it confirms that the implementation of private batteries should be preferred regarding unbalance levels, as illustrated by the Figures 4.6 and 4.7. Indeed, this option reduces the mean and maximum unbalance levels, with respect to case A, by 24% and 42% respectively, whereas shared storage units only decrease those levels by 10% and 13%.

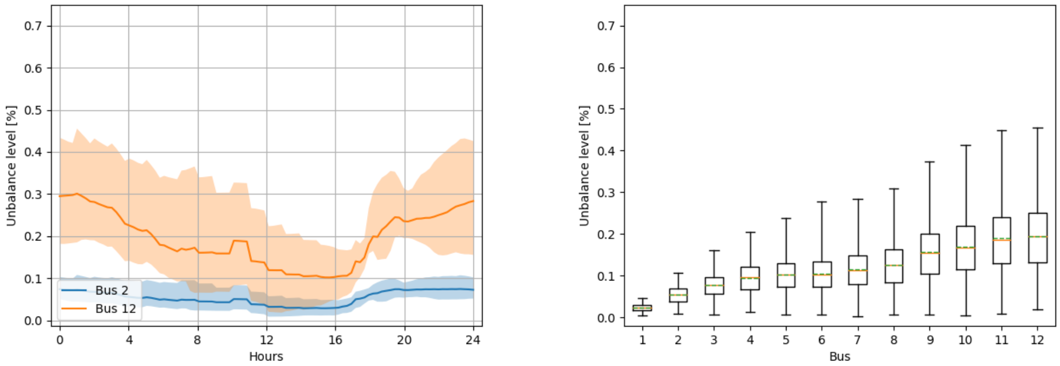
Despite these results, all cases respect the EN 50-160 standard, which limits the voltage unbalances to 2% maximum. The values observed throughout the previous figures are well below that limit. The overall maximum unbalance level is observed for case A, and it only reaches 0.673%.

	Case			Ratio [/]	
	A	B	C	B/A	C/A
Mean Unb. [%]	0.269	0.204	0.24	0.758	0.892
Max. Unb. [%]	0.673	0.390	0.584	0.579	0.868

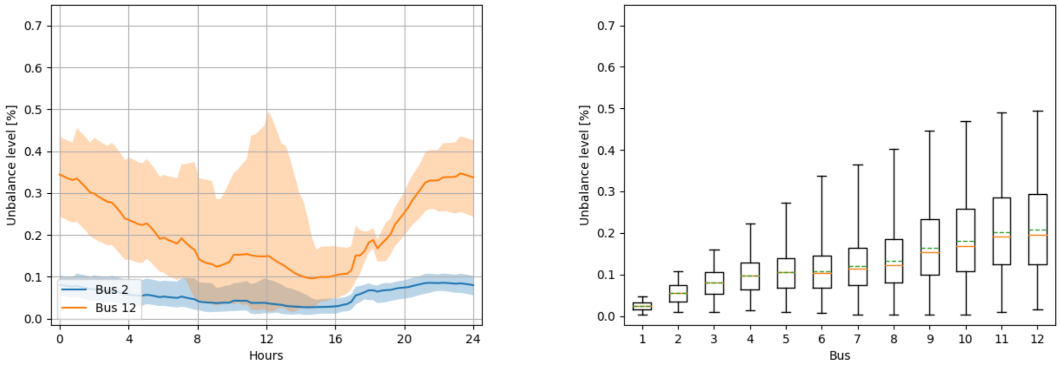
Table 4.1: *Comparison of the mean and maximum unbalance (unb.) levels at the bus "B12", between cases, in* ***July****. The first three columns report the observed values for each case. The last two columns display the ratios of cases B and C with respect to case A.*



(a) *Daily evolution - Case A* **(b)** *Monthly distribution - Case A*

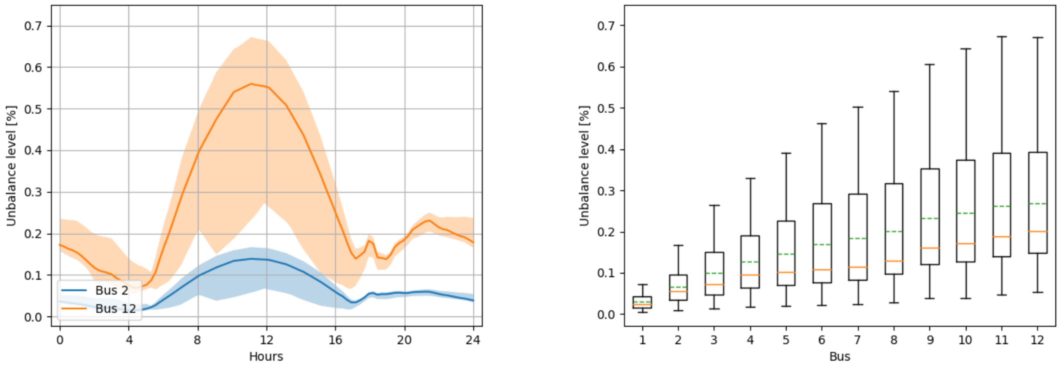


(c) *Daily evolution - Case B* **(d)** *Monthly distribution - Case B*

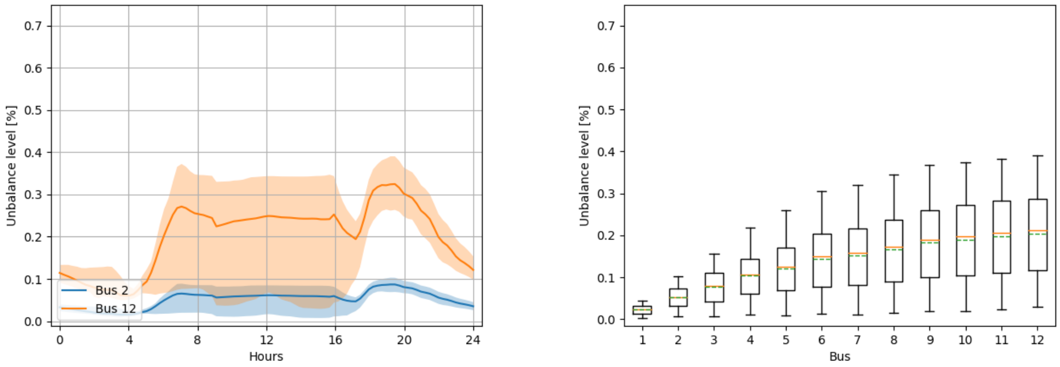


(e) *Daily evolution - Case C* **(f)** *Monthly distribution - Case C*

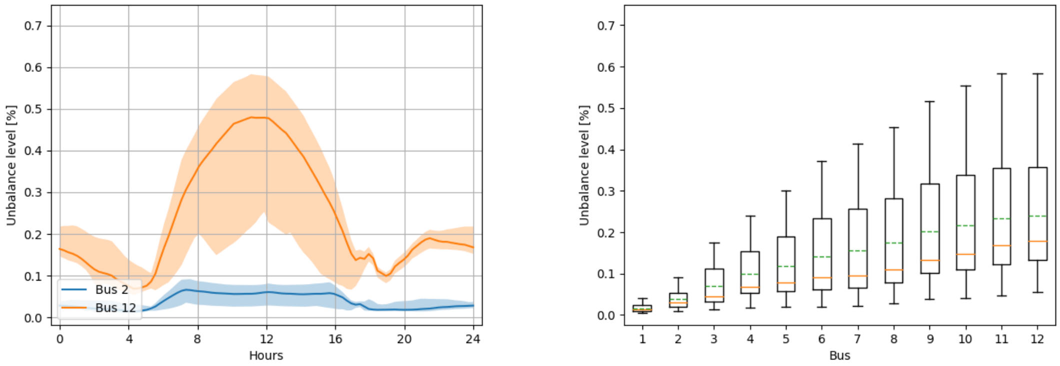
Figure 4.6: *Unbalance levels in* ***January*** *for cases A, B and C. On the left, evolution of the voltage unbalance at the buses "B2" and "B12" throughout the day; for case A (a), case B (c) and case C (e). On the right, boxplots of the voltage unbalances for the entire month for case A (b), case B (d) and case C (f). The same explanations as for Figure 4.3 apply.*



(a) *Daily evolution - Case A* **(b)** *Monthly distribution - Case A*



(c) *Daily evolution - Case B* **(d)** *Monthly distribution - Case B*

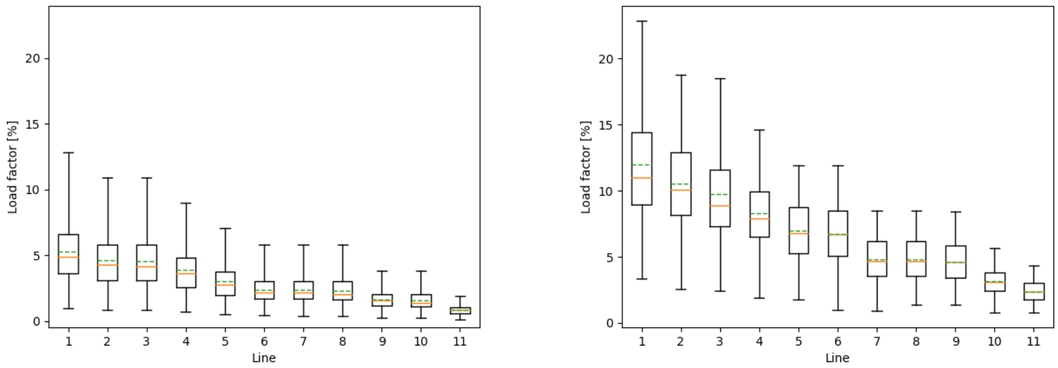


(e) *Daily evolution - Case C* **(f)** *Monthly distribution - Case C*

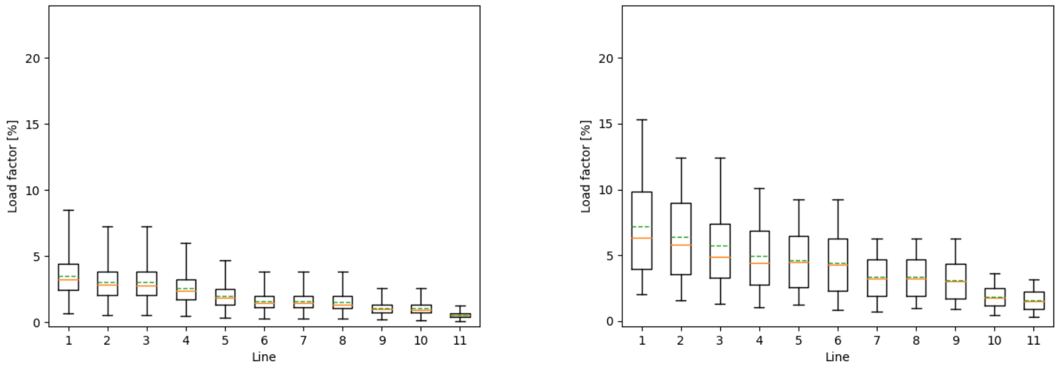
Figure 4.7: *Unbalance levels in* ***July*** *for cases A, B and C. On the left, evolution of the voltage unbalance at the buses "B2" and "B12" throughout the day; for case A (a), case B (c) and case C (e). On the right, boxplots of the voltage unbalances for the entire month for case A (b), case B (d) and case C (f). The same explanations as for Figure 4.3 apply.*

4.1.4 Impact on the load factor of power lines

In order to assess how the management of the batteries affects the load factor of the power lines, it is interesting to first understand how they are impacted by the addition of PV panels, EVs and HPs to the community, as it was previously done regarding voltage fluctuations in Section 4.1.2. To do so, Figure 4.8 compares the power line load factors for scenarios 1 and 2.



(a) *Scenario 1 - January* **(b)** *Scenario 2 - January*



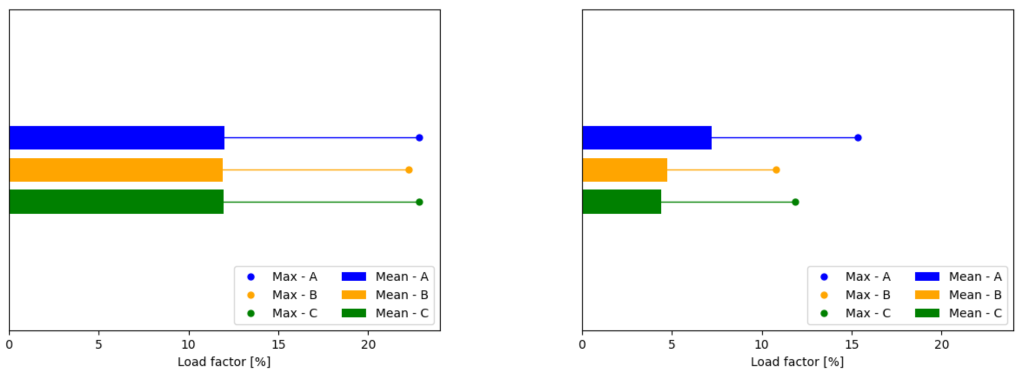
(c) *Scenario 1 - July* **(d)** *Scenario 2 - July*

Figure 4.8: *Comparison of the load factor of power lines between scenario 1 and scenario 2*

A first observation is that the power factor of the lines decreases as the line number increases. This is expected since the loading factor of a line directly depends on the power going through it. Thus a decrease in supplied power leads to a decreased load factor. Since line 1 connects the transformer to the first bus, all the power exchanged between the transformer and the community passes through it. On the other end, line 11 connects the buses "B11" and "B12" together and only two houses are connected to the bus "B12". This means that line 11 only transports the power needed for the supply of these two houses. This reduction in the power supplied by the line explains how the line loading percent decreases as we move further away from the transformer.

The figure also shows how scenario 2 results in a higher load factor overall. This is obviously due to the increased load between the scenarios and the re-injection of power inherent to the implementation of PV panels. With a maximum load factor of about 23% for line 1, the community still has the capacity to host more technologies or more houses. There is room for development!

Let us now have a look at how the types of batteries (shared vs. private) affect the load factor of the power lines of scenario 2. Figure 4.9 compares how the different cases impact the average load factor of the power line number 1 (because it is the line with the highest load factor). Table 4.2 displays the different values observed in Figure 4.9 for the month of July since the limited solar generation in January does not allow the cases B and C to cause significant impact, as illustrated by Figure 4.9a.



(a) *January* **(b)** *July*

Figure 4.9: *Comparison of the average load factor of the power line 1 between cases A, B and C, in January (a) and July (b).*

A first comparison between the two months shows that the lines are under a greater stress during January than during July. This is due to the massive difference in the load of heat-pumps between the two months and the lack of PV production in January. This leads to a much higher demand for power during the winter, giving rise to higher load factors of power lines.

Furthermore, in July (Figure 4.9b), both cases B and C cause a reduction of the average load factors, with respect to case A. Indeed, in the latter, due to the absence of storage options, all excess energy produced in the community is fed back into the medium-voltage grid. In the other cases, thanks to the implemented batteries, that energy is stored inside the community, enabling a decrease of the load factor. However, case B has a slightly higher average load factor. This is explained by the fact that the management of the private batteries causes the different PV owners to re-inject the excess power around the same time, and thus more of it is fed back into the medium-voltage grid than for case C. Remember that private batteries are charged in priority, and that the remaining power is then used to balance the consumption of the house. On the other hand, for case C, it is the opposite: the production of PV panels is first balanced with the consumption of the house, and the battery bank is then asked to charge up following the levels of excess electricity. Thereby, the management of the shared battery bank allows to re-inject less power into the higher-voltage grid and is thus more advantageous for this matter. To illustrate this, Table 4.2 confirms that shared batteries decrease the average load factor by 38.8% with respect to case A. That is 4.7% more than with private batteries.

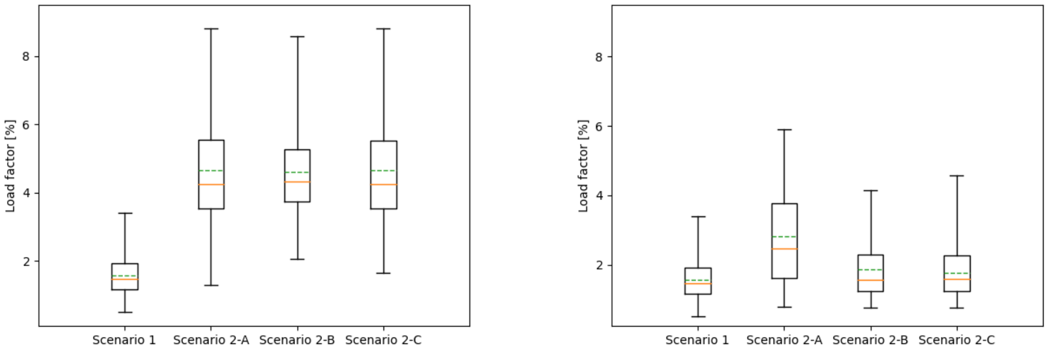
Regarding the maximum load factors observed, since case B is more optimal for the shaving of the different peaks, it outperforms case C by a few percentages (a decrease of 7% more than case C, with respect to case A, as displayed in Table 4.2).

	Case			Ratio [/]	
	A	B	C	B/A	C/A
Mean L.F. [%]	7.220	4.757	4.419	0.659	0.612
Max. L.F. [%]	15.338	10.805	11.865	0.704	0.774

Table 4.2: *Comparison of the mean and maximum load factor (L.F.) of line 1 between cases in* ***July****. The first three columns report the observed values for each case. The last two columns display the ratios of cases B and C with respect to case A.*

4.1.5 Impact on the load factor of the transformer

As previously done with power lines, this section studies how the management of the batteries affects the load factor of the transformer. Figure 4.10 compares the load factor between scenario 1 and the three cases of scenario 2. Table 4.3 compares the mean and maximum values obtained throughout the different cases of scenario 2 in July .



(a) *January* **(b)** *July*

Figure 4.10: *Comparison of the transformer load factor between scenario 1 and scenario 2 (for cases A, B and C), in January (a) and July (b).*

	Case			Ratio [/]	
	A	B	C	B/A	C/A
Mean L.F. [%]	2.816	1.871	1.780	0.664	0.632
Max. L.F. [%]	5.904	4.159	4.567	0.704	0.774

Table 4.3: *Comparison of the mean and maximum load factor of the transformer between cases in* ***July****. The first three columns report the observed values for each case. The last two columns display the ratios of cases B and C with respect to case A.*

As the power line 1 and the transformer 1 are in series, it is expected to see similar results between both analyses. As before, a first comparison between scenario 1 and scenario 2 (case A) shows how the implementation of the different technologies leads to higher load factors. All values are increased: upper and lower limits of the range of values, median, mean, quartiles. In January, the average load factor of scenario 2 is around three times as high as in scenario 1.

Additionally, the cases B and C do not show a significant improvement for the month of January, with respect to case A: only case B is slightly better, but the difference is very slim. For July however, case B shows once again a visible reduction of the load factor, at all levels: median, mean and extrema. Indeed, the implementation of private batteries reduces, in this case, the mean and maximum transformer load factors by 33.6% and 29.6%, respectively. Case C also shows a decrease of both values, of 26.8% and 22.6%. The same justification is used as for the lines: this is due to the management of both types of batteries.

As a side note, one could be surprised by the very low values of the transformer load factor and could wonder if it was not oversized. The fact is that in this model, the transformer only serves for this community, it only has one thread. But in real life, these transformers are connected to multiple threads, i.e. multiple streets, communities, etc. So indeed, the simulated community only accounts for a small load factor, because it leaves room for other threads to be connected to the transformer. With that said, the numbers are still below average because of the small size of the modelled community.

4.1.6 Discussion

This section compared lots of data regarding the power quality aspects of the community, throughout two different scenarios and three different cases. In the end, not having any storage implemented (case A) is the less preferred solution regarding technical issues. Cases B and C are two very different ways of dealing with the excess production and the consumption peaks. The implementation of private batteries showed better results for voltage fluctuations and unbalance levels. However, in terms of the different load factors imposed on the components, the shared battery bank seemed to outperform the private batteries from case B: the total energy fed back into the grid is more limited via the implementation of shared batteries; but this solution has a smaller impact on the voltage rise. In the end, the two solutions present a certain trade-off: one is better at handling the voltage rise but has a reduced impact on the evening consumption peak while it is the opposite for the other solution. Therefore, the choice between the implementation of private batteries or a shared battery bank might depend on the situation. It also depends on other parameters, which is why other complementary studies could be beneficial, such as a financial analysis comparing the two cases, or a social study analysing if citizens might prefer one option or the other and why.

4.2 Technical impact of the penetration level of fully-equipped houses on the low-voltage grid, as a function of the battery management

The previous section showed the benefits linked to the implementation of shared batteries in a low-voltage energy community, in comparison to the implementation of private batteries. However, all calculations considered the average penetration levels for 2050 of PV panels, electric vehicles and heat pumps. Of course, these technologies will not be spread evenly across the Belgian grid. Indeed, some areas, such as rural residential neighbourhoods, are more suited for solar production systems as they usually have more roof surface. On top of that, heat pumps are also found more and more in single-family houses, especially those equipped with PV panels because of the synergy existing between the two technologies. As a result, a question arises: what is the impact of the penetration level of these various technologies on the communities equipped with shared battery banks? How useful is this solution for higher or lower penetration levels?

Because section 4.1 showed that the solutions proposed by cases B and C were not that effective during winter (due to the low solar production), this section only focuses on the month of July. As a reminder of section 3.4.3, the modelled network has been simulated with penetration levels of fully-equipped houses (house with all three technologies implemented) ranging from 0% up to 100%, with 20% increments. This means that the houses that only had one or two technologies implemented are not implemented anymore. The data and the results are discussed hereafter.

4.2.1 Impact on the voltage unbalance

Let us first look at the impact of the penetration levels on the voltage unbalance levels. As a reminder, the EN50-160 standard sets the maximum unbalance levels of low-voltage network at 2%. The following figure (Figure 4.11) shows how voltage unbalance vary as a function of the penetration levels.

A first observation is that the average unbalance levels vary depending on the penetration levels. They increase as the penetration level goes from 0% to 40%, before going back down again for higher penetration levels. The maximum values follow the same trend. The differences in unbalance between penetration percentages could be linked to the distribution of the fully equipped-houses across the three phases, which was depicted in Figure 3.13. For example, the penetration level of 40% has the most uneven distribution of fully-equipped houses throughout all the different penetration levels. Indeed, in this simulation, phase C hosts four fully-equipped houses while phase A only has one. This obviously leads to voltage unbalances. In order to study how beneficial the cases B and C can be, it is needed to compare their results with those of case A (without any storage), which is thus the reference. That way, it is the change in voltage unbalance with respect to case A that is analysed. This allows to interpret how helpful the solutions of private or shared batteries are.

The figure also shows that the various voltage unbalance levels follow the same trend previously observed in Section 4.1.3. The implementation of private batteries is the most effective across all penetration levels, for the diminution of both mean and maximum unbalance levels. The option of the shared battery bank still provides a visible, positive impact. In order to facilitate the interpretation of the results, Tables 4.4 and 4.5 display the different values of mean and maximum unbalance percentages for the different cases and penetration levels, as well as the ratio of those values with respect to case A.

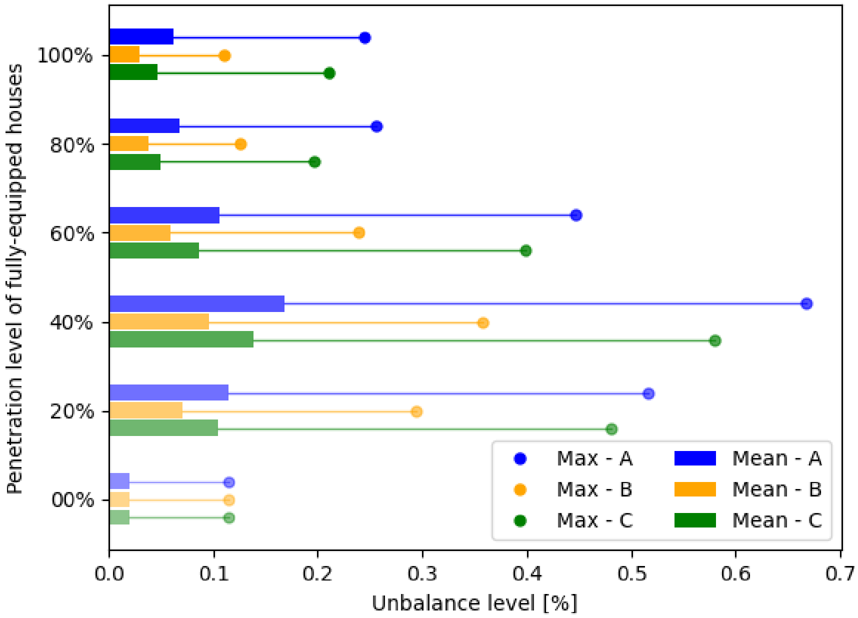


Figure 4.11: *Mean (bars) and maximum (dots) voltage unbalance as a function of the penetration level of fully-equipped houses for all three cases.*

	Mean unbalance [%]			Ratio [/]	
	Case A	Case B	Case C	B/A	C/A
100%	0.062	0.030	0.047	0.479	0.757
80%	0.067	0.038	0.049	0.570	0.735
60%	0.106	0.060	0.086	0.566	0.812
40%	0.169	0.096	0.138	0.570	0.819
20%	0.115	0.071	0.105	0.620	0.913
0%	0.020	0.020	0.020	1	1

Table 4.4: *Comparison of the* ***mean*** *unbalance levels between cases, for different penetration levels. The first three columns report the observed values for each case. The last two columns display the ratios of cases B and C with respect to case A.*

	Maximum unbalance [%]			Ratio [/]	
	Case A	Case B	Case C	B/A	C/A
100%	0.245	0.110	0.211	0.452	0.863
80%	0.255	0.126	0.196	0.495	0.769
60%	0.446	0.239	0.398	0.536	0.892
40%	0.668	0.358	0.579	0.536	0.867
20%	0.515	0.294	0.481	0.571	0.933
0%	0.114	0.114	0.114	1	1

Table 4.5: *Comparison of the* ***maximum*** *unbalance levels between cases, for different penetration levels.The first three columns report the observed values for each case. The last two columns display the ratios of cases B and C with respect to case A.*

The different ratios are difficult to interpret. Indeed, there is no clear relation that can be identified between the degree of improvement provided by the implementation of a solution and the penetration levels of fully-equipped houses. A general trend can still be considered: the higher the implementation level, the more both options seem to be effective. However, this trend is not followed throughout all penetration levels. Although the different configurations of the community might have an impact, no explanation has been found for this so far.

In order to summarise this, cases B and C are both beneficial in terms of voltage unbalance. Nevertheless, the implementation of private batteries should be preferred as it leads to a bigger drop of the mean and maximum unbalance levels. Moreover, for higher penetration levels, the solutions perform better as the distribution of the fully-equipped houses is more evenly spread across all phases.

The worst situation occurs for a penetration level of 40%, since the distribution of the equipped houses is then very disparate across the three phases, causing voltage unbalance.

4.2.2 Impact on the load factor of the power lines

Now that the levels of voltage unbalance have been analysed, it is also interesting to look at the impact of the penetration of fully-equipped houses on the load factor of power lines. Figure 4.12 displays the mean and the maximum load factors of line 1 for all cases. As previously done, Tables 4.6 and 4.7 present the values of the mean and maximum load factor of line 1 for the different cases and penetration levels, as well as the ratio of those values with respect to case A.

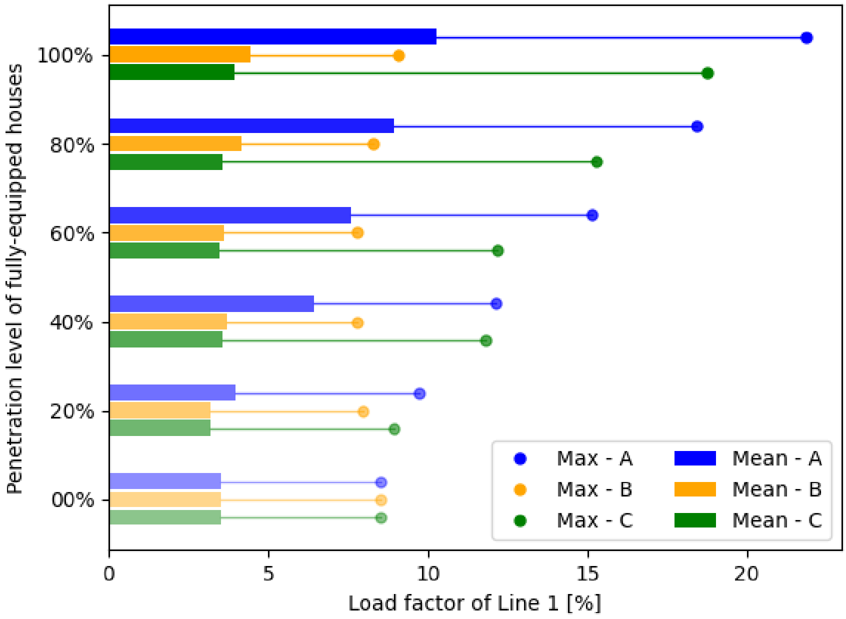


Figure 4.12: *Mean (bars) and maximum (dots) load factor of the power line 1, as a function of the penetration level of fully-equipped houses for all three cases.*

Again, the results follow the same trend as previously observed in Section 4.1.4. Indeed, cases B and C both induce a significant improvement of the load factor, with case C having the most impact due to the reduced amount of energy fed back into the medium-voltage grid. However, the solution offered by private batteries outperforms that of the shared battery bank in terms of maximum load factors.

The two following tables confirm this as cases B and C reduce the mean load factor by up to 56.9% and 61.6% respectively, for a penetration level of 100%. They also decrease the maximum load factor by 58.5% and 14.3%.

	Mean load factor [%]			Ratio [/]	
	Case A	Case B	Case C	B/A	C/A
100%	10.286	4.435	3.955	0.431	0.384
80%	8.922	4.152	3.578	0.465	0.401
60%	7.574	3.615	3.466	0.477	0.458
40%	6.432	3.684	3.575	0.574	0.557
20%	3.972	3.188	3.178	0.803	0.800
0%	3.531	3.531	3.531	1	1

Table 4.6: *Comparison of the* ***mean*** *load factor of line 1 between cases, for different penetration levels. The first three columns report the observed values for each case. The last two columns display the ratios of cases B and C with respect to case A.*

	Maximum load factor [%]			Ratio [/]	
	Case A	Case B	Case C	B/A	C/A
100%	21.860	9.066	18.743	0.415	0.857
80%	18.421	8.287	15.290	0.450	0.830
60%	15.136	7.757	12.183	0.512	0.805
40%	12.110	7.753	11.821	0.640	0.976
20%	9.727	7.958	8.950	0.818	0.920
0%	8.517	8.517	8.517	1	1

Table 4.7: *Comparison of the* ***maximum*** *load factor of line 1 between cases, for different penetration levels. The first three columns report the observed values for each case. The last two columns display the ratios of cases B and C with respect to case A.*

The tables also highlight how the reduction of the load factors grows more important as the penetration levels increase. To summarise this, case B and C are both beneficial for the decrease of mean and maximum load factors. If the priority is set on minimising the mean load factor, then the implementation of shared batteries should be favoured. However, if it is more crucial to limit the maximum values, then private batteries will perform better. Both options offer a greater reduction of the load factors with respect to phase A as the penetration levels of fully-equipped houses reach higher values.

4.2.3 Impact on the load factor of the transformer

Using the same methodology as before, Figure 4.13 displays the mean and the maximum load factors of the transformer. The Tables 4.8 and 4.9 present the values of the mean and maximum load factor of the transformer for the three cases and penetration levels, as well as the ratio of those values with respect to case A.

The impact on the transformer load factor is very similar to the one of the power lines. Even though the values are different, the ratios are almost identical, and follow the same pattern. Indeed, cases B and C both reduce the transformer load factor. The shared batteries are better at decreasing the average value while the private ones are better at decreasing the maximum values.

The two following tables highlight how the various ratios are very similar to those of the load factor of the line. This emphasize how the two solutions are as beneficial for the lines than for the transformer, which is expected since they are in series with one another. A general remark regarding the various load factors observed for the lines and the transformer is that the numbers are still relatively low and do not raise any concern of a potential overloading of the components.

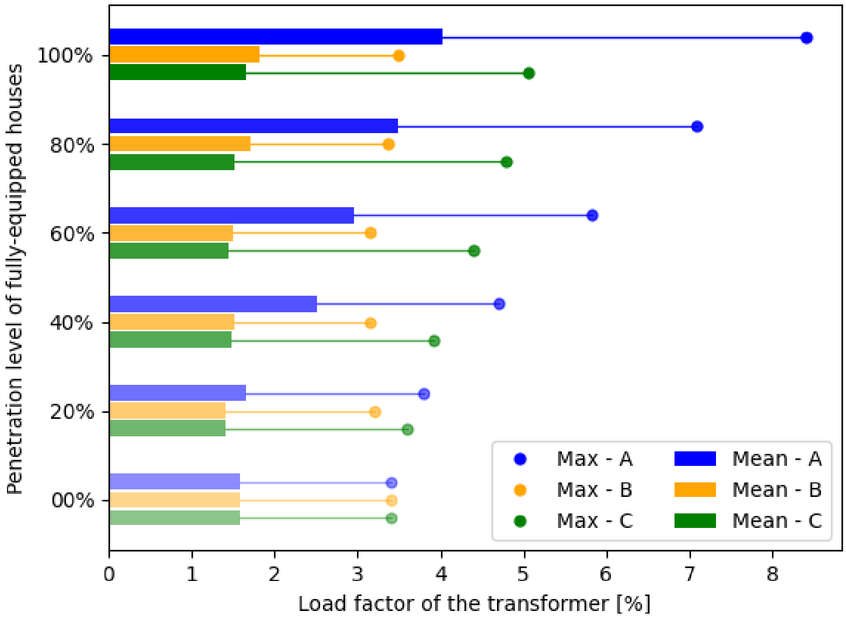


Figure 4.13: *Mean (bars) and maximum (dots) load factor of the transformer as a function of the penetration level of fully-equipped houses for all three cases.*

	Mean load factor [%]			Ratio [/]	
	Case A	Case B	Case C	B/A	C/A
100%	4.034	1.816	1.659	0.450	0.411
80%	3.497	1.704	1.517	0.487	0.434
60%	2.965	1.493	1.449	0.503	0.489
40%	2.511	1.507	1.475	0.600	0.588
20%	1.648	1.409	1.406	0.855	0.853
0%	1.578	1.578	1.578	1	1

Table 4.8: *Comparison of the* ***mean*** *load factor of the transformer between cases, for different penetration levels. The first three columns report the observed values for each case. The last two columns display their ratios with respect to case A.*

	Maximum load factor [%]			Ratio [/]	
	Case A	Case B	Case C	B/A	C/A
100%	8.414	3.489	5.063	0.415	0.602
80%	7.090	3.369	4.797	0.475	0.677
60%	5.826	3.147	4.396	0.540	0.755
40%	4.702	3.144	3.923	0.669	0.834
20%	3.802	3.204	3.591	0.843	0.945
0%	3.409	3.409	3.409	1	1

Table 4.9: *Comparison of the* ***maximum*** *load factor of the transformer between cases, for different penetration levels. The first three columns report the observed values for each case. The last two columns display their ratios with respect to case A.*

4.2.4 Discussion

Regarding the implementation of a shared battery bank (case C), no clear relation has been established between the level of voltage unbalance and the penetration level of the fully-equipped houses. Indeed, even though this solution seems to be more favorable for greater penetration levels, the improvement brought by the implementation of the shared battery fluctuates for the various penetration levels. Multiple reviews of potential causes, such as the distribution of the houses in the community or the types of houses that are equipped, have been looked into with no success so far. A plausible explanation would be that too many parameters change at once, which makes the understanding of the correlation between the unbalance and the penetration levels impossible with the performed analyses. A slower approach which would limit the number of variables in the simulations could potentially help uncovering the underlying relations between all studied variables. In contrast, regarding the load factors, the relation is clear: the reduction of the mean and maximal values is increased for higher penetration levels.

On the other hand, the implementation of private storage units is also beneficial for the studied constraints, and the relation is clear: the higher the penetration level, the greater the attenuation of the constraints!

To conclude, both private and shared batteries can be beneficial to the grid, but the implementation of private storage units should be preferred. Indeed, even though the mean load factors obtained for this solution are a bit higher than with shared batteries, the maximal values need to be addressed in priority since they are the first to cause the overloading of components.

4.3 Future perspectives

These different observations show the potential behind energy communities, but also remind ourselves that this tricky concept still has its challenges. These obstacles will need to be overcome in the future because whether we want it or not: solar panels, heat pumps and electric vehicles are already becoming more and more present throughout the entire grid. Just like the perfect situation, the perfect solution does not exist. Maybe the answer lies in the balance: energy communities would be combined with individual storage units to bring the best out of both options. As mentioned before, many complementary studies and pilot projects are needed for the successful development of the emerging concept that are energy communities. For example, financial studies could evaluate potential monetary gains for the inhabitants or analyse different ways to regulate the energy transactions within the community. Also, the model used in this work could be refined. New battery management algorithms could be designed specifically for energy communities, potentially considering the charging of the batteries directly from the grid instead of only using solar panels. Finally, the storage units modelled in this work were batteries, because they are already being presented by the Flemish region as a solution. However, the results obtained can be transposed to other means of storage, which could then be more eco-friendly. Or, the batteries from the EVs could be used as storage units, thanks to «vehicle-to-grid» technologies. These contributions could show a totally different aspect of the potential behind the concept of energy communities.

Chapter 5

Conclusion

Even though the development of renewable energy communities is supported by the EU, many obstacles still need to be overcome. From a political point of view, many improvements need to be made in terms of promotion, information and regarding the complexity of the administrative process. Besides that, many technical challenges still need to be addressed in order for the RECs to develop further.

One of these challenges is to evaluate the impact of renewable energy communities on power quality aspects of low-voltage distribution networks, compared to an already existing solution: the implementation of private domestic batteries. Through this master's thesis, the issue was addressed by modeling a community of 20 houses, which could be equipped with technologies such as PV panels, EVs or HPs, depending on the simulated scenario. Although the model could be further refined, interesting results were already observable: by 2050, the implementation of private and shared batteries both allow a significant reduction of the constraints imposed on the grid. Indeed, adding private, domestic storage units for each house equipped with PV panels significantly reduces the average load factors of the lines and of the transformer, by up to 34%. In addition, the voltage rise is significantly limited, resulting in a drop (up to 42%) of the unbalance levels. In contrast, the implementation of community-shared batteries has more moderate impact: the unbalance levels are reduced by up to 13% only, and the maximal load factors drop by 22.5%.

These results were then re-evaluated as a function of the penetration levels of fully equipped houses, i.e. houses that were equipped with all technologies. A clear relation was found between the usefulness of the implementation of private batteries and the penetration levels: the higher the penetration level, the greater the attenuation of voltage unbalances and load factors. This relation is also observable for the community-shared batteries, even though the results for the unbalance levels slightly fluctuate.

To conclude, this study explored the potential of energy communities despite the many challenges that still lie ahead. Despite the promising outcomes shown for such communities, additional research is required in order to further develop many other aspects of this concept. For example, the addition of other promising concepts, such as «vehicle-to-grid» or alternative means of storage, could help demonstrate the great potential of renewable energy communities towards a greener future.

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Appendices

Appendix A

Benefits & Barriers: a literature review of energy communities

With the ever growing demand for energy, technologies such as solar panels are becoming more and more common. However, such installations have a technical cost. Indeed, the grid was not originally designed to sustain the loads and decentralised generators which penetrate the distribution grid even more everyday. Also, the regulation of various power quality issues is made more difficult. Thus, local means of energy management are thus becoming indispensable from a technical point of view, but not only. In this context, this literature review highlights some of the benefits that drive the implementation of renewable energy communities. The latter does not come without its various challenges, which are also covered by this review. Both aspects are grouped together throughout the different categories that are covered that are the social and financial barriers and benefits of RECs. Note that some of following points are derived from, or can be applied to other concepts, such as micro-grids for example.

Social benefits and barriers

This first category includes different aspects and effects of RECs, which have a direct impact on people. For example, this encompasses their level of education, their behavior and habits, their perspectives and opinion on various matters, their level of comfort or their independence.

A first impact of these communities is the fact that people, thanks to their involvement in the community, will acquire knowledge and develop many skills. And this could have a direct impact on their level of education, on their general knowledge and on their professional proficiency. Developing general or acute knowledge about energy systems, energy management, production units are a few hard-skills that one could acquire while taking part in a REC. On top of that, the members of such communities will challenge their team-working capabilities and their sense of compromise. Some will grow and evolve as leaders while others could improve their problem-solving skills. In the end, thanks to this social, environmental and technical engagement, the different members will grow both on personal and professional levels.[47; 48]

Also, taking concrete actions towards a better energy management and being directly confronted to the problematic will help people fully grasp what is at stake as well as raising climate change awareness. This could potentially change some people's point of view on the matter and trigger a wider consciousness of energy issues among citizens and communities, that will in turn enable them to contribute more broadly to the energy transition. Being involved in solving the issue will help community members to change their consumption habits which will set a positive example for others to follow and influence the way people apprehend renewable sources of energy.[49; 47; 48; 50]

According to a comparative literature review of energy communities in the UK, Germany and the USA, RECs boost community empowerment.[47] Giving the people the opportunity to take matters into their own hands will build strong community cohesiveness. The different part-takers will develop a strong sense of belonging which is very important and can help manage stress and other behavioral issues. In fact, authors of [51] state that when one feels that he has support and is not alone, he is more resilient, often coping more effectively with difficult times in his life. They will also grow feelings such as pride and a sense of accomplishment. Ultimately, RECs will enhance people's sense of purpose and usefulness, and have the potential the truly impact their mood and mental health.

Developing energy communities will help to grow more independent from energy suppliers. When looking at the troubling times our society had to overcome in the previous years, one can easily understand the need to be more self-sufficient. For example, the war between Russia and Ukraine has had a huge influence on the price of oil and gas in many European countries, to the point where the poorest can not afford it anymore. This is typically an example of where energy communities could help many people maintain constant energy prices regardless of the variations of the market. On the same note, RECs offer a solution to power outages from the grid. In one way or the other, energy clusters push the consumer's independence and provide a safer and more stable energy source.[50]

However, a crucial point in the development of RECs is the amount of time and effort the community needs to engage for the community to stay up and running. Authors of [47] found that the fact that nowadays most people are already engaged in other activities could slow down the development of an energy cluster. Another point that was highlighted is the "Not-In-My-Back-Yard" (NIMBY) opposition from people who do not like taking on new things and are thus against changes in their direct environment. This type of opposition is common in the energy sector, and usually encountered with wind turbine or overhead high-voltage line construction projects.

In spite of all the previous arguments, the biggest impediment in the popularisation of RECs is the lack of knowledge and formations. Indeed, the development of such communities requires a certain knowledge of electrical and energy systems. Even though many of the part-takers will develop some of these skills as well as many others, one can not hope to build and run such a community without proper knowledge. This means that training courses must be available for people to follow if one hopes to see energy communities spread in residential areas.[47]

Economical benefits and barriers

Even though energy communities are usually based on volunteer work, they do generate employment. Indeed, the different technologies that constitute the community are always installed by professionals. The skills and tools required to install photovoltaic panels, batteries, turbines, or correctly install cables can not be achieved by anyone who has not received proper training. On the legal aspect, only certified professionals can endorse the responsibility of such installations, and their society is there to protect them from taking on all the responsibilities in the case of an accident. The implementation of RECs will thus participate to the creation of jobs. Local companies could really benefit from this. Also, local banks can be relied upon to help funding the installation of the system. This whole concept has potential to generate a great value which, if contained locally, could help the area to flourish economically.[49; 52]

Also, thanks to energy communities, the amount of energy transmitted through long lines is reduced since the decentralized generators cover part of the demand. The energy that is produced locally does not have to be transported over long distances. In that way, energy communities help save energy since their production is less affected by line losses. The energy saved can be seen as a direct energetic and economical gain.[53]

Another aspect in which energy communities have been proven successful is the direct reduction of energy costs. For example, authors of [54] conclude that, if

40% of all energy communities' customers had individual PV panels, then Peer-to-Peer (P2P) electricity sharing could reduce costs by about 30%, when compared to excess energy trading with a traditional grid. A case study dedicated to the state of Texas also shows economic benefits: an energy cluster of 50 residential houses, each equipped with PV panels, was created and it was concluded that, thanks to the sharing of the PV production, cost savings could be improved for all participants.[55] Authors of [56] also state that large economic savings can be observed. Finally, the authors of [57] even conclude that P2P electricity trading is more economically beneficial than trading with the grid. RECs can thus be a direct source of financial benefits for the entire community.[47; 50; 58]

However, energy communities do not come without costs. The initial investments needed are high and are not quickly repaid. This constitutes a common financial barrier for most projects. This problem can be solved thanks to external funds. In Belgium, there has been many funding opportunities for PV installations (green certificates, green loans), but these funds require a political engagement, which is still not strong enough in the case of energy communities.[59; 47]

Another barrier for the development of RECs is the lack of financial framework, especially concerning the monetarisation of the energy fluxes in between prosumers. This remains a big unknown and does not help attract investors as they can not fully grasp the returns on investment that are expected. The establishment of a legal framework, which would also cover the topic of monetary exchange, is needed in order to progress further.[47]

Others

On top of the different advantages cited earlier, energy communities drive technological innovation. They really are a place to spark innovation. It has also been observed that RECs boost the political participation of the citizen, pushing them to reach new level of engagement. RECs have the potential to educate children in a more eco-friendly environment, to discover new passion, challenges, problems and solutions.[4; 47; 50]

Undoubtedly, energy communities will help reach emission and renewable targets set by the 'Green deal' where the Belgian energy system must achieve carbon neutrality by 2050. The large-scale installation of PV panels for the residential part of low-voltage grids can bring us closer to this objective, as long as the problem related to congestion and the quality of the supplied power are taken care of. On top of that, energy communities have been considered as effective change agents which influence the general attitude towards Renewable Energy (RE) sources. They have been attributed as being able to create favorable conditions for RE-related policies and programs.[47]

Another advantage of energy communities is that, just like microgrids, they are very useful for the electrification of remote places. Electrification is an important problem in many developing countries and the democratization of such energy systems could really help shape the future of these countries. Indeed, REC provide an enabling framework which is required to quantify the different energy exchanges inside the community. Building on that, tariff-related policies can easily be developed.

One of the major obstacle encountered with REC projects is the absence of legal framework. Despite the many decrees that are present, some crucial aspects such as financial regulations of transactions are not defined. In Belgium, one still can not decide on its own to develop an energy communities. The only RECs that already exists are pilot projects. In their case, many authorisations and exemptions have been required in order for the projects to start.[49; 47; 60]

Along with the precedent point, a lack of political support and/or of governmental guidance has been observed and identified as a barrier to the development of RECs. The political engagement helps encouraging the citizen to participate in renewable projects and helps change the general opinion when it comes to RE sources. If the politics are not engaged or do not show interest in those projects, if the administrative paperwork and procedures are too long or complicated, then it is most likely that many RE projects will not make it through. The engagement of our leaders, their enthusiasm and their guidance is required for energy communities to start developing.[49; 59; 58]

Another difficulty arouse during the realisation of this master's thesis. The study of these communities relies on information such consumption data, which can easily be measured but are really difficult to gain access to, due to privacy rights. The same goes for technical data from grid components which are classified. This really slows down the study of such communities.

A last potential issue is that some could use such projects as financial investments. Indeed, the tariffs that are received for feeding energy into the grid need to be adjusted carefully as the objective of such communities is still to promote self-consumption as well as energy sharing with surrounding loads and not to push people to re-inject most of their production in return of economic profits.

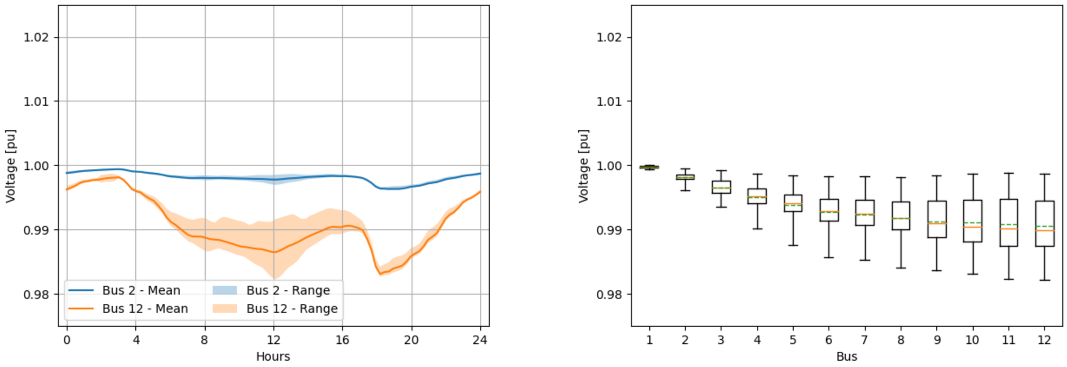
Appendix B

Comparison of the voltage fluctuations for cases A, B and C, in July

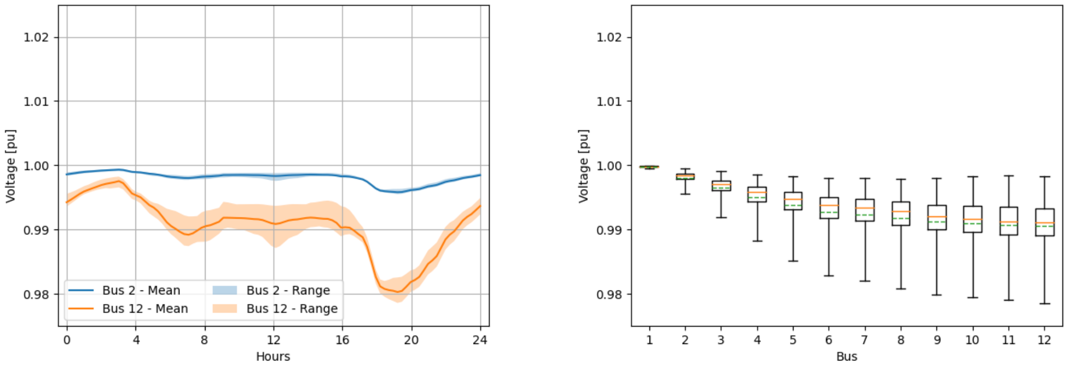
Figures B.1, B.2 and B.3 show the analysis of the voltage fluctuations for the month of July, as it was done previously for January. The modelled scenario is scenario 2, and all three cases are studied. The three figures correspond to the results for phases A, B and C.

In terms of interpretation, the implementation of private batteries (case B) performs much better at maintaining a reduced voltage rise around noon. This is visible on the three phases thanks to the daily evolution curves, shown on the left side of the figures. Additionally, during the evening consumption peak, case B results in a major reduction of the voltage fluctuations on phases B and C, which both have high penetration of PV-equipped houses. However, for phase A, the solution of private batteries performs slightly worse than the two other cases, due to the limited amount of PV-equipped houses on that phase (there is only 1).

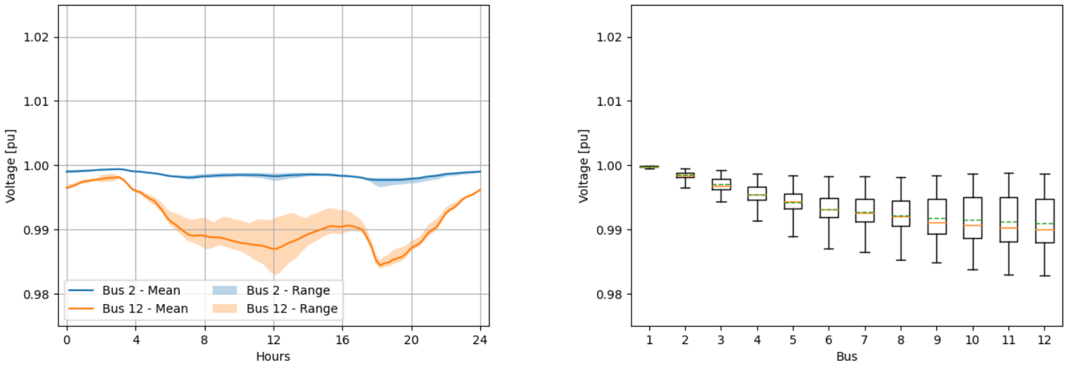
On the other hand, the shared batteries also show a beneficial impact on the voltage fluctuations, even though it is more limited than with private batteries. The general shape of the curves are similar to those from case A; but the implementation of the shared battery results in a visible limitation of the voltage fluctuations. Indeed, the values are spread closer to the nominal voltage of 1pu. The boxplots confirm this by highlighting that the distribution is less spread out than for case A.



(a) *Daily evolution - Case A* **(b)** *Monthly distribution - Case A*

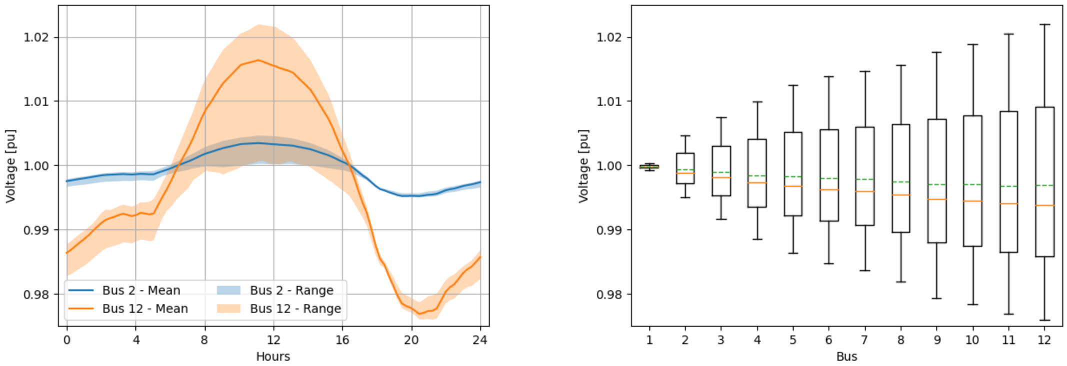


(c) *Daily evolution - Case B* **(d)** *Monthly distribution - Case B*

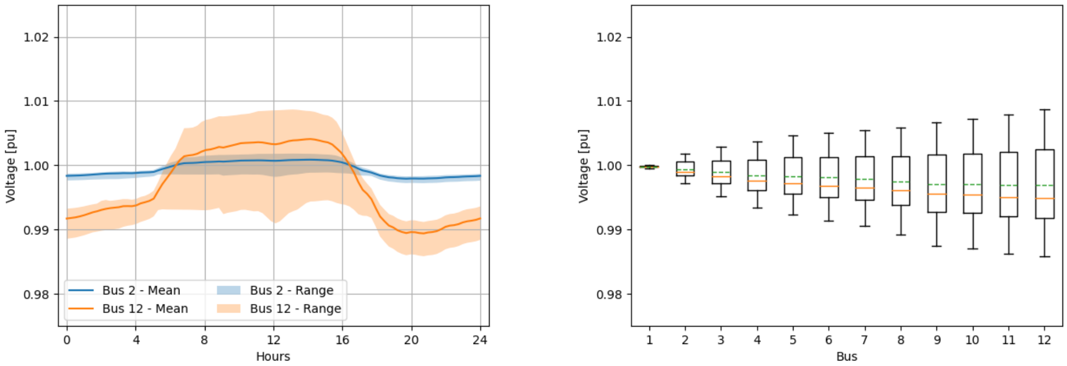


(e) *Daily evolution - Case C* **(f)** *Monthly distribution - Case C*

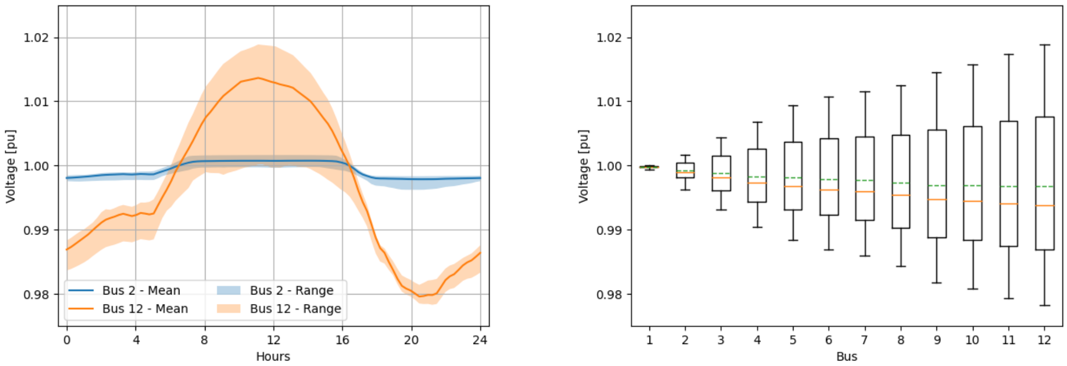
Figure B.1: ***July - Phase A.*** *On the left, evolution of the voltage magnitude at buses 2 and 12 throughout the day; for case A (a), case B (c) and case C (e). The solid lines show the evolution of the average voltage magnitude. The shaded areas represent the total range of obtained values. On the right, monthly distribution of the voltage magnitude at each bus; for case A (b), case B (d) and case C (f). The lower and upper whiskers extend to the minimum and maximum values, respectively. The black boxes determine the first and third quartiles. The solid orange lines show the median values of the data while the dashed green lines show the mean values.*



(a) *Daily evolution - Case A* **(b)** *Monthly distribution - Case A*

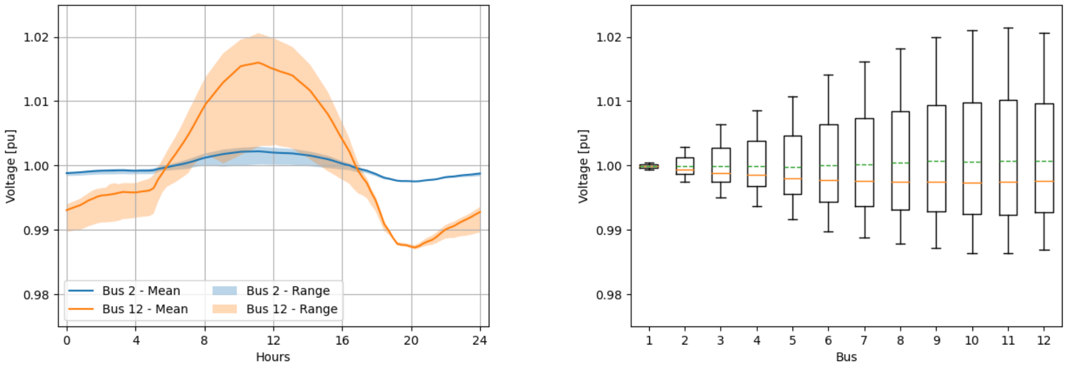


(c) *Daily evolution - Case B* **(d)** *Monthly distribution - Case B*

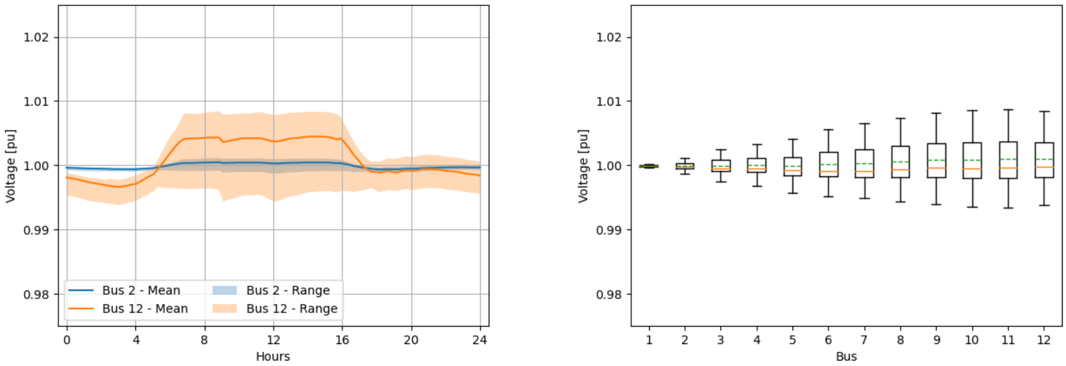


(e) *Daily evolution - Case C* **(f)** *Monthly distribution - Case C*

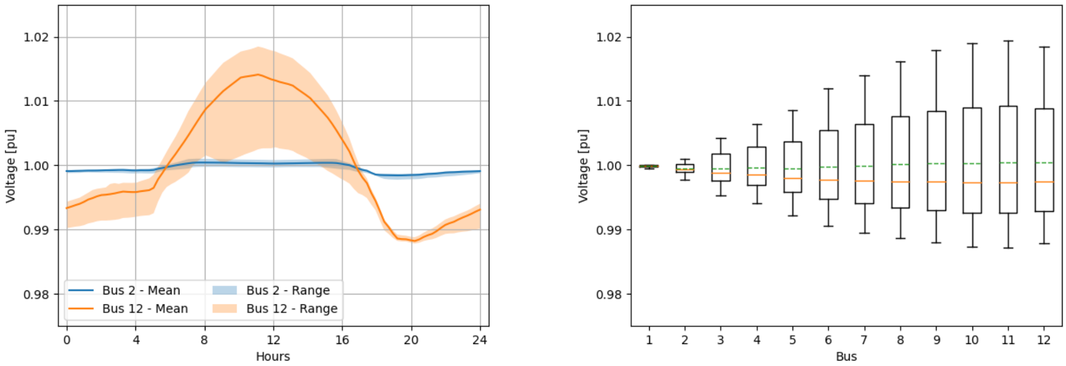
Figure B.2: ***July - Phase B.*** *On the left, evolution of the voltage magnitude at buses 2 and 12 throughout the day; for case A (a), case B (c) and case C (e). On the right, monthly distribution of the voltage magnitude at each bus; for case A (b), case B (d) and case C (f). The same explanations as for Figure B.1 apply.*



(a) *Daily evolution - Case A* **(b)** *Monthly distribution - Case A*



(c) *Daily evolution - Case B* **(d)** *Monthly distribution - Case B*



(e) *Daily evolution - Case A* **(f)** *Monthly distribution - Case C*

Figure B.3: ***July - Phase C.*** *On the left, evolution of the voltage magnitude at buses 2 and 12 throughout the day; for case A (a), case B (c) and case C (e). On the right, monthly distribution of the voltage magnitude at each bus; for case A (b), case B (d) and case C (f). The same explanations as for Figure B.1 apply.*

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