Louvain School of Management

Grid management and modeling of local balancing in Renewable Energy Communities

NON CONFIDENTIAL

Authors : Craciun Ana, Lavry Marie
Supervisor(s) : Per Joakim Agrell
Academic year 2020-2021

Acknowledgements

This thesis concludes our five years of studies in Business Engineering at the Louvain School of Management, before starting our professional career in technology companies in Dublin.

Therefore, we would like to thank Professor Per Joakim Agrell for his time and help throughout this project which was both challenging and interesting. Furthermore, we thank him for for the valuable input he has provided us, as well as the reflection and improvement tracks to carry our project even further. We are also deeply grateful for the support and patience of our families and friends, without whom none of this would have been possible.

Contents

Abbreviations

BESS	Battery Energy Storage System
CEC	Citizen Energy Community
CEER	Council of European Energy Regulators
DER	Distributed Electricity Resources
DG	Distributed Generation
DMS	Distribution Management System
DSO	Distribution System Operator
EED	Energy Efficiency Directive
EMS	Energy Management System
EU	The European Union
EV	Electric Electric Vehicle
ICT	Information Communications Technology
IEM	Internal Energy Market
LRA	Local and Regional Authorities
LCOE	Levelised Cost Of Electricity
MS	Member States
NIMBY	Not In My Backyard
P2P	Peer-to-Peer
PV	PhotoVoltaic
RE	Renewable Energy
REC	Renewable Energy Community
RED	Renewable Energy Directive
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
SG	Smart Grid
V2G	Vehicle-to-Grid
WTP	Willingness to Pay

1 Introduction

1.1 Overall Context

"Right here, right now is where we draw the line. The world is waking up. And change is coming whether you like it or not." quoting Greta Thunberg [BBC, 2019]. The young climate activist has understood the severe consequences of climate change, and is asking each and every one of us, to take action today to give our children a better world tomorrow.

Among all the aspects of our daily lives that need to be redesigned and sustainability improved so as to respect the boundaries of the planet, the energy system is one of the most prominent. As of today, transportation and energy sectors are the two major contributors of carbon dioxide emissions in Europe [IEEP, 2021]. Alongside the fact that the energy generation is polluting, the energy transport leads to large losses as energy is consumed far from where it is produced, while the demand is increasing due to demographic and economic growth [EPA, 2020]. It goes without saying that an energy transition is necessary to ensure access to affordable, reliable and sustainable energy, and the importance of this structural change is highlighted by the Sustainable Development Goal 7 "Affordable and Clean Energy" [United Nations, 2020].

The expansion of Renewable Energy Sources such as wind turbines and solar panels is leading to a decentralisation of energy generation, and thus marking a turning point in the energy system [Guille et al., 2017]. The integration of these Distributed Energy Resources thereby fosters the emergence of Renewable Energy Communities (RECs) that empower their members to produce and consume Renewable Energy locally. The participants of these communities become prosumers since they are active in the consumption and generation of energy, but also in the decision-making regarding the management of the community. These communities are value-driven, therefore the objective is to generate benefits that are shared fairly among all members rather than maximising profits [Caramizaru and Uihlein, 2020].

The integration of ICTs in these energy communities ensures the optimisation of RE management by counterbalancing energy consumption, storage and exchanges with the main grid. As a matter of fact, the bi-directional communication flow enables the system to have access to the consumption data of the members, but also to inform them of the dynamic pricing in real time. The digitalisation of the network therefore leads to the emergence of demand response, whereby the consumers shift their electricity demand according to the financial incentives, in order to adapt it to the supply [Kathan et al., 2007]. These innovative Smart Grids have the advantage of being sustainable, efficient and reliable, while allowing the members to save energy and reduce their electricity bills.

Therefore, local energy communities implement the principle of energy democracy as all members are empowered to optimise energy management by balancing supply and demand. Besides, these organisational structures are in line with four of the main principles of the regenerative economy, notably “Innovative, Adaptive, Responsive”, “Empowered Participation”, “Robust Circulatory Flow”, and “Seeks Balance” [Fullerton, 2015]. As RECs are part of a regenerative approach, allowing each element to contribute to the health of the whole ecosystem in a sustainable way, it is interesting to explore their functioning further, so as to enhance their development.

Thesis Research Objective

The aim of this master thesis is therefore to analyse the ”Grid management and modeling of local balancing in Renewable Energy Communities”.

1.2 Contribution

The aim of this thesis is to analyse and then modelize the functioning of communities, with a view to define to what extent they can meet the energy needs of their members, while reducing the carbon footprint and energy poverty. The ultimate goal of this project would be to enhance the expansion of these local energy communities by providing opportunities for improvement.

1.3 Motivation

It is true that we have been concerned about the impact of climate change for a while, and this is why we are doing our best to reduce our carbon footprint along with our energy and water consumption. Besides, our interest in energy management and renewable sources comes from the Research and Development course given by professor H. Jeanmart, as well as from the Business Game given by Luminus at the LSM Cup 2020. In addition, the lockdown imposed by the Belgian government due to the global pandemic has made us more aware of the local dynamics and the impact that strong local communities can have. As a result, these factors have sparked a growing interest in the management of Renewable Energy Communities, which address contemporary global challenges.

1.4 Structure

The thesis follows a structure that reflects the main steps taken to conduct this research. In order to approach the topic of energy communities and Smart Grids, the research was first concerned with Distributed Energy Resources, their attractiveness, penetration and as well as their key enablers in the electricity market. Afterwards, an extensive analysis of the literature review was conducted to gain a clear understanding of Renewable Energy Communities, their main activities, organizational structures and the regulatory environment in which they evolve.

The main social, economic and environmental benefits of Renewable Energy Communities were then analysed. Following this, the research was focused on the enablers of flexibility and the concept of demand response within energy communities. Furthermore, the challenges and drivers for the implementation of the RECs were discussed, with a focus on national and European regulations. Thereafter, the Smart Grids and their main components were developed, before analysing a practical example with the case of Simris, Sweden.

With a view to testing the outcomes of the literature, a simulation model of an Renewable Energy Community has been built. The results of the model were analyzed in detail before comparing them with the theoretical highlights in the discussion section.

To conclude, it seemed appropriate to first provide the main managerial recommendations arising from this research, then the similarities between the findings and the literature, before formulating the critiques of the model. Finally, some improvement for future work were suggested.

1.5 Limitations

Inevitably, some intrinsic limitations have been placed on this academic research. As indicated in the structure, a literature review was conducted followed by the REC modeling based on collectively-owned generation assets structure. Given our limited skills and knowledge of the Gurobi software, we limited ourselves to this specific case, whereas it would have been also interesting to model the self-consumption and individual-owning of generation assets.

Furthermore, it would have been valuable to analyze and modelize the Citizen Energy Communities, as they are also part of energy communities. This study would have been interesting to investigate on the differences with the RECs, especially on the geographical and sustainable aspects. When it comes to the Renewable Energy Sources, this research focused on the most widespread installations, i.e. solar panels and wind turbines, without taking into account other technologies such as biomass and hydro-power.

Finally, another important limitation is that this research remained mainly theoretical. It could have been interesting to interview members and managers of such an energy communities, as well as local, national and European regulators. Through interviews with actors actively involved in energy communities, it would have been possible to get more practical insights on the benefits, incentives and daily challenges within RECs.

2 Distributed Energy Resources

Distributed Generation (DG) is generally defined as a source of electrical energy having a limited capacity, directly connected to the distribution network of the power system where it is consumed by end-users [Akorede et al., 2010].

Furthermore, Distributed Energy Resources (DER) refers to any small scale electricity generation device that is located near the consumer at the distribution level. Some specificities might been added, such as limiting of their capacity to 30MW, and stating that they must be located at the consumer's home or in the vicinity so as to meet the local need. These sources are divided into two groups: thermal energy sources such as natural gas or biogas generators, and renewable production sources including wind turbines and solar [de Villena Millan, 2021]. In this thesis the main focus is set on wind turbines and solar panels. These technologies are deployed by consumers whom therefore become active consumers, or by small companies connected to the main distribution network [Gopstein et al., 2021].

The DER are nowadays perceived as a way to efficiently provide a growing energy demand. As Renewable Energy Sources provide an intermittent generation and are divided in multiple small to medium units, it can be complex to rely on one production unit. Therefore, researchers propose an approach where multiple DER installations are aggregated to form a virtual power plant. A virtual power plant interconnects the production units and centralizes the generated energy in order to redistribute it to the consumers. The objective of a virtual plant organization is to provide an enhanced visibility, and control on DER generation at large scale [Lopes et al., 2007].

2.1 Wind Turbine Generation

A wind turbine is a device that converts the kinetic energy of the wind into mechanical energy, which is then turned into electrical energy. There are several main factors that can affect the quantity of electrical energy produced, which are the size and shape of the blades of the wind turbine, but also the wind speed and the air temperature. A distinction must be made between wind turbines that are erected on land, called onshore wind turbines, and those that are located on the sea, called offshore wind turbines. Offshore wind turbines can produce up to twice as much electricity as onshore wind turbines because they are subject to a stronger and more constant wind [Komusanac et al., 2021].

Onshore wind energy is at the heart of the local energy transition. Wind energy has significant advantages such as the fact that it is clean, unlimited, locally available and affordable. Moreover, wind energy does not produce greenhouse gases, and each kWh produced avoids the emission of 500 to 600g of CO2.

Although wind energy varies significantly over time, it is nevertheless predictable as it is following a specific pattern over the year (Appendix 15.1). In fact, there is more wind and therefore more electricity produced in winter when the demand for electricity is higher, especially between the months of January and March, while it is lowest in summer when the pressure is higher [Engie, 2020]. During the month of February, wind power generates more than 55 GW per hour 90% of the time in Europe, which roughly equals the electricity demand per hour in Germany [Komusanac et al., 2021]. The wind forecasts are also becoming more and more accurate through technological breakthroughs.

The growing wind capacity in Europe reaches 220 GW in 2020, of which only 11% is generated by offshore wind turbines, if considering the 27 countries of the European Union as well as the United Kingdom (Figure 1). Therefore, wind power generation provided 16% of the electricity consumed in Europe. The leading countries in terms of wind power generation capacity are Germany with 63 GW, Spain with 27 GW, the UK with 24 GW, France with 18 GW, and Italy having 11 GW [Komusanac et al., 2021]. Furthermore, to honour the commitments within the Paris Agreement, the wind turbines capacity will be increased by 105 GW over the next 5 years [United Nations, 2015].

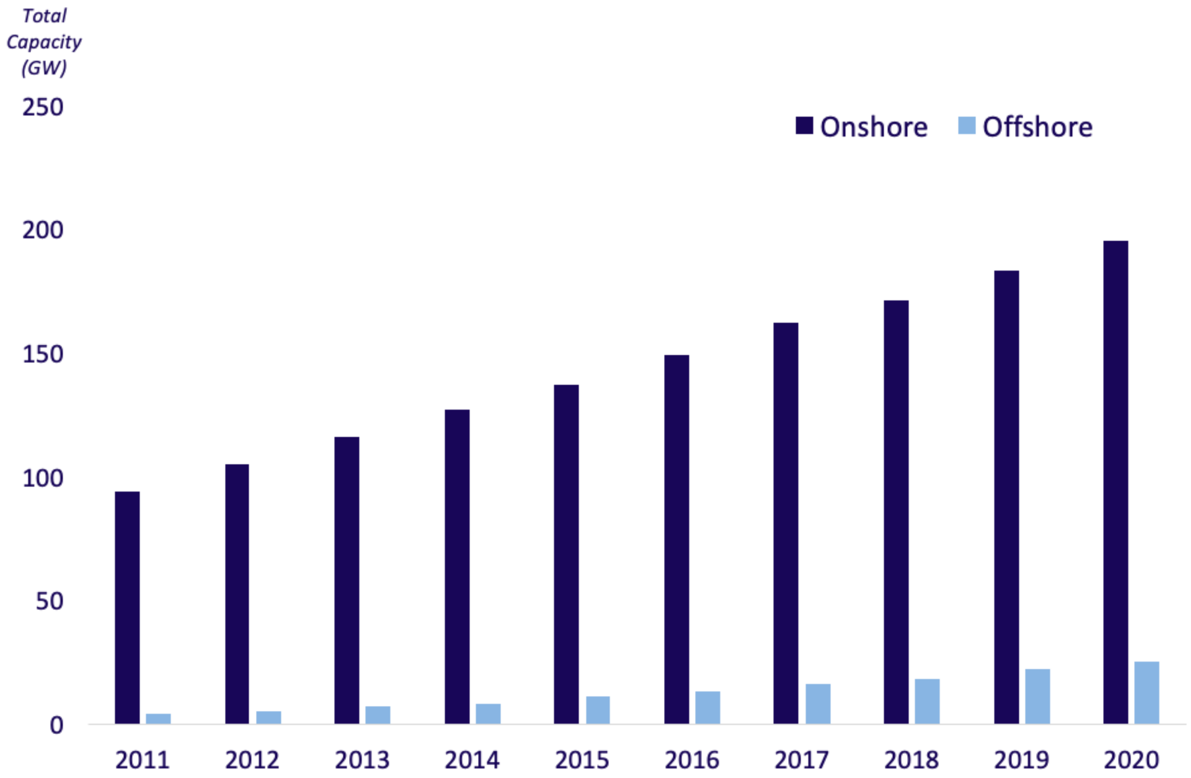


Figure 1: Wind capacity evolution in Europe [Komusanac et al., 2021]

To show the real output that wind turbine can provide, it is important to take into account the capacity factor of the wind turbine, which is the ratio between the measured wind power generation and the maximal electricity output over the same period. Thus for onshore wind turbines, the average capacity factor is 25%, but this ratio can reach 30 to 35% for new wind turbines. As for offshore wind turbines, the average capacity factor is 42%, but new turbines can reach a significantly higher ratio of 55%.

Investments in wind energy has increased considerably in the last few years as it provides the investor with a stable, long-term and sustainable income. The Levelized Cost of Energy (LCOE) measures the overall cost of generating one MWh of electricity. The LCOE can therefore be calculated by taking the net present value of the construction, operation and maintenance costs of the power generation asset, and dividing it by the amount of electricity generated over the same time period [Corporate Finance Institute, 2021]. Therefore, the LCOE for onshore wind turbines equals 59€/MWh, and 84€/MWh for offshore, which is much lower than that of coal and natural gas with respectively 90€/MWh and 95€/MWh (Appendix 15.2).

However, approximately 70% of the production cost of wind power comes from the initial investment, while operation and maintenance costs are relatively low compared to fossil fuel technologies. The approximated investment for an onshore wind turbine is between 1 and 1,7 million €/MW and the annual maintenance costs are around 40.000€/MW [Combe, 2020]. The generation of electricity from wind is therefore highly cost-competitive as technologies are becoming increasingly efficient, while allowing for a reduction in balance-of-plant, operations and maintenance expenses as well as greater bargaining power with suppliers [BloombergNEF, 2020]. The lifespan of wind turbines is about 25 years, but given the global expansion of this technology, recycling them is becoming a considerable challenge.

2.2 Photovoltaic Generation

In the late 30s, it became technologically possible to convert solar energy into consumable electricity through the use of photovoltaic systems, more commonly known as solar panels. The photovoltaic technology is one of the fastest growing renewable energy technology in the world as it is considered clean and sustainable for meeting the demand of a growing world's population. A solar panel is composed of multiple interconnected cells which ensure the conversion function between light sun radiation and electricity. This technology can be used for self-consumption in a stand-alone way, in an aggregated way in a photovoltaic farm setting, but it can also be connected to the main grid.

As for the drivers that favour the replacement of fossil energy sources by Renewable Energy Sources, it should be noted that investments in research and innovation play a major role in reducing the manufacturing costs of these sustainable technologies.

Furthermore, as part of the Clean Energy for all Europeans package, Member States of the European Union have implemented specific support measures for Renewable Energy. These measures incentivize a long term commitment in encouraging investments and improving grid access for Renewable Energy. The best-known incentive mechanisms for Renewable Energy production are feed-in-tariffs. These tariffs are a cost compensation that guarantee a fixed price for green producers, allowing them to break even with their investments and other variable costs. Due to the feed-in-tarrifs the investments are eased, hence the costs of production are lower, resulting in lower prices for Renewable Energy [Couture and Gagnon, 2010].

The European solar power sector has proven a strong resilience during the Covid-19 crisis, and still increases notably. Indeed, European Union members have implemented 18,2GW in 2020, which is a 11% increase with regards to the 16,2 GW installed in 2019, leading to a total capacity of 137,2 GW in Europe [Schmela, 2020]. The prospects for the 2020-2024 period are highly positive, with a growth medium scenario of 23% for 2021 where new 22,4GW will be added to the cumulative capacity. Moreover, a total of 115,5GW will be added over the period, achieving a capacity of 252,9GW by the end of 2024 (Figure 2).

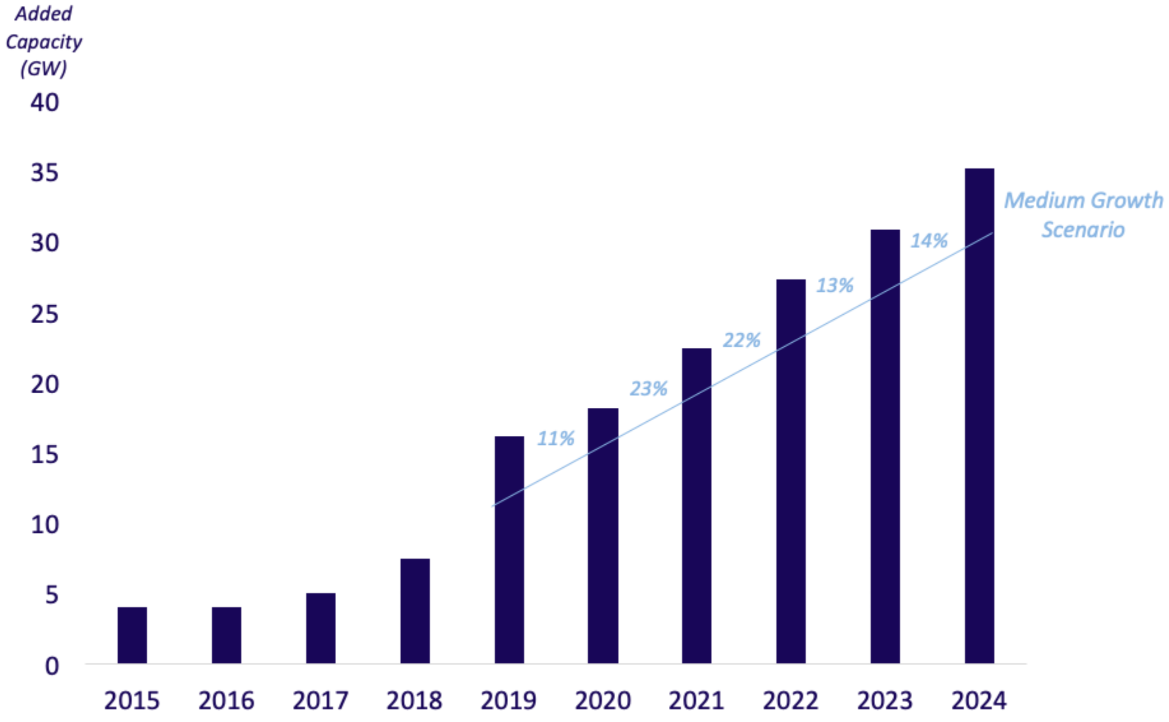


Figure 2: Annual growth of added solar capacity in Europe [Schmela, 2020]

Due to the increasingly important place that solar energy occupies in the energy mix, it is possible to measure its economic sustainability by using the Levelized Cost of Electricity, which measures the overall cost of generating one kWh of electricity [Schmela, 2020]. In

2020, solar power can be generated at a LCOE of 5c€/kWh in Northern European countries and at 3c€/kWh in Southern European countries, while these costs are expected to decrease respectively down to 2c€/kWh and 1c€/kWh by 2050 [Schmela, 2020]. As a result, it would therefore be possible for the solar power systems to outcompete industrial and wholesale prices everywhere in Europe.

2.3 Drivers of DER Integration

The emerging adoption of DER such as PV and wind turbines technologies are mainly due to commercial and regulatory drivers.

Commercial Drivers

The main commercial driver is the fact that the DER integration comprises the uncertainty of electricity market. It goes without saying that an important capital is required when building a new power plant, and there are high risks associated with these investments. Therefore, smaller capacity generation projects such as DER represent a lower investment and a decreased financial risk. Moreover, since the implementation of these solar and wind technologies, there has been a significant decrease in the generation costs as mentioned within the LCOE analysis, mainly due to technological progress (Sections 2.2 and 2.3).

Secondly, when the implementation of DER is as close as possible to the load, there is an increased enhancement of the power and supply quality. In addition, when the DG is allowed to be in full island mode, the outages are prevented which further improves the reliability of supply. It is why, DER are considered as a very efficient way to enhance quality and security of energy supply.

Regulatory Drivers

The regulatory drivers for DER integration are mainly European policy packages.

The first drivers are the targets and policies issued by the European Union within the Clean Energy for all Europeans package. This package sets as target that 20% of energy generation in Europe should come from RES by 2020 [European Commission, 2016]. The directives in this package focus on diversifying the energy sources and enhancing the energy security of supply. Indeed, Distributed Generation is one of the most reliable alternatives since it is situated close to the consumers, there would be a limited impact on the whole network in case of an outage. In addition, by diversifying the energy sources and generating energy locally, the national regulators obtain an enhanced control on the overall energy generation. This is an substantial matter, as fossil-based fuel is mostly supplied from remote areas where the politic situations are unpredictable, representing a risk for secure energy supply.

The last driver is the support for competition policy. Regulators in favor of a reform of the electricity supply sector are fully supporting the creation of a playing field and the increase of the number of competitors in the electricity market. As a consequence, the customer's choice will evolve, the prices will decrease and the quality of the service will improve. Through DG integration, clear competition rules, economic benefits and subsidies, there will be multiple new small generators that will be able to trade on this new electricity market. These policies will encourage the emerge of Renewable Energy technologies and lead to a decarbonization of the electricity markets [Lopes et al., 2007].

2.4 Challenges of DER Integration

On the one hand, the revolution within the generation technologies, in alliance with European policies have encouraged an increasing integration of DER. This integration now constitutes one of the main tools for moving towards a decarbonized energy generation while escaping a fossil dependent scheme.

On the other hand, the regulatory framework must be further improved to foster the integration of DER. Worldwide energy regulation frameworks define the way that the electricity sector is behaving, and provide the rules which specify how distributed generation should be integrated. However, these regulation structures are focused on centralised energy generation and have to be adapted to accommodate these new technologies. These challenges may evolve from the fact that the network tariffs are inadequately designed, and the metering technologies must be updated to integrate the DERs and allow the development of energy communities. Therefore, there is an increasing necessity to establish basic rules regarding the energy exchanges between DER owners and the distribution network, on this new electricity market where prosumers are able to resell their production (Section 6.1).

Besides, there are some downsides to the DER integration, as an increased decentralization of energy generation may also come with technical challenges. The technical issues can be unbalances, over and under voltages which can prevent the smooth functioning of the distribution network. In fact, the main electricity grids have been designed many decades ago on a one direction flow of electricity base, and was therefore not designed to take-in and redirect an important amount of Distributed Energy (Section 6.2) [de Villena Millan, 2021].

2.5 New Electricity Market

The large integration of DER has encouraged the creation of frameworks for trading electricity in a decentralized fashion, resulting in a true empowerment of the customers. Nonetheless, the rules by which the customers interact with the main grid must be further defined and adapted within national regulations. Hence, this implies that DER owners are limited in their ability to use their facilities. Namely, from a regulatory point of view, they only have the possibility of using as much as possible of the produced energy and selling the surplus on the main grid. Therefore, new regulations are foreseen and expected to foster the exchanges between customers, including DER owners and simple users on the main grid, with the common goal of maximizing the use of the energy generated at local scale [de Villena Millan, 2021].

3 Renewable Energy Communities

The emergence of energy communities stems from the desire to find alternative ways of governing and organising energy systems in order to achieve sustainability [Van Der Schoor et al., 2016]. The Clean Energy for all Europeans Package acknowledges the fundamental role of consumers in the energy transition [European Commission, 2016]. The new directives give consumers the opportunity to actively participate in the European energy market in order to achieve its full potential. This made it possible to define the role of prosumers, who are active consumers. In fact, they can generate their own energy, store it, share it, consume it or sell it back to the market, as well as providing flexibility services through demand-response and storage. Active consumers can refer to individuals, groups of individuals, households, small businesses or local authorities who may act autonomously or within organisations.

Therefore, energy communities enable the current system to be restructured by organising collective energy initiatives based on open participation and democratic governance while offering benefits to community members. The primary objective of these non-commercial entities is hence to provide environmental, social and economic benefits to the community rather than to make a profit [Caramizaru and Uihlein, 2020].

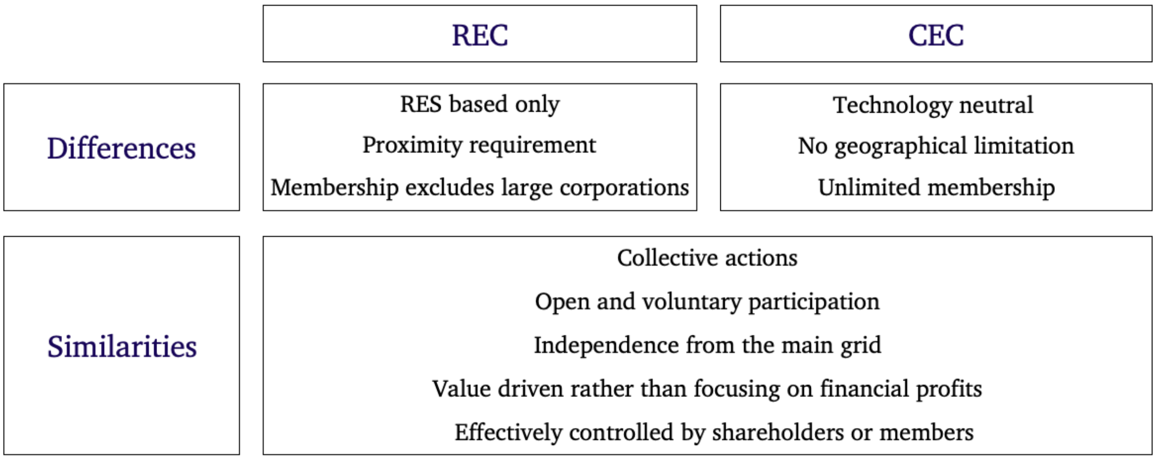
The Clean Energy Package established two distinct definitions of energy communities, namely Citizen Energy Community (CEC) which is included in the Electricity Market Directive [European Parliament and Council, 2019], and Renewable Energy Community (REC) defined in the Renewable Energy Directive [European Parliament and Council, 2018].

3.1 Citizen and Renewable Energy Communities

Both types of energy communities have a number of similarities in their governance, ownership, control and purpose. Indeed, REC and CEC require a legal entity whose membership structure must be based on the open and voluntary participation of members. Access must be open, and all participants have also the right to leave the community at any time. The effective control and ownership of these communities must be given to participants by taking joint action. Finally, these communities should be value-driven for their members rather than focusing on making financial profit [Frieden et al., 2019a].

The two types of community energy also present some differences in terms of geographical scope, activities and membership structure [Frieden et al., 2019b]. Renewable Energy Communities are local communities with a requirement for proximity so that the members who actually own and effectively control the project are in its vicinity. In contrast, Citizen Energy Communities do not require the generation and consumption of electricity to be located in the same area. Furthermore, while CEC are technology-neutral and therefore operate with renewable as well as fossil-fuel based energy, REC rely solely on Renewable Energy. Finally, the CEC allow households, local authorities, small, medium and large enterprises to join the community as long as the energy sector is not their main economic activity and they do not participate for commercial purposes. As for the REC, they have more restricted membership rules as they do not allow large companies to be shareholders or members of the local community.

REC and CEC are therefore two types of energy community that have quite similar characteristics, with the difference that REC are local communities that operate only with Renewable Energy and exclude access to large companies as members (Figure 3). The emphasis of this thesis is placed on local communities, and thus on Renewable Energy Communities.



	REC	CEC
Differences	RES based only Proximity requirement Membership excludes large corporations	Technology neutral No geographical limitation Unlimited membership
Similarities	Collective actions Open and voluntary participation Independence from the main grid Value driven rather than focusing on financial profits Effectively controlled by shareholders or members	

Figure 3: REC and CEC comparison [Frieden et al., 2019a]

3.2 Energy Democracy

Renewable Energy Communities (REC) are therefore decentralised and renewable-based energy projects that promote sustainable electricity production and consumption. In contrast to traditional energy grids where consumers are passive, local communities have sparked a real change in consumer behaviour through customer-empowerment practices, leading to community-driven initiatives.

These local communities are therefore in line with the concept of energy democracy, which is the transfer of power associated with all aspects of the energy sector to consumers [Gancheva et al., 2018]. This energy community therefore allows the members to be an intrinsic part of the production and management of electricity in order to achieve the sustainable development objectives set by the European Union. The energy democracy concept highlights that fossil-fuel based energy networks and profit-maximising energy multinationals have largely contributed to increased inequities, vulnerabilities and inequalities among consumers [Stephens, 2019]. The impact of the energy system on the cultural, economic and political aspects of society shows that moving from fossil-fuel to renewables is not just a technology change, it is an opportunity to shift power leading to a societal change.

The concept of energy democracy is therefore supported by several complementary principles [Energy Democracy, 2021]. Firstly, it enables universal access and social justice so that everyone can benefit from clean and affordable energy, which can also lead to local economic growth. Furthermore, it involves the use of renewable, sustainable and local energy to create thriving communities independent of fossil fuels. People using energy must have ownership and be actively involved in the decision-making process of projects so that they meet their needs. This can be done through collaborations between local authorities and consumer groups which can be organised as cooperatives. Therefore, democratic control of local communities requires the fullest transparency and accountability. Ultimately, this must lead to a just transition that creates fairly remunerated and unionised jobs.

3.3 Activities

The Local Energy Communities aim to balance the production and consumption of Renewable Energy by maximising the benefits for the members. Most of these sustainable initiatives are involved in the generation of clean electricity, but they are also becoming energy and energy service providers. It is therefore interesting to analyse the range of activities that local energy communities can undertake.

The first activity is the generation and thus the production of energy from Renewable Energy Sources (RES) such as photovoltaic panels, onshore wind turbines, micro-hydro or biomass. The participants can therefore collectively use or own the energy generation assets (Section 2).

Then, members can consume the electricity produced, and they can also share locally the electricity from the community-owned facilities with other members of the community [Caramizaru and Uihlein, 2020]. The Renewable Energy Directive distinguishes between individual and collective renewables self-consumption. On the one hand, renewables self-consumers are members of the local community who generate renewable electricity for their own consumption and who can then store or resell it as long as it is not their main commercial activity. On the other hand, collective self-consumers of jointly acting renewables self-consumers are a group of at least two members who are located in the same area, and who generate electricity and then store or sell it for non-business reasons [Frieden et al., 2019a]. The concept of collective self-consumption has been recognised in some national legal frameworks such as in France and Austria, and is therefore contributing to the emergence of a sharing economy [Council of European Energy Regulators, 2019b].

In addition, the micro-generation allows the sale of electricity to other community members. Thus, Peer-to-Peer (P2P) trading involves the sale of energy between participants, including automatic execution and settlement of the transaction [Anisie and Boshell, 2020]. This can be done directly between the participants, or indirectly via a certified third party such as an aggregator. The latter aims to combine customer loads or generated electricity for sale, purchase or auction in the electricity market. P2P trading can take place between members of a local community, but also on a larger scale. The Brooklyn micro grid is an energy community that interconnects households via a low-voltage network so that members can sell and buy energy via smart contracts using blockchains. The power flow is controlled with a bi-directional metering system and Information and Communication Technologies (Section 7.3).

A number of local energy communities also manage and own the power distribution system. As these cooperatives are small, they are exempt from the EU unbundling rule which requires that energy suppliers and generators be separated from the operators of the energy distribution networks [Gancheva et al., 2018]. This would be because a company that manages both the production and distribution of energy would have an incentive to prevent competitors from accessing the network, leading to higher prices for consumers. This rule is intended to ensure fair competition [European Parliament and Council, 2009].

Finally, local energy communities can also provide a range of ancillary energy services to their members. This may include services concerning energy storage, energy savings, advice on energy efficiency measures, financial services as well as energy monitoring and management via the integration of Smart Grids [Caramizaru and Uihlein, 2020]. For instance, the Belgian cooperative Ecopower aims to invest in Renewable Energy, to supply 100% green energy to its members, and to promote a rational and conscious use of energy [Rescoop, 2021]. Therefore, the cooperative enables its 60,000 members to control their energy consumption.

Indeed, they have access to an online tool called Energie ID which allows them to monitor their consumption in real time and to compare it with their consumption history. The cooperative can then identify energy efficiency needs and advise members through a social media platform. Local communities are constantly striving to improve their energy services offering by exploring new technologies such as virtual power plants and energy storage as well as the use of blockchain for P2P trading. In addition, the storage that can be provided by Electric Vehicles (EV) thus increases the flexibility by maximising the local use of the energy produced [Gancheva et al., 2018]. The Vehicle-to-Grid principle enables excess energy to be stored so that cheaper energy can be consumed at peak consumption times (Section 5.1).

3.4 Structural Organisation

The organisational structure of local energy communities can vary by taking different forms of legal entity. Although their primary objective is to maximise benefits to the members, these legal entities may include cooperatives, partnerships, community trusts and foundations, limited liability companies, non-profit customer-owned enterprises, housing associations and municipal ownership [Gancheva et al., 2018]. Besides, these local energy ownership models are regulated according to three key identical processes, namely remunicipalisation, devolution and participative governance.

Firstly, remunicipalisation consists of increasing municipal control over local energy management. Therefore, local authorities have an operational role and participate in economic decisions instead of the energy companies. Secondly, devolution involves increasing the strategic and political role of local authorities in energy policy. Hence, the government transfers its power to the local authority in relation to the regulation and implementation of energy networks. Finally, participative governance refers to the process of increasing energy democracy and member involvement in energy management [Gancheva et al., 2018]. This would help to align the energy network with local needs, while also increasing the transparency and accountability of management. As a result, local communities and citizens are motivated by a willingness to manage energy networks locally and to overcome corporate and government stranglehold on energy services.

The most common and fastest growing organisational structure for local energy communities is undoubtedly the cooperative. Local residents jointly own and manage these energy projects which include both Renewable Energy Sources and energy efficiency systems [Yildiz et al., 2015]. This democratic structure allows members to invest in electricity generation projects by buying shares in the project, and generally to consume and share the electricity produced [Walker, 2008]. This type of legal entity is especially prevalent in countries with a strong community tradition, such as Germany, but also where renewables are more advanced.

The functioning of cooperatives is defined by internally agreed key principles. Firstly, these members-led initiatives are open and voluntary. As with any local energy community, this means that there are no barriers to becoming a member as long as these local members are committed and accept their new responsibilities. For buildings where the landlords also co-own the RE installations, the tenants can either decide to participate in the energy sharing agreement, or to be supplied independently [Council of European Energy Regulators, 2019b].

Secondly, cooperatives are based on democratic governance as decisions are taken on the principle of "one member, one vote". As a result, each member has an equal vote and can participate in decision-making and energy policies, although day-to-day operations are managed by elected representatives. Thirdly, members can buy shares in the project providing access to energy and other benefits, but this contribution must be equitable among members allowing democratic capital control. Profit distribution is regulated and limited in the form of capped dividends as maximising return on capital is not the primary objective of these legal entities. Apart from these restricted compensations, the surplus is reinvested to support the main objectives of the members and the community. The fourth principle specifies that cooperatives must remain independent and autonomous, and therefore cannot be controlled by private companies nor by public authorities. The following principle specifies that cooperatives provide education and training to members and employees so that they can fully assume their role, as well as to external people so as to communicate the benefits of such an organisation. Finally, the last two principles state that cooperatives should collaborate with other cooperatives at local, regional and national levels and that they should above all prioritise the needs of their members by ensuring the sustainable development of the community [Gancheva et al., 2018].

After cooperatives, the partnership is the most common organisational structure for local energy communities. The particularity of partnerships is that the voting and ownership rights are proportional to the capital invested by each participant, which differs from the "one member, one vote" principle inherent in cooperatives [Caramizaru and Uihlein, 2020]. In addition, the governance of these projects is often assigned to the management board. The first type of partnership is the "joint and several" limited partnership with the specificity that each member is liable. The second type is the "limited" partnership including a separate company so as to limit the liability of individual investors regarding the project's debt [Gancheva et al., 2018]. Therefore, partnerships are particularly convenient for large-scale projects requiring significant investments, such as collectively owned wind farms.

3.5 Regulatory Environment

Given the specific characteristics of local energy communities, it is essential to adapt the regulatory framework to support their proper functioning and thus the achievement of their sustainable objectives.

At the European level, there are four policies that have a major impact on the regulation of local energy communities. The Renewable Energy Directive (RED) and the Energy Efficiency Directive (EED) are respectively intended to ensure the development of Renewable Energy and energy efficiency [European Parliament and Council, 2018] [European Parliament and Council, 2012]. These two directives also set out the support mechanisms that the Member States (MS) can put in place to foster the development of these sustainable initiatives. Furthermore, the Internal Energy Market (IEM) Directives governs the operation of the electricity market and may therefore adapt the requirements to access the distribution network and become a supplier, in order to further integrate the RECs [European Parliament and Council, 2019]. Finally, the State Aid Rules establish incentives for prosumers that are in line with the electricity market, such as feed-in tariffs or financial compensations.

At national level, Member States can transpose or supplement European policies on the regulation of Renewable Energy Communities according to their national context, challenges and objectives. Therefore, the key regulatory frameworks vary widely between countries, leading to disparities in the promotion of local collaborative initiatives. When comparing the measures taken by the countries, the majority of countries have not provided relevant definitions in the field of energy legislation such as for "Local Energy Community" or "energy cooperative" with the exception of Greece and Poland.

It is also notable that all countries provide support mechanisms for Renewable Energy installations, ranging from feed-in tariffs, feed-in premiums to quota obligations depending on the country. Most, but by no means all countries also offer tax incentives for renewables, which is the case for Spain and Germany for example. Only a minority of countries offer priority access to the network for RE installations, but often at a cost for the prosumers. When it comes to the simplification of procedures for RE assets, some countries provide this but often only for one type of installation having a small and limited capacity [Gancheva et al., 2018].

Considering the case of Belgium, the Walloon region has legally defined the concept of "self-producer", while the Flemish region has defined the concept of "prosumer tariff". The country of over 11 million inhabitants has established support mechanisms for RE installations, including tax incentives. Priority access is also provided for these sustainable facilities, but the connection is charged at a fixed fee. Finally, Belgium authorises a simplification of the procedures for PV installations only [Gancheva et al., 2018].

4 Sustainable Benefits

The development of Renewable Energy Communities brings a series of benefits to the project members, but also to the end-users of the main network. These benefits have social, economic and environmental dimensions and ensure the sustainability of these local initiatives.

4.1 Benefits for the REC

4.1.1 Social

The first social benefit of these energy communities is the empowerment of consumers. Indeed, consumers become co-owners of the renewable installations, but above all they become an integral part of the management and control of the energy system. The principle of ”one member, one vote” promotes joint and democratic decision-making in cooperatives, leading to energy democracy [Caramizaru and Uihlein, 2020]. This social innovation allows all members to give their opinion and contribute equally to the development of the project. This prosumerhip energy model also allows members to become active consumers by generating their own energy and managing their consumption efficiently, according to dynamic prices. The recognition of consumers as having a fundamental role in local communities underpins all the environmental benefits and economic advantages associated with these energy models.

The concept of energy democracy supports another social benefit which is citizenship energy. Indeed, these initiatives educate participants and raise their awareness of current climate issues by encouraging them to participate in responsible collective actions [Gancheva et al., 2018]. For example, Courant d'Air is a Belgian cooperative that tries to provide citizens with access to Renewable Energy by initiating sustainable energy projects for the common good. This cooperative plays an important role in sensitising the citizens of East Belgium to climate change and the importance of using clean energy efficiently [Caramizaru and Uihlein, 2020]. Furthermore, educated participants owning the RE installations and being actively involved in the management of the REC, are much less reluctant to install large devices such as wind turbines. Members' acceptance of sustainable energy projects increases because it becomes their project that they undertake for the common good, which greatly reduces the ”Not In My Backyard” (NIMBY) effect [Salgado et al., 2020].

The growing acceptance of the project by the members leads to a strong social cohesion locally. As members have a sense of attachment to their community due to their involvement and the shared benefits, a sense of collective belonging and trust will appear [Caramizaru and Uihlein, 2020]. In the GreenCom Networks energy community near Munich, members became prosumers who can exchange their surplus electricity within the community. The supply and demand of electricity is optimised, which increases the independence of the community from the main grid while reducing the costs. In addition, members receive a financial bonus for each kWh used in locally balancing energy. Each member of the community can therefore rely on the other members to ensure that their electricity needs are met, which enhances the sense of local cohesion [Sawyer, 2020].

Last but not least, local energy communities foster inclusiveness. According to the Renewable Energy Directive, participation must be voluntary and open to all local citizens on the basis of non-discriminatory criteria [European Parliament and Council, 2018]. The aim is to include as many participants as possible in the community so that they can enjoy the benefits it offers regardless of their income or access to capital. Reducing electricity bills, increasing resilience and security of electricity supply therefore contributes to energy poverty reduction [Gancheva et al., 2018]. As an illustration, the Ecopower cooperative has been recognised as having the fairest energy billing structure in the Flemish region as the members are charged 19c€/kWh while the average tariff was 25c€/kWh in the region in 2017 [Salgado et al., 2020].

4.1.2 Economic

Renewable Energy Communities (REC) bring economic benefits to members not only by allowing them to share and reduce costs, but also by sharing financial gains and boosting the local economy.

On the one hand, the investment costs of community-ownership models are shared between all members, which makes it possible to install larger Renewable Energy assets. In addition, aggregation of demand allows the community to benefit from economies of scale but also from bargaining power with the suppliers. By participating in these local communities, members have lower investment costs, especially regarding upfront investments, leading to a proportionally larger production capacity. Looking at the battery, having a common storage system requires a larger battery, but this lowers the storage price per kWh for participants [Salgado et al., 2020].

On the one hand, financial benefits from local initiatives are shared among the members. The income from the project is thus distributed among the members on a restricted basis, often as capped dividends, and the surplus is reinvested to support the members and the community. The Belgian cooperative Ecopower has set a cap of 6% on the interest that can be earned by members, as the objective is not to maximise profit but rather social welfare. However, the ability of a community to share the gains equitably among members is crucial to its sustainability. Otherwise, some unsatisfied members may decide to leave the community to create a fairer network that suits them better. The challenge comes from the heterogeneity of households with different consumption profiles such as students, teleworking and non-teleworking workers, families, and retirees. Households that match their consumption to generation should receive a higher remuneration as they create more value than those who consume energy mainly during peak times when generation is low and demand is high [Caramizaru and Uihlein, 2020].

What is more, households belonging to the community achieve financial gains by reducing their electricity bills. Even if the initial shared investment is significant, the marginal costs of the DER and battery are negligible and the grid costs are reduced (Section 6.1). As a result, self-consumption is an important source of revenue, and the use of batteries maximises self-consumption [Anisie et al., 2019]. Besides, the principle of demand response allows for locally balancing energy and thus to reduce the electricity bill of the community members. The consumers will therefore change their energy consumption manually or automatically according to the dynamic pricing that reflects the real-time generation. Consumers who are inclined to shift their demand will therefore consume energy when energy is cheaper, thereby providing a financial reward. For instance, smart heating systems in the Nordics enable peak shifting. Consumers define on an app the temperature they want to reach at each hour in each room of their homes, and the system will compute how long it takes to heat each area, considering the real time price of electricity. The system will therefore automatically decide to heat the room when the demand and the price of electricity are low. This could save up to 750€ per year, which is 25% of the average annual electric heating bill in the Nordics. The payback period of the system is about two years but is expected to decrease over time with the improvement and expansion of the technology [Sawyer, 2020].

If national regulations allow, households connected to the grid can resell their surplus electricity back to the grid, which another source of income. The remuneration from the re-injection of electricity into the grid is made possible by the implementation of feed-in tariffs or net-metering systems [Sawyer, 2020].

Ultimately, the aim of these energy systems is to maximise welfare locally and will therefore contribute to local economic development. Hence, the maintenance and management of facilities used for the production, distribution and storage of energy can directly create jobs locally. The reduction of energy imports reduces capital outflow and therefore also leads to the indirect creation of local jobs. In addition, the resilience of energy communities ensures a secure supply of energy, which promotes the development of local businesses. Overall, the development of these Renewable Energy communities fosters the local circular economy by establishing commercial relationships with local companies, using local banks or investing money in local sustainable projects [Vansintjan, 2019].

4.1.3 Environmental

The development of RECs enhances the integration of DERs, thus promoting the expansion of Renewable Energy locally. As a result, it is estimated that almost half of Europeans, or nearly 260 million citizens, could generate their own energy by 2050, and that 37% of the energy generated by citizens would come from collective initiatives such as cooperatives [Vansintjan, 2016]. Energy communities, households, small businesses and public entities could together own 45% of the Renewable Energy generation in Europe by 2050 (Firgure 4).

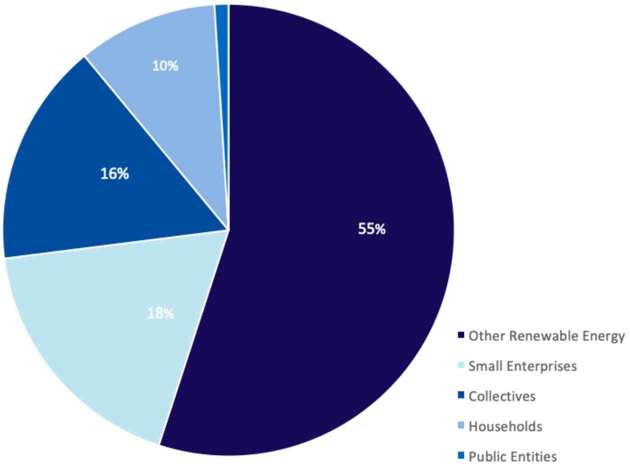


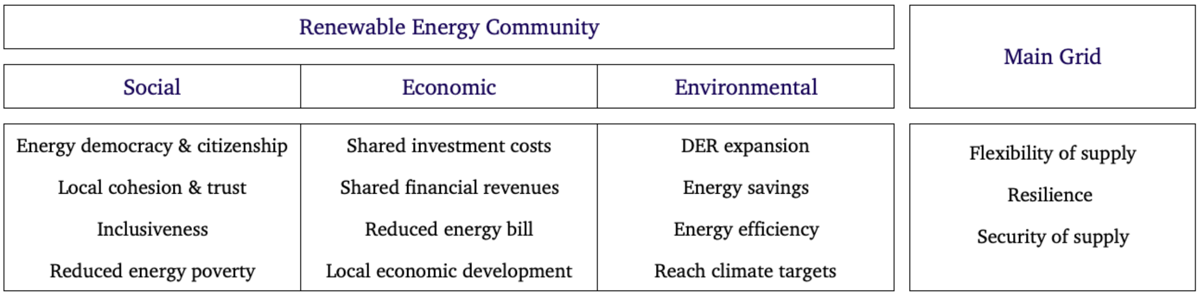
Figure 4: Energy generation by investor group in 2050 [Vansintjan, 2016]

Lastly, all the social, economic and environmental benefits mentioned above support the successful and lasting development of Renewable Energy Communities. This enables to reach the environmental targets set at European level, but also at national and local levels so as to address the challenges related to climate change. Therefore, these energy projects contribute to increasing the use of Renewable Energy, energy savings and energy efficiency, and decreasing energy consumption resulting in a lower carbon footprint [Gancheva et al., 2018]. For instance, the cooperative Ecopower focuses on providing education and technical advice to help the members save energy by consuming more efficiently. As a result, members have almost halved their energy consumption in 10 years, from 3,47 kWh/year in 2007 to 1,76 kWh/year in 2017 [Salgado et al., 2020]. Besides, the European Green Deal outlines the key targets that the Commission has set for 2030 such as achieving at least a 40% reduction in greenhouse gas emissions compared to 1990, a 32% share of Renewable Energy and a 32.5% improvement in energy efficiency [European Commission, 2019].

4.2 Benefits for the Main Grid

Alongside the benefits to local communities, RECs are also of great value to the main network. Therefore, energy communities can leverage the supply flexibility of the main grids by providing them with energy when they do not generate enough electricity to cover the demand of their end-users [Sawyer, 2020]. As the main grid and RECs do not have the same operating, storage management nor the same generation and demand profiles, it is therefore conceivable that the local communities have an energy surplus at the time of peak-consumption for the main grid.

Moreover, the expansion of Renewable Energy Communities enhances the resilience of the main grid by providing a secure energy supply. As a matter of fact, centralised power plants are increasingly vulnerable to power outages due to natural disasters or cyber attacks (Section 7.5). Therefore, diversifying energy sources by connecting local communities to the main grid would improve the outage management of the latter. As fossil-fuels are notably supplied from distant countries with potentially unstable political relations such as Russia or Iraq, European main grids could benefit from a secure local supply through the RECs (Section 2.3).



Renewable Energy Community			Main Grid
Social	Economic	Environmental	
Energy democracy & citizenship Local cohesion & trust Inclusiveness Reduced energy poverty	Shared investment costs Shared financial revenues Reduced energy bill Local economic development	DER expansion Energy savings Energy efficiency Reach climate targets	Flexibility of supply Resilience Security of supply

Figure 5: Main benefits of the RECs [By the Author]

To conclude this section, a table outlines the diverse benefits that the development of Renewable Communities has brought to their members but also to the main grid (Figure 5).

5 Flexibility

To achieve a resilient electricity network in line with the energy transition, there is a growing need for flexibility. Flexibility can come from both the demand and the supply side and can cope with increasing energy demand and intermittent RE supply. At an individual level, flexibility can be defined as the variation of generation injection or consumption behaviours as a reaction to external signals [SGTF, 2015]. As a result, flexibility leads to a cost-effective balancing of demand and supply within the community-ownership project.

5.1 Flexibility of Supply

The European Commission forecasts that 70% of energy consumed in 2050 will be Renewable Energy as mentioned in the Energy Roadmap 2050. Renewable Energy Communities should therefore be designed with the aim of increasing the integration of Distributed Energy Resources (DERs) including renewable generation, storage and electric vehicles. Wind turbines and photovoltaic panels are the renewable technologies that are currently experiencing the greatest expansion (Section 2.3). Most of the electricity generated is issued from small-scale decentralised plants, with the exception of offshore wind turbines. Thus, there are multiple regional wind parks or PV farms, but there is also a micro-generation of electricity in the households that install PV on their roof. This includes consumers in the energy supply by empowering them to manage and control their electricity generation and thus reduce their bills (Section 4.2).

As the energy output of wind turbines and solar panels depends on weather conditions, it is variable although following a certain pattern. The complex predictability of the energy produced constitutes a challenge for the planning, management and balance of the system. However, it is becoming increasingly feasible to accurately predict energy production due to technological advances (Section 2.2). In addition, energy communities can include advanced Information and Communications Technologies (ICTs) that provide real-time information on electricity generation and demand, as well as the functioning of the entire grid operations. This allows for short-term reactions as well as implementing a flexible and dynamic energy management. Increasing the responsiveness of the grid makes it possible to balance the supply and demand of electricity from renewables in real time.

The installation of storage capacity ensures the security of supply and the stability of the network. This would allow energy to be stored when there is a high supply, and inject it back into the community when energy demand exceeds production. Hence, the management of electricity storage support a balance between demand and supply, leading to economic benefits. In the case of micro-generation, storage capacities can be installed in households and are thereby managed by the prosumers. Nevertheless, batteries require a sizeable initial investment and the optimum storage capacity must be determined with the aim of maximising the benefits to the community.

The inclusion of electric cars in the community-energy project also increases flexibility. Vehicle-to-Grid (V2G) allows the storage of electricity surplus in the batteries of consumers' cars when there is a high supply and low demand. The cars will then feed the electricity back into the community when the demand for electricity exceeds generation, limiting the expensive imports from the main grid. This leads to an increased resilience of the network but still requires the agreement of the members who own the electric vehicles (Section 3.3).

Similarly, establishing a connection between the REC and the main network also enhances the flexibility of the local community. Even though the REC can operate in island mode, this integration allows electricity to be supplied to members even when local generation and storage are not sufficient, albeit usually at a higher cost.

5.2 Demand Response

The successful operation of energy communities relies mainly on the empowerment and engagement of consumers. This creation of flexibility on the demand side is therefore the basis of the demand response. The Federal Energy Regulatory Commission defines demand response as the change in electricity consumption by the end-user in response to changes in electricity prices over time [Kathan et al., 2007]. More concretely, when Renewable Energy Sources provide a high supply, the price of electricity decreases and this price variation is directly communicated to the consumers through ICTs, leading to an increased energy consumption in real time. Conversely, when supply is low, the price rises so as to discourage consumers from using electricity at that time. Therefore, it is no longer supply that adapts to demand, but demand that adapts to supply, resulting in peak shaving. Consequently, the consumers control the optimization of their consumption based on the external signals received, which also gives them the opportunity to reduce their electricity bill.

Prosumers have the flexibility at any time to choose the intensity of flexibility they decide to provide according to their preferences and pace of life. The first option is to deliver maximal flexibility by letting the AI system manage the energy consumption of smart appliances according to price signals and predefined consumer preferences. Secondly, they can also opt for the comfort option which consists of manually deciding which appliances will continue to operate at a certain capacity regardless of price and supply fluctuations, and the rest of the appliances will be managed by the AI system. The last option is to use the full capacity of the devices regardless of price signals and without the intervention of AI systems. This option can be used on an ad hoc basis but does not enable the consumer to contribute to the improvement of social welfare when it is activated.

Therefore, contributing to this flexibility on the demand side is a choice. The participation in the energy community is open and voluntary, and the prosumer has the choice between several aggregators or suppliers (Section 3.1). The different offers should be clear and transparent so that they make a decision with a clear understanding of the benefits and constraints, such as the shared costs and risks associated with each option [SGTF, 2015].

5.3 Key Enablers

Besides the flexibility arising from the supply, it is interesting to highlight the key components allowing the active participation of the consumers leading to the demand side flexibility, which is inherent to REC operations. First of all, it is important to have clear regulations and market rules at the EU, national and local levels to ensure the inclusivity, efficiency, security and stability of the network (Section 6.3).

In addition, dynamic pricing provides incentives for active consumer engagement leading to demand response. This flexibility requires a real time data flow between the different network components, which is enabled by ICTs. Smart meters installed in consumers' homes are also essential as they allow the users to know their consumption and the electricity price in real time. Finally, smart appliances in households can be automatically or manually managed to change their energy consumption according to external signals and consumer preferences (Section 7.1). Nevertheless, it is important to avoid all smart appliances being set up similarly to prevent them from reacting in the same way to price fluctuations, thus creating congestion and new demand peaks.

5.4 Value of Flexibility

The flexibility brought to the demand side will therefore result in value creation for the stakeholders as it could lead to avoided costs or gained benefits. Thus, prosumers can save money on their electricity bills by reducing their energy demand, increasing collective self-consumption, using storage to consume electricity when it is cheaper, as well as aggregating and shifting their demand according to dynamic pricing. In addition, the deployment of flexibility enhances the independence of the energy community from the main grid, thus lowering costs by reducing the energy imports and the collective connection capacity [Council of European Energy Regulators, 2019b]. As flexibility providers, prosumers can also benefit from indirect financial benefits such as tax relief and subsidies (Section 4.2).

What is more, the expansion of Renewable Energy Sources supports the energy transition and the decarbonisation of the energy system. Environmental benefits are also driven by a reduction in energy consumption and energy losses as electricity is consumed closer to where it is generated (Section 4.3). By empowering consumers to manage their resources, they become more aware of their impact on the environment, leading to a more responsible consumption [Council of European Energy Regulators, 2019b]. Besides, given the flexibility provided by energy communities, energy utilities may decide to avoid or delay costly investments to improve the main grid.

6 Challenges and Drivers

6.1 Regulatory Challenges

This part aims to analyze the regulatory implications and challenges of developing Renewable Energy Communities. The following challenges have been highlighted by the Council of European Energy Regulators. The council has been launched in 2000 in order to ensure cooperation between national regulators, in order to create a competitive energy market and establish best practices in the energy field [Council of European Energy Regulators, 2019a].

The following sections will state the regulatory questions and issues linked to the main functions of an energy community. The latter are selling and sharing electricity, efficiently consuming electricity and owning the RE assets.

6.1.1 Self-consuming and Selling Electricity

The energy sharing and selling matter can reveal to be more complex than a basic supplier-customer relationship. Indeed, the energy community can cover the role of producer, supplier, service provider, aggregator, and even grid operator all at once. These activities rise complex issues which are controlled by the Electricity Market Regulation and need a specific attention [European Parliament and Council, 2019].

The first issue consists in the fact that the net-metering is reducing incentives for consumers to make flexibility efforts. The net-metering scheme is deployed to measure and bill either the net consumption or production of electricity by consumers with small production facilities. The prosumers are compensated for their investment and production through the reduction of their energy bill. This scheme reveals to be an issue for regulators as it reduces the sensitivity to the price of electricity and discourages prosumers to adapt their demand to generation. Therefore, the benefit for the whole community might be impacted by this scheme since energy sharing will provide a positive impact only if the consumers are correctly incentivized to adapt their consumption pattern.

Moreover, it is important that the network costs remain equally divided without discrimination, specifically for vulnerable participants who could not actively take part in self-generation. It is following this opinion that the CEER is suggesting not to use a net-metering scheme as it reduces the sensibility of the consumer to changing prices [Council of European Energy Regulators, 2019b].

The second challenge consists in the relationship and coordination between supplier and the local generation source. The local demand will be partially provided by local shared production, and in most cases, the rest of the demand will be ensured by a backup supplier. The challenge here is the coordination between local and backup suppliers. Hence, one customer will be provided from multiple sources: local supply source or a licensed backup supplier. The regulations regarding the obligations of the licensed suppliers are complete and clearly stated in MS frameworks. The supplier is obligated to balance the system at all times by optimizing the equilibrium between production and demand as well as ensuring customer protection and information. However, the regulations stating the obligations of the local supply source are not clearly defined, specifically in matters of consumer protection and information. This gap in regulatory framework reveals a true challenge for transposing the European Directives from the Clean Energy Package to the MS national law [European Commission, 2016].

The third substantial challenge is represented by the balancing responsibility resulting in an abuse of power from the supplier's side. The challenge comes specifically from the fact that the licensed supplier and local energy source might supply the same customers. In the case where there isn't any shared responsibility of balancing, the licensed supplier is wholly responsible for balancing and providing the difference in energy to the customers in order to match their demand. In this situation, there might be abuses from the side of the external supplier since it might provide more energy when it is more expensive and less when it is cheap, and therefore participate to the increase of the price per kWh sold. On top of that, for each imbalance incurred, there could be a penalty for the supplier and that cost could also be passed within the customer's bill.

The fourth challenge comes from the fact that in most Member States' regulations it is not specified who is in charge of collecting any taxes and levies applied to the energy community. Most countries, such as Luxembourg and Austria do not apply taxes for energy communities. However, there are some exceptions such as France which decided to apply taxes on all energy consumed and collectively self-produced. On the main grid it is usually the licensed supplier who is responsible for administrative tasks, such as the collection of fees and levies.

The first possibility is that the energy communities will take that responsibility. In that case, an additional administrative burden will be added on the energy community. As a result, the latter might also face an increased cost charged to all members.

The second possibility is that the MS may decide to leave the responsibility of levies collection in the hands of the licensed supplier. In this situation, the supplier will be as well responsible for the levies with regard to other energy sources, which will lead to more complex levies structures. Due to this complication of the structure, suppliers may decide to charge higher costs for the local community. For the members of the Renewable Energy Community, an incurred risk is to not being in a position to find an affordable supplier offer.

The fifth challenge regards the right of changing supplier, to which all members of an energy community are entitled as it is clearly stated in the Clean Energy Package [European Commission, 2016]. In theory, this principle seems clear and firm, however in practice, it can occur that consumers are not effectively capable of using the right of choosing their supplier. In the situation where the supplier is highly linked to the community or when the supplier fills multiple functions such as assets management, the tie between supplier and community is more complex. Therefore, it might require a long-term engagement between the two parties, especially when substantial investments are involved. The challenge, in this case, is to maintain the right to switch supplier in complex schemes. The fact that the customer is part of an energy community can therefore hinder that right, and this is not accurately supervised by the MSs' legal contract frameworks.

The last challenge with regard to the rights of the Renewable Energy Community members is focused on the vulnerable consumers. Within the same perspective as the right of changing supplier, when the members are willing to terminate their contracts with the supplier, they should be free to do so without any additional burden. However, in some national regulations such as France for instance, the consumers do not have the right to end their contracts at any time without a proportionate fee or binding conditions [Council of European Energy Regulators, 2019b].

6.1.2 Efficient Consumption and Flexibility

Firstly, the rising of flexibility schemes is also incurring multiple regulatory questions and challenges (Section 5). It has been stated that RECs should be value-driven and provide social advantages rather than focusing on profits (Section 3.1). Therefore, market participants, such as aggregators, are expected to use the flexibility in the most valuable way for the best interest of the community. An issue arises when the flexibility is used for individual purposes such as selling the electricity when it is most expensive to the main grid, without trying to maximize the profit for the community. This sub-optimal operations of the power system might lead to a cost increase for the energy community as a whole.

Secondly, when discussing flexibility, the situation can also be challenging for vulnerable consumers as they might not have a true flexibility potential, despite substantial incentives for demand response. The consumers having a willingness to pay inferior to the price during peak time would find themselves forced to reduce their basic consumption through imposed flexibility policies or to consume as usual at a higher price. In this situation, the disadvantaged customers will see their costs increase or well being decrease by being part of an energy community [Council of European Energy Regulators, 2019b]. This situation might go against the will of European Directives, specially RED II, which promotes social aid and assistance [European Parliament and Council, 2018].

6.1.3 Owning and Operating Electricity Grids

The last challenge for the RECs is organizing and operating the grid whilst their rights are not clearly entitled in European and national regulations. With respect to the activities of owning and operating the electricity grid, the electricity market directive states that the Citizen Energy Communities have fully the right to provide all these activities. On the other hand, such rights are not stated in the RED II regulations for the Renewable Energy Communities [European Parliament and Council, 2018] [Council of European Energy Regulators, 2019b].

6.2 Non-Regulatory Challenges

6.2.1 Dynamic Retail Pricing

With the aim of implementing a demand-response mechanism, price signals are needed to encourage consumers to adapt their electricity demand to the supply in exchange for financial benefits. This requires the setting up of a time-differentiated pricing system which can consist of time-of-use pricing, including peak and off-peak prices, or real-time pricing.

Nonetheless, the negative effects of these price fluctuations should be avoided [CEDEC, 2014]. In case of abundant supply, electricity prices are low and this can quickly lead to a peak in energy demand, resulting in a sharp increase in prices afterwards. Consumers who had started time-consuming activities, such as starting a washing machine, taking advantage of low electricity prices will therefore see the price increase during the course of their activities. They will therefore end up paying much more than the price initially announced. Consequently, it is important to ensure that tariffs do not change too abruptly, but rather to ensure a smooth fluctuation of tariffs to guarantee a certain stability for consumers. It may therefore be interesting to consider price caps by defining price intervals so that, from a psychological and economic point of view, consumers do not change their consumption too abruptly.

6.2.2 Technical Standards

Most of the technologies needed to operate energy communities are already developed but it is essential to ensure the interoperability of these technologies and their integration into the main grid. The European Council has stated that the EU and its Member States want to invest more in renewable, safe and sustainable low carbon technologies but there is a need for technical standards related to these technologies.

Therefore, the three European Standards Organisations (ESOs) namely CEN, CENELEC and ETSI have the mission to develop standards for the next generation electricity networks, the Smart Grids. The European Commission mandated these organisations to determine a technical reference architecture, consistent standards for data exchange and communication protocols, as well as sustainable standardization processes to foster stakeholder interaction and interoperability. Besides, these organisations have been given the task of defining standards for information security and data privacy [CENELEC, 2021].

6.3 Drivers

After highlighting the challenges related to the development of Renewable Energy Communities, it is interesting to consider the drivers that favour their expansion while mitigating the associated risks.

6.3.1 Members Willingness

The first key success factor is the determination of the members, the fact that they believe in the project and their involvement in achieving the common objectives. In fact, the willingness of citizens to take action to solve social and environmental problems strongly enhances the emergence of energy communities. Besides their ecological and social awareness, the fact that they have a high level of education and a desire to be energy self-sufficient are significant factors. The rise of collective projects is also stronger in countries with a tradition of collective ownership, such as Denmark, Germany and Belgium [Caramizaru and Uihlein, 2020].

6.3.2 Social Acceptance

Developing technologies that are technically efficient and economically viable is not enough as they need to be socially accepted by consumers to be successfully implemented and used [Dütschke et al., 2017]. Nevertheless, wind turbines entail some drawbacks according to citizens, such as noise, intermittent shades and visual impact on the landscape. The main negative local externalities of solar panels are that they are not aesthetically pleasing, the space they occupy, their weather-dependent efficiency and initial cost. As a result, citizens are concerned of losing a certain quality of life which leads to the NIMBY effect. It is therefore interesting to analyse the drivers that favour a supportive behaviour, and not only a tolerance of consumers towards local energy communities [Fraunhofer, 2015].

It is essential to educate citizens on the ecological, social and economic benefits of developing these energy projects so as to entice them to participate, but also to communicate the costs and potential risks associated with the project. What is more, the decision-making process must be fair and members must have confidence in the integrity and expertise of the managers. According to Wise Power, the European wind energy acceptance project, the fairness of a project depends on the ability of managers to be open, inclusive, transparent, responsive, flexible and accountable [Bickley, 2017]. It is also important to note that joint-ownership or community co-ownership of renewable technologies greatly increases the local acceptance of sustainable projects as customers feel more involved and empowered [Musall and Kuik, 2011].

6.3.3 Mobile Technology and Innovation

The breakthroughs in digitisation and the integration of innovative technologies into energy communities foster their development by being better adapted to members' needs. Indeed, mobile tools and applications can be used to connect with citizens as a means of increasing their awareness, understanding, social acceptance and engagement with local communities [Thomson et al., 2013]. These technologies are embedded in the daily lives of potential members enabling them to learn about the functioning and benefits of energy communities. As mobile technologies can be connected to advanced metering infrastructures, prosumers can also manage and control their electricity consumption in real time via the app. These technologies can also analyse members' consumption and behaviour so as to offer them suggestions for optimising their energy consumption and lowering their bills. It is also possible to pay energy bills and give feedback via these apps.

Alongside the technological advances of smart appliances, some countries such as Germany are also pioneering virtual power plants as a means of balancing the energy supply [Gancheva et al., 2018]. These virtual power plants allow decentralised producers to aggregate their production even if they are not geographically close, and to sell their electricity on the market (Section 3.3). This increases the inclusiveness of small producers by pooling and optimising the generation, storage and consumption of the electricity produced.

6.3.4 EU Legislation Role

Although Member States have a major role in transposing and implementing rules, EU policy-makers have an important role in maintaining a stable regulatory environment and establishing common energy policy that support the development of Renewable Energy [Gancheva et al., 2018]. The Energy Policy Framework established at European level sets out minimum requirements for the promotion of these communities and encourages MS to design support mechanisms, including financial support.

What is more, energy market rules should sustainably support the different services provided by energy communities such as energy efficiency, storage, distribution as well as aggregation.

These rules must be non-discriminatory and must not limit market access to smaller producers by allowing them to have simplified procedures or to aggregate their energy production via virtual power plants. It is therefore important that these policy frameworks remain stable over time, and that the rules are coherent and consistent without contradicting each other.

6.3.5 National Legislation Role

National legislation must first define Renewable Energy Communities but also recognise their role and needs for sustainable development [Gancheva et al., 2018]. Member States should follow the example of the European Commission which has clearly established in the Clean Energy Package the role of local communities in the energy transition so as to address climate change. National policy-makers should therefore set clear national energy objectives, determine how energy communities can enable them to achieve these targets and then set specific goals for the expansion of these energy communities. For instance, Denmark has taken measures to promote community ownership models by setting clear targets. Hence, the Renewable Energy Act requires that for projects involving wind turbines over 25m in height, project managers must offer at least 20% of the project's ownership shares to local residents within 4,5km. As a result, community power projects are dominant in Denmark instead of privately owned projects. Furthermore, Danish legislation provides that an energy producer wanting to have access to the main grid only has to pay for the connection to the nearest technically feasible point of the network. The energy utilities therefore have to invest in the necessary expansion of this network.

Besides, specific policies and rules must be established at national level to foster the development of Renewable Energy Communities. National policies can encourage citizens to participate in these communities by providing financial incentives and support mechanisms such as tax reductions, low-cost loans and grants, feed-in tariffs or net metering schemes [Caramizaru and Uihlein, 2020]. It is important that policy frameworks are clear and explicitly communicated to be impactful. Since profit maximisation is not the primary objective of these community-owned renewable projects, financial returns are uncertain over the long term and these projects are therefore perceived as risky. These initiatives may therefore have difficulty in raising funds, which is why national financial support schemes are highly valued [Salgado et al., 2020]. What is more, some MS do not have clear rules on the resale of surplus energy outside the community or Peer-to-Peer trading, which is an obstacle to energy sharing.

Member States should also simplify and adapt the regulatory and administrative procedures for small RE projects as an opportunity to boost investments. Indeed, these bureaucratic processes are complex, time-consuming and costly and therefore constitute a major barrier to the expansion of local energy projects. Although necessary, these requirements for community-owned projects should be streamlined such as construction permits, environmental impact assessment, electricity generation licenses, health and safety controls, limited capacity requirements and grid connection permits. It is also important to ensure that local communities have appropriate technical information and know-how for the successful development of the project, otherwise appropriate training, mentoring and guidance should be provided [Salgado et al., 2020].

6.3.6 Local and Regional Authorities Role

Complementing European and national frameworks, Local and Regional Authorities (LRA) can implement local policies to enhance the integration of community-powered projects according to the local context. LRAs can therefore outline how these energy communities can contribute to achieving local energy goals, and then provide them with the appropriate financial and strategic support mechanisms. The key factor is to give the LRAs as much autonomy and responsibility as possible like in Germany, so that they can help the energy projects to be as adapted as possible to the local context to enhance their impact [Gancheva et al., 2018].

There is therefore a real opportunity to achieve mutually beneficial and sustainable partnerships between local authorities and energy communities to leverage their contributions to local objectives through their expansion. RE project leaders can take over the management of the project by bringing in technical expertise, while LRAs can provide the necessary space, administrative support, and enhance local acceptance and engagement of local stakeholders. Alongside all these benefits, local authorities can also contribute to reducing the risk associated with energy projects by investing in or enabling them to access external finance at preferential rates [Gancheva et al., 2018]. For example, German local authorities can secure long-term, low-cost financing from the public bank KfW or institutional investors which they can use to fund Renewable Energy Communities.

6.3.7 Risk Management Strategy

When developing Renewable Energy Communities, it is essential to consider the potential challenges and associated risks (Section 6.1). A risk can be defined as the "Probability of occurrence of an unknown event or uncertain condition that can have either a positive or negative impact on project objectives" [Weaver, 2008]. Despite the diversity of risks, a key success factor for energy communities is to have a clear and effective overall process for managing the risks that arise during the project.

First, Risk Management Planning should be put in place to determine the roles of the community members in risk management, procedures and processes for systematically reviewing and reporting potential risks. Then, Risk Identification allows the identification of risks that may possibly impact on the project. Risk Analysis consists of analysing the probability of occurrence of the risk as well as its impact, while Risk Prioritisation allows to rank them on the basis of their probability of occurrence and the degree of impact. During risk response planning, risk managers will decide how to react to this risk. They can thus opt for Risk Avoidance, Risk Acceptance, Risk Insurance or Risk Mitigation depending on the situation and their risk aversion. Finally, Risk Monitoring and Control allows for regular tracking of the evolution of risk, as well as the implementation and results of the strategies put in place to address it [Vikas et al., 2019].

7 Smart Grid

7.1 Smart Grids and REC Development

Smart Grids (SG) are local electrical networks that use automation and Information and Communication Technologies to monitor and optimize the production and consumption of electricity in real time. Through ICT integration, the local grid control is centralized and thus supports the durability and efficiency of Renewable Energy Communities. Smart Grids use innovative and advanced technologies to optimise the management of electricity locally, which can also be used in Renewable Energy Communities to enhance their development. Therefore, it is interesting to analyse the different components of the SGs, as well as their functioning and the benefits for the end-users.

These smart and local electricity grids are therefore more resilient than traditional grids due to the information exchange and energy management system, but also due to the fact that they can exchange electricity with the traditional grid in the event of a shortage or oversupply. In addition to the reliability of this network, it is also sustainable as energy is exclusively produced from Renewable Energy Sources. In addition, it reduces transportation electricity losses since it is generated within the local communities. These more reliable, flexible and efficient Smart Grids make electricity more affordable and accessible for the entire community.

There are three trends that favour the development of smart girds within energy communities. These trends are the increase in demand for electricity, the automation and digitalisation of activities, as well as the decentralisation of electricity production capacity due to the integration of DERs [Guille et al., 2017]. The COVID-19 pandemic also favours the emergence of Smart Grids as it has resulted in an increase in digitalization and local cohesion of citizens.

It is therefore interesting to determine the full range of benefits that a SG would bring. First of all, it fosters the introduction of Renewable Energy and the achievement of the EU's climate objectives. In addition, it increases security of supply and facilitates the efficient operation of the electricity grid. Smart Grids also empower consumers within an energy community to play an active role in controlling their consumption and making savings on their electricity bills. Finally, it allows to create new jobs locally and therefore fosters economic growth [Polymeneas et al., 2020].

One of the most important challenges of current clean energy production consists in the fact that Renewable Energy Sources are by definition intermittent. To ensure a balanced energy flow, an Energy Management System will optimize the transmission of bulk energy between the Distribution Management System and Battery Energy Storage System (BESS). In this way, the Smart Grids are dependent on BESS that allows energy produced to be stored and then re-injected according to the needs of the electrical network [Fradelle, 2017].

With the help of this control systems, the local grid becomes an intelligent system as it is able to orchestrate the production of energy from multiple sources in order to meet the demand of the end-users [Wood, 2020]. Therefore, the customers's advantages go far beyond their energy demand satisfaction as they benefits from low prices, clean energy, as well as high reliability and security.

7.2 Automation and Digitalization

Smart Grids are the center of technology innovation, allowing for the modernisation of the aging electricity grid. The innovation that differentiates Smart Grids is based on automation systems and digital integration. Automation systems provide the Smart Grid with the capacity to self-manage its activities by taking technical or managerial decisions. Therefore, it is the Energy Management System (EMS) which is empowered to optimize the self-management through Information and Communication Technologies (ICTs) by considering the most significant challenges of the Smart Grid.

The first substantial challenge is the management of peak energy consumption since an inaccurate management of theses peaks can lead to high expenses among other disadvantages. From a managerial point of view, if there is a sub-optimal handling of the peaks resulting in constant shortfall, the managers could be advised to make new investments in capacity expansion. By defining an optimal load management for all periods, the automation of the system allows to increase the resilience of the community and prevent unnecessary investments in any additional capacity.

The second challenge is the variability of generation rates which depend on the meteorological conditions and the time of the day. Through real-monitoring, the smart system is capable of constructing accurate forecasts and provide incentives for load management in real-time. Moreover, thanks to real-time control, an automated system is able to prevent any outages or technical issues even before reaching the user or before damaging the network [Ministry of Power, 2013].

Finally, one of the most considerable variables to take into account is the production capacity of the Renewable Energy Sources. Indeed, the EMS allows to increase the integration of the DER by compensating the irregularity of the energy produced by an automated optimal management of the energy in real time. It has a responsibility to decide where the energy should flow between storage and consumption by end-users. Therefore, the EMS will take optimal storage decisions based on the real time and forecasts demand, in order to create reliable reserves in case of shortfalls [Sibelga, 2020].

7.3 Bi-Directional Flow Communication

Sustainable energy development requires a Smart Grid with online control capabilities as well as two-way interaction with consumers. What characterizes therefore the two-way stream between consumers and smart grid management systems is the constant exchange of information (Figure 6). On the one hand, the information gathered and sent to the energy utilities concerns the energy consumption of households in real time, as well as the types of smart appliances they use. This data will therefore be analysed to forecast future energy demand, define incentives to adapt demand to supply, optimise storage management, and prevent potential outages on the network [Golshannavaz et al., 2014].

On the other hand, this type of two-way communication flow is the key enabler of demand responses schemes. Through this bi-directional communication, the REC members are informed about their past and current energy consumption, as well as the dynamic prices in real time to encourage them to adapt their energy demand during the peak times. Therefore, the network acts as a two-way communication channel to optimise energy flows through dynamic tariffs and load shifting [Ministry of Power, 2013].

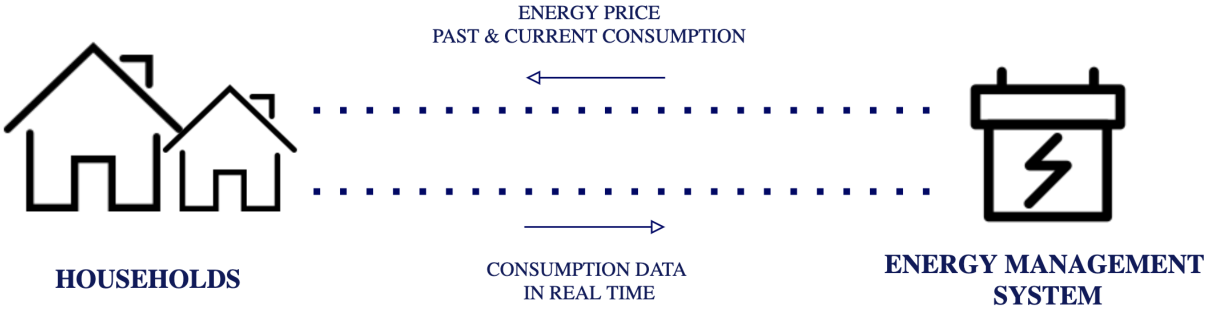


Figure 6: Bi-Direction Flow Communication [By the Author]

7.4 Key Components

7.4.1 Smart Appliances

Electrical appliances evolve by further integrating smart technologies. Therefore, smart appliances are smart and connected equipment which can be found in households, such as a fridge, a dishwasher, an air conditioner or a washing machine. These devices enable cooperation between service providers and end-users, who adapt their energy consumption based on external signals and predefined settings. Smart appliances can therefore automatically change their consumption on the basis of the maximum capacities imposed by consumers at peak-consumption times, but also with regard to the external price signals received. These devices can be programmed or will automatically operate when energy is cheaper in order to adapt the demand to the RE supply [SGTF, 2015]. These devices can also show consumers information about their energy consumption as well as the price of energy in real time through the smart-meter.

The principle of demand response is therefore put in place due to these smart appliances, which make it possible to optimise the use of energy via peak levelling, consumer empowerment and consumption reduction. However, consumers can always override the automation system if they absolutely want to use certain appliances despite the cost of energy at that moment.

The practical integration of these smart appliances nonetheless presents certain challenges, such as their interoperability in order to optimally coordinate several tools in the same home. Moreover, households are not inclined to use overly sophisticated interfaces and are concerned about the cost, reliability, security and privacy of these new technologies [European Parliament, 2016].

7.4.2 Smart Meters

Smart meters provide the Smart Grid interface between the consumer and the energy provider. Smart meters are devices that are installed at the consumer's premises to digitally collect data about the consumer's electricity consumption in real time. The data will be analysed by the Energy Management System (EMS) in order to manage the network operations in an efficient way (Section 7.4). Besides, smart meters allow as well the EMS to communicate the dynamic electricity tariffs to the consumers and their smart appliances, leading to demand response [Mrabet et al., 2018]. These devices are therefore one of the key enablers of two-way communication leading to optimal electricity management [Wang et al., 2011].

7.4.3 Distributed Energy Resources

Distributed Energy Resources refers to power generation resources that are directly connected to medium voltage or low voltage Energy Management Systems. The DERs ensure therefore the bulk energy generation at a local scale. The produced energy will be transmitted to the Energy Management System which will decide weather the energy will be allocated to households or storage based on forecasting and real time data (Section 2).

7.4.4 Battery Energy Storage Systems

The Battery Energy Storage System (BESS) is composed of connectable battery modules, allowing the required storage capacity to be reached. The BESS is at the center of the energy system. Its main function is to provide a additional energy supply when the power produced by Renewable Energy Sources is not sufficient, or when RES equipment is defective. Therefore, the BESS will provide the necessary generation so as to meet the load demand in case of shortfall.

On the contrary, when the necessary conditions meet and the solar panels or wind turbines overproduce, the power surplus will be stored in the storage system. Once the batteries are fully charged, the excess energy will be sold on the main grid. As a result, the BESS plays a substantial role for the local electricity grid using intermittent RES [Ngoc, 2014]. What is more, the parameters for optimising energy use are a high power density, high charging and discharging efficiency, good cycling capacity and long lifespan [Akorede et al., 2010].

7.4.5 Energy Management System

In a nutshell, EMS is the system that aims at achieving energy efficiency by optimizing the transmission processes. The system therefore receives a series of inputs such as household energy consumption, battery storage state, and renewable electricity generation in real time. Based on this information, the system will automatically take a decision to optimise energy use by either allocating the energy produced to households or to storage, or by selling it on the main network, or by buying energy from this network [Ngoc, 2014].

Decisions regarding the optimisation of energy management are made on the basis of specific operational objectives that aim to maximise the welfare of community members. Therefore, the objective is to satisfy as much of the energy demand as possible while minimising the costs involved and maximising the revenues. In terms of environmental objectives, the aim is to minimise the carbon footprint by reducing loss and energy consumption. However, this implies compliance with the technical limits of the network. It is essential to respect certain constraints, in particular those linked to the functioning of the DERs and storage system, voltage requirements, harmonization between voltage and frequency, and load requirements for the devices. Disregarding these limitations may result in energy losses or power outages, reducing the net power on the network.

7.4.6 Distribution Management System

The Distribution Management System (DMS) plays a central role within the Smart Grid by covering the “last mile” in the delivery of electricity. Therefore, the DMS has the key role of ensuring secure and reliable network operations while keeping all market actors informed all the time [Golshannavaz et al., 2014]. This system enables two-way management of energy and data flows between the EMS and the smart meters, which enables dynamic pricing leading to demand response. It is through an automated smart metering system, which is operated by the DMS, that the information is collected in real time. In such a system where the share of intermittent Renewable Energy is at its highest, it is important to ensure fast, automated and reliable data communication as well a close monitoring of the grid [van den Oosterkamp and Koutstaal, 2014].

7.4.7 Outage Management System

A Smart Grid can regularly fall victim to unexpected energy outages due to natural events or cyber attacks. For maintenance scopes, there can also be scheduled outages. No matter if the outage is scheduled or not, they are not without economic consequences and can even potentially impact the health of people who no longer have access to electricity. It goes without saying that these situations must be prevented at all costs.

One of the main features of a Smart Grid is its self-healing capability. Self-healing capabilities minimize outages because they enable self-evaluations that continuously inspect, evaluate, respond, and troubleshoot problems automatically. This is made possible by the widespread deployment of Outage Management System that monitor and control the network to identify and report anomalies through sensors, smart devices and automated controls. [Chakraborty, 2018].

7.4.8 SCADA

As with the Outage Mangement System, in the event of an interruption in the supply of electricity to the network, there may be serious consequences. The progress of new digital technologies, such as remote control and remote monitoring of the electrical network, led to the development of a new system Supervisory Control and Data Acquisition (SCADA). This allows to reduce the cost of power transmission, but also to increase the control of the transmission and the efficiency of the network, leading to an increased reliability for the utility as a whole.

Beyond control, the SCADA system will gather information and analyse the data environment in real time, which is aided by data acquisition through the smart metering and the sensors. Moreover, SCADA systems are closed systems that require little technical maintenance. As a final note, it is important to point out that these control opportunities can turn into cyber security threats. This leads to a significant need for detection of network risks and vulnerabilities [Safa et al., 2016].

7.5 Cyber Security Risk

Smart Grids depend on ICTs for their operation, but this makes them vulnerable cyber attacks. These attacks can have a varying degree of impact and can potentially lead to power outages, data thefts or installation damages. It is therefore essential to protect the network against these possible cyber attacks so as to ensure efficient and secure information and power flows on the network.

Key Security Requirements

Since information security is essential for Smart Grid operations, the National Institute of Standards and Technology (NIST) has established four requirements which are in order of importance: availability, integrity, accountability and confidentiality [Mrabet et al., 2018].

Availability of information refers to the reliable access and use of information at any given time. Therefore, it ensures that data transmission is not delayed, blocked or damaged, thus enabling a good communication flow. The integrity of the information means that it has not been altered or deleted by an unauthorized entity. Integrity attacks aim, for example, to modify customer account data, billing data, sensors values or control commands. Regarding accountability, it refers to the traceability and recording of any action taken within the Smart Grids. Finally, confidentiality relates to the fact that the personal information of the network's stakeholders will not be accessed or disclosed to unauthorized persons or entities.

Attack Types

Smart Grids are complex networks that involve a large number of stakeholders and devices between which there is a significant flow of information and energy. These networks have various access points which must be protected with advanced security technologies to prevent attacks. There are three types of attacks that are the most frequent for electricity networks, namely Integrity Violation, Privacy Violation and Denial of Service attacks.

The data contained in the devices may be subject to Integrity Violation attacks that compromise the integrity and accountability of the network. A typical example may be the modification of the information read by smart meters in order to increase or reduce the household's electricity bill. Authentication schemes and end-to-end encryption help to manage these integrity attacks. The purpose of Privacy Violation attacks is to gain access to consumers' private information. Smart meters collect information in real time about the electricity consumption allowing thieves to know when customers are not at home. Finally, Denial of Service (DoS) attacks occurs when someone outside the network overloads devices with a data stream to make network services or information inaccessible to users.

Countermeasures

Given the variety and the severity of attacks that can compromise the information security criteria, an effective information security risk management must be implemented. It is therefore essential to take preventive countermeasures, set up defensive actions during the attacks, and finally to review and improve these preventive measures after each attack. The risk management process must therefore be dynamic so as to adapt to a changing and complex environment.

As a preventive measure, the Intrusion Detection System (IDS) analyses the network traffic in real-time to detect unauthorised activities such as energy theft by customers or DoS attacks by hackers. Moreover, the Network Data Loss Prevention (DLP) system prevents the destruction or theft of information within the Smart Grids. In addition, Security Information and Event Management Systems (SIEM) enables to collect and analyse all data from network devices to identify unauthorised operations. A Secure Network Protocol (DNP3) is also used to ensure the integrity of data transmission.

Cryptography algorithms and especially encryption play a fundamental role to preventively ensure the integrity, confidentiality and non-repudiation of the data. The Advanced Encryption Standard (AES) algorithm is frequently used to achieve symmetric key encryption, where data is encrypted and decrypted using the same key. The RSA algorithm can also be used to perform asymmetric key encryption, when two different keys (public and private) are needed to encrypt and decrypt information. Furthermore, Public Key Infrastructure (PKI) is designed to ensure the secure transfer of information on the Smart Grids, using digital certificates for authentication and public keys for encryption. Therefore, the Certificate Authority (CA) is a third party that issues a certificate that confirms the identity of the entities before they enter into communication [ABB, 2012].

When a Denial of Service attack is detected, it is essential to mitigate it as quickly as possible. Hence, the Pushback method makes it possible to block all requests sent from the IP address of the unauthorised entity overwhelming the devices with a consequent flow of information. Besides, the reconfiguration method ensures the reorganization of the network so as to isolate the attacker and thus limit the negative impact.

After an attack, the Forensic Analysis is set up to determine the authors, reasons, procedure and consequences of the incident. Following this analysis, it is necessary to determine the weak points of the network to be strengthened so as to prevent future attacks. Finally, all security technologies must be updated according to the results of the investigation.

8 Simris Case Study

The European Union Horizon 2020 innovation program has launched the InterFlex project in order to investigate how local flexibility integration can enhance energy independence from the main distribution network. This project involves multiple European partners that are engaged to deploy Smart Grid projects and promote DER integration. One of these projects is Simris, in Sweden, detailed hereby. The aim of these initiatives is to increase renewables integration and achieve the objectives set by the new Clean Energy Package [Interflex, 2019].

In Simris, the energy distributor E-ON has developed a local energy system, fully powered by Renewable Energy Sources and that has the capability of going into island mode. In addition, smart appliances enabling demand response have been installed within households in order to improve the flexibility of the system. What is more, the energy is generated locally by a wind turbine and a PV farm of respectively 500 kW and 440 kW installed capacity. These RE devices are connected to a smart control system and a Battery Energy Storage System (BESS) having a capacity of 330 kWh. Besides, the energy system connects to the main grid when the BESS is fully charged so as to transfer excess production.

Furthermore, E-ON has implemented a flexibility market for the active customers having installed solar panels or heat pumps in their households. Therefore, those customers receive a compensation based on their energetic contribution to the common Smart Grid. For the purpose of providing full transparency, a platform has been created to follow electricity generation, storage level and interactions with the main grid in real time. Following the basic consumer rights for energy communities, all the households in the local area of Simris are allowed to participate. In addition, all participants have the right to change their supplier at any time [Council of European Energy Regulators, 2019b].

In a nutshell, the scope of this project is firstly to develop a local energy community including island mode and demand response capacities. Secondly, the goal is to develop a sustainable model based on flexibility. Thirdly, this energy community strives to actively engage the members so as to meet their energy needs. Therefore, the concept of this organization is based on the genuine belief that members will be collaborating to locally produce their own electricity in an environmental friendly fashion for the next thirty years [E-ON, 2020].

This case study provides a practical example of a Smart Grid implementation for a local community. Therefore, the Renewable Energy Community modeling that will be presented and analysed is mostly based on this case (Section 9). Indeed, the organisation, the electricity flows and installed Renewable Energy capacities have been sized accordingly.

9 Methodology

9.1 Overall Approach

A structured approach was followed in an attempt to obtain conclusive results from the modelling. First and foremost, it was essential to draw on the literature review to get a clear understanding of the functioning of Renewable Energy Communities, as well as their purpose, legal frameworks, components, challenges and benefits for all stakeholders. This theoretical study was complemented with the Simris case study so as to analyse the real stakes involved in the development of a local energy community. Based on all this research, a first tactical model of a REC was designed with clear objectives, components, functioning processes and hypotheses of potential results. A a second strategical model was then developed to further analyse the capacity expansion aspect within energy communities.

The two mathematical models of the energy community then had to be written down on paper, carefully choosing the indices, parameters and variables needed to define the objective function and the modelling constraints. This was followed by formulating hypotheses and researching accurate values for the parameters in the literature, before optimizing the model through the Gurobi tool. It was then made possible to identify some minor inconsistencies that allowed for improvement, analyse the results of the model and vary some parameters to perform sensitivity analyses. The final step consisted in comparing the results obtained with those found in the literature review so as to draw meaningful managerial and theoretical conclusions.

9.2 Model Explanation

Through this Renewable Energy Community simulation, it is aimed to offer a practical view of dynamic interactions of this specific electricity market, as well as test and complet the theoretical concepts that have been previously stated. The model was therefore designed to meet members' non-essential demand for electricity using Renewable Energy, while maximising benefits for the whole community. Based on the literature review and the Simris case study, the model has been created to optimize the energy flows within the REC for a typical average day of 24 hours (Figure 7).

The Renewable Energy Sources installed within the Smart Grid, include one wind turbine and a PV farm which produce and then transmit clean energy in bulk to the Energy Management System (EMS), which constitutes the control system. Therefore, most of the energy is generated by the wind turbine, while a significant micro-generation is expected from the PV during the brightest hours of the day. The EMS aggregates all the generation and transmits most of the electricity to the distribution system to fulfill real-time demand. Thereafter, the distribution system will ensure the last mile delivery for the Renewable Energy, which is intended to effectively serve the demand of the members (Section 7.4). The EMS is also responsible for deciding the quantity of energy that will be input and output from the Battery Energy Storage System (BESS), so as to optimise the energy flow.

Besides, there will also occur electricity exchanges with the main electricity grid as the REC is not acting in full island mode (Section 5.1). It it noteworthy to mention that the imports will lead to price disadvantages for the members since the prices applied on the main grid are superior to those applied within the Smart Grid. Within this simulation, the Renewable Energy Community is also allowed to resell its production surplus to the main grid, even if it will not bring a substantial profit to the Smart Grid. Given the fact that RE are mostly intermittent and have a low production cost, the energy will be mostly sold at a price approximating the marginal cost (Section 4.2).

The households have a specific expected non-essential demand for each hour, as well as a specific willingness to pay for electricity. As the generation of Renewable Energy varies throughout the day, the electricity supplied to the consumer can come from DERs, storage but also from the main gird. These variations in energy supply will cause electricity prices to fluctuate, and the system will therefore serve consumers whose willingness to pay is respected. One of the objectives of this simulation is to test the demand response principle, and thus to analyze the shift in demand resulting from price incentives (Section 5.2).

The most substantial part of the analysis to follow will be focused on this specific dynamic tactical model, which also include sensitivity analyses based on demand and generation changes. To go into a strategical analysis, a capacity expansion model will be assessed in a second part. This strategical model will be based on an entire year and will assess the optimal storage capacity to be invested in, with the aim of optimising the social welfare. Although batteries bring flexibility to local communities by allowing cheaper peak-time electricity consumption, they also require significant financial investments (Section 5.1). It is therefore interesting to balance these two factors when determining the optimal capacity of batteries. To further develop the strategic model, a brief analysis of the impact of an additional wind turbine on welfare will be conducted.

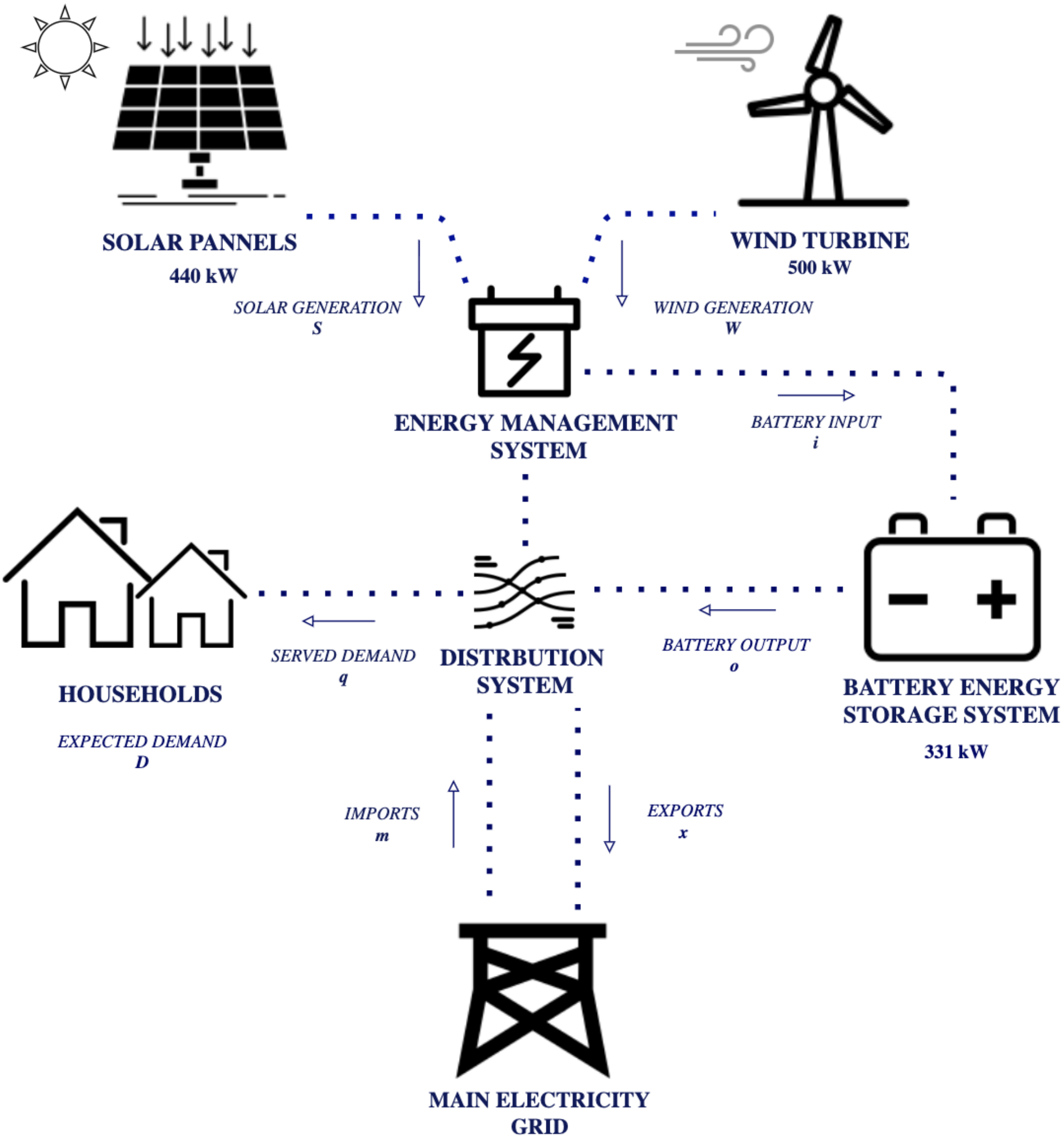


Figure 7: Energy flow within the Renewable Energy Community [By the Author]

9.3 Objectives

Hereby are stated the main objectives of both the tactical and strategical models.

Tactical Model

Optimize the total economic welfare of Renewable Energy Community members by maximizing the value of the served demand, while minimizing value of the net energy imports, in order to increase the benefits for the community.

Strategical Model

Optimize the total economic welfare of Renewable Energy Community members by maximizing the value of the served demand, while minimizing investments in capacity expansion and value of net energy imports, in order to increase the benefits for the community.

9.4 Data Description and Assumptions

This section is dedicated to the description of the data input as parameters for the energy flows modeling of the Renewable Energy Community. All the values of the parameters of this simulation are referenced in the model value table (Appendix 15.3).

Tactical Model

The price per unit of kWh for imported electricity (PM_t) refers to the price that households will pay when they consume energy imported from the main grid. This price is a bi-hourly tariff that fluctuates throughout the day and includes the price of energy, network costs, charges and VAT. From 7am to 10pm the imported electricity is paid at the daytime rate, which is 28,42c€/kWh for peak hour consumption, while the rest of the time it is paid at the nighttime rate, which is equivalent to 26,54c€/kWh for off-peak hour consumption [Energie.be, 2021].

The price per unit of kWh for exported electricity (PX_t) corresponds to the export tariff and therefore to the price that the system receives for injecting energy into the main grid. The value of this excess energy is defined individually by the distribution and supply companies, but it is always lower than the retail electricity price, and is often around 6c€/kWh [Carbontrack, 2016].

The willingness to pay (V_l) corresponds to the price that each household would agree to pay per kWh for their non-essential consumption. Compared to the average electricity price of 27,02€/kWh, 3% of consumers accept a maximum price increase of 50% to get local Renewable Energy, 9% accept an increase of 25%, 30% accept an increase of 10%, and 58% have a willingness to pay equal to the current price [Statista Research Department, 2021]. Given that this simulation is a deterministic model, it is assumed that the willingness to pay as well as the imports prices are fixed and predefined.

The expected demand (D_{lt}) per household and per time period is assumed, within this simulation, to be the desired demand by households excluding their basic consumption necessities. Therefore this demand, which is based on a real sample of end-users, consists in the non-essential electricity needs and varies throughout the day according to the consumers' lifestyle (Appendix 15.4). In order not to have a uniform expected demand for all members, three groups of consumers were formed having a different demand per hour. It has been assumed that 50% of the members have a demand per hour equal to that of the real sample, 25% have a demand 25% higher, and 25% have a demand 25% lower.

The present REC simulation has been sized according to Simris case study (Section 8). In this case, the capacity installed for wind and solar energy are respectively equal to 500 kW and 440kW [E-ON, 2020]. Generation profiles for the wind turbine (W_t) and solar panels (S_t) have been defined based on the ENTSOE Data Platform generation profiles for all the Belgian onshore wind turbines and solar panels with regard to the total installed capacity within the country. Both generation profiles have been created based on average generation per hour for an entire year [ENTSO-E, 2021] and resized based on the installed wind energy capacity within the energy community.

The BESS used for this model has been sized according to the Samsung SDI storage Lithiuinmion battery, which is also present in the Simris energy community. When charged properly, the Li-ion batteries enable the best performances in storage resulting in a storage efficency of 100% (η^{EB}). Besides, the maximum capacity of the battery (E^B) is 331 kWh [E-ON, 2020]. It is assumed that the discharging efficiency is 100% (η^{OB}), therefore the battery can fully discharge the maximum capacity in one hour. As a result, the maximal quantity of electricity that the battery can output in one hour (O^B) equals to 331kWh.

Besides, the charge is considered to be fully complete after a period of 2 hours. Therefore the maximum quantity of electricity that can be input in the battery (I^B) can not be higher than half of the full capacity. Moreover, the charging efficiency (η^{IB}) is estimated at 80% [Systems, 2020].

Strategical Model

The strategical model is focused on the capacity expansion, which is an extension of the tactical model. Therefore, it assesses the optimal storage capacity with respect to the yearly cost of investment. The only addition parameter is the investment required to acquire one additional unit of storage (C^{EB}), and thus 1 more kWh. This has been computed based on the Samsung SDI battery used in the Simris Smart Grid, and the price has been discounted with regard to the lifespan of this battery. The resulting investment cost is therefore approximated at 30,31€ [EVWest, 2016].

9.5 Variables

The tactical and strategical models will strive to optimize the following variables.

Tactical Model

Firstly, the goal is to minimize the quantity of electricity imported from the main grid for each hour (m_t), as it is the most expensive source of energy. However, this electricity can not always guarantee to be fully renewable, as it highly depends on the country's energy mix.

Secondly, the model strives to optimize the benefit provided to the community by exporting the production energy surplus to the main grid. Therefore, the second variable is the electricity quantity exported in kWh during one hour (x_t).

Thirdly, the model strives to optimize the quantity of electricity actually served to each member of the community per hour (q_{lt}). The goal is to satisfy the major part of the expected demand, but there may be gaps between expected and served demand, notably due to dynamic pricing.

In forth place, through the clearing constraint, the model strives to clear the market and balance the supply and demand by using the local generation, storage as well as energy exchanges with the main grid. Therefore, the quantity of electricity that is input (i_t^B) and output (o_t^B) from the battery each hour is optimised by the system so as to complement the electricity generated by the RES. However, these variables are capped by the specific capacity and efficiency constraints of the battery (Section 9.4) Lastly, the system will optimise the amount of electricity stored in the battery during each period (e_t^B). This variable represents the battery state per hour.

Strategical Model

The strategic model aims to optimise an additional variable compared to the tactical model. In fact, the model focuses on the capacity expansion strives to optimise the total battery capacity for the whole year (y^{EB}).

9.6 Hypothesis

Having defined the parameters and variables, it has been possible to formulate hypotheses concerning the expected results of both the tactical and strategical models. These hypotheses are based on the design of the model and the literature review.

Tactical Model

Hypothesis 1: The price of electricity fluctuates on an hourly basis depending on the expected demand and real time power generation.

Hypothesis 2: By the principle of demand response, the demand effectively served to each household fluctuates according to their willingness to pay and the price of electricity.

Hypothesis 3: If the electricity generation exceeds the expected demand of the households, the surplus is charged into the battery. If not, the shortage is compensated by the electricity stored in the battery.

Hypothesis 4:If the expected household demand is met and the batteries are fully charged, the excess energy generated is then exported to the main grid.

Hypothesis 5: In case the generated electricity and the stored electricity are not sufficient to serve the expected demand, the shortage is imported as long as the price does not exceed the willingness to pay.

Hypothesis 6: Renewable Energy Communities bring positive welfare to the community.

Strategical Model

Hypothesis 7: The maximum storage capacity of the batteries increases, resulting in lower imports from the main grid.

Hypothesis 8: The welfare increases compared to the tactical model.

10 Social Welfare Modeling

10.1 Tactical Model

Indexes

$t = 1, \ldots, 24 =$ Time periods in hours
$l = 1, \ldots, 280 =$ Member households in energy community

Parameters

$\mathrm{PM}_t =$ price per unit of kWh for imported electricity in period t

$PX_t =$ price per unit of kWh for exported electricity in period t

$W_t =$ electricity quantity in kWh, generated by wind power in period t

$S_t =$ electricity quantity in kWh, generated by solar power in period t

$D_{lt} =$ expected demand in kWh, by member l in period t

$V_l =$ willingness to pay in EUR/kWh, by member l

$E^B =$ maximal capacity of battery, in kWh

$E^B_{initial} =$ initial capacity of battery, in kWh

$I^B =$ maximal quantity of electricity in kWh, that can be input in the battery in an hour

$O^B =$ maximal quantity of electricity in kWh, that the battery can output in an hour

$\eta^{EB} =$ efficiency of electricity storage for one period

$\eta^{IB} =$ efficiency of electricity input (charge)

$\eta^{OB} =$ efficiency of electricity output (discharge)

Variables

$\mathrm{m}_t =$ electricity quantity in kWh, imported in period t

$x_t =$ electricity quantity in kWh, exported in period t

$q_{lt} =$ quantity of demand in kWh, effectively served, in period t to customer l

$e_t^B =$ quantity of electricity in kWh, stored in the battery, in period t

$i_t^B =$ quantity of electricity in kWh, that is input in the battery (charged), in period t

$o_t^B =$ quantity of electricity in kWh, that is output by the battery (discharged), in period t

Objective Function and Constraints

$$\min \quad PM_t \cdot m_t - PX_t \cdot x_t - \sum_{l \in L} V_l \cdot q_{lt}$$

$$\begin{aligned}
i_t^B + x_t + \sum_{l \in L} q_{lt} &= m_t + o_t^B + Wt + S_t && \forall t \in T && (1) \\
e_1^B &= \eta^{EB} \cdot E_{initial}^B + \eta^{IB} \cdot i_1^B - \eta^{OB} \cdot o_1^B && && (2) \\
e_t^B &= \eta^{EB} \cdot e_{t-1}^B + \eta^{IB} \cdot i_t^B - \eta^{OB} \cdot o_t^B && \forall t \in T && (3) \\
E_{initial}^B &= e_{24}^B && && (4) \\
o_t^B &\leq O_t^B && \forall t \in T && (5) \\
i_t^B &\leq I_t^B && \forall t \in T && (6) \\
e_t^B &\leq E^B && \forall t \in T && (7) \\
m_t &\leq \sum_{l \in L} D_{lt} && \forall l, t \in L, T && (8) \\
q_{lt} &\leq D_l t && \forall l, t \in L, T && (9) \\
q_l t, m_t, x_t, e_t^B, o_t^B, i_t^B &\geq 0 && \forall l, t \in L, T && (10)
\end{aligned}$$

(1) Market clearing constraint
(2) Initial storage constraint
(3) State of the storage constraint
(4) Initial and final storage constraint
(5) Battery output constraint
(6) Battery input constraint
(7) Battery capacity constraint
(8) Limit on imports constraint
(9) Limit on served demand constraint
(10) Non negativity constraints

10.2 Strategic Model

Parameters

C^{EB} = Investment necessary to acquire 1 kWh additional unit of storage.

Variables

y^{EB} = Optimal battery capacity in kWh.

Objective Function and Constraints

$$\begin{aligned}
\min \quad & (C^{EB} \cdot y^{EB}) + 365 \cdot (PM_t \cdot m_t - PX_t \cdot x_t - \sum_{l \in L} V_l \cdot q_{lt}) \\
\text{s.t.} \quad & \\
& e_t^B \leq y^{EB} \qquad \forall t \in T \quad (1) \\
& y^{EB} \geq 0 \qquad (2)
\end{aligned}$$

(1) Limit on the battery state
(2) Non negativity constraint

11 Analysis

11.1 Tactical Model

This section is dedicated to the analysis of the results obtained for the variables of the tactical model, to then be compared with the literature review in the discussion (Section 12). All of these findings are included in the table of quantitative results (Appendix 15.5). Regarding the variable that computes the amount of energy effectively served to each customer per hour, an aggregation of the results matrix was done for all the 280 customers per hour so that the results are readable.

11.1.1 Electricity Price Analysis

It is noteworthy that the price of electricity actually paid by consumers fluctuates throughout the day (Appendix 15.5). Until 6am, aggregated expected demand and power generation are at their minimum and do not exceed 56kWh and 68,8kWh respectively. Since generation is higher than the non-essential expected demand, the price of electricity is at its minimum and it equals the marginal cost of 6c€/kWh.

Thereafter, there is a sharp increase in electricity demand until 8am as consumers start their day. This change in the trend of the demand curve will therefore equalise demand and generation a little after 6am, leading to a new equilibrium price of 7,5c€/kWh from 7am. It can be said that the market is cleared at this time. During the same period, the generation gradually increases but remains lower than the demand. The demand is mainly met by energy from wind turbines and batteries as the sun is gradually rising.

The expected demand for electricity slowly decreases from 8am to 3pm, while the generation increases strongly during this period due to the photovoltaic panels. Energy generation and demand therefore equalise around 10am, resulting in a price change to 6c€/kWh at the beginning of the next period. Therefore, the price is once again equal to the marginal price at 11 am. Thereafter, production exceeds demand and the surplus will be used to charge the batteries.

The trends reverse again after 3pm as the demand for electricity surges while generation drops due to lower sunlight. The two curves will cross again between 5pm and 6pm, leading to a new clearing price of 27,02c€/kWh as of 6pm. This price corresponds to the lowest willingness to pay and also to the storage price during the period. Demand continues to soar until reaching a peak at 10pm, while overall generation decreases even though there is a slight increase in wind turbine output.

The electricity demand is therefore met by discharging the batteries from 8pm until they are half full at 9am to comply with the storage requirement. Electricity is imported from the main grid at 11pm in order to satisfy the demand, and the price therefore decrease to 26,54c€/kW which is the night tariff on the main grid. Non-essential energy demand falls sharply and ultimately evens out generation in the last hour of the day. As a result, generation exceeds demand at midnight, leading to a price of 6c€/kWh which corresponds again to the marginal price.

Therefore, changes in electricity prices occur when there are shifting trends in energy generation and expected demand, hence a new equilibrium price is determined at the intersection of these two curves (Figure 8). These results from the model therefore validate hypothesis 1.

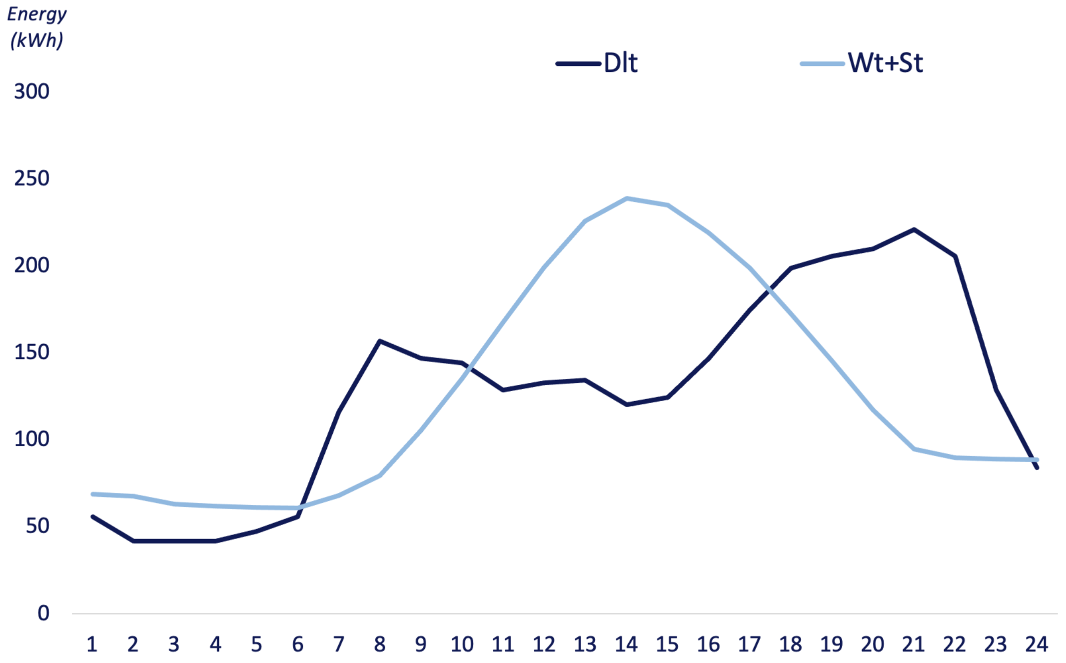


Figure 8: Daily aggregated served load and generation profiles [By the Author]

11.1.2 Served Demand Analysis

The results show that the actual demand served is not always equal to the expected demand, especially from 6pm to 10pm, except at 8pm (Figure 9). To explain the unsatisfied demand, it is necessary to analyse the times of the day when the expected demand exceeds the energy generation (Figure 8). Indeed, the generation is not sufficient during the morning peak consumption from 7am to 10am, but it is compensated by the batteries so the demand is met.

In the evening, generation is lower than demand from 6pm to 11pm but the batteries cannot compensate for all the unsatisfied demand as they have to comply with the storage constraint. As the batteries have to be half full at the end of the day, they are used to compensate for the highest expected demand only which is at 8pm and 9pm. Therefore, the demand will be fully met by the batteries and the generation at 8pm, and partially satisfied at 9pm.

For 6pm, 7pm and 10pm, the system will use the low amount of energy generated to first satisfy the members having the highest WTP. For those with the lowest WTP of 27,02c€/kWh, the system will randomly meet the demand of some of them with the remaining locally generated energy at 27,02c€/kWh. The demand of the others will therefore not be met either by generation, storage or potential import of energy from the main grid since the import day tariff is 28,42c€/kWh, which is higher than their WTP. Therefore, the demand is not met for 23% of members having the lowest WTP at 6pm, 48% of these members at 7pm and 91% of them at 10pm. However at the price of the electricity locally generated, these consumers are indifferent to consume or not since their profit is zero when the price is equal to their willingness to pay.

Regarding the lack of generation compared to the expected demand at 11pm, it cannot be compensated by batteries but is covered by the import of energy from the main grid. Indeed, the price of electricity has shifted to the night tariff which is 26,54c€/kWh and therefore lower than the lowest WTP. All demand will therefore be met.

This highlights that the real-time price of electricity and the willingness to pay of households leads to a shift in the served demand for electricity, showing the principle of demand response. However, in addition to these two factors, the amount of electricity actually served is also strongly dependent on the flexibility provided by the battery, which therefore partially validates hypothesis 2.

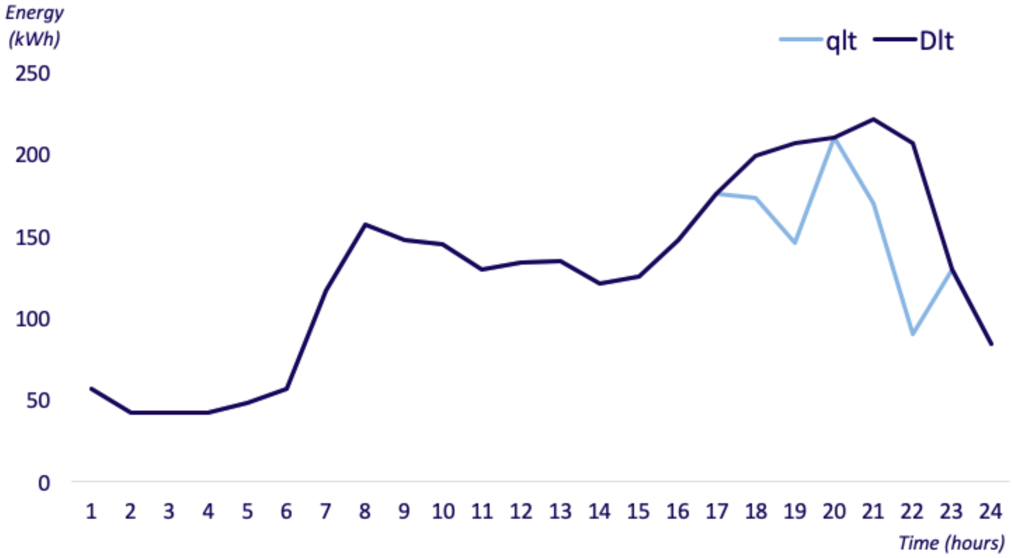


Figure 9: Peak shaving between expected and actually served demand [By the Author]

11.1.3 Storage Analysis

The system starts with the batteries half full, and therefore charged at 167 kWh. When analysing the level of storage, it is interesting to compare the expected demand with the generation (Figure 8). As electricity production exceeds demand until 6am, the surplus electricity is stored in the batteries. The trend reverses between 7am and 10am, so the batteries are discharged to compensate for the lack of generation during the consumption peak and to meet the households' demand.

Thereafter, electricity generation exceeds demand between 11am and 5pm due to the high solar output, which enables the batteries to be charged to their maximum capacity of 331 kWh by 3pm. As the batteries are full, the system exports the energy surplus to the main grid from 3pm to 5pm. The electricity stored in the batteries is saved between 6pm and 7pm even if demand exceeds generation, so that the greatest shortfall in generation can be compensated for when demand is highest, which occurs between 8pm and 9pm. However, this compensation is limited by the storage constraint requiring the battery to be half charged at the end of the day. The battery's state of charge therefore stagnates at 162kWh from 9pm on wards, until it increases slightly at midnight when generation again exceeds demand.

The analysis of the storage therefore leads to the conclusion that the system charges the batteries when the production is higher than the demand, and discharges them when the generation is not sufficient to meet the non-essential energy needs of consumers. However, the system makes smart decisions by prioritising the demands that need to be met by the batteries, while respecting the storage constraint. This therefore validates hypothesis 3.

11.1.4 Export Analysis

The batteries are fully charged at 331kWh from 3pm on wards, while the energy production still exceeds the expected demand until 5pm. This is mainly due to the fact that these are off-peak hours for the electricity consumption, while the energy generation of the solar panels is substantial due to the high luminosity. The surplus energy is therefore exported to the main grid from 3pm to 5pm so as to maximise the welfare of the community.

These results confirm hypothesis 4 which states that the excess energy is exported to the main grid if the expected demand is fulfilled and the batteries are fully charged.

11.1.5 Import Analysis

By analysing the results, it is observable that the expected energy demand is lower than the generation between 7am and 10am, but the shortfall is compensated by the energy stored by the batteries. Importing from the main grid is therefore not necessary to meet the demand.

Similarly, the generation is not sufficient to cover the demand from 6pm to 11pm, but the batteries counterbalance this from 8pm to 9pm. At 6pm, 7pm and 10pm, the system first satisfies the demand of members with a larger WTP and decides not to use the available storage. As the remaining members have a WTP lower than the day rate of electricity on the main grid, there is no import and their demand is not met. However, at 11pm the price of electricity from the main grid becomes lower than their WTP, leading to electricity imports.

Since imports are relatively expensive, they are considered a backup to cover demand if participants are willing to pay accordingly. Imported electricity is therefore never used to either charge batteries or export energy, so there can be no imports and exports within the same period. These results therefore support hypothesis 5 which implies that if demand is not matched by generation and storage, the shortfall is compensated for by importing energy at a price which respects the members' willingness to pay.

11.1.6 Overall Welfare Analysis

The objective of the system is to maximize the value of the served demand, while minimizing value of the net energy imports. The results highlight that the welfare amounts to 811,37€ on an average day for the community, which can therefore be interpreted as a collective benefit.

Participating in these Renewable Energy Communities therefore brings a positive welfare to the members, which would contribute to their expansion. Consequently, these observations support hypothesis 6. However, the system does not specify how this collective gain is shared between the members of the local energy community (Section 13.4).

11.1.7 Sensitivity Analysis

Summer Analysis

To analyse the summer scenario, different values are defined for three parameters which are the expected demand of the households, the electricity generation of the wind turbines and the solar panels (Appendix 15.6). Overall, it can be observed that the welfare in summer is only 751,05€ per day, which is lower than that of an average day being 811,37€ (Appendix 15.7).

During the summer months, the total electricity generation per day is 3123 kWh, which is slightly higher than the average day with 3053 kWh. Solar generation is almost doubling the average generation, especially between 10am and 6pm, while wind generation is almost halved, especially between 9pm and 1am. Besides, the expected demand is lower in summer, especially from 6am to 11pm. However, it is observable that the decrease in generation is greater than the decrease in desired demand from 9pm to 1am.

As a result, the batteries, which have been fully charged since 6pm, will not be used to compensate for the lack of generation from 7pm to 8pm. The system will preserve them for maximum discharge at 9pm and 10pm to compensate for the considerable generation shortfall, while respecting the storage constraint. Even with the batteries, only 40% of the demand is actually served at 10pm. Energy will therefore be imported from the main grid at 11pm and midnight to meet demand, at the night tariff price of 26,54c€/kWh. The demand will be met at 1am by the battery as the system starts a new cycle, resulting in an electricity price of 7,5c€/kWh which is the storage price.

As there is more sunlight in the summer, the batteries can be charged as early as 10am, but also until 5pm and 6pm. Compared to the average day, electricity is therefore cheaper at 6pm and 10pm as it equals the marginal price, and demand is served at 6pm as generation exceeds demand. As solar panels generate more electricity during off-peak consumption, energy is exported to the main grid from noon to 4pm. The total amount exported in the summer is about three times the amount exported on an average day, but it is only paid for at a marginal price of 6c€/kWh. Moreover, energy imports from the main grid are more than 2,5 times higher in summer, even though they are rather expensive.

As a result, the gains obtained by members in the summer are less than on an average day of the year since there is a time lag between producing energy and consuming it. Indeed, PV generate energy mainly during off-peak consumption, whereas wind generates less energy during peak-consumption. Even if the total electricity generated and the amount of energy actually served is similar, the energy management during the day differs and leads to higher costs.

Winter Analysis

As for the summer scenario, the winter scenario involves changing the parameters of non-essential energy demand, as well as solar and wind generation (Appendix 15.6). The total welfare in winter amounts to 756,89€ and is therefore also lower that for an average day (Appendix 15.9).

The amount of electricity generated in winter is 2649kWh, which is below the average generation of 3053kWh. Although wind power generation in winter is stronger throughout the day, being 40% higher than on an average day, the solar generation is reduced by 80%. As for the expected demand, it is 60% higher than the average demand, especially during the morning and evening consumption peaks. This significant gap between generation and demand will lead to an increase in the price of electricity, in the cost of storage and in the share of demand that is not effectively served.

The generation is not sufficient to cover the demand from 7am to 11am. To supply all the demand at 7am, the system decides to import electricity from the main grid which is still at night tariff of 26,54c€/kWh, as it is cheaper than the price of the storage and lower than the WTP of 27,02c€/kWh. Thereafter, the system prefers not to discharge the batteries to compensate for the small generation shortfall in the morning, as it wants to maximise the storage to compensate for the large generation shortfall expected in the evening. Furthermore, the price of storage is equal to the smallest WTP so these members are indifferent between consuming electricity from batteries or not being served.

PV generation is at its highest between noon and 3pm, which will allow the batteries to be fully charged from 3pm to 5pm. While respecting the storage constraint, the batteries are discharged to the maximum at 6pm and 7pm, which are the times with the largest gaps between generation and expected demand. The generation is also not sufficient to cover all the demand from 8pm to 11pm so the system will decide to satisfy the participants with the highest WTP first so as to maximise the total welfare. Since the import price is at the daytime tariff of 28,42c€/kWh until 10pm, which is higher than the lowest WTP, the system decides not to satisfy their demand before 11pm by importing at the nighttime tariff of 26,54c€/kWh.

In a nutshell, the welfare in winter is lower than the welfare of an average day as the generation is not sufficient to cover the demand, especially during the two consumption peaks. As a consequence, the price of electricity rises sharply leading to the application of the demand response principle. However, the system optimises the resource management through demand forecasts and thus achieves to serve 80% of the expected demand.

The results of the sensitivity analyses in summer and winter indicate a lower welfare result than on an average day during the year. It can be deduced that the maximum welfare is reached in the intermediate seasons like spring and autumn, when the generation is more balanced between the two RES, and less extreme compared to the demand.

11.2 Strategical Model

The results of the strategical model suggest that the optimal maximum battery capacity is 462,1kWh, which is greater than that of the tactical model being 331kWh. This finding was obtained by relaxing the storage constraints in the strategical model, and was then tested by setting the storage capacity to 462,1kWh in the tactical model to analyse the results under the same conditions as the first model. The resulting welfare is 837,05€, from which 10,88€ must be subtracted, which is the daily investment cost of expanding the battery capacity

(Appendix 18). Indeed, each incremental kWh for the battery costs 30,31€ per year, and 131kWh must be added. This increase in battery capacity results in a welfare of 826,17€, which is higher than that for the tactical model, being 811,37€.

Through the expansion of the battery capacity, the system can store energy from 11am until 5pm, and thus benefit from an additional two hours of storage. The additional 131kWh of storage are used to supplement generation to meet demand partially at 8pm and fully at 9pm and 10pm, when the gap between electricity generation and demand is the highest. As a result, 96% of the demand is effectively served due to the increase in battery size, compared to 92% previously. This therefore increases the demand served only for those members having the lowest willingness to pay as they were the only ones not all served. This in turn lessens the demand response.

However, the price of electricity and storage remains the same as in the tactical model, which are always lower than the smallest WTP. Besides, the import of energy from the main grid is also similar at 11pm as the batteries are discharged to meet the peak demand at 10pm, but they have to meet the end of day storage constraint.

These results therefore validate the hypothesis 7 as the system increases the optimal storage capacity of the battery. Despite the high upfront cost, this strategic investment increases the benefits and therefore the welfare of the community by increasing the actual demand served to members having the lowest WTP. These results therefore support the last hypothesis.

Wind Turbine Capacity Expansion

The strategic model is based on an analysis of increased storage capacity, but the analysis can be taken a step further by considering an expansion of wind turbine capacity. As noted in the analysis of the demand served, the installed Renewable Energy capacity is not sufficient to meet demand during the morning and evening peak hours. Consequently, the system relies on batteries as buffers. The batteries are sufficient to meet the demand during the morning, but this is not always the case in the evening leading to the demand response principle. Moreover, energy imports are necessary in the evening, which can considerably increase the costs for the system.

Through the demand response methods, a certain flexibility is imposed on the members, especially for those with the lowest WTP. These techniques might therefore be perceived as being unfair for those members. With this in mind, a capacity expansion of the wind turbine is considered. The purpose of this analysis is to examine the impact of this expansion on the price level and on the attempt to create a fairer system for all members, particularly for those with a lower WTP. The wind turbine installed capacity can not possibly be increased by percentage as it is used by entire unit, one new whole turbine is therefore installed in this simulation. In the case where the wind turbine generation is doubled, the demand response methods are no longer implemented as the expected demand is served for all members.

Following the wind turbine expansion, the prices decrease until the marginal cost of 6c€/kWh from 9am until 7pm and 11pm until 7am. During the morning and evening peak hours, the and price slightly increases by reaching 7,5c€/kWh at 8am, but also between 8 and 10pm. However, this price remains trivial in comparison with the previous scenarios. Since generation becomes largely sufficient, the system is now exporting 1724,52kWh/day and no more expensive imports are required.

The resulting simulation leads to an annual welfare of 358.596,32€. The annual investment and maintenance costs for the additional wind turbine amount to 47.000€ per year. Therefore, the daily welfare accounts for 853,68€ which is the highest welfare achieved within this modelling. It is noteworthy that through this expansion investment, all expected demand is effectively served and multiple exports towards the main grid are accounted, while increasing the welfare. Therefore, the community now has additional resources to potentially welcome new members.

12 Discussion

This section is intended to compare the modelling results with theoretical results from the literature review. Therefore, the comparison addresses the main social, economic and environmental impacts of Renewable Energy Communities. The discussion will be concluded with a reflection on the fair sharing of benefits among members, as well as on the optimal investments for capacity expansions, leading to open pathways for future work.

Social Impact

This prosumership model enforces the principle of customer empowerment stated in the literature as members become prosumers (Section 4.1). This is achieved through a collective ownership of the Renewable Energy Sources by the 280 members, who are also involved in the decision-making of the project. The transfer of power has therefore passed to the consumers, which is evidence of energy democracy, but it is assumed in the simulation that the consumers have chosen to let the EMS optimally manage the smart appliances' energy consumption. The flexibility that consumers have in deciding to override the system occasionally is not captured in this model.

This simulation is faithful to the theoretical inclusiveness of RECs as there are no membership requirements other than geographical proximity (Section 3.1). However, the fairness of the simulation is put into perspective as the system decides to satisfy the demand of the members with the highest willingness to pay first, with the aim of maximising welfare. As a result, only 9% of the demand from members with the lowest WTP is effectively served at 10pm in the tactical model. One explanation lies in the fact that there is not enough generation to meet all the demand. The strategic model thus revealed that an expansion of battery capacity would increase welfare from 811,31€ to 826,17€ by significantly improving the demand served for members having a lower WTP. Besides, the strategic analysis was also further developed by pointing out that the addition of a second wind turbine could satisfy 100% of the members' demand by reaching a maximum welfare of 853,68€. This scenario allows a large amount of energy to be exported daily at marginal cost to the main grid, but which could instead be sold to local initiatives to support their development.

These capacity expansion models would therefore allow to serve all the demand, avoiding situations where members limit their consumption or consume electricity above their WTP (Section 4.2). However, wanting to serve members with a smaller WTP leads to a fairer system if they are vulnerable people who cannot pay more for energy, not because they have a low utility for this non-essential energy even if they can afford to pay more. Although the model does not distinguish between the two categories of participants.

According to the model, a member's daily electricity bill is 46% that of a main grid household, taking into account the variation in price and demand per hour. The emergence of RECs therefore makes it possible to increase electricity access to vulnerable people, leading to a reduction in energy poverty as outlined in the literature (Section 4.1).

Economic Impact

As a first point, it is important to highlight that REC members act together as an entity by aggregating their demand, which enables them to obtain more bargaining power with suppliers and economies of scale. Regarding community-owned assets, the investment costs are shared, making it possible for the members to proportionally acquire larger installed capacity and to benefit from more flexibility. In the literature review it is stated that investing in additional storage capacity will decrease storage prices for all participants (Section 4.1). Nevertheless, the capacity expansion simulation presented in the strategical model was not able to prove this theoretical statement. Indeed, the model has optimized the installed storage capacity by making the trade-off between the investment costs and the social welfare. Therefore by adding more capacity than 462kWh would have required a more important investment and impacted negatively the welfare, even if it would have decreased the storage prices.

The investment in the storage added capacity is approximated by the model around 6.000€. Moreover, the investment in one additional unit of wind turbine accounts for 1.175.000€ in Europe. Despite the fact that costs are shared within the community, these costs may remain quite high. This supports the literature stating that national legislation should further recognize the role and impact of RECs in Renewable Energy, following the example of the European Commission in supporting these entities. Therefore National regulators should on the one hand set national targets for the expansion of RECs, and on the other hand provide financial means to support them (Section 6.3). Regulations would have to be established at the national level to foster the growth of REC and encourage citizens to become members through financial incentives such as feed-in tariffs, grants or low cost loans.

As a second point, it has been established in the literature that RECs are a fairly young concept, hence the existing regulations on the import and export tariffs is scarce. A more precise regulation should be established to promote energy exchanges with the main grid, especially by improving the conditions for the resale of energy surplus. By increasing generation capacity in the strategical model, power exports become more important, although at low prices. Alternatives to selling energy back to the main grid may be to sell the electricity to local projects or other neighbouring communities, as well as welcoming new members in order to strengthen local cooperation and economic development.

The third point concerns the benefits provided by the connection to the main grid. The main network plays a backup role by creating more flexibility through imports, while guaranteeing security of supply (Section 5.1). However, this represents a very significant cost to the REC. With this in mind, the model delays importing as much as possible and hence does not import until 11pm when the import tariff goes within the night price range. Otherwise, it is financially more advantageous to not serve demand and apply demand response techniques rather than importing.

The forth highlight of the modelling is that the electricity bill is significantly lowered through load management, automation, collective self consumption and prioritizing managerial decisions. Going even further than the literature, the model states that the electricity bill of REC members is only 46% that of a main grid household. The Energy Management System is using the data collected and communicates with the users through the bi-directional flow. Using this data, the EMS optimizes the demand served and applies peak shaving techniques when meeting the demand reduces the community's gain (Sections 5.2). In this simulation, the EMS makes managerial decisions by optimising the storage and keeping the energy for the peak consumption hours. Besides, the system also optimizes the collective self consumption by shaving the peak through dynamic pricing until most of the demand is met in order to avoid imports. Indeed, the EMS communicates in real time the prices and optimal consumption choices for the smart appliances of each household through ICTs. However, the model does not allow members to override the system and still consume even if the energy price is above their WTP as stated in the literature (Section 7.2).

Environmental Impact

The modelling results suggest that the development of RECs has a positive impact on the environment. In this way, the tactical model reflects the principle of demand response as demand adapts to the available supply, leading to a decrease in energy consumption which is in compliance with the literature (Section 5.2). The model therefore shows that AI systems optimise the management of storage, consumption and resale of energy through forecasts leading to energy efficiency and savings (Section 4.1). However, only members with the lowest energy utility are incentivised to reduce their energy consumption in the model as the prices do not exceed the upper WTP. What is more, the tactical simulation reveals that 96% of the non-essential consumer demand is met by Renewable Energy Sources rather than polluting fossil fuels. These results are encouraging with regard to the further integration of DERs into the energy system, and would make it possible to achieve the environmental objectives set by the European Commission (Section 4.1).

Based on the simulation, the generation of local DERs is able to fulfil the demand, which implies, but cannot be proven, that it would reduce the energy losses related to the long energy transports occurring in the main grid (Section 5.4). Besides, the substantial energy exports to the main grid featured in the strategic model would diversify the energy mix of the national grids and thus increasing the share of demand met by RES.

Through collective ownership, dynamic pricing and load shifting used in the model, members adopt collective responsible actions and become aware of current energy challenges, which supports the principle of energy citizenship (Section 4.1). The fact that the resulting welfare is positive despite the initial investments and disadvantages brought about by DERs, would motivate members to accept this trade-off for the common good. These objective results instigate an increase in social acceptance of DERs (Section 6.3).

Open questions for future work

The strategic model shows that an expansion of generation capacity can satisfy 100% of the non-essential energy demand of community members while maximising the welfare. However, it is worth considering whether this constitutes a real advantage. This implies that there is no more load shifting, whereas it enabled raising consumers' awareness of energy challenges and reducing their consumption, which has a certain environmental cost even if it comes from RES. The question that arises then is what is the ideal percentage of non-essential demand that should be served? To what extent is the objective of maximising welfare, and thus the value of demand served through local DERs, optimal for minimising the carbon footprint?

The Renewable Energy Community achieves an average gain of 853.68€ per day. This brings to mind the question of how to share the benefits among the members? As these communities are value-driven, the objective is not to maximise the individual profit of members but rather the common good (Section 3.1). Considering the example of cooperatives based on the "one share, one vote" principle, each member has invested the same amount and therefore receives the same capped dividend often around 6%. The rest of the profit is reinvested in the development of the community (Section 3.4). Although very fair, does this distribution of profits incentivise members to reduce their energy consumption or to adapt it to the supply, leading to peak shifting? Shouldn't there also be a bonus payment for each kWh not consumed by a household compared to its usual consumption, as a way of rewarding its effort and environmental impact? (Sections 4.1 and 13.4)

13 Conclusion

As a conclusion to this thesis, recommendations for the management of a Renewable Energy Community will be formulated arising from the discussion. A theoretical conclusion will then outline the results of the model that not only contradict the literature review, but also support it or even further refine it. A critique will be made towards the assumptions of the model without which the results would probably have been different, before ending with a refection on the potential future work.

13.1 Managerial

The first managerial recommendation that emerges from the thesis is to collaborate with the Member States, Local and Regional Authorities, as well as the main grid managers from the outset of the project. Involving the MS and LRAs by pointing out how the project would contribute to achieving the energy goals would encourage them to provide more financial support mechanisms and to establish policies supporting the expansion of the RECs. It would also be beneficial to have a close relationship with the main grid operators to reach beneficial agreements, notably by optimising energy export and import prices.

To ensure that the AI system is able to optimise renewable energy management, it is recommended to invest in state-of-the-art technology to provide the most accurate generation and demand forecasts possible. While it is important to allow members to override the system, this should remain occasional so as to maximise the common good. Therefore, there is a need to provide additional remuneration for the members participating in load shifting. Mobile technologies and apps also enable direct communication with each household to advise them on their energy consumption, but also to inform them of their environmental impact.

Last but not least, dynamic pricing allows load shifting but it is important that the energy price is never higher than the smallest capacity to pay of the members. This maximises the inclusiveness of the community towards the most vulnerable and thus contributes to reducing energy poverty. Members whose willingness to pay is higher than the price of electricity can still be incentivised to reduce their demand through remuneration for each kWh not consumed compared to their usual demand. In the same way, they can be incentivised through effective communication via mobile technology about the impact of their energy savings on the environment, and about the savings they can make compared to what they intended to pay.

13.2 Theoretical

Through this research it has been shown that by increasing the share of integrated DERs in the Renewable Energy Community it is possible to support 100% of the expected energy demand for non-essential needs. However, incentives to save energy will be lacking, so there is no longer demand response. The purpose of demand response is indeed twofold: on the one hand, these methods allow to regulate the peak during high consumption hours and on the other hand, it is a nudge to consume more responsibly. Although the energy is produced by RES, using wind turbines, PV and batteries have an environmental cost, so increasing the consumption of RE still leads to a carbon footprint.

Throughout the literature, there are many references to the economic benefits that members experience by reducing their electricity bills significantly. The model developed earlier reveals the electricity bill would be equal to only 46% of that of a household operating in the classical distribution system. Through this precise figure, it is possible to affirm that the access to electricity will be enhanced as assumed in the literature.

It is mentioned in the literature that the storage prices would be strongly reduced by increasing the installed storage capacity. According to the strategical model, this statement can be tempered and contextualized through the investment required to obtain this additional capacity. The model optimizes the additional capacity by trying to reduce the negative impact of the upfront investments. Therefore, this capacity remains relatively low since a significant investment cost is taken into account, which prevents this capacity expansion from having a significant impact on the level of storage prices.

13.3 Critique

The first critique related to the construction of the model lies in the fact that prices have been assumed to be deterministic, based on multiple sources. This model is therefore stationary and does not take into account time series. However, the spot prices in the electricity market fluctuate every hour or even every 15 minutes in reality. The result of the model could have been significantly impacted by taking into account the variation in import and export prices.

The objective of the model is to maximise the value of the non-essential demand for energy that is actually served to the members, notably for the purpose of analysing the demand response principle. It would have been interesting to see to what extent RES can also satisfy the essential demand that must be met every hour for every household, alongside the dispensable demand.

Furthermore, it was assumed in the model that energy exchanges with the main grid, as well as local distribution, would not suffer from energy losses during transport resulting from voltage differences for example. Furthermore, it was considered that there is no limit to the amount of energy that the community can import from the main grid, and that it would purchase all the energy that the community wants to export when necessary. These assumptions do not take into account the energy needs of the main grid, nor its generation capacity. Therefore, the results of the model could be impacted by considering this decrease in flexibility, which is more faithful to reality.

Ultimately, four groups of consumers having different willingness to pay were defined based on a consumer preferences survey. However, knowing the willingness to pay is an idealistic scenario and indeed impossible in reality. The utility that each consumer gives to electricity varies constantly according to his or her desires and needs, and the system cannot therefore deduce it.

13.4 Future work

Following the above critique, it would be interesting as a future work to improve the Renewable Energy Community model, which is based on collective-ownership. This implies taking into account the necessary consumption that must be served for each household, the energy losses incurred in transport, as well as the limits of energy import and export with the main grid depending on its energy needs and generation.

This modelling computes the daily gains obtained for the whole community, but it could also calculate the benefits awarded to each member. One can imagine that all members would receive the same percentage of the gains on a daily basis since they have invested the same amount. A second part of the gains would be used to remunerate the members who have participated in load shifting. They would therefore receive the difference between their real consumption and their usual consumption per hour, multiplied by a certain factor to be determined. This approach to remunerating members would make the community more involved in the current environmental challenges. The remaining part of the benefits would be used for further development of the community.

To go even further, a new modelling could be carried out to represent the dynamics of a community where some members would individually own RE installations such as solar panels. However, this simulation would be even more complex as it would have to optimise energy exchanges between members through dynamic pricing according to individual generation and individual demand, while maximising the total welfare.

On a final note, although this thesis could have been further explored, we have learned a lot and we have been able to make a modest contribution in addressing the challenges our society is facing. ”I have learned you are never too small to make a difference.”, quoting Greta Thunberg [BBC, 2019]. Even locally, and even in small communities.

14 References

[ABB, 2012] ABB (2012). Dnp3 communication protocol manual. *Relion.*

[Akorede et al., 2010] Akorede, M. F., Hizam, H., and Pouresmaeil, E. (2010). Distributed energy resources and benefits to the environment. *Renewable and Sustainable Energy Reviews*, 14(2):724 – 734.

[Anisie and Boshell, 2020] Anisie, A. and Boshell, F. (2020). Peer-to-Peer Electricity Trading. *International Renewable Energy Agency Available at : https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/*$IRENA_{P}eer - to - peer_{t}rading_{2}020.pdf$.

[Anisie et al., 2019] Anisie, A., Ocenic, E., and Boshell, F. (2019). Market Integration of Distributed Energy Resources. *International Renewable Energy Agency Available at : https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/*$IRENA_{M}arket_{i}ntegration_{d}istributed_{s}ystem_{2}019.pdf$.

[Badouard et al., 2020] Badouard, T., Moreira de Oliveira, D., Yearwood, J., Torres, P., and Altmann, M. (2020). Energy costs, taxes and the impact of government interventions on investments. *Available at : http://trinomics.eu/wp-content/uploads/2020/11/Final-Report-Cost-of-Energy-LCOE.pdf.*

[BBC, 2019] BBC (2019). Greta thunberg quotes: 10 famous lines from teen activist. *Available at : https://www.bbc.co.uk/newsround/49812183.*

[Bickley, 2017] Bickley, J. (2017). Fostering social acceptance for wind power. *WISE Power Project Available at : http://wisepower-project.eu.*

[BloombergNEF, 2020] BloombergNEF (2020). New energy outlook 2020. *Available at : https://about.bnef.com/new-energy-outlook/?ref=WindEurope.*

[Caramizaru and Uihlein, 2020] Caramizaru, A. and Uihlein, A. (2020). Energy communities: an overview of energy and social innovation. *Publications Office of the European Union.*

[Carbontrack, 2016] Carbontrack (2016). Use more solar – or sell it back to the grid? *Available at https://carbontrack.com.au/blog/use-solar-sell-back-grid/.*

[CEDEC, 2014] CEDEC (2014). Smart Grids for Smart Markets. *Available at http://www.cedec.com/files/default/*$cedec_{s}mart_{g}rids_{p}osition_{p}aper - 2.pdf$.

[CENELEC, 2021] CENELEC, C. (2021). European standardization smart grids. *Available at : https://www.cencenelec.eu/standards/Sectorsold/SustainableEnergy/SmartGrids/Pages.*

[Chakraborty, 2018] Chakraborty, D. (2018). Smart grids: what is a smart electrical grid - electricity networks in evolution. *Smart grids: what is a smart electrical grid – electricity networks in evolution.*

[Combe, 2020] Combe, M. (2020). Quels sont les coûts de l'éolien et du solaire ? *Techniques de l'Ingénieur, Available at: https://www.techniques-ingenieur.fr/actualite/articles/quels-sont-les-couts-de-leolien-et-du-solaire-86713/.*

[Corporate Finance Institute, 2021] Corporate Finance Institute (2021). Levelized cost of energy (lcoe). *Available at : https://corporatefinanceinstitute.com/resources/knowledge/finance/levelized-cost-of-energy-lcoe/.*

[Council of European Energy Regulators, 2019a] Council of European Energy Regulators (2019a). Ceer report: About the european energy regulators. *Available at : https://www.ceer.eu/*$eer_{a}bout$.

[Council of European Energy Regulators, 2019b] Council of European Energy Regulators (2019b). Regulatory Aspects of Self-Consumption and Energy Communities CEER Report. *Customers and Retail Markets and Distribution Systems Working Groups.*

[Couture and Gagnon, 2010] Couture, T. and Gagnon, Y. (2010). An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy Policy*, 38(2):955–965.

[de Villena Millan, 2021] de Villena Millan, M. (2021). Smart regulation for distribution networks–modelling new local electricity markets and regulatory frameworks for the integration of distributed electricity generation resources. *Université de Liège,Liège, Belgique.*

[Dütschke et al., 2017] Dütschke, E., Schneider, U., and Wesche, J. (2017). Knowledge, use and effectiveness of social acceptance measures for wind projects. *Zeitschrift für Energiewirtschaft*, 41(4):299–310.

[E-ON, 2020] E-ON (2020). Live from simris. *Local Energy Systems Available at :* $https://www.eon.se/en_US/om-e-on/local-energy-systems/live-from-simris.$

[Energie.be, 2021] Energie.be (2021). Le prix de l'électricité en belgique en 2021. *Available at : https://www.comparateur-energie.be/blog/prix-electricite-belgique/wallonie.*

[Energy Democracy, 2021] Energy Democracy (2021). Principles of energy democracy. *Available at: https://energy-democracy.net/principals/.*

[Engie, 2020] Engie (2020). Engie : Wind energy. *Engie Renewable Energies Available at : https://www.engie.com/en/activities/renewable-energies/wind-energy.*

[ENTSO-E, 2021] ENTSO-E (2021). Entso-e. *Available at : https://www.entsoe.eu/data/transparency-platform/.*

[EPA, 2020] EPA (2020). Sources of greenhouse gas emissions. *Environmental Protection Agency.*

[European Commission, 2016] European Commission (2016). Clean energy package com (2016)860. *Available at: https://eur-lex.europa.eu/legalcontent/ EN/TXT/?uri=COM:2016:0860:FIN.*

[European Commission, 2019] European Commission (2019). The european green deal com(2019)640. *Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN.*

[European Parliament, 2016] European Parliament (2016). Smart appliances and the electrical system. *Available at : https://www.europarl.europa.eu/thinktank/en/document.html?reference=*$EPRS_BRI(2016)595859.$

[European Parliament and Council, 2009] European Parliament and Council (2009). Directive 2009/72/ec of the european parliament and of the council of 13 july 2009 concerning common rules for the internal market in electricity and repealing directive 2003/54/ec. *Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0072.*

[European Parliament and Council, 2012] European Parliament and Council (2012). Directive 2012/27/eu of the european parliament and of the council of 25 october 2012 on energy efficiency, amending directives 2009/125/ec and 2010/30/eu and repealing directives 2004/8/ec and 2006/32/ec. *Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012L0027.*

[European Parliament and Council, 2018] European Parliament and Council (2018). Directive (eu) 2018/2001 of the european parliament and of the council of 11 december 2018 on the promotion of the use of energy from renewable sources. *Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L2001.*

[European Parliament and Council, 2019] European Parliament and Council (2019). Regulation (eu) (2019)943 of the european parliament and of the council of 5 june 2019 on the internal market for electricity. *Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32019R0943.*

[EVWest, 2016] EVWest (2016). Samsung sdi ess energy storage battery. *Available at :* $https://evwest.com/store/product_info.php?products_id = 486.$

[Fradelle, 2017] Fradelle, B. (2017). Microgrids : une solution énergétique pérenne ? *Tactis Available at : https://www.tactis.fr/microgrids/.*

[Fraunhofer, 2015] Fraunhofer, I. (2015). Status quo of social acceptance strategies and practices in the wind industry. *Wise Power Project EU, Available at :www.wisepower-project.eu.*

[Frieden et al., 2019a] Frieden, D., d'Herbemont, S., and Roberts, J. (2019a). Energy Community Definitions. *Compile.*

[Frieden et al., 2019b] Frieden, D., Tuerk, A., d'Herbemont, S., Roberts, J., and Gubina, A. (2019b). Collective self-consumption and energy communities: Overview of emerging regulatory approaches in Europe. *Compile.*

[Fullerton, 2015] Fullerton, J. (2015). Regenerative capitalism. *Capital Institute.*

[Gancheva et al., 2018] Gancheva, M., O'Brien, S., Crook, N., and Monteiro, C. (2018). Models of Local Energy Ownership and the Role of Local Energy Communities in Energy Transition in Europe. *European Committee of the Regions.*

[Golshannavaz et al., 2014] Golshannavaz, S., Afsharnia, S., and Aminifar, F. (2014). Smart distribution grid: Optimal day-ahead scheduling with reconfigurable topology. *IEEE Transactions on Smart Grid*, 5(5):2402–2411.

[Gopstein et al., 2021] Gopstein, A., Nguyen, C., O'Fallon, C., Hastings, N., and Wollman, D. (2021). Nist framework and roadmap for smart grid interoperability standards, release 4.0. *Special Publication (NIST SP), National Institute of Standards and Technology, Gaithersburg, MD.*

[Guille et al., 2017] Guille, C., Herger, J., and Scalise, J. (2017). Harnessing the value of grid-edge technologies. *Bain Company, Available at: https://www.bain.com/insights/harnessing-the-value-of-grid-edge-technologies.*

[IEEP, 2021] IEEP (2021). Climate change energy. *Available at : https://ieep.eu/work-areas/climate-change-and-energy.*

[Interflex, 2019] Interflex (2019). Sweden - simris. *Available at : https://interflex-h2020.com/interflex/project-demonstrators/sweden-simris.*

[Kathan et al., 2007] Kathan, D., Godding, G., Irwin, R., Martinez, C., McOmber, N., Roder, A., Thomas, K., and Brotman, C. (2007). Assessment of demand response and advanced metering. *Federal Energy Regulatory Commission.*

[Komusanac et al., 2021] Komusanac, I., Brindley, G., Fraile, D., and Ramirez, L. (2021). Wind energy in europe: 2020 statistics and the outlook for 2021-2025. *WindEurope.*

[Lopes et al., 2007] Lopes, J. P., Hatziargyriou, N., Mutale, J., Djapic, P., and Jenkins, N. (2007). Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. *Electric power systems research*, 77(9):1189–1203.

[Ministry of Power, 2013] Ministry of Power (2013). National smart grid mission. *Ministry of Power, Government of India, Available at https://www.nsgm.gov.in/en/content/smart-grid.*

[Mrabet et al., 2018] Mrabet, Z. E., Kaabouch, N., Ghazi, H. E., and Ghazi, H. E. (2018). Cyber-security in smart grid: Survey and challenges. *Computers Electrical Engineering*, 67:469 – 482.

[Musall and Kuik, 2011] Musall, F. D. and Kuik, O. (2011). Local acceptance of renewable energy—A case study from southeast Germany. *Energy policy.*

[Ngoc, 2014] Ngoc, L. (2014). Control and management strategies for a microgrid. *Université de Grenoble.*

[Pimm et al., 2018] Pimm, A., Cockerill, T., and Taylor, P. (2018). The potential for peak shaving on low voltage distribution networks using electricity storage. *Journal of Energy Storage*, 16:231–242.

[Polymeneas et al., 2020] Polymeneas, E., Rubin, A., and Tai, H. (2020). Modernizing the investment approach for electric grids. *McKinsey Company Availble at : https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/modernizing-the-investment-approach-for-electric-grids.*

[Rescoop, 2021] Rescoop (2021). Ecopower. *Available at: https://www.rescoop-mecise.eu/aboutmecise/ecopower.*

[Safa et al., 2016] Safa, H. H., Souran, D. M., Ghasempour, M., and Khazaee, A. (2016). Cyber security of smart grid and scada systems, threats and risks. pages 1–4.

[Salgado et al., 2020] Salgado, A., Anisie, A., and Boshell, F. (2020). Community-Ownership Models. *International Renewable Energy Agency.*

[Sawyer, 2020] Sawyer, L. (2020). Smart Energy Prosumers. *Smart Energy Europe.*

[Schmela, 2020] Schmela, M. (2020). Eu market outlook for solar power 2020-2024. *Available at: https://www.solarpowereurope.org/european-market-outlook-for-solar-power-2020-2024/.*

[SGTF, 2015] SGTF (2015). Regulatory recommendations for the deployment of flexibility. *EU Smart Grid Task Force-EG3 Report.*

[Sibelga, 2020] Sibelga (2020). Réseaux d'énérgie: Qu'est-ce qu'un microgrid ou micro-réseau ? *Sibelga.*

[Statista Research Department, 2021] Statista Research Department (2021). Energy transition: acceptance of higher electricity prices in france 2017. *Available at: https://www.statista.com/statistics/769125/acceptance-french-rise-bill-electricity-for-energies-renewable/.*

[Stephens, 2019] Stephens, J. (2019). Energy Democracy: Redistributing Power to the People Through Renewable Transformation. *Environment: Science and Policy for Sustainable Development.*

[Systems, 2020] Systems, P. (2020). Lithium-ion battery charging advantages. *PowerTech Systems - PowerTech Systems.*

[Thomson et al., 2013] Thomson, J., Tobias, M., Denny, B., and Cunningham, K. (2013). Getting Smart Grid customers plugged in Motivating change through mobile and social technology. *Deloitte Center for Energy Solutions Available at : https://www2.deloitte.com/be/en/pages/energy-and-resources/articles/getting-smart-grid-customers.html.*

[United Nations, 2015] United Nations (2015). Paris agreement. *United Nations Treaty Collection, Chapter XXVII 7. d Available at : https://treaties.un.org/.*

[United Nations, 2020] United Nations (2020). 17 SDG goals. *Available at: https://sdgs.un.org/goals.*

[van den Oosterkamp and Koutstaal, 2014] van den Oosterkamp, P. and Koutstaal, P. (2014). The role of dsos in a smart grid environment. *European Commission.*

[Van Der Schoor et al., 2016] Van Der Schoor, T., Van Lente, H., and Scholtens, B. (2016). Challenging obduracy: How local communities transform the energy system. *Energy Research and Social Science.*

[Vansintjan, 2016] Vansintjan, D. (2016). Potential for citizen-produced electricity in the EU. *European Renewable Energies Federation Available at : https://www.greenpeace.org/static/planet4-eu-unit-stateless/2018/08/ea9146d5-ea9146d5-160926-potential-of-energy-citizens-media-briefing.pdf.*

[Vansintjan, 2019] Vansintjan, D. (2019). Mobilising European Citizens to Invest in Sustainable Energy. *Rescoop Mecise, Available at : https://www.rescoop.eu/toolbox/mobilising-european-citizens-to-invest-in-sustainable-energy.*

[Vikas et al., 2019] Vikas, L., Nikola, S., and Bruno, R. (2019). Recommendations for smart grid security risk management. *Cyber-Physical Systems.*

[Walker, 2008] Walker, G. (2008). Community renewable energy: What should it mean? *Energy Policy.*

[Wang et al., 2011] Wang, W., Xu, Y., and Khanna, M. (2011). A survey on the communication architectures in smart grid. *Computer Networks*, 55(15):3604 – 3629.

[Weaver, 2008] Weaver, P. (2008). The meaning of risk in an uncertain world. *Project Management Institute.*

[Wood, 2020] Wood, E. (2020). Microgrid defined: Three key features that make a microgrid a microgrid. *Microgrid Knowledge Available at https://microgridknowledge.com/microgrid-defined/.*

[Yildiz et al., 2015] Yildiz, O., Rommel, J., Debor, S., Holstenkamp, L., Mey, F., Muller, J., Radtke, J., and Rognli, J. (2015). Renewable energy cooperatives as gatekeepers or facilitators? Recent developments in Germany and a multidisciplinary research agenda. *Energy Research and Social Science.*

15 Appendix

15.1 Predictable Wind Generation

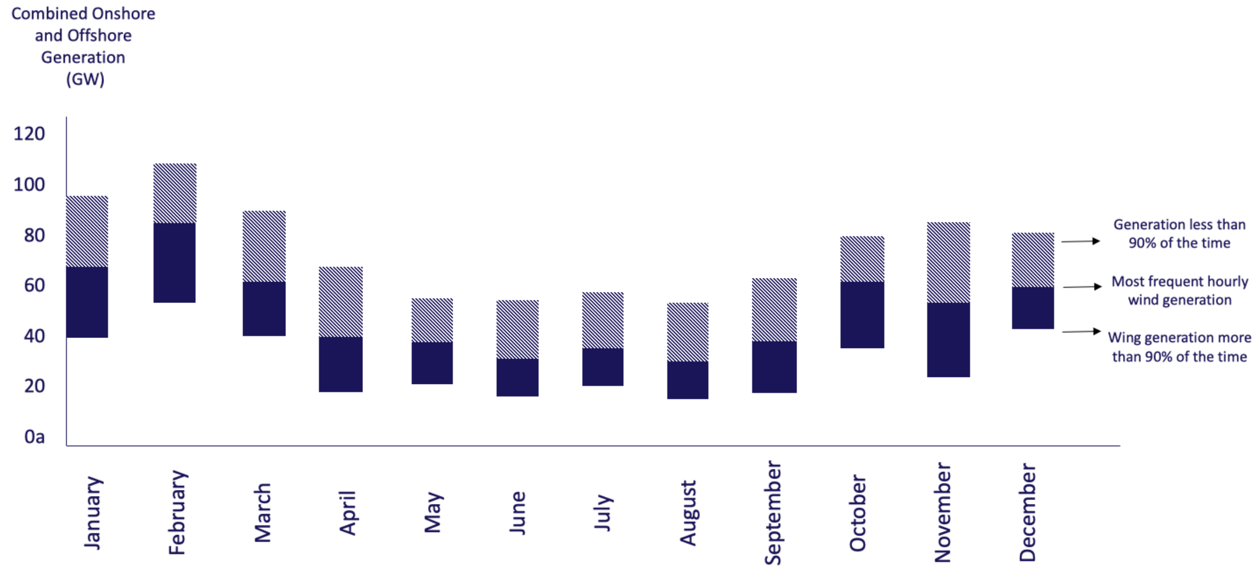


Figure 10: Spread of hourly wind energy generation in Europe [Komusanac et al., 2021]

15.2 LCOE for Renewable Energy Sources

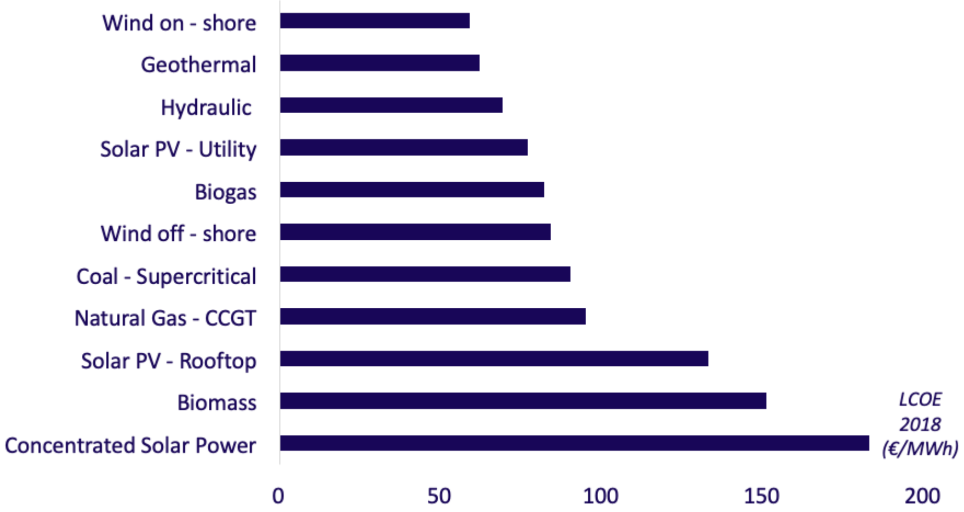


Figure 11: LCOE for energy sources types in 2018 [Badouard et al., 2020]

15.3 Tactical Model Parameters

Hours	Dlt (KWh)	Wt (KWh)	St (KWh)	PMt (€/KWh)	PXt (€/KWh)
1	0,20	68,80	0,00	0,2654	0,06
2	0,15	67,60	0,00	0,2654	0,06
3	0,15	63,00	0,00	0,2654	0,06
4	0,15	62,00	0,00	0,2654	0,06
5	0,17	61,20	0,00	0,2654	0,06
6	0,20	60,70	0,10	0,2654	0,06
7	0,42	65,40	2,50	0,2654	0,06
8	0,56	66,50	13,10	0,2842	0,06
9	0,53	67,30	38,00	0,2842	0,06
10	0,52	64,00	71,30	0,2842	0,06
11	0,46	61,00	106,60	0,2842	0,06
12	0,48	63,30	136,10	0,2842	0,06
13	0,48	68,00	157,80	0,2842	0,06
14	0,43	71,20	167,70	0,2842	0,06
15	0,45	76,50	158,50	0,2842	0,06
16	0,53	77,40	141,60	0,2842	0,06
17	0,62	81,70	117,30	0,2842	0,06
18	0,71	85,00	87,40	0,2842	0,06
19	0,74	87,70	57,60	0,2842	0,06
20	0,75	88,90	28,30	0,2842	0,06
21	0,79	86,20	8,50	0,2842	0,06
22	0,74	88,40	1,20	0,2842	0,06
23	0,46	89,10	0,00	0,2654	0,06
24	0,30	88,60	0,00	0,2654	0,06

Members L	Vl
1 - 162	0,2702
163 - 246	0,2972
247 - 270	0,3378
271 - 280	0,4053

Efficiency η	Value
η EB	100%
η OB	100%
η IB	80%

Storage Limits	Value
EB	331,00
OB	331,00
IB	166,50

Figure 12: Tactical model parameters table [By the Author]

15.4 Household Expected Demand

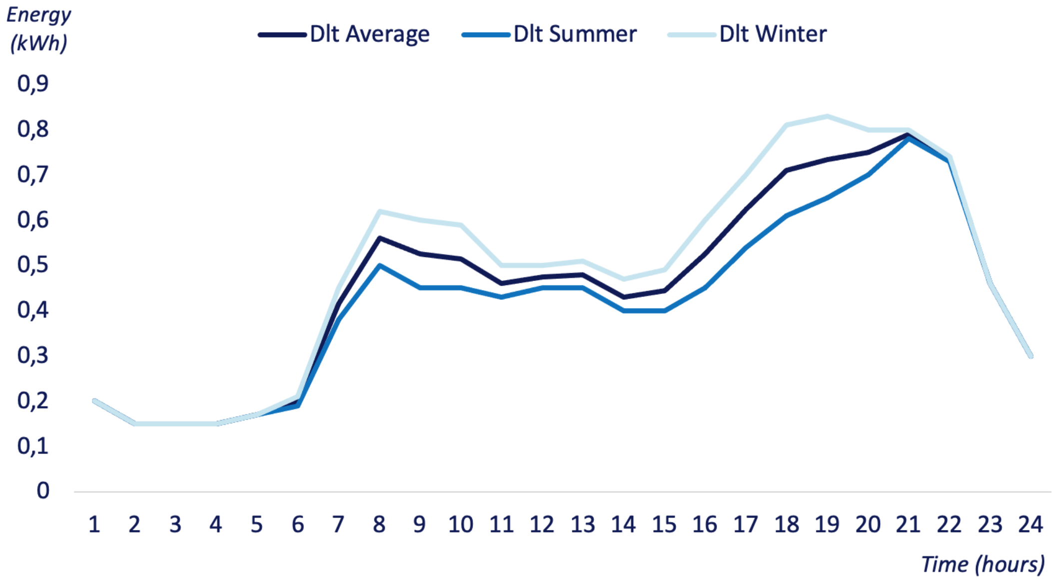
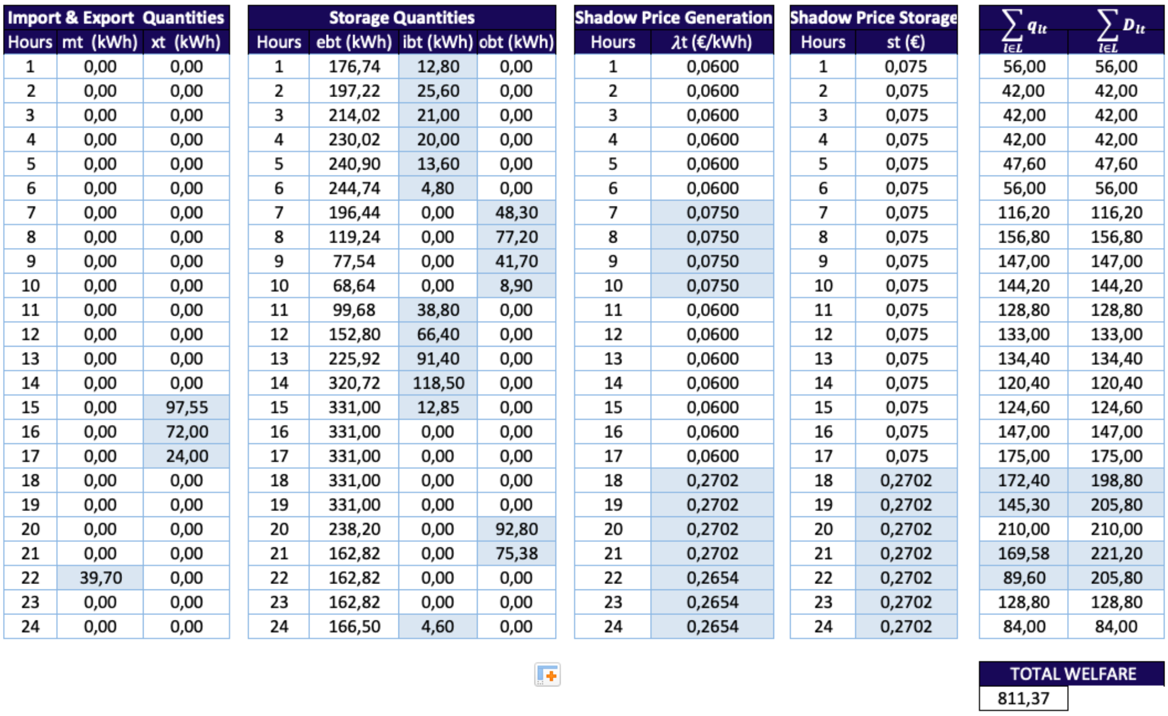


Figure 13: Household non-essential demand for 1 day [Pimm et al., 2018]

15.5 Tactical Model Results



Import & Export	Quantities	
Hours	mt (kWh)	xt (kWh)
1	0,00	0,00
2	0,00	0,00
3	0,00	0,00
4	0,00	0,00
5	0,00	0,00
6	0,00	0,00
7	0,00	0,00
8	0,00	0,00
9	0,00	0,00
10	0,00	0,00
11	0,00	0,00
12	0,00	0,00
13	0,00	0,00
14	0,00	0,00
15	0,00	97,55
16	0,00	72,00
17	0,00	24,00
18	0,00	0,00
19	0,00	0,00
20	0,00	0,00
21	0,00	0,00
22	39,70	0,00
23	0,00	0,00
24	0,00	0,00

Storage Quantities			
Hours	ebt (kWh)	ibt (kWh)	obt (kWh)
1	176,74	12,80	0,00
2	197,22	25,60	0,00
3	214,02	21,00	0,00
4	230,02	20,00	0,00
5	240,90	13,60	0,00
6	244,74	4,80	0,00
7	196,44	0,00	48,30
8	119,24	0,00	77,20
9	77,54	0,00	41,70
10	68,64	0,00	8,90
11	99,68	38,80	0,00
12	152,80	66,40	0,00
13	225,92	91,40	0,00
14	320,72	118,50	0,00
15	331,00	12,85	0,00
16	331,00	0,00	0,00
17	331,00	0,00	0,00
18	331,00	0,00	0,00
19	331,00	0,00	0,00
20	238,20	0,00	92,80
21	162,82	0,00	75,38
22	162,82	0,00	0,00
23	162,82	0,00	0,00
24	166,50	4,60	0,00

Shadow Price Generation	
Hours	λt (€/kWh)
1	0,0600
2	0,0600
3	0,0600
4	0,0600
5	0,0600
6	0,0600
7	0,0750
8	0,0750
9	0,0750
10	0,0750
11	0,0600
12	0,0600
13	0,0600
14	0,0600
15	0,0600
16	0,0600
17	0,0600
18	0,2702
19	0,2702
20	0,2702
21	0,2702
22	0,2654
23	0,2654
24	0,2654

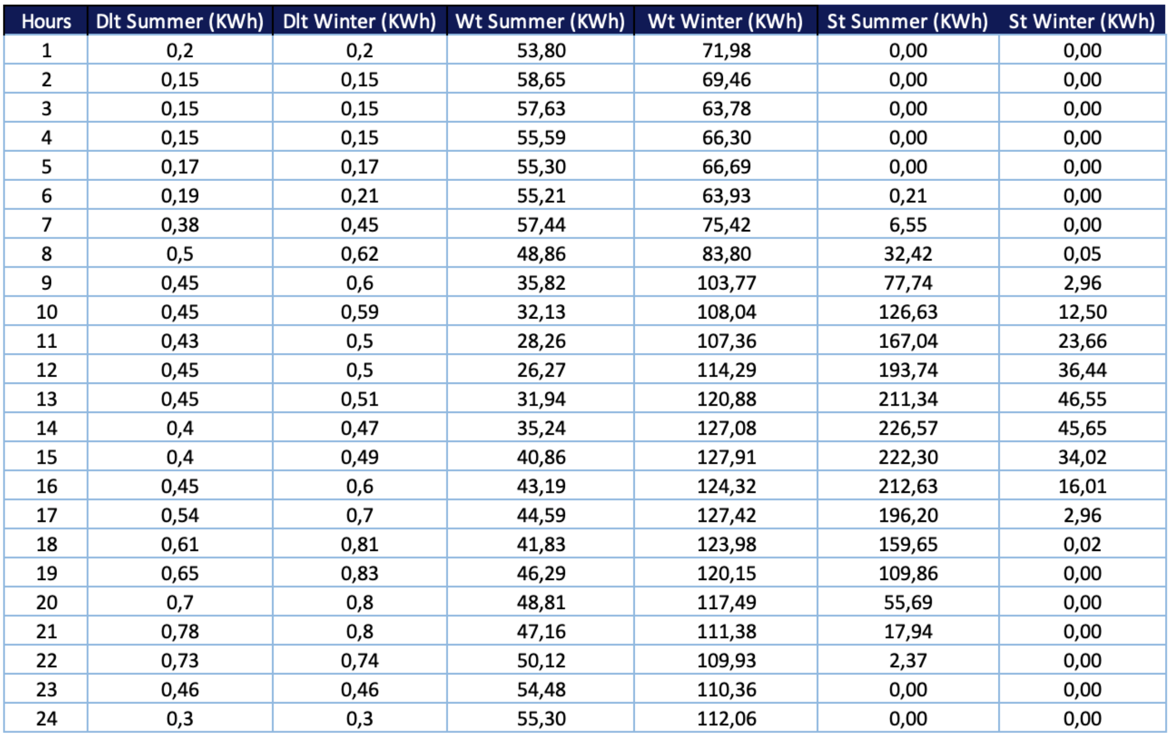
Shadow Price Storage	
Hours	st (€)
1	0,075
2	0,075
3	0,075
4	0,075
5	0,075
6	0,075
7	0,075
8	0,075
9	0,075
10	0,075
11	0,075
12	0,075
13	0,075
14	0,075
15	0,075
16	0,075
17	0,075
18	0,2702
19	0,2702
20	0,2702
21	0,2702
22	0,2702
23	0,2702
24	0,2702

$\sum_{l\in L} q_{lt}$	$\sum_{l\in L} D_{lt}$
56,00	56,00
42,00	42,00
42,00	42,00
42,00	42,00
47,60	47,60
56,00	56,00
116,20	116,20
156,80	156,80
147,00	147,00
144,20	144,20
128,80	128,80
133,00	133,00
134,40	134,40
120,40	120,40
124,60	124,60
147,00	147,00
175,00	175,00
172,40	198,80
145,30	205,80
210,00	210,00
169,58	221,20
89,60	205,80
128,80	128,80
84,00	84,00

TOTAL WELFARE
811,37

Figure 14: Quantitative results table for the tactical model [By the Author]

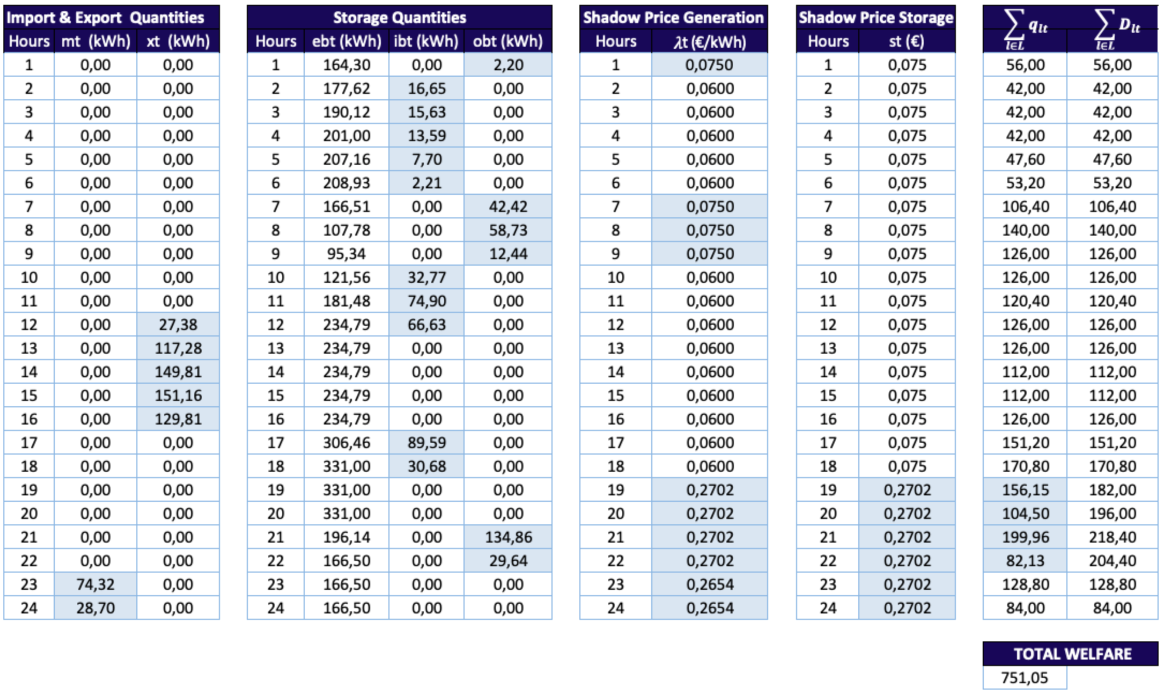
15.6 Tactical Model Sensitivity Analysis Parameters



Hours	Dlt Summer (KWh)	Dlt Winter (KWh)	Wt Summer (KWh)	Wt Winter (KWh)	St Summer (KWh)	St Winter (KWh)
1	0,2	0,2	53,80	71,98	0,00	0,00
2	0,15	0,15	58,65	69,46	0,00	0,00
3	0,15	0,15	57,63	63,78	0,00	0,00
4	0,15	0,15	55,59	66,30	0,00	0,00
5	0,17	0,17	55,30	66,69	0,00	0,00
6	0,19	0,21	55,21	63,93	0,21	0,00
7	0,38	0,45	57,44	75,42	6,55	0,00
8	0,5	0,62	48,86	83,80	32,42	0,05
9	0,45	0,6	35,82	103,77	77,74	2,96
10	0,45	0,59	32,13	108,04	126,63	12,50
11	0,43	0,5	28,26	107,36	167,04	23,66
12	0,45	0,5	26,27	114,29	193,74	36,44
13	0,45	0,51	31,94	120,88	211,34	46,55
14	0,4	0,47	35,24	127,08	226,57	45,65
15	0,4	0,49	40,86	127,91	222,30	34,02
16	0,45	0,6	43,19	124,32	212,63	16,01
17	0,54	0,7	44,59	127,42	196,20	2,96
18	0,61	0,81	41,83	123,98	159,65	0,02
19	0,65	0,83	46,29	120,15	109,86	0,00
20	0,7	0,8	48,81	117,49	55,69	0,00
21	0,78	0,8	47,16	111,38	17,94	0,00
22	0,73	0,74	50,12	109,93	2,37	0,00
23	0,46	0,46	54,48	110,36	0,00	0,00
24	0,3	0,3	55,30	112,06	0,00	0,00

Figure 15: Changing parameters for summer and winter sensitivity analysis [By the Author]

15.7 Tactical Model Results Summer



Import & Export Quantities		
Hours	mt (kWh)	xt (kWh)
1	0,00	0,00
2	0,00	0,00
3	0,00	0,00
4	0,00	0,00
5	0,00	0,00
6	0,00	0,00
7	0,00	0,00
8	0,00	0,00
9	0,00	0,00
10	0,00	0,00
11	0,00	0,00
12	0,00	27,38
13	0,00	117,28
14	0,00	149,81
15	0,00	151,16
16	0,00	129,81
17	0,00	0,00
18	0,00	0,00
19	0,00	0,00
20	0,00	0,00
21	0,00	0,00
22	0,00	0,00
23	74,32	0,00
24	28,70	0,00

Storage Quantities			
Hours	ebt (kWh)	ibt (kWh)	obt (kWh)
1	164,30	0,00	2,20
2	177,62	16,65	0,00
3	190,12	15,63	0,00
4	201,00	13,59	0,00
5	207,16	7,70	0,00
6	208,93	2,21	0,00
7	166,51	0,00	42,42
8	107,78	0,00	58,73
9	95,34	0,00	12,44
10	121,56	32,77	0,00
11	181,48	74,90	0,00
12	234,79	66,63	0,00
13	234,79	0,00	0,00
14	234,79	0,00	0,00
15	234,79	0,00	0,00
16	234,79	0,00	0,00
17	306,46	89,59	0,00
18	331,00	30,68	0,00
19	331,00	0,00	0,00
20	331,00	0,00	0,00
21	196,14	0,00	134,86
22	166,50	0,00	29,64
23	166,50	0,00	0,00
24	166,50	0,00	0,00

Shadow Price Generation	
Hours	λt (€/kWh)
1	0,0750
2	0,0600
3	0,0600
4	0,0600
5	0,0600
6	0,0600
7	0,0750
8	0,0750
9	0,0750
10	0,0600
11	0,0600
12	0,0600
13	0,0600
14	0,0600
15	0,0600
16	0,0600
17	0,0600
18	0,0600
19	0,2702
20	0,2702
21	0,2702
22	0,2702
23	0,2654
24	0,2654

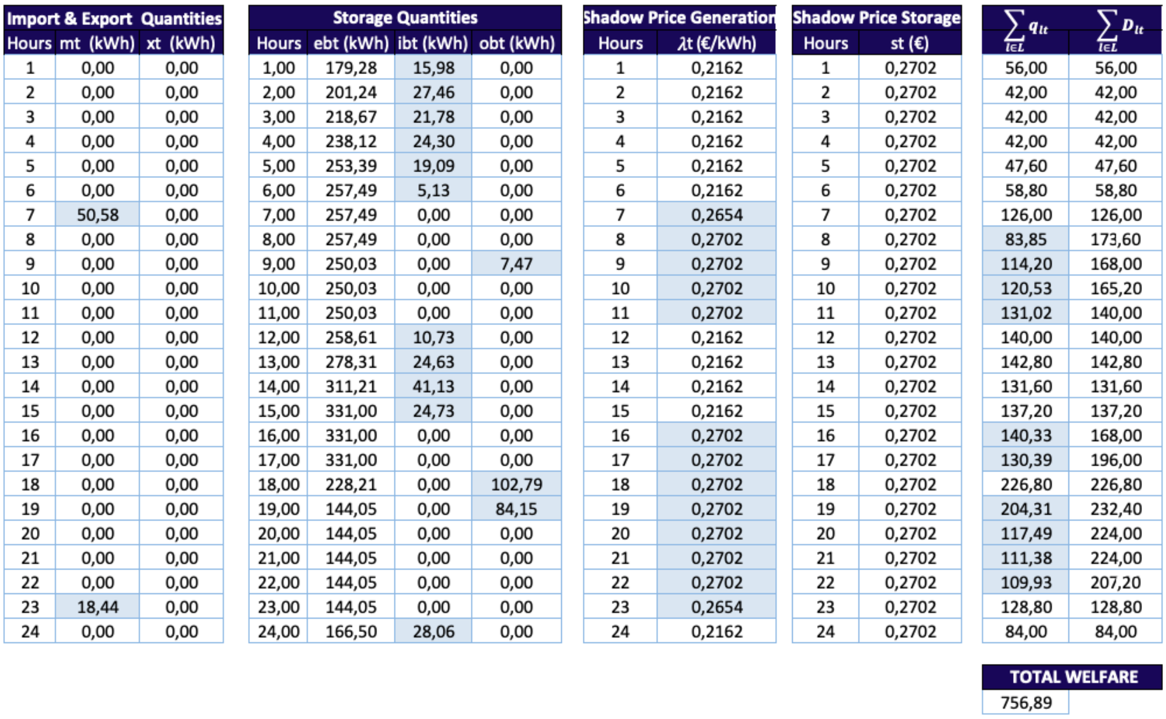
Shadow Price Storage	
Hours	st (€)
1	0,075
2	0,075
3	0,075
4	0,075
5	0,075
6	0,075
7	0,075
8	0,075
9	0,075
10	0,075
11	0,075
12	0,075
13	0,075
14	0,075
15	0,075
16	0,075
17	0,075
18	0,075
19	0,2702
20	0,2702
21	0,2702
22	0,2702
23	0,2702
24	0,2702

$\sum_{l \in L} q_{lt}$	$\sum_{l \in L} D_{lt}$
56,00	56,00
42,00	42,00
42,00	42,00
42,00	42,00
47,60	47,60
53,20	53,20
106,40	106,40
140,00	140,00
126,00	126,00
126,00	126,00
120,40	120,40
126,00	126,00
126,00	126,00
112,00	112,00
112,00	112,00
126,00	126,00
151,20	151,20
170,80	170,80
156,15	182,00
104,50	196,00
199,96	218,40
82,13	204,40
128,80	128,80
84,00	84,00

TOTAL WELFARE
751,05

Figure 16: Quantitative results table for the summer sensitivity analysis [By the Author]

15.8 Tactical Model Results Winter



Import & Export Quantities		
Hours	mt (kWh)	xt (kWh)
1	0,00	0,00
2	0,00	0,00
3	0,00	0,00
4	0,00	0,00
5	0,00	0,00
6	0,00	0,00
7	50,58	0,00
8	0,00	0,00
9	0,00	0,00
10	0,00	0,00
11	0,00	0,00
12	0,00	0,00
13	0,00	0,00
14	0,00	0,00
15	0,00	0,00
16	0,00	0,00
17	0,00	0,00
18	0,00	0,00
19	0,00	0,00
20	0,00	0,00
21	0,00	0,00
22	0,00	0,00
23	18,44	0,00
24	0,00	0,00

Storage Quantities			
Hours	ebt (kWh)	ibt (kWh)	obt (kWh)
1,00	179,28	15,98	0,00
2,00	201,24	27,46	0,00
3,00	218,67	21,78	0,00
4,00	238,12	24,30	0,00
5,00	253,39	19,09	0,00
6,00	257,49	5,13	0,00
7,00	257,49	0,00	0,00
8,00	257,49	0,00	0,00
9,00	250,03	0,00	7,47
10,00	250,03	0,00	0,00
11,00	250,03	0,00	0,00
12,00	258,61	10,73	0,00
13,00	278,31	24,63	0,00
14,00	311,21	41,13	0,00
15,00	331,00	24,73	0,00
16,00	331,00	0,00	0,00
17,00	331,00	0,00	0,00
18,00	228,21	0,00	102,79
19,00	144,05	0,00	84,15
20,00	144,05	0,00	0,00
21,00	144,05	0,00	0,00
22,00	144,05	0,00	0,00
23,00	144,05	0,00	0,00
24,00	166,50	28,06	0,00

Shadow Price Generation	
Hours	λt (€/kWh)
1	0,2162
2	0,2162
3	0,2162
4	0,2162
5	0,2162
6	0,2162
7	0,2654
8	0,2702
9	0,2702
10	0,2702
11	0,2702
12	0,2162
13	0,2162
14	0,2162
15	0,2162
16	0,2702
17	0,2702
18	0,2702
19	0,2702
20	0,2702
21	0,2702
22	0,2702
23	0,2654
24	0,2162

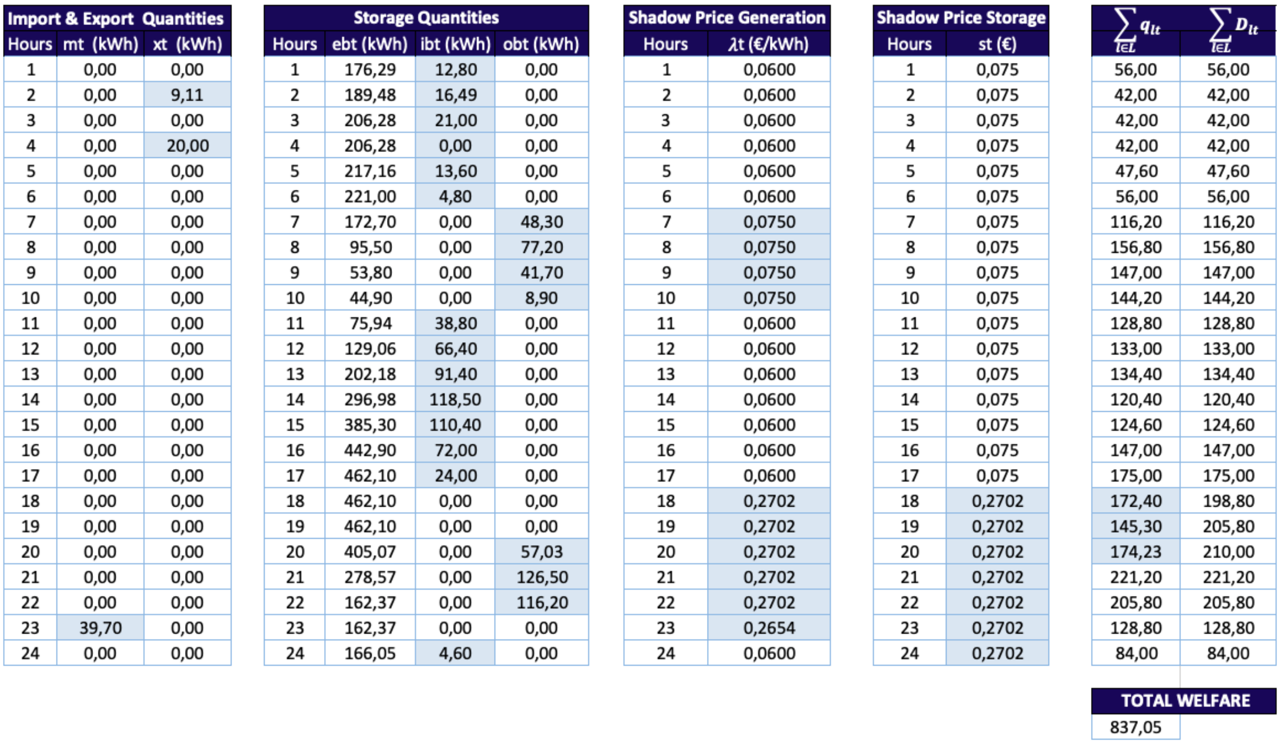
Shadow Price Storage	
Hours	st (€)
1	0,2702
2	0,2702
3	0,2702
4	0,2702
5	0,2702
6	0,2702
7	0,2702
8	0,2702
9	0,2702
10	0,2702
11	0,2702
12	0,2702
13	0,2702
14	0,2702
15	0,2702
16	0,2702
17	0,2702
18	0,2702
19	0,2702
20	0,2702
21	0,2702
22	0,2702
23	0,2702
24	0,2702

$\sum_{l \in L} q_{lt}$	$\sum_{l \in L} D_{lt}$
56,00	56,00
42,00	42,00
42,00	42,00
42,00	42,00
47,60	47,60
58,80	58,80
126,00	126,00
83,85	173,60
114,20	168,00
120,53	165,20
131,02	140,00
140,00	140,00
142,80	142,80
131,60	131,60
137,20	137,20
140,33	168,00
130,39	196,00
226,80	226,80
204,31	232,40
117,49	224,00
111,38	224,00
109,93	207,20
128,80	128,80
84,00	84,00

TOTAL WELFARE
756,89

Figure 17: Quantitative results table for the winter sensitivity analysis [By the Author]

15.9 Strategical Model Results for Storage



Import & Export Quantities		
Hours	mt (kWh)	xt (kWh)
1	0,00	0,00
2	0,00	9,11
3	0,00	0,00
4	0,00	20,00
5	0,00	0,00
6	0,00	0,00
7	0,00	0,00
8	0,00	0,00
9	0,00	0,00
10	0,00	0,00
11	0,00	0,00
12	0,00	0,00
13	0,00	0,00
14	0,00	0,00
15	0,00	0,00
16	0,00	0,00
17	0,00	0,00
18	0,00	0,00
19	0,00	0,00
20	0,00	0,00
21	0,00	0,00
22	0,00	0,00
23	39,70	0,00
24	0,00	0,00

Storage Quantities			
Hours	ebt (kWh)	ibt (kWh)	obt (kWh)
1	176,29	12,80	0,00
2	189,48	16,49	0,00
3	206,28	21,00	0,00
4	206,28	0,00	0,00
5	217,16	13,60	0,00
6	221,00	4,80	0,00
7	172,70	0,00	48,30
8	95,50	0,00	77,20
9	53,80	0,00	41,70
10	44,90	0,00	8,90
11	75,94	38,80	0,00
12	129,06	66,40	0,00
13	202,18	91,40	0,00
14	296,98	118,50	0,00
15	385,30	110,40	0,00
16	442,90	72,00	0,00
17	462,10	24,00	0,00
18	462,10	0,00	0,00
19	462,10	0,00	0,00
20	405,07	0,00	57,03
21	278,57	0,00	126,50
22	162,37	0,00	116,20
23	162,37	0,00	0,00
24	166,05	4,60	0,00

Shadow Price Generation	
Hours	λt (€/kWh)
1	0,0600
2	0,0600
3	0,0600
4	0,0600
5	0,0600
6	0,0600
7	0,0750
8	0,0750
9	0,0750
10	0,0750
11	0,0600
12	0,0600
13	0,0600
14	0,0600
15	0,0600
16	0,0600
17	0,0600
18	0,2702
19	0,2702
20	0,2702
21	0,2702
22	0,2702
23	0,2654
24	0,0600

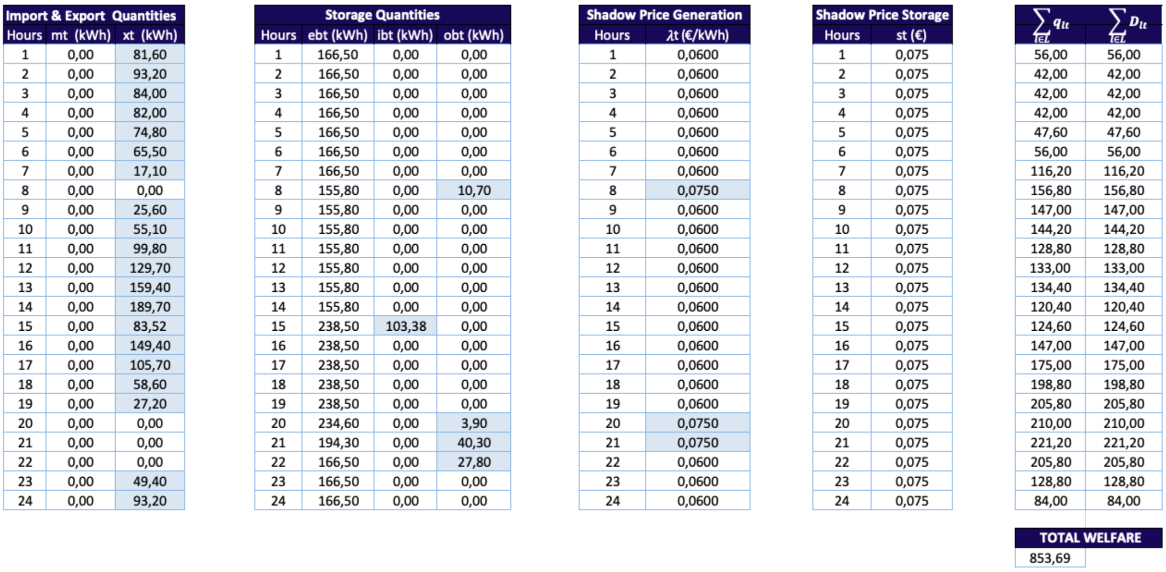
Shadow Price Storage	
Hours	st (€)
1	0,075
2	0,075
3	0,075
4	0,075
5	0,075
6	0,075
7	0,075
8	0,075
9	0,075
10	0,075
11	0,075
12	0,075
13	0,075
14	0,075
15	0,075
16	0,075
17	0,075
18	0,2702
19	0,2702
20	0,2702
21	0,2702
22	0,2702
23	0,2702
24	0,2702

$\sum_{l \in L} q_{lt}$	$\sum_{l \in L} D_{lt}$
56,00	56,00
42,00	42,00
42,00	42,00
42,00	42,00
47,60	47,60
56,00	56,00
116,20	116,20
156,80	156,80
147,00	147,00
144,20	144,20
128,80	128,80
133,00	133,00
134,40	134,40
120,40	120,40
124,60	124,60
147,00	147,00
175,00	175,00
172,40	198,80
145,30	205,80
174,23	210,00
221,20	221,20
205,80	205,80
128,80	128,80
84,00	84,00

TOTAL WELFARE
837,05

Figure 18: Quantitative results table for the storage capacity expansion [By the Author]

15.10 Strategical Model Results for Wind Turbine



Import & Export Quantities		
Hours	mt (kWh)	xt (kWh)
1	0,00	81,60
2	0,00	93,20
3	0,00	84,00
4	0,00	82,00
5	0,00	74,80
6	0,00	65,50
7	0,00	17,10
8	0,00	0,00
9	0,00	25,60
10	0,00	55,10
11	0,00	99,80
12	0,00	129,70
13	0,00	159,40
14	0,00	189,70
15	0,00	83,52
16	0,00	149,40
17	0,00	105,70
18	0,00	58,60
19	0,00	27,20
20	0,00	0,00
21	0,00	0,00
22	0,00	0,00
23	0,00	49,40
24	0,00	93,20

Storage Quantities			
Hours	ebt (kWh)	ibt (kWh)	obt (kWh)
1	166,50	0,00	0,00
2	166,50	0,00	0,00
3	166,50	0,00	0,00
4	166,50	0,00	0,00
5	166,50	0,00	0,00
6	166,50	0,00	0,00
7	166,50	0,00	0,00
8	155,80	0,00	10,70
9	155,80	0,00	0,00
10	155,80	0,00	0,00
11	155,80	0,00	0,00
12	155,80	0,00	0,00
13	155,80	0,00	0,00
14	155,80	0,00	0,00
15	238,50	103,38	0,00
16	238,50	0,00	0,00
17	238,50	0,00	0,00
18	238,50	0,00	0,00
19	238,50	0,00	0,00
20	234,60	0,00	3,90
21	194,30	0,00	40,30
22	166,50	0,00	27,80
23	166,50	0,00	0,00
24	166,50	0,00	0,00

Shadow Price Generation	
Hours	λt (€/kWh)
1	0,0600
2	0,0600
3	0,0600
4	0,0600
5	0,0600
6	0,0600
7	0,0600
8	0,0750
9	0,0600
10	0,0600
11	0,0600
12	0,0600
13	0,0600
14	0,0600
15	0,0600
16	0,0600
17	0,0600
18	0,0600
19	0,0600
20	0,0750
21	0,0750
22	0,0600
23	0,0600
24	0,0600

Shadow Price Storage	
Hours	st (€)
1	0,075
2	0,075
3	0,075
4	0,075
5	0,075
6	0,075
7	0,075
8	0,075
9	0,075
10	0,075
11	0,075
12	0,075
13	0,075
14	0,075
15	0,075
16	0,075
17	0,075
18	0,075
19	0,075
20	0,075
21	0,075
22	0,075
23	0,075
24	0,075

$\sum_{l \in L} q_{lt}$	$\sum_{l \in L} D_{lt}$
56,00	56,00
42,00	42,00
42,00	42,00
42,00	42,00
47,60	47,60
56,00	56,00
116,20	116,20
156,80	156,80
147,00	147,00
144,20	144,20
128,80	128,80
133,00	133,00
134,40	134,40
120,40	120,40
124,60	124,60
147,00	147,00
175,00	175,00
198,80	198,80
205,80	205,80
210,00	210,00
221,20	221,20
205,80	205,80
128,80	128,80
84,00	84,00

TOTAL WELFARE
853,69

Figure 19: Quantitative results table for the wind turbine expansion [By the Author]

LOUVAIN-LA-NEUVE | BRUXELLES | MONS | TOURNAI | CHARLEROI | NAMUR
Place des Doyens, 1 bte L2.01.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/lsm**