Energy transition at mixed business parks

A case study and guideline for consultants, government officials and entrepreneurs

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Preface

My academic education started in September 2015, when I enrolled in the bachelor Aerospace Engineering. Over the course of six years, I completed the bachelor program, while combining my studies with speedskating on professional level. As such, I am a registered TU Delft Elite Sports Athlete, which helps me finding the optimal balance between sports and studies.

In the Aerospace bachelor, I realised that minor improvements in engine efficiencies and aerodynamics where not enough to stop global warming. Therefore, I bridged to the master Sustainable Energy Technology in February 2021. By September 2022, I finished all the regular courses in the Cluster Wind & Economic. I started a company internship at Antea Group in the Energy Transition Advisory Group under the supervision of Joris Knigge. In this group, I got to know many professionals all dealing with various questions and challenges in the energy transition. During the last months of my internship, I got to work on a project where the municipality of Heerenveen asked Antea Group to perform a pilot at the mixed business park Heerenveen-Zuid. The business area is suffering from grid congestion for the delivery of electricity, meaning that existing companies cannot increase their capacity and that new companies cannot establish themselves at the park because the distribution service operator Liander is not able to connect the companies to the grid. Liander does not want to apply congestion management and therefore, the municipality approached Antea Group. I assisted Søren Winkel, Keje Spijkerman and Dieuwke Martens-Bakker in the first steps of the pilot.

In the last month of my internship, January 2023, the idea grew that probably many more mixed business parks were facing the same problems and that the approach applicable to Heerenveen-Zuid, might also work for others. However, this idea proved too big to work out in my internship, and Antea offered me to delve into this for my graduation project.

With the guidance of Michiel Fremouw and Jaco Quist, the link with industrial ecology and energy symbiosis was made. Because industrial ecology often focuses on large industrial clusters, the framework must be adapted to a mixed business park, where small to medium enterprises often form the majority of businesses. Early signals suggested that a shared approach, rather than every business for themselves, yielded more benefits in terms of economics and sustainability. Energy symbiosis provided a framework that makes the evaluation of the shared energy use possible on mixed business parks.

This thesis report is the final deliverable for the master graduation program of the Msc. Sustainable Energy Technology at the TU Delft. In this report I describe the problem, analyse relevant literature, formulate a methodology, generate and analyse the results and provide conclusion and recommendations for the improvement of energy management at mixed business parks.

I would like to thank my supervisors from both the TU Delft and Antea Group for their guidance and support. In particular, I would like to extend my gratitude to Joris Knigge, for sharing his experience and his enthusiasm for the energy transition.

Jeroen Janissen, 2024

Executive summary

Climate change, driven by greenhouse gas emissions (GHGs) like CO_2, threatens our lifestyle. The Netherlands committed to the Paris Climate Agreement in 2015, urging global GHG reduction to limit global warming. The European Union (EU) Fit for 55 sets Dutch targets of 55% emission mitigation by 2030 and 95% by 2050. Meeting this demands extensive integration of renewable energy sources, mainly solar photo voltaic (PV) and wind, and electrifying industrial processes. This pushes the electricity grid to its physical limits: due to high demand and supply peaks of electricity, transmission lines or other components in the grid can become overloaded. Consequently, the operators of the high-voltage transmission grid and the medium and low-voltage grid (DSOs) are not able to connect new clients to the grid or expand the connection of current clients. This is called transport or grid congestion.

Grid congestion obstructs new connections and expansion, especially in mixed business parks in NL, hindering electrification of production, adoption of EVs, and renewable projects. Updating energy infrastructure is costly and slow, leading to long waiting lists. Alternative solutions like improving energy management within parks through energy symbiosis are crucial. The main research question for this thesis is:

"How can renewable energy configurations be designed for and implemented on mixed business parks, to increase the use of renewable electricity and reduce grid congestion?"

The energy management consists of production, storage, distribution and demand management of energy. In this thesis, different configurations of RES, storage and demand flexibility have been tested on a case study in Heerenveen. For all configurations that deploy solar PV, both the South and the East/West orientations have been evaluated.

Firstly, a 4-step approach to engaging stakeholders is outlined, which forms the structure of the thesis, facilitating a complete walkthrough of the process. Secondly, a newly developed tool combining Excel, Python and EnergyPLAN is introduced to simulate various configurations due to the inadequacy of existing tools in studying grid congestion.

The configurations have been evaluated on 9 different criteria. These criteria measure the performance of each configuration in terms of economics, technology, social and environment. Comparison with the baseline scenario, in which no action is taken, has resulted in the following conclusions. A configuration with 6 MWp rooftop solar PV in East/West orientation and 15% demand flexibility yields the highest score. This configuration outperforms the other configurations in terms of grid congestion reduction, economics and spatial integration. In terms of CO_2 reduction, the configurations that deploy 3 MW wind energy in combination with 3 MWp solar achieve the highest scores, but these are harder to integrate on the business park and are faced with significantly higher investment costs. The optimal configuration reduces the CO_2 emissions with 25% and grid congestion with 12%.

The implications of integrating Solar PV and flexibility include economic benefits for users, adaptation requirements, and providing an example for park managers, governments, and Distribution System Operators (DSOs).

Finally, the implementation of the energy transition on mixed business parks is highlighted for its significant contribution to sustainability goals regionally and nationally, aligning with broader objectives outlined in national energy and climate policies. Mixed business parks serve as catalysts for renewable energy adoption, innovation, and economic growth, playing a pivotal role in shaping a sustainable energy future.

This section provides recommendations for various stakeholders involved in the energy transition of mixed business parks:

1. **Transmission System Operators (TSOs) and Distribution System Operators (DSOs):** Collaborate closely with park stakeholders to assess grid capacity, invest in advanced grid management technologies, engage in regulatory dialogue, and incentivize investments in grid infrastructure upgrades or flexibility integration.
2. **Province and Municipality:** Develop comprehensive energy transition strategies, prioritize investments in sustainable infrastructure, promote public-private partnerships, foster collaboration between different levels of government and industry stakeholders, and invest in capacity-building initiatives.
3. **Users on the parks:** Conduct energy audits, explore opportunities for on-site renewable energy generation, collaborate with neighbouring businesses for energy synergies, engage in demand response programs, and implement energy management systems.
4. **Companies and suppliers:** Continue investing in research and development, foster partnerships with park stakeholders, offer tailored solutions, prioritize providing comprehensive technical support, training, and maintenance services.
5. **Consultants:** Stay updated on the latest developments, adopt a holistic approach to energy management consulting, create long-term partnerships with park stakeholders, and provide tailored advisory services.
6. **Park management and entrepreneurial organizations:** Proactively engage with park stakeholders, organize knowledge-sharing events, workshops, and networking opportunities, advocate for supportive policies and incentives, and facilitate collaboration and innovation within mixed business parks.

Throughout the thesis, various limitations have been identified, falling into two categories: limitations due to the chosen scope and limitations stemming from simplifications and assumptions in the research design. Firstly, the thesis lacks a comprehensive treatment of other energy management aspects besides electricity, particularly regarding heat demand integration and industrial symbiosis. It overlooks leveraging residual heat and waste streams, critical elements highlighted in recent studies for enhancing energy efficiency and fostering circular economy principles. Secondly, the focus on direct economic benefits neglects broader considerations such as environmental and societal impacts, which recent research emphasizes as integral components of sustainable energy systems' value propositions. Thirdly, simplifications in the research design may undermine the robustness and applicability of the findings. Recent advancements in grid optimization techniques stress the importance of considering distributed energy resources and demand response flexibility to enhance the accuracy and practical relevance of energy management strategies within mixed business parks. In conclusion, while the thesis contributes significantly to understanding energy transition dynamics in mixed business parks, addressing these limitations through further research and methodological refinement will enhance academic rigor and inform more effective policymaking in sustainable energy transitions.

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List of Acronyms and Abbreviations

Tabel 0.1 List of Acronyms and Abbreviations

Acronym or Abbreviation	**Definition**
AHP	Analytical Hierarchy Process (for determining criteria weights)
BIZ	Business Investment Zone (Internationally sometimes called Business Improvement District or BID)
CBS	Statistics Netherlands ("Centraal Bureau voor Statistiek")
CCGT	Combined Cycle Gas Turbine
CDOKE	Temporary regulation on the capacity of local authorities for climate and energy policy ("Tijdelijke regeling capaciteit decentrale overheden voor klimaat- en energiebeleid")
CES	Cluster Energy Strategy
CHP	Combined production of heat and electrical power
CO_2	Carbon Dioxide
CRI	Commercial Readiness Index
DSO	Distribution System Operator (in Heerenveen: Liander)
EED	Energy Efficiency Directive
EIA	United States Energy Information Administration
EIGEN	Energy Hubs on business parks for the Integration of Large Scale Renewable Energy ("Energy Hubs op bedrijventerreinen, gericht op het inpassen van grootschalige hernieuwbare energie")
ESCo	Energy Service Company
EU	European Union
GHG	Greenhouse gas
IE	Industrial Ecology
IEA	International Energy Agency
JRC	Joint Research Centre of the European Commission
KNMI	Royal Netherlands Meteorological Institute ("Koninklijk Nederlands Meteorologisch Instituut")
LCOE	Levelised Costs of Energy
LCOH	Levelised Costs of Heating
LED	Light Emitting Diode
MCDM	Multi-Criteria Decision Making
NPV	Net Present Value
OCGT	Open Cycle Gas Turbine
PBL	Netherlands Environmental Assessment Agency ("Planbureau voor de Leefomgeving")
PNNL	Pacific Northwest National Laboratories

PV	Photovoltaic
PVB	Program for Sustainable Business Parks ("Programma Verduurzaming Bedrijventerreinen")
PVGIS	Photovoltaic Geographical Information System
REAP	Rotterdam Energy Approach and Planning
RES	Renewable Energy Sources
RES	Renewable Energy Sources
RVO	Netherlands Enterprise Agency ("Rijksdienst voor Ondernemend Nederland")
SDE++	Stimuleringsfonds Duurzame Energietransitie ++
SET	Sustainable Energy Technology
SME	Small to Medium Enterprise
SOC	State of Charge (of a battery)
STES	Seasonal Thermal Energy Storage
TNO	Netherlands Organisation for Applied Scientific Research ("Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek")
TSO	Transmission System Operator (in The Netherlands: Tennet)
TU	University of Technology
UK GOV	Government of the United Kingdom
UN	United Nations
V2G	Vehicle to Grid

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1. Introduction

In 2015, together with 194 other countries, The Netherlands signed and ratified the Paris Climate Agreement of the United Nations (UN) (UN, 2016). In this agreement, all countries pledge to do their best to reduce the emissions of greenhouse gasses (GHGs) in order to limit the global temperature rise to 2 degrees Celsius, while aiming for 1.5 degrees (UN, 2016). In 2019, the national government accepted the National Climate Agreement which contains emission reduction targets for five sectors: electricity generation, industry, agriculture and land-use, transport and buildings (Rijksoverheid, 2019). According to this agreement, the emissions of GHGs should be reduced by 49% in 2030 and by 95% in 2050 compared to 1990 levels. The European Union (EU) Fit for 55 package, of which the Netherlands is one of the main advocators, aims for 55% emission reduction in 2030 (European Commission, 2021). For the electricity generation, this means that in 2030, 70% of all electricity is produced using renewable energy sources (RES). In 2050, all electricity should be from RES and the emissions of GHGs should be reduced by 95% compared to 1990 levels. In terms of electricity use, mixed business parks represent a significant consumer, with a large reduction potential (Ban, Jeong, & Jeong, 2016; CBS, 2021b). However, many barriers complicate the transition to RES and lower GHG emissions (Rodin & Moser, 2021). In the specific case of the Netherlands, an additional factor is hindering electrification and increased production of renewables: grid congestion (Antea Group, 2023; Firan, 2022; Koster, 2021; Van Hest & Kleinnijenhuis, 2022). The integration of RES on mixed business parks requires more investigation on case level (Butturi et al., 2019) and is also a focus point for the Energy Transition Advisory Group at Antea Group Nederland. This advisory group has an interest in the integration of RES both for business parks that have ambitions with respect to renewable energy production and business parks that are struggling with grid congestion. The advisory group worked a pilot project in Heerenveen-Zuid, which will be used as a case study.

The main research question is:

"How can renewable energy configurations be designed for and implemented on mixed business parks, to increase the use of renewable electricity and reduce grid congestion?"

The aim of this thesis is to analyse the energy management of an existing mixed business park and develop a guideline for the energy transition on mixed business parks. This guideline can be used by for government officials, consultants, park managers and entrepreneurs to deploy RES, energy storage and demand flexibility to transition mixed business parks to renewable energy. To divide the main research question into smaller steps, five sub questions have been formulated.

1. *"Which steps are required to engage stakeholders in the energy transition on mixed business parks?"*
2. *"What tools are available for the optimisation of energy management on mixed business parks?"*
3. *"How can renewable energy configurations be simulated to increase the use of RES and reduce grid congestion on mixed business parks?"*
4. *"What are the effects and opportunities for the stakeholders on a mixed business park when renewable energy is implemented?"*
5. *"How does the implementation of the energy transition on mixed business parks contribute to the sustainability goals on the local, regional and national level?"*

For this, scientific literature and commercial guidelines for the energy transition on business parks have been evaluated. A method is proposed that integrates stakeholder management and energy management in one integral guideline. The guideline is therefore a combination of a process description, useful for business park managers, local authorities and consultants, and a technical model that is used to analyse and optimise the electricity management on the business park. This technical model is applied to a case study: business park Heerenveen-Zuid.

The idea for the topic of this thesis originated during the company internship at Antea Group. The municipality of Heerenveen approached the Energy Transition advisory group of Antea Group when one of the mixed business parks in Heerenveen, Heerenveen-Zuid, started to suffer from grid congestion. The task for the advisory group was to investigate the problem and propose solutions for grid congestion management. The mixed business park Heerenveen-Zuid suffers from grid congestion for the demand of electricity. The distribution network operated by Liander is nearing its maximum transport capacity. Therefore, permits to increase the connection capacity of firms, or new connections for firms that want to establish on the park cannot be issued. This is preventing the electrification of production processes, installation of RES and the growth of the business park.

Throughout this thesis, the case study will be used to illustrate the process. Furthermore, the data collected during this pilot project has been used for this thesis with the permission of the firms on the mixed business park that participated in the project.

The structure of this thesis is as follows. Chapter 2 describes the research motivation and the research gap. It concludes with the research questions for this thesis. The research questions are the input for Chapter 3, the research design. This chapter describes the methodology to answer the research questions and introduces the case study. Chapter 4 inventories the different aspects of energy management and the implementation of RES or grid congestion management on mixed business parks, which is required to identify the inputs, outputs and throughputs of the case study energy model in Chapter 5. In Chapter 5, the energy balance of the mixed business park is analysed in detail. The results from the case study RES configurations are presented in Chapter 6, followed by an analysis and interpretation of these results. Chapter 7 than describes the effects on the stakeholders of implementing the optimal configuration and discusses the implementation itself. Chapter 8 discusses the research design and results on a higher level and provide insight in the scientific and social relevance of the case study results, including the limitations of this study. Chapter 9 presents the conclusions and recommendations.

2. Literature Study

This chapter presents the literature study of the energy transition on mixed business parks. It starts with describing the motivation for researching the energy management on mixed business parks. Based on the motivation, a literature study is performed to identify the research gap. The research gap forms the input for the research questions. The case study is introduced in the final section.

2.1 Research motivation

This section provides background information on the Dutch energy transition and the transition framework of mixed business parks.

2.1.1 Background: The Dutch energy transition

The energy transition in the Netherlands is slowly gaining momentum. Figure 1 shows the yearly electricity generation per source in the Netherlands. Figure 2 zooms in on the yearly electricity generation of low-carbon sources as defined by the International Energy Agency (IEA): solar photo-voltaic (PV), wind, biofuels, hydro and nuclear (IEA, 2023).

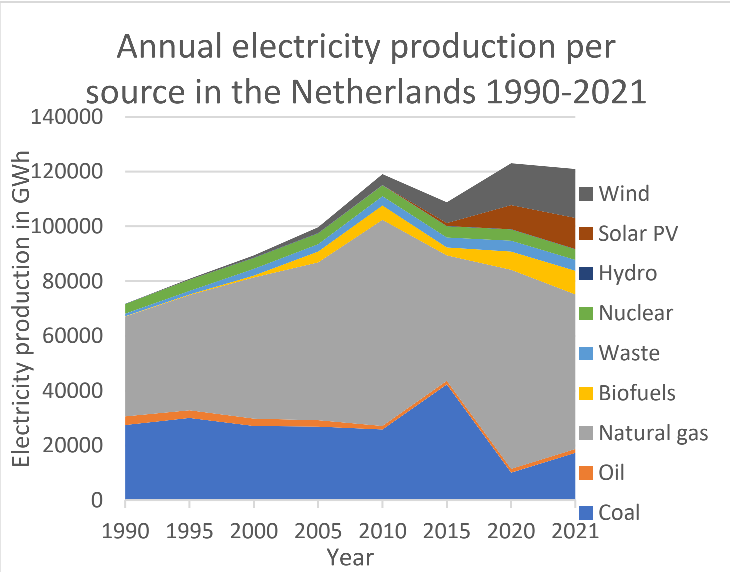

Figure 2.1 Annual electricity generation per source in the Netherlands between 1990 and 2021. Data from (IEA, 2023).

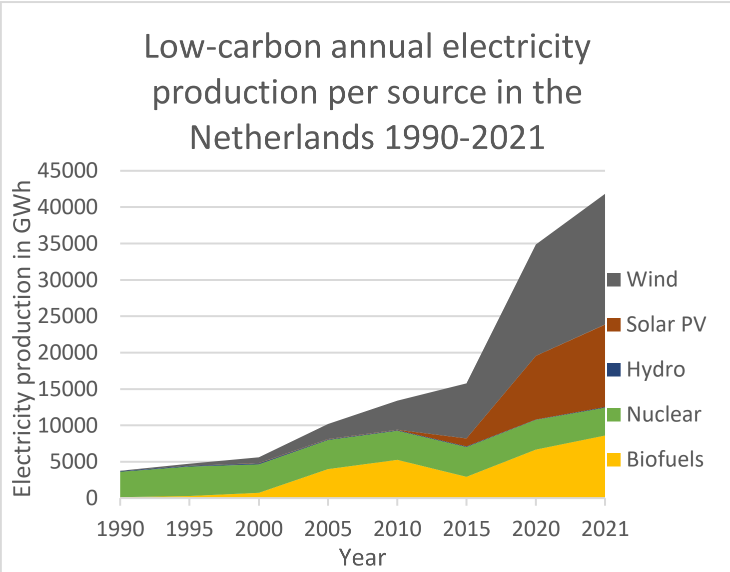

Figure 2.2 Low-carbon annual electricity generation per source in the Netherlands between 1990 and 2021. Data from (IEA, 2023).

Figure 1 shows that since 1990, the total electricity production increased from 72 TWh to 121 TWh. Figure 2 shows that the electricity generation using solar, wind, biofuels, waste and hydro has increased from 4 TWh to 41 TWh during the same period.

Several things can be concluded from Figures 2.1 and 2.2. First, compared to 1990, the electricity mix is more diversified, but fossil fuels coal, oil and gas still make up the majority of power production in 2021. Second, the share of renewable energy has grown over the past 30 years, but due to rising total demand, fossil fuels are still used extensively. Third, the exponential increase in solar PV installations is flattening: between 2015 and 2020, the annual increase in solar PV production was 51% whereas in 2021, solar PV production increased with 29% compared to 2020. Fourth, the Netherlands Environmental Assessment Agency (PBL) estimates that in 2030, the electricity production will be between 150 and 170 TWh (PBL, 2023a). With the policy goal of 70% renewable production, this equals 120 TWh. If wind and solar are to provide most of the renewable electricity, production must **triple**. The mitigation measures of the Climate Agreement and recent policy measures have been evaluated by the PBL and it was found that additional measures have to be taken to reach the targets for GHG emissions and renewable electricity production in 2030 (PBL, 2023a). For this, it is important to take closer look where the energy is used.

The industrial sector is responsible for a quarter of the total final energy consumption in the Netherlands, 700 PJ or 195 TWh (CBS, 2021). 400 PJ is used by large industrial companies that are subjected to many environmental and efficiency regulation. The other 300 PJ, or 83 TWh is used at small, mixed business parks that are typically found around villages and cities (CBS, 2021). Mixed business parks can play an important role in the energy transition, as has been noted by many authors since the beginning of the 21st century. (Anastasovski, 2023; Ban et al., 2016; Boix, Montastruc, Azzaro-Pantel, & Domenech, 2015; Lambert & Boons, 2002; Rodin & Moser, 2021).

2.1.2 Institutional context of the energy transition in the Netherlands

Renewable energy policies in the Netherlands can be identified on three levels: national, regional and local. On the national level, sustainability targets are developed based on international agreements and EU policies (European Commission, 2021; Rijksoverheid, 2024b; UN, 2016). These national targets are translated into regional energy strategies, which specify the renewable energy generation that is to be produced in each region. On the regional level, the provinces determine what kind of RES are used in the regional energy strategies (Provincie Fryslân, 2022). On the local level, the municipalities regulate the use of land through the zoning plan (in Dutch: “bestemmingsplan”). Starting from the First of January 2024, the zoning plan will be changed into the environmental plan (“omgevingsplan”) (Rijksoverheid, 2016). In the end, the municipality determines what kind, how much and where RES generation is realised. In overview, the renewable energy policies are organised top-down, but with a lot of responsibility and freedom on the regional and local level.

On the national level, three concepts play a central role in the formation of policies and regulations for the energy transition on mixed business park.

First, the nitrogen crisis. In the Netherlands, the emissions of nitrogen in the form of ammonium and nitrous oxides are damaging Natura-2000 nature conservation reserves and air quality. Because of this, the Council of State (Raad van State) has removed the construction exemption (Rijksoverheid, 2022). Therefore, all construction projects, including those related to energy infrastructure and RES capacity must undergo an assessment of the nitrogen emissions during construction phase. If nitrogen emissions are expected to be too high, permits are not issued. This is delaying energy infrastructure and RES projects, slowing down the energy transition (Beek et al., 2023; Jetten, 2022; NetBeheer Nederland, 2023b; Van Hest & Kleinnijenhuis, 2022). This creates a snowball effect: a slower energy transition means more fossil fuels are used, increasing nitrogen emissions, making it even more difficult to get permits for new RES capacity and energy infrastructure. This process is shown visually in Figure 2.3.

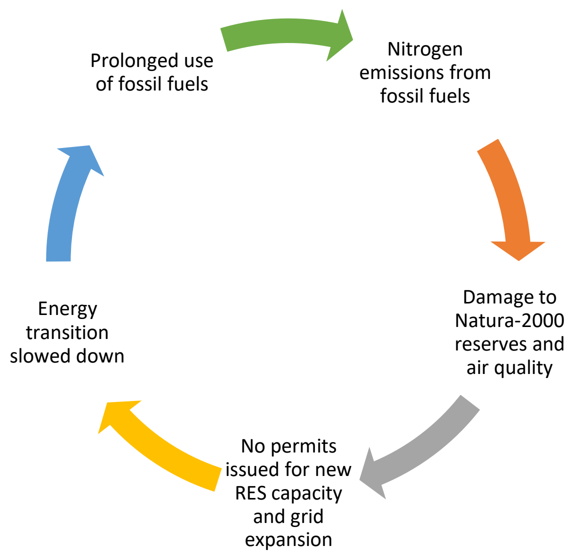

Figure 2.3 The snowball effect showing the relationship between the nitrogen crisis and the energy transition (Beek et al., 2023; NetBeheer Nederland, 2023b).

Second, regulations focused on energy management and savings of individual firms. Three regulations are important for companies on mixed business parks.

1. The European Union requires an Energy Efficiency Directive (EED) audit for large companies (RVO, 2017). The EED applies to companies with a workforce larger than 250 full-time employments or with an annual turnover of 50 million and an annual balance sheet of more than 43 M€.
2. Energy label C obligation for offices (RVO, 2018). All buildings that are used as an office space require an energy label C or better (B, A, A+, etc.). If an office does not meet this requirement, additional isolation, integration of RES or other energy saving measures must be taken. Else, the company is not allowed to use the building as an office. This obligation has been in place for quite some time but starting 2023 the municipalities and environmental agencies are enforcing this obligation.
3. Energy conservation obligation (RVO, 2022b). For each industrial and commercial sector, qualified measures for energy conservation with a payback period of five years or less are identified by the Dutch Enterprise Agency (RVO) (RVO, 2022c). All locations of companies with an electricity consumption of more than 50,000 kWh or a natural gas consumption of more than 25,000 m^3 equivalent are obliged to implement these measures. They must report on the implementation of these measures every four years.

Third, strategies and regulations aimed at the energy transition of the industry sector. Two strategies are applicable to mixed business parks.

1. CDOKE regulation (RVO, 2022d). The CDOKE funding is aimed at supporting the sustainability policies of regional and local governments. With the funding, provinces and municipalities can hire staff or external experts for strengthening of their organisation in support of the energy transition. The CDOKE regulation aims to contribute to the national CO_2 emission reduction targets of 55% in 2030 and net-zero in 2050 (Rijksoverheid, 2019). Although the application for the regulation is closed, a new application round will be started in the coming years (RVO, 2022d).
2. Cluster Energy Strategy (CES) (VNCI, 2022). The CES aims to accelerate the energy transition in five industrial clusters: Delfzijl (Noord-Nederland), Amsterdam (Noordzeekanaal), Sittard

(Chemelot), Sluis (Zeeland) and Rotterdam (Rotterdam/Rijnmond). The sixth cluster, CES 6, is for all industry outside these five main clusters. CES 6 is applicable to most of the mixed business parks, as these are found scattered over the country. This also holds for the mixed business park Heerenveen-Zuid.

The goal of CES 6 is to streamline the energy transition of large industrial companies outside the five main clusters by collaborating with provinces and grid operators. The objectives are improving the access to energy infrastructure, simplifying licensing and permit procedures and coordinating infrastructure planning and usage (VNCI, 2022).

The nitrogen crisis, the energy saving regulations and the regulations aimed at the energy transition of the industrial sector together set the scene for the energy transition. Together with the urgent problem of grid congestion as discussed in Chapter 1, these three concepts determine how the energy transition in the Netherlands will be realised on national, regional and local level.

2.1.3 Narrowing down the energy transition: Electricity.

Energy is more than just electricity. In fact, electricity use currently represents approximately one-fifth of the final energy use of the Netherlands (IEA, 2023). For example, Dutch households use four to five times as much energy from natural gas (mainly for space heating, but also hot water and cooking) compared to electricity (IEA, 2023). Therefore, it seems that by considering electricity only, the topic of energy management on business parks is not covered completely. However, for this thesis, the focus is on electricity. This is because of several reasons.

First, in contrast to residential consumption the electricity use on mixed business parks is slightly larger than the natural gas use (CBS, 2021b). Therefore, the situation cannot be compared to residential areas, where the main energy carrier is natural gas. Secondly, due the electrification of production processes, space heating and the commercial vehicle fleet, the electricity demand on business parks is increasing, while the demand of fossil fuels is decreasing (CBS, 2021b). Third, the central concept of the heat transition in the Netherlands is that natural gas is replaced by other means of heating (Rijksoverheid, 2021). These other sources, for example heat pumps, often require electricity to provide heat. Therefore, the focus on electricity as main energy carrier on business parks is reasonable. Finally, this thesis project is to be conducted in a restricted timespan. Hence, including all aspects of the energy transition in this thesis would result in a shallow investigation of the energy management. From literature, it is clear that more experimental research and case studies are needed for the integration of RES on mixed business parks (Butturi et al., 2019).

2.1.4 Mixed business parks in the Dutch energy transition.

Since the end of the 20th century, sustainable transitions of mixed business parks have been a focus point for researchers. For this transition, the concept of industrial ecology plays a vital role. In 1997, a review of this concept was published, containing the three basic principles of industrial ecology (Erkman, 1997).

1. It is a systemic, comprehensive, integrated view of all the components of the industrial economy and their relations with the biosphere.
2. It emphasizes the biophysical substratum of human activities, i.e. the complex patterns of material flows within and outside the industrial system, with current approaches which mostly consider the economy in terms of abstract monetary units, or alternatively energy flows.
3. It considers technological dynamics, i.e. the long-term evolution (technological trajectories) of clusters of key technologies as a crucial (but not exclusive) element for the transition from the actual unsustainable industrial system to a viable industrial ecosystem.

The concept of IE opened the door to another key feature of the biosphere: working together. In nature, symbiosis is the intensive collaboration of two different organisms. This was adapted for industrial sites as Industrial Symbiosis (Lowe & Evans, 1995). The main focus of Industrial Symbiosis is improving collaboration to close the loop of material and energy flows and match the in- and outputs of industrial systems (Lowe & Evans, 1995). Business parks that adopt aspects of industrial ecology and industrial symbiosis are termed eco-industrial parks. These eco-industrial parks exist on two levels: the first level is the large industrial cluster, such as found near the Ports of Rotterdam and Amsterdam. The second level is the mixed business park that is typically found near residential areas all over the country. This division is found in the two different definitions of eco-industrial parks. The first focuses on technical sustainable performance, while the second focuses on societal sustainable performance (Lowe & Evans, 1995).

1. An industrial system of planned materials and energy exchanges that seeks to minimise energy and raw materials use, minimise waste, and build sustainable economic, ecological and social relationships.
2. A community of businesses that collaborate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community.

It was argued that the distinction between these definitions, the former focusing on physical flows (materials and energy) and the latter focusing on organisational and societal processes, reflects the nature of the problems in establishing industrial symbiosis at level 1 and level 2 eco-industrial park, respectively (Lambert & Boons, 2002). This also reflects the difference in size: level 1 industrial parks are characterised by large scale industrial firms, whereas level 2 industrial parks are characterised by small and medium-sized enterprises.

However, the integration of RES on mixed business parks requires a combination of both levels. This is because of the inherent characteristics of RES, especially solar and wind: both are considered intermittent sources of energy. This means that the supply of energy is no longer only driven by the demand, as is customary in the Dutch electricity network. Rather, the supply is now also driven by external (weather) factors such as solar irradiation and wind speed. Implementing RES therefore requires an integral approach on the electricity system as a whole (Martinot, 2016), as well as for business parks (Butturi et al., 2019). Furthermore, there is a significant benefit of implementing RES on the business park as a system, rather than optimising the energy management of each firm separately. This is because of the diversity of economic activities on a mixed business park. A case study in Italy showed the potential of the shared approach: shared production and consumption of power from RES yields economic benefits, increased the self-consumption of the locally produced electricity and reduced GHG emissions (Ceglia et al., 2023). This shows the rationale behind energy symbiosis.

Industrial symbiosis follows the principles of circular economy in the sense that material flows are closely studied. When considering the electricity flow and the integration of RES, energy symbiosis captures the matter more closely and is useful for the analysis of mixed business parks (Butturi et al., 2019). Energy symbiosis consists of multiple forms of energy: heat, cooling and power. As heat demand is electrified (see previous subchapter) and cooling is already provided by means of electricity, for this thesis, the focus will be on electricity.

2.1.5 Renewable energy on mixed business parks: an integral approach

Implementing RES on mixed business parks is not possible in one go. From literature, it becomes clear that integrating RES on a mixed business park or community requires a combination of solutions

(GridFlex, 2020; Haque, Nguyen, Bliek, & Slootweg, 2017; Olek & Wierzbowski, 2015). This is also noted by numerous other studies (Asrari, Ansari, Khazaei, & Fajri, 2020; Bjarghov et al., 2021; Mendes et al., 2018; Schleicher-Tappeser, 2012; Zhang, Troitzsch, Hanif, & Hamacher, 2020).

In overview, the solution lies in a combination of three key aspects:

1. Renewable energy generation.
2. Flexibility in the form of storage or demand response.
3. A (virtual) market in which the local users and producers of electricity have insight in actual and predicted supply and demand and can trade power.

Several studies have provided analyses and optimisation tools for energy management with RES on mixed business parks (Demartini, Tonelli, & Govindan, 2022; Mousqué, Boix, Montastruc, Domenech, & Négny, 2020; Neri, Butturi, Lolli, & Gamberini, 2023), which show the great potential of implementing energy management with RES. To study the effect of different aspects of RES, different configurations will be analysed and compared to the baseline case.

In terms of the implementation of the above three aspects, an approach consisting of seven phases has been identified (Rodin & Moser, 2021). Figure 2.3 shows these seven phases that consist of stages and actions to go from one to the next phase.

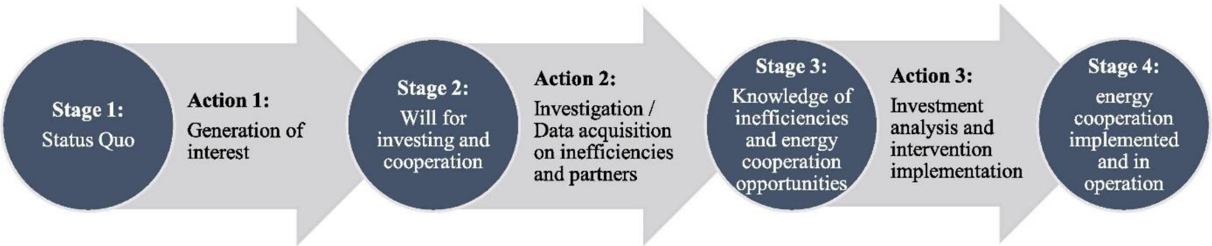

Figure 6.4 Four stage approach for energy transitions on mixed business parks (Rodin & Moser, 2021).

These 4 stages present the steps required to go from status quo or baseline condition to an energy cooperation. The term energy cooperation will be used to define a situation in which the three aspects of the integral energy solution as mentioned above are present.

One the one hand, presenting and following the steps to go from status quo to a working energy cooperation is the important. On the other hand, the effect of these steps must be evaluated too. A systematic approach to evaluate the effects of implementing energy symbiosis on mixed business park is not present in current literature, let alone an application of this approach to a case study (Susur, Hidalgo, & Chiaroni, 2019).

2.2 Research gap

Previous sections have shown that the energy transition in the Netherlands is gaining momentum, and that electrification is driving an increase in electricity demand. Industrial ecology studies the implementation of measures on industrial sites to stimulate resource efficiency and sharing. Energy symbiosis focuses on the energy flows in an industrial environment. In general, the development of tools for the study of industrial symbiosis and the investigation of industrial symbiosis from a modelling point of view is necessary (Demartini et al., 2022). With the current problem of grid congestion in the Netherlands, energy symbiosis with a specific focus on electricity requires more research. Furthermore, the traditional frameworks to study and increase industrial symbiosis on industrial sites do not apply well to renewable energy on mixed business parks (Butturi et al., 2019). In fact, the methodology to study and evaluate the development of energy cooperations or eco-industrial parks on specific case studies requires more research and implementation (Susur et al., 2019). Therefore, a research gap is identified that considers the implementation of energy symbiosis on mixed business parks with a focus on electricity management and grid congestion.

Furthermore, this thesis aims to develop a guideline that supports mixed business parks to implement the solution coming out of the energy management analysis. As identified in (Rodin & Moser, 2021), energy cooperation on mixed business parks is very challenging and therefore a guideline is welcome for the sector.

2.2 Research questions

The main research question for this master thesis project is:

"How can renewable energy configurations be designed for and implemented on mixed business parks, to increase the use of renewable electricity and reduce grid congestion?"

The main research question consists of several aspects, which will be addressed in sub questions.

1. *"Which steps are required to engage stakeholders in the energy transition on mixed business parks?"*
2. *"What tools are available for the optimisation of energy management on mixed business parks?"*
3. *"How can renewable energy configurations be simulated to increase the use of RES and reduce grid congestion on mixed business parks?"*
4. *"What are the effects and opportunities for the stakeholders on a mixed business park when renewable energy is implemented?"*
5. *"How does the implementation of the energy transition on mixed business parks contribute to the sustainability goals on the local, regional and national level?"*

2.3 Introduction of Case Study Heerenveen-Zuid

The idea for the topic of this thesis originated during the company internship at Antea Group in 2022. The municipality of Heerenveen approached the Energy Transition advisory group of Antea Group when one of the mixed business parks in Heerenveen, Heerenveen-Zuid, started to suffer from grid congestion. The task for the advisory group was to investigate the problem and propose solutions for grid congestion management. The mixed business park Heerenveen-Zuid suffers from grid congestion for the demand of electricity. The distribution network operated by Liander is nearing its maximum transport capacity. Therefore, permits to increase the connection capacity of firms, or new connections for firms that want to establish on the park cannot be issued. This is preventing the electrification of production processes, installation of RES and the growth of the business park.

Furthermore, Heerenveen has the ambition to reduce its CO_2 emissions with 49% in 2030 (Gemeente Heerenveen, 2020). It is not clear compared to which year this is, but given the trend in CO_2 emissions between 2010 and 2022 (Rijksoverheid, 2024a), at least 128 kton must be mitigated.

Combining the ambitious target of CO_2 reduction with the current problem of grid congestion, makes this case very suitable for this thesis.

Throughout this thesis, the case study will be used to illustrate the process. Furthermore, the electricity consumption data collected during this pilot project has been used for this thesis with the permission of the firms on the mixed business park that participated in the project.

3. Research design

The aim of this thesis is to answer the research questions and develop a guideline for mixed business parks to integrate RES. In this chapter, each step of the research project is discussed, giving information about the content to be researched and the method to answer the research questions.

First, the research flow diagram shows the various parts of the research project. Then, the steps of the guideline are elaborated upon. The case study will be performed based on these steps.

3.1 Research flow diagram

The research flow diagram is a visual representation of the research process. For each phase of the thesis project, it shows the subject, methodology, inputs and outputs. Figure 3.1 shows the diagram.

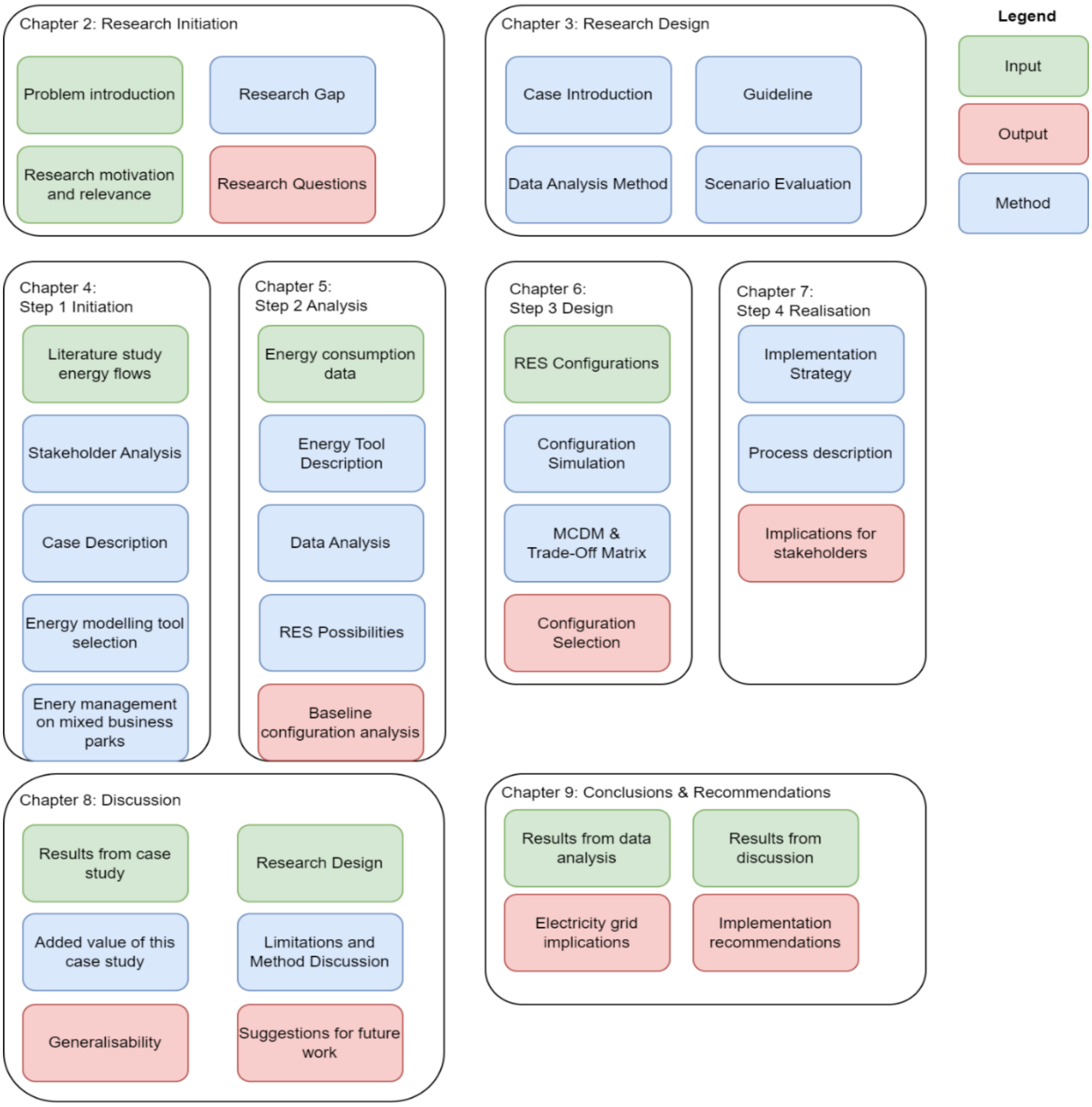

Figure 7.1 Research Flow Diagram

From Figure 3.1, this thesis has a superstructure that consists of 3 layers: (1) introduction and research design, (2) core chapters and case study and (3) discussion and conclusion. This way, it also represents a structure for a guideline that be used directly on a mixed business park. Therefore, this document is both the report of the thesis project and a product in the sense that it can be applied to similar cases as the case study in this thesis.

3.2 Guideline content and structure

The principles of IE, energy symbiosis and eco-industrial parks as described in previous chapter form the foundation for the guideline. Furthermore, the concepts of the energy hub or the smart multi-energy system help defining the boundaries of the system in which the energy management can be optimised using RES (Butturi et al., 2019; Geidl et al., 2007).

In terms of the structure of the guideline, a 4-step approach seems most appropriate (Rodin & Moser, 2021). The steps are comparable to what is accustomed in many different sectors such as the building sector, health care and technology: initiation, analysis, design, realisation. In each step, the emphasis is on a different part of the energy transition on mixed business parks. Therefore, each step starts with a literature study and then implements the method described in the next subsection. This also means that the results of the analysis will be presented per step and not in a single results chapter.

3.2.2. Step 1: Initiation of energy transition on mixed business parks

The initiation phase is the first phase of any project. In this phase, it is important to identify the driver for the transition; sketch the proposed transition and identify and engage important stakeholders.

First, the two major drivers on the ambition side are to improve the use of RES on the park or to reduce the carbon footprint of manufacturing or other commercial processes. One major driver from the problem side is the aforementioned grid congestion on the distribution network that the Netherlands is facing (Jetten, 2022; Van Hest & Kleinnijenhuis, 2022). The creation of a shared vision or ambition is important to set the scene for the transition (Susur et al., 2019). Getting stakeholders enthusiastic for this vision is important for all the steps of the process.

Second, organising the stakeholders surrounding the mixed business park requires a good understanding of the nature of the park, the local and regional authorities and the position of the DSO. This calls for a stakeholder analysis. The approach taught in the course *Sustainable Energy Innovations and Transitions* has been used (Kamp, 2022). This is supplemented with a discussion of the engagement of these stakeholders to organise them for the transition on the park.

Third, a comprehensive analysis of the energy management on the mixed business park is essential to investigate the problem and propose possible solutions. For this, existing scientific literature and commercial reports and guidelines have been studied. This also includes the selection of tools or the development of a new tool to study the electricity consumption on the park and to simulate possible alternative configurations. This tool consists of multiple modules and requires inputs, objectives and outputs.

The input for the energy analysis tool is gathered:

- Electricity consumption data,
- Generation potential for RES (roofs suitable for PV panels, wind turbine sites, etc.),
- Grid situation in terms of congestion,
- Storage options.

Objectives for the configurations include:

- Reduction of grid congestion by reducing peak demand and supply;
- Increasing the share of RES in the electricity mix of the business park;
- Increasing the energy autonomy of the business park.

Outputs include:

- Average electricity demand,
- Energy mix (which sources provide how much energy),
- Peak demand and supply,
- Average annual cost of electricity based on average annual cost per source,
- Required storage capacity.

Fourth, the main characteristics of the mixed business park are described: what is the location of the park; what kind of firms operate on the park; how is the park organised, etc.

The result of the initiation phase is an overview of the mixed business park. This includes the characteristics, the problem description or transition driver, the main stakeholders surrounding this problem or driver and insight in the energy management on the park. Also, the requirements for the energy simulation tool are identified and existing scientific and commercial tooling is reviewed for its suitability to the current problem.

3.2.3 Step 2: Analysis of the energy balance on mixed business parks

In the second phase, the problem is analysed more thoroughly.

First, based on the analysis of existing tooling, a tool is selected or modified and expanded to be used on the energy consumption data of the mixed business park.

Secondly, the supply and demand of electricity on the business park is studied in more detail. The supply of electricity is coming from the grid and from local sources such as solar PV fields and roofs, wind turbines and local (co-)generation. For the consumption of every user and for the aggregated (the sum of all individuals) consumption of the park, a consumption profile is generated. A consumption profile is an overview of the required electrical power as a function of time. This profile can be constructed on a daily, weekly or annual basis to show fluctuations, for example to identify peak hours, differences between night and day consumption, weekdays or weekend/holidays and seasonal variation. For the collection of data, multiple options exist. In overview, the options include:

1. Construction of user profile based on literature,
2. Construction of user profile based on interviews with the user,
3. Installation of a separate measurement unit at the user,
4. Calculated based on the data from the local grid operator.

These options will be evaluated.

The user profiles correspond to specific economic activities. Coupling of the user profile to a specific economic activity (warehousing, distribution, food production, offices, retail, catering, etc.) allows for the analysis to be performed on mixed business parks where the economic activities are known, but no actual consumption data is available.

The consumption data is presented in annual and weekly overviews. This allows for analysis of the consumption profile of the business park in terms of seasonal and daily variation.

Third, the potential for RES on the mixed business park is discussed. This is based on the analysis of the energy balance on the park and the physical characteristics of the park such as the available roof area and the available area for wind energy.

3.2.3 Step 3: Design of renewable energy configurations on mixed business parks

In the third step, the possibilities for the energy transition on the park are developed and analysed.

First, based on the local and regional sustainability ambitions and the energy consumption analysis, several configurations are developed for the transition of the mixed business park. Based on the study of energy management on the park in Step 1, different configurations are developed that deploy a variety of RES production, storage solutions and demand response.

Second, these configurations are simulated using the tool as described in Step 2. An investigation of the annual and weekly consumption of electricity is performed.

Third, the configurations are analysed using Multi-Criteria Decision Making (MCDM). Before the simulation, a set of criteria are identified that capture the performance of each configuration on social, technical, economic and environmental level. The configurations are scored based on these criteria. The results are presented in a Trade-Off Matrix, which shows the scores for all different criteria for each configuration. Based on the importance or weight of the criteria, a final score per configuration is calculated.

Fourth, the results of the trade-off are analysed and a sensitivity analysis is performed to investigate the robustness of the performance of each configuration. Furthermore, additional analyses are performed that examine the increase of the battery size and the use of excess RES production for seasonal heat storage.

3.2.4 Step 4: Implementation of the energy transition on mixed business parks

Now that the most optimal configuration has been identified, the final step of the guideline describes the implementation of the chosen configuration.

First, the implications of implementing the optimal configuration on the mixed business park are discussed from a stakeholder perspective. This includes all main stakeholder groups that were identified in Step 1. The implications discuss both the opportunities and the risks for these stakeholders.

Second, the implementation strategy is discussed. This entails a description of steps that the mixed business park must take for the successful implementation of the chosen configuration.

1. Feasibility study: investigation of financial, legal and technical feasibility of the chosen configuration.
2. Financing decision: this determines the financing sources and the revenue streams.
3. Distribution of ownership and responsibilities
4. Contracting suppliers of solar PV panels and monitoring systems
5. Planning of operation, maintenance and end-of-life.

It is not within the scope of this thesis to discuss the realisation of the proposed solution. However, by describing the implementation plan, this can serve as a guideline for stakeholders on the mixed business park to organise the subsequent phases of the development.

4. Step 1: Initiation of energy transition on mixed business parks

The first step of the guideline is the initiation. In this step, the first inventory is made. This consists of four aspects:

1. The energy management of the mixed business park,
2. The stakeholders on the mixed business park,
3. The method to study the energy flows on the mixed business park.
4. The description of the mixed business park that is used for the analysis.

Together, these four aspects are the starting point of the transition of the mixed business park. From this starting point, it is possible to analyse the energy flows in more detail and propose possible options for the energy transition.

This chapter is structured as follows. In Section 4.1, the energy management on mixed business parks is discussed. This entails the system description and the analysis of possible transition guidelines. Part of these transition guidelines are input for the stakeholder analysis in Section 4.2, in which the most important stakeholders on the mixed business park are identified and the relationships between them are investigated. To study the energy flows on the mixed business park, a tool must be selected and developed, which is the subject of Section 4.3. Finally, the mixed business park of Heerenveen-Zuid will be discussed in more detail to serve as a case study in Section 4.4.

4.1 Energy management on mixed business parks

Energy management on mixed business parks consists of several aspects. Production, conversion, distribution and consumption represent the main superstructure of the energy system. An overview is shown in Figure 4.1.

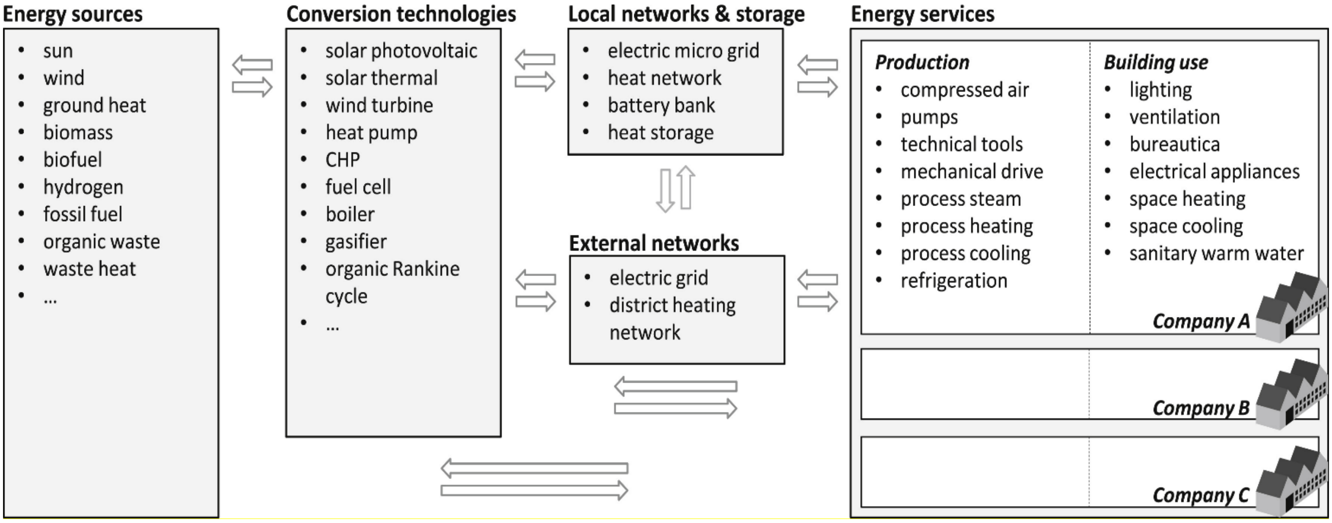

Figure 8.1 Energy System superstructure for mixed business parks (Timmerman et al., 2014).

The four aspects of energy management are treated in the following subsections.

4.1.1 Production

In the Netherlands, fossil fuels coal and natural gas provide most of the electricity, as was observed in Figure 2.1. This is the electricity that is coming from the grid. Mixed business parks, depending on the commercial activities, also use locally produced electricity, for example from gas generators. These generators use natural gas to produce heat and electricity. From Figure 2.2, in terms of RES, solar PV and wind energy are the dominant sources of electricity.

Intermittent energy sources

Solar PV panels and wind turbines can be installed at or near mixed business parks to provide electricity. These facilities however do not produce constant nor adaptable power. This is a challenge for both users and grid operators. The integration of these sources requires back-up or storage for when the sun is not shining and the wind is not blowing. For business parks close to river streams, the installation of a hydroelectric plant is also a way to produce electricity. Especially in mountainous terrain, the combination of wind, solar and hydro is favourable because the seasonal variability of the sources partially cancels out, as is shown for Switzerland in Figure 5. Although hydroelectric potential in the Netherlands is limited, the combination of solar PV and wind is still very favourable and provides a good power supply coverage because the sources are negatively correlated on all timescales from hours to years (Li, Janik, & Schwarz, 2023; Widen, 2011).

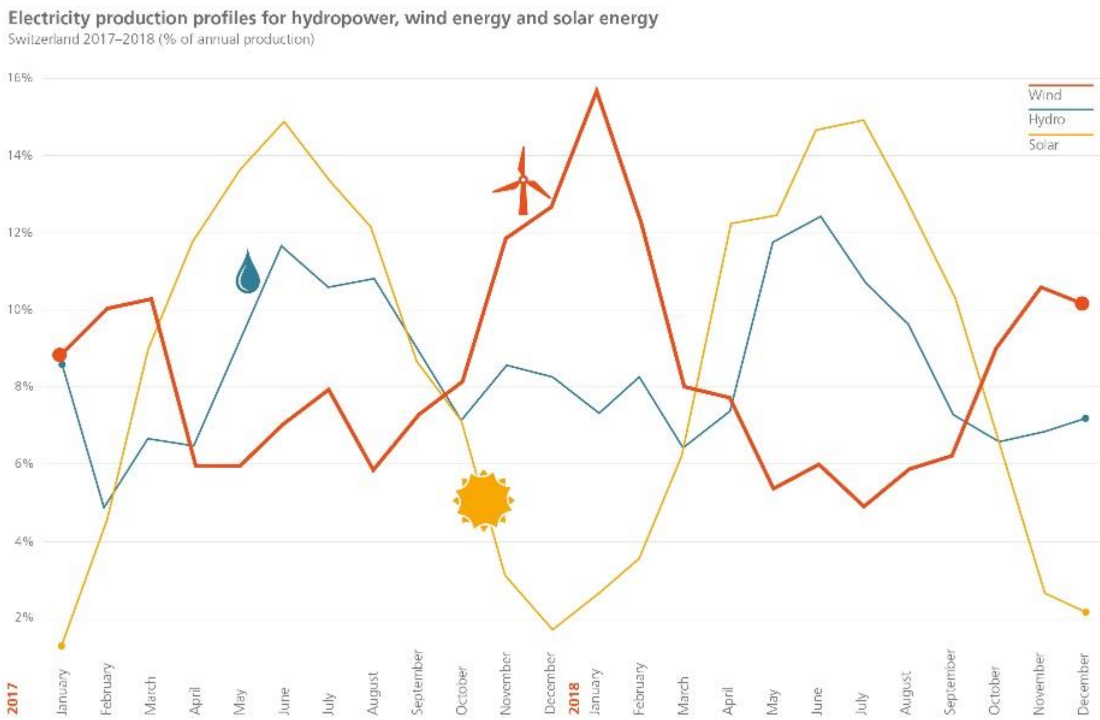

Figure 4.2 Electricity production of Solar PV (yellow), wind (red) and hydro (blue) in Switzerland for 2017 and 2018 (SFOE, 2020). Clearly, wind and solar show little correlation, which is useful to achieve a year-round production of RES.

One final consideration for the installation of PV panels on mixed business parks is the lay-out of the panels. For the highest annual yield, fixed panels should face south. However, in the case of mixed business parks with grid congestion problems, where the majority of available space is on flat rooftops, east-west orientation has three main benefits (Khatib & Deria, 2022; Litjens, Worrell, & van Sark, 2017):

1. **More efficient use of available area.** Due to self-shading of south oriented panels, more space should be added between rows of panels. On small areas such as rooftops, east-west oriented panels can be placed closer to one another. Although the yield per square meter of panel is lower in this orientation, the yield per square meter roof may be higher.
2. **Lower peak injection around noon.** South oriented panels have a high peak injection of power between 11.00 hrs and 13.00 hrs. This can cause transport congestion in the distribution network of the mixed business park. East-west oriented panels typically have a lower peak injection around noon and a more spread-out generation profile.

3. **Lower structural weight.** Due to the space requirement for self-shading of south oriented panels, these constructions are exposed to wind uplift. Therefore mounting and support structures for south oriented panels are generally heavier than for east-west oriented panels, up to 33% (Khatib & Deria, 2022). On rooftops, the load capacity of the roof is a major constraint for the number of panels that can be installed without requiring additional strengthening of the roof.

Biomass and waste combined heat and power

The combined production of heat and power (CHP) can be very efficient (up to 90%) and is considered an important aspect of industrial ecology and energy symbiosis, also because waste streams can be used as fuel (Butturi et al., 2019). However, although efficiency is higher than for single purpose gas generators, GHG emissions are still in place and when the resulting heat is not properly used (for example when there is no space heating requirement during the summer months or thermal storage is unavailable), efficiencies drop significantly. Furthermore, biofuels and hydrogen to supply CHPs are not commercially interesting at this point, have multiple drawbacks, such as competition with food crops and the policies for biofuel consumption in the EU are focussed on the transport sector (IEA, 2021; Naylor et al., 2007). Furthermore, compared to other forms of low-carbon electricity generation, biomass ranks as the worst technology in terms of aggregate footprint (land, water, carbon emissions and levelized costs) (Ristic, Mahlooji, Gaudard, & Madani, 2019). In conclusion, biomass CHP should be avoided and waste CHP can only be an asset if other forms of generation are not sufficient.

4.1.2 Storage

For energy storage, the focus is on batteries and thermal storage. Battery storage is suitable for timescales up to weeks, thermal storage is suitable for seasonal storage. The combination of CHP with thermal storage is beneficial because excess heat produced in warmer periods can be stored for colder periods (Smith, Mago, & Fumo, 2013). Without thermal storage, it is very difficult to utilise the heat from CHP effectively. Because the focus of the guideline is on electricity, the model does not implement thermal storage. In Chapter 6.4.3, thermal storage is briefly discussed. The focus is on electrical storage in batteries.

Battery storage is gaining more applications on commercial scale. Energy Storage NL has an overview of all industry partners that are developing battery storage systems (Energy Storage NL, 2024). Operational examples specifically targeted at the integration of RES include Giga Storage’s Rhino and Buffalo project (Giga Storage, 2023).

4.1.3 Distribution

The distribution of electricity within the mixed business park is an important aspect of integrating RES and preventing grid congestion. As mentioned in the previous chapter, a central aspect of the optimisation of energy management of the business park is the monitoring and trade of supply and demand. An structure to monitor and control the in- and outflow of electricity from various sources and consumers must be implemented (Anastasovski, 2023; Bjarghov et al., 2021).

4.1.4 Consumption: user patterns and demand response

Energy consumption on mixed business parks consists of electricity and natural gas, as noted in previous chapter. Interestingly, the consumption of energy, and electricity in particular, follows a pattern. This user pattern is different for each type of commercial activity that takes place at the businesses on the park. Combined, the user patterns form the aggregated user demand profile of the business park.

Because of the diverse nature of commercial activities on business parks, no scientific data is available that specifies the daily or weekly consumption patterns per commercial activity type. Therefore, this data must come from actual user measurements. However, this data collection is very time consuming and requires consent from all involved companies. To gain some insight beforehand in the energy use of individual firms and commercial activities, the Rotterdam Energy Approach and Planning (REAP) project can be used (Tillie et al., 2009). This includes the annual heat, cold and electricity use per square meter of offices, supermarkets, shops and schools: some of activities that are often found at mixed business parks. Furthermore, efforts have been made previously to estimate the energy consumption at mixed business park based on floor area (Maes et al., 2011), but due to large uncertainties this method is not accurate enough for the modelling of grid congestion. Finally, interviews with the entrepreneurs on the business park could provide some information on daily and weekly patterns, for example when offices are occupied; equipment and heavy machines are used and if the businesses apply continuous or batch processes.

Collecting consumption data about the user patterns is very important, but also very time consuming. To gain insight in an early phase of the project, a simple classification can be made according to the following. This based on scientific reference (van Zoest, El Gohary, Ngai, & Bartusch, 2021) and talks within the Energy Transition Advisory Group of Antea Group.

1. Consumption during office hours (9:00 hrs – 17:00 hrs on Weekdays)
2. Consumption during opening hours (retail, supermarkets)
3. Consumption during full week (hotels, continuous processes).

Because of the intermittent nature of RES, it is becoming increasingly important that consumers play a more active role on the electricity market (Stawska, Romero, de Weerdt, & Verzijlbergh, 2021; Verzijlbergh, Vries, & Lukszo, 2014). Demand response in the case of high penetration of RES or put simply: using more energy when RES generation is high and using less energy when it is not, is one of the key mechanisms in the energy management on mixed business parks. This could mean that the user patterns of individual firms but also of the aggregated park changes. In fact, the DSO Liander has set up a regulation with a single large user on a mixed business park in Leeuwarden to reduce demand during peak hours, such that local grid congestion was reduced and new firms could be established on the park (Liander, 2022). In the simulation, demand response is modelled as flexibility of the demand.

4.1.5 Energy management optimisation

In terms of energy management on mixed business parks, three different concepts require more attention: grid congestion, energy autonomy and economic optimisation. These can function both as purpose as well as an instrument to increase the use of RES on business parks.

Grid congestion

Due to increased electricity consumption and decentralised electricity generation using solar PV and wind turbines, it was expected that the electricity distribution grid in the Netherlands would require congestion management in the future, especially due to cost-minimising electric vehicle charging (Verzijlbergh et al., 2014). Grid congestion, or transport congestion on the electricity grid occurs when the hardware that manages the electricity, such as cables and transformers, cannot deliver the required capacity to transport electricity. This can occur both for the supply as well as the demand of electricity. An interview with experts dr. Correljé and Michael Pollitt shows that grid congestion is currently affecting many parts in the Netherlands including mixed business parks, even in the absence of EV charging peak demand (Van Hest & Kleinnijenhuis, 2022). Suddenly, level 2 eco-industrial parks must minimise their collective energy use to maintain or expand their businesses.

Currently, grid congestion on the low-voltage or distribution network in the Netherlands is causing significant problems on mixed business parks: new solar roofs cannot be connected to the grid; businesses cannot electrify their fleet because their grid connection does not allow the installation of charging stations and new companies cannot establish themselves at the park (Firan, 2022; Liander, 2022; Van Hest & Kleinnijenhuis, 2022). Studies that aim to solve grid congestion at mixed business parks have not been published yet, perhaps partly because this is mostly a Dutch phenomenon (Jetten, 2022).

To prevent grid congestion with energy management, peak exchanges must be reduced. Therefore, the objective of energy optimisation should be to reduce the peak demand and peak supply of electricity daily.

Energy autonomy

In order to increase the share of renewable energy in the energy mix of mixed business parks, the use of locally produced renewable electricity without exchange with the grid, or energy autonomy, should be maximised (Butturi et al., 2019). Energy autonomy has multiple benefits, as highlighted both in residential and commercial communities (Juntunen & Martiskainen, 2021). From literature, energy autonomy on mixed business parks can be beneficial for several reasons (Maes et al., 2011):

- It increases the security of the supply of electricity because the location is no longer dependent on the grid.
- It can boost the image of companies because they are using their own locally produced renewable energy, something that is becoming more and more important for consumers.

To enhance energy autonomy with energy management, the total annual volume of electricity drawn from the grid must be minimised.

Economic benefits

For economic benefits, two aspects of the costs associated with energy use must be studied: the costs of energy consumption and the cost of the connection to the grid. Depending on the type of connection and the contract with the DSO and the energy supplier, these costs consist of variable and fixed costs. To simplify the approach for the mixed business park, the situation is considered where all the firms participating in the energy management optimisation share a connection and that power is bought at the (wholesale) spot market.

First, in contrast to the fixed prices that most households pay, the wholesale price of electricity fluctuates (EEX, 2023). In general, prices during the day are higher than during the night. During peak demand hours, between 8.00-12.00 and 16.00-20.00 hrs, prices are the highest. Especially due to the integration of RES in the electricity grid, the price of electricity is becoming volatile and can even decrease below zero (Paraschiv, Erni, & Pietsch, 2014). This means that consumers are actually paid for withdrawing power from the grid at that moment. If a smart grid can control the amount of power it consumes and feeds back into the grid, power can be bought at cheap moments and sold at expensive moments.

For this thesis, the day-ahead prices for electricity of the NordPOOL market have been used for the simulated year (NordPool, 2023). On this platform, the hourly spot prices are determined for each hour for the next day. By taking the NordPOOL dataset of The Netherlands, the total costs of electricity for each configuration can be obtained.

Second, the connection costs depend on the size of grid connection and the monthly peak exchanges with the grid. First, it might be that some configurations require a bigger connection based on the simulation. Using average prices of three major DSOs, the costs of capacity expansion are €22/kW (Enexis, 2023; Liander, 2023b; Stedin, 2023). Next, monthly peak exchanges are charged with €2/kW each month. Together, this yields the total annual connection costs.

To gain economic benefits with energy management, the total annual price paid for electricity must be minimised.

4.1.6 Analysis of Commercial Guidelines for the Energy Transition on Mixed Business Parks

To overcome the challenges associated with the realisation of energy symbiosis on business parks, the development of a guideline is useful. Several commercial and public firms have developed guidelines for the energy transition. The analysis of these guidelines forms part of the input for the guideline to be developed in this thesis.

Several guidelines exist for the transformation of business parks into energy hubs. Some target business parks specifically, others consider a broader spectrum of stakeholders and locations. The analysis of the guidelines is based on the drafters, the target audience, the central theme and the structure. Pros and cons of each guideline are discussed.

Firan Energy Hubs guideline

The Firan Energy Hubs guideline is a guideline to improve the integration of renewable energy in industrial parks, mixed business parks, electricity charging stations and other locations that are confronted by grid congestion (Simonse, 2021). It can also be used at locations that wish to become energy independent. The focus of the guideline is on electricity, although hydrogen as a conversion or storage technology is mentioned.

The guideline is *drafted by* Firan and Qirion, both daughter companies of Alliander. Alliander has four daughter companies: Liander, Qirion, Firan and Kenter. Liander is one of the three largest DSOs (together with Enexis and Stedin) and tasked with the delivery of electricity to 5.8 million customers. Kenter is tasked with energy measurement services of commercial customers. Firan and Qirion are active in the energy network: Firan designs, realises and operates energy infrastructure on DSO level, Qirion has the same core activities on the TSO level.

The *target audience* of the guideline is very broad: commercial real estate developers, operators of the energy system, owners of renewable energy projects such as wind or solar PV farms and business parks.

The *central theme* of the guideline is the concept of an Energy Hub. The concept of an energy hub as defined by Firan is shown in Figure 6.

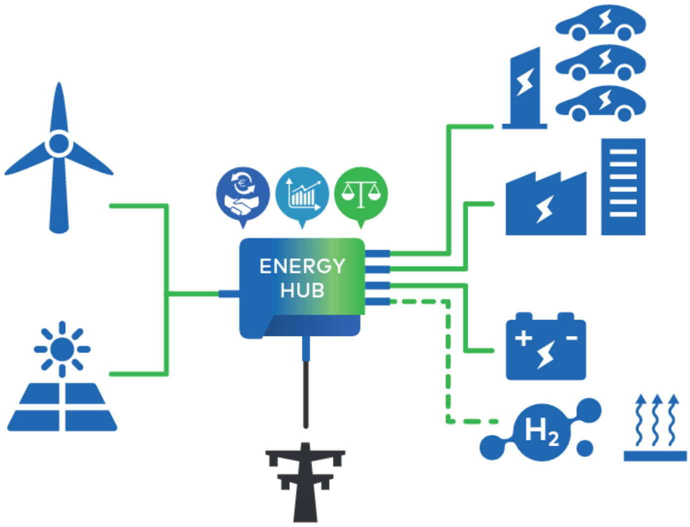

Figure 4.3 The Energy Hub concept as defined by Firan (Simonse, 2021).

In overview, the energy hub consists of 3 aspects: renewable energy generation on the left, demand and storage on the right and a central part in which from left to right the trading of electricity, forecasting of demand and balancing of supply and demand is depicted.

The guideline is *structured* in four steps. Step 1 discusses the start of the project: defining the problem, forming a consortium with the most important stakeholders and setting a shared ambition. Step 2 discusses the investigation of the possibilities: energy analysis, simulations and technical, financial and legal checks. This step should yield several different configurations of the energy hub. Step 3 discusses the design of the hub: collaboration, choosing the best energy hub configuration and financing decisions. Finally, Step 4 discusses the realisation of the energy hub: drafting contracts, realising the technical installation, maintenance and exploitation.

Several aspects of the guideline are useful for the development of the guideline for this thesis project. The guideline provides an overview of the complete process, covers the most important aspects of the energy management as identified in Section 4.1, identifies two go/no-go moments and provides an overview of the design constraints.

However, the guideline is also incomplete. First, although go-no go moments are a good addition to the guideline, it is unclear what the criteria for either a go or a no-go are. Furthermore, the method in which the steps should be taken is not present. Next, Step 2 describes the energy analysis but does not provide any means of analysing the energy consumption by means of a model, or what kind of data should be used for the analysis. Finally, the guideline states that it can be used for different objectives and locations, but general criteria to determine which configuration of the energy hub, as developed in Step 2, is optimal are missing.

TNO Quick Start Guide

The Netherlands Organisation for Applied Scientific Research (TNO) Quick Start Guide is a guideline to reduce the (fossil) energy use on mixed business parks (TNO, 2021). It is a tool that was developed as part of the 'accelerator program to make business parks more sustainable' (Nordkamp, Bakker, Schutte, Strijker, & Bosma, 2021). The focus of the guideline is on building a small group of initiators to implement quick wins in energy saving.

The guideline is *drafted* by TNO. TNO is a research institute in Den Haag that conducts research in various fields. TNO is one of the go-to partners for the Dutch government for scientific research.

The *target audience* of the guideline is business park managers and business associations.

The *structure* of the guideline resembles in some respects the guideline of Firan, although this one distinguishes six steps: organising a group of frontrunners, problem statement, selecting a solution, preparing a tender for the proposed solution, selecting a suitable candidate and execution. Per step, there are additional toolboxes that provide step-by-step procedures for going through the step.

Several aspects of the guideline are useful for the development of the guideline for this thesis project. First, the inclusion of additional toolboxes makes it much more user friendly than the Firan guideline. Furthermore, emphasis is made on approaching the different types of stakeholders, aiming to ensure maximal cooperation. As noted in Chapter 2.3, this is indeed crucial. Finally, the guide lists several options of quick-wins, such as retrofitting lighting using Light-emitting diodes (LEDs), to get a head start.

However, the guideline is also incomplete. Because the guide focusses on quick-wins, a thorough analysis of the energy consumption is missing, and the long-term outlook of the business park is not addressed. This makes the guide less appropriate for locations facing grid congestion and for locations with long-term problems, goals or ambitions. Furthermore, the interaction of different solutions is not addressed. As noted in Chapter 2.2, integration of RES and congestion management involve three aspects: renewable generation, storage or flexibility and a local energy market.

Topsector Energie Guide smart energy systems and PVB Toolkit

The next commercial guideline to be evaluated is the guideline Smart Energy Systems in combination with the PVB Toolkit. The guideline aims to alleviate grid congestion by the implementation of collective smart energy systems. Collective smart energy systems are defined by REBEL as a combination of a local energy market with an information technology layer. In academic literature, these energy systems are often referred to as smart grids. The guideline focusses on the electricity supply.

The guideline and the toolbox are *drafted* by REBEL. REBEL is a private consultant with its HQ in Rotterdam and experts around the world. The consultants focus on sustainability, healthcare, transportation and spatial development. TKI Urban Energy is a part of Topsector Energie. Topsector Energie is an organisation that receives subsidies from the national government for research and development in the energy sector. TKI Urban Energy uses this subsidy for research and pilots in the build environment.

The *target audience* of the guideline is energy cooperations and business park managers.

The *structure* of the guideline is as follows. First, the motivation for the guideline is explained. Smart energy systems can reduce grid congestion, increase the integration of renewable energy and yield economic benefits in the form of demand response based on electricity price, smaller capacity subscription for commercial users and flexibility trading. Then, the guideline explains the physical and virtual layer of the smart energy system. It also discusses several (theoretical) examples of business parks facing grid congestion, a community charging station for electric vehicles and cable pooling for renewable energy generation. Finally, the guideline treats organisational aspects of the smart energy system. The steps are differentiated for different initiators such as energy cooperations, local governments or business parks.

Several aspects of the guideline are useful for the development of the guideline for this thesis project. First, the motivations for the guideline are well described and the notification of financial incentives can be valuable to get entrepreneurs on board. Next, the interaction between different aspects of the system is taken into account. The guideline integrates tooling from the energyefficientsme.eu database to provide technical simulations such as an energy potential scan to evaluate the production of renewable energy on the business park.

However, the guideline is incomplete. It does not contain the simulation of different configurations using actual experimental or company consumption or production data. Furthermore, although different perspectives are incorporated, a method to involve other stakeholders is not very clear.

EIGEN Blueprint for large scale deployment of renewable energy

The final guideline to be evaluated is the blueprint for the large scale deployment of renewable energy on business parks published by the research consortium EIGEN (EIGEN, 2023). The guideline aims to increase the deployment of renewables through the establishment of an energy hub and is explicitly targeted at business parks that are facing transport grid congestion.

The guideline is *drafted* by research consortium Energy Hubs on business parks for the Integration of Large-Scale Renewable Energy (EIGEN). This research consortium is a collaboration of 16 different partners: research institutes, universities, DSOs, consultancy firms and suppliers of renewable energy solutions and network services.

The *target audience* of the guideline is local governments, consultants, entrepreneurial organisations and individual firms.

The *structure* of the guideline is presented in four steps: (1) Exploration, (2) Research & Design, (3) Realisation and (4) Asset management & Exploitation. Each step contains a number of intermediate steps and uses different external tools. Every step includes a stakeholder analysis, expected duration of the step.

The guideline is *useful* is many aspects. To begin with, the concept of the energy hub to mitigate grid congestion is also the main idea of this thesis. Furthermore, the guideline includes effective toolboxes to execute for example the energy investigation and modelling. Next, every step defines the most important stakeholders and a method to include these stakeholders in a meaningful manner.

In overview, the guideline seems very complete. It can therefore be used in the development of the guideline in this thesis. The insights from literature, expert interviews and the case study will provide insight in the suitability of the steps and content described in the EIGEN guideline. One remark that can be made beforehand is that already in Step 1 of the guideline, the very labour-intensive collection of consumer data is executed.

Conclusion about existing commercial guidelines

The analysis of the commercial tooling in previous section shows that there are several missing aspects in all the tools. One thing that stands out is the lack of using actual data to investigate the feasibility of implementing solutions. Furthermore, none of the guidelines integrate stakeholder involvement, energy simulations and a long-term outlook. In the light of the grid congestion problem that large portions of the Netherlands are experiencing or will experience in the near future, as noted in previous chapters, the need for such a guideline seems high.

Furthermore, evaluation methods for mixed business parks with renewables exist, but more research should be done on the application level and in case studies (Butturi et al., 2019). Furthermore, tooling developed for industrial ecology on mixed business parks have focussed on two aspects: (1) physical flows of materials and energy and (2) social-economical aspects (organising the stakeholders, decision-making, business plans, etc.) (Eilering & Vermeulen, 2004). A coupling between thesis tools is not present in current literature and only to some extent in existing commercial guidelines. Therefore, rather than just provide an energy management model, this thesis research will integrate this tool into a guideline for stakeholders in mixed business parks to use RES to solve grid congestion.

4.2 Stakeholder identification on mixed business parks

The discussion of the energy management and the guideline in previous section considers the energy system from a technical perspective. This section highlights the people and organisations in this system. For this, a stakeholder map is developed. This analysis is also based on the discussion of the commercial guidelines in previous section.

4.2.1 Stakeholder Mapping

Due to the nature of the problem the stakeholders can differ, but in the case of energy management (especially electricity), the following stakeholders apply.

- Entrepreneurs and business owners on the park
- Park management
- Entrepreneurial organisation
- Local government
- Provincial and national government
- Distribution service operator (DSO)
- Transmission system operator (TSO)
- Regulators
- Energy service companies
- Developers of electricity grid solutions

As is clear from the list of stakeholders, this is a very diverse group. To organise a transition with such a heterogeneous set of stakeholders, (Callon et al., 1992) developed the Techno-Economic Network to map the relationships and exchanges between different actors surrounding a transition. Figure 7 shows the five categories in which the stakeholders are grouped and Figure 8 shows the relationships between the stakeholders on the mixed business park.

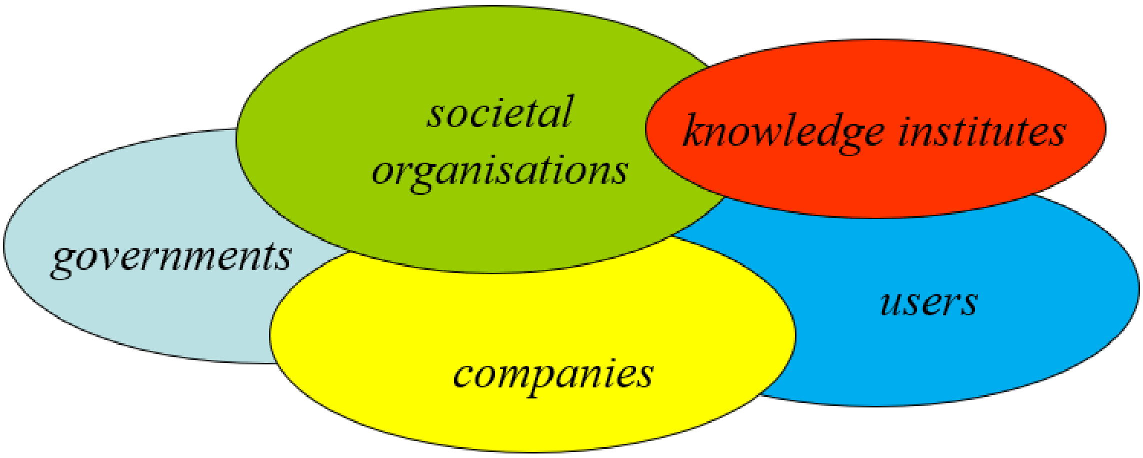

Figure 4.4 Stakeholder groups in transitions (Callon et al., 1992).

The five groups in sustainable transitions represent different sectors in society. For the energy management transition on mixed business parks, the following stakeholders per group are identified.

Governments: municipalities, regional governments (provinces in the Netherlands) and the national government.

Companies: DSO, TSO, measurement companies, energy service providers, electricity grid solution providers, installation companies of renewable energy, consultants.

Societal organisations: entrepreneurial organisations, park management.

Knowledge institutes: universities and expertise centra.

Users: entrepreneurs on the mixed business park.

Because the energy management on mixed business parks is still in early development, several remarks should be made:

Several companies such as the DSO, TSO, societal organisations, knowledge institutes and (in the case of public services on the mixed business parks) users are (partly) state owned.

Some stakeholders are vertically integrated in the market, in the sense that for example Liander is the DSO, provides energy services with its daughter company Firan and is part of expertise centra such as Project EIGEN.

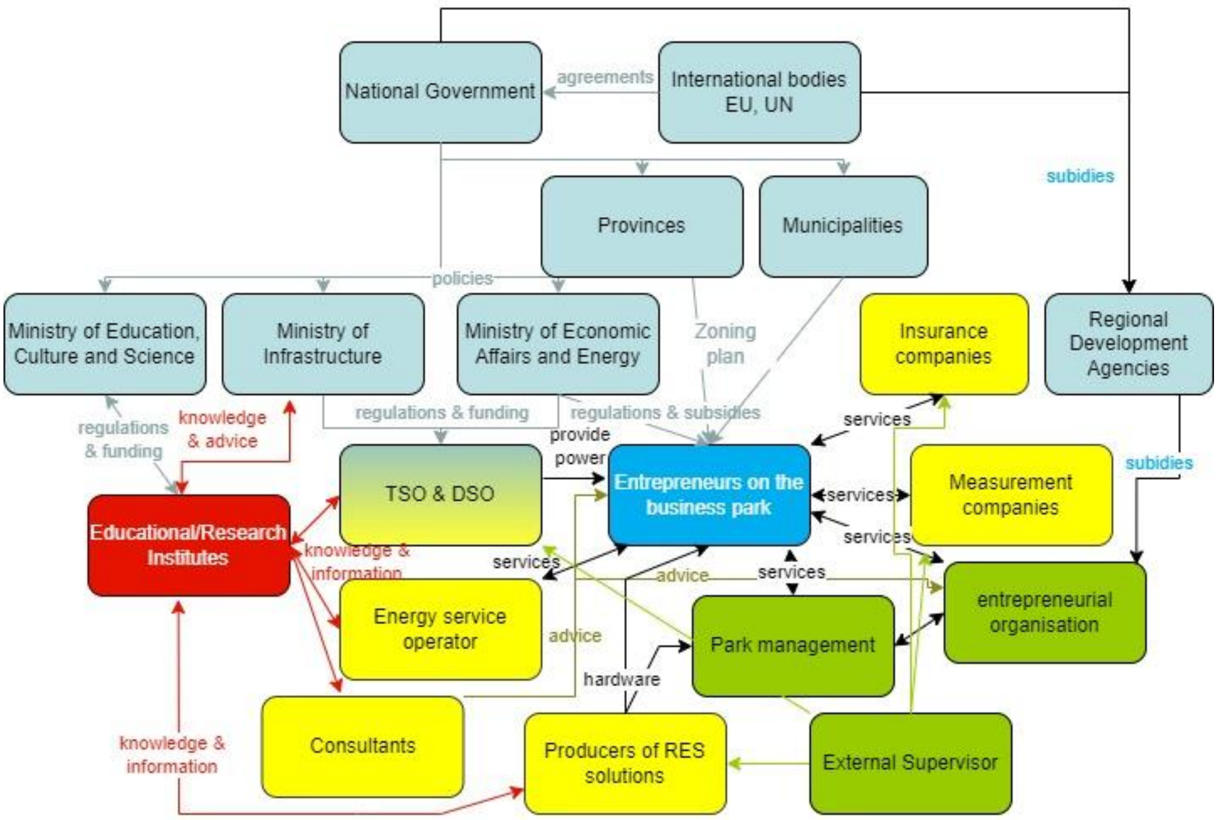

Figure 4.5 Stakeholder map for energy management on mixed business parks.

The stakeholder map shows the different stakeholders per category and explains the relationships between them. The entrepreneurs on the business park are the centre of the stakeholder map.

The EU and UN are involved because they provide subsidies and draft agreements that shape policies on national level. Examples of subsidies include the program for Renewable Energy Communities, the implementation of charging infrastructure and Project DOEN (EU, 2018; INTERREG DOEN, 2023; RVO, 2022a). The Paris Agreement is the leading international agreement concerning the energy transition

(UN, 2016). The national and regional governments draft policies that are executed by the ministries and the municipalities, although the municipalities have some freedom to choose their own accents. An example of a project of the municipality is the LEEF-Project in Heerenveen (Gemeente Heerenveen, 2023). The provinces and municipalities have an important instrument in determining the development of a specific area: the zoning plan and the environmental regulation (Dutch: omgevingsverordening or omgevingsvisie), respectively. This determines what kind of activity or occupation may take place on a specific piece of land. For every location in The Netherlands, it is possible to obtain the most recent information on an interactive map (Rijksoverheid, 2023).

The TSO and DSO are multi-coloured because they represent companies but are 100% publicly owned and must obey to many laws and regulations. Therefore, they cannot act as independent companies, for example because they have an obligation to connect users to the grid if the permit is issued (Rijskoverheid, 1998).

The regional development agencies are funded by the national government but can also receive international subsidies such as INTERREG. These development agencies are important stakeholders because they organise pilot projects on different business parks, that yield important do's and don'ts for the development of an advanced energy management system on a mixed business park (OostNL, 2022).

Universities and other research institutes play a central role in the development of knowledge surrounding energy management on industrial and mixed business parks. Research projects include Smart Energy Hubs (OostNL, 2022), EIGEN (EIGEN, 2023), GEAR@SME, BE+ (Nordkamp et al., 2021), HOLON (HOLON, 2023) and more . TNO, TU Eindhoven, TU Twente and TU Delft participate in one or more of these research consortia, together with DSOs, consultants and other firms that provide platform services for sharing of electricity or develop large scale RES generation for business parks.

Most of the companies surrounding the energy transition on mixed business parks provide services to the users. For a commercial user of electricity, the following stakeholders are most important:

1. The DSO, who manages the connection of the user to the grid. The DSO charges the users for the capacity of the connection to the grid and for the monthly peak exchange on this connection.
2. The energy service operator, who is a retailer of electricity and supplies the electricity to the user.
3. The consultants, who advise the users on their individual energy consumption and perform energy savings analyses (in Dutch: Energiebesparingsonderzoeken).
4. The producers of RES solutions. These are the companies that realise rooftop PV panels, heat pumps, etc.

4.2.2 Stakeholder Engagement

Now that the playing field of the stakeholders has been established, the stakeholders must be engaged in the transition. For this, multiple strategies exist. The focus of this thesis is on providing practical insights to organise and engage stakeholders in the optimal way. A detailed strategy for the engagement of stakeholders is not within the scope of this thesis.

To begin with, some effort must be done to recruit a decent number of entrepreneurs active on the park to make the transition successful. This can be difficult because mixed business parks are often characterised by small to medium sized enterprises (SMEs) and the business owners do not have much spare time to engage in a transition project (Lambert & Boons, 2002). Because scientific publications about recruitment on business parks is not available, lessons can be drawn from the agricultural sector

(Weigel, Paul, Ferraro, & Messer, 2021) and General Practitioners (McKinn, Bonner, Jansen, & McCaffery, 2015), where businesses are also often run by a few individuals whose focus is primarily on keeping the business going. Two main takeaways from these articles are:

1. Financial incentives are effective, but costly (Weigel et al., 2021). The case study of Heerenveen-Zuid has shown that for business parks that suffer from grid congestion, the financial consequences for locked-in users are often severe, increasing their motivation to contribute to a shared solution.
2. Recruitment at business events is suitable for experiments that require a high response rate (McKinn et al., 2015).

Secondly, recent research has highlighted the importance of organisation and collaboration on the park through a Business Investment Zone (BIZ) for the energy transition (de Zoete – van der Hout & Koning, 2020; Moore & Mell, 2023; Wiesman, 2023). First, the BIZ eliminates the problem of free-riders: users on the park that do not collaborate on the solution, but profit from the effort of others (Bedrijven Investerings Zone, 2024). Furthermore, the BIZ provides the mixed business park with financial strength for realising the transition. If a BIZ is not present, it is essential to establish a BIZ in this step.

Finally, it is essential to establish robust mechanisms for keeping all parties informed and involved (Kola-Bezka, 2023; Komendantova, Riegler, & Neumueller, 2018). This involves organizing a variety of information sessions, focus groups, and other interactive platforms aimed at fostering open dialogue and transparency. By regularly updating stakeholders on the progress, challenges, and opportunities associated with the transition, concerns can be addressed in a timely manner, and collective buy-in can be strengthened. Additionally, these engagements serve as opportunities to gather valuable feedback, insights, and suggestions from diverse stakeholders, thereby fostering a sense of ownership and shared responsibility for the transition. Furthermore, by facilitating communication channels that encourage active participation and collaboration, stakeholders can contribute their expertise, resources, and perspectives towards shaping a sustainable and inclusive energy future for the business park and the wider community.

4.3 Energy modelling tool

The analysis in Section 4.1 concludes that the inclusion of a technical tool to model the electricity flows on the mixed business park is important. Therefore, based on objectives and requirements a tool has been developed. The electricity simulation tool is used in multiple steps of the guideline. In Step 2, the actual electricity data is used in the tool to generate a detailed image of the balance between consumption and production of electricity and the status or severity of grid congestion on the park. In Step 3, the tool is used to simulate configurations using different options of renewable energy generation and storage to find the optimum solution for the park.

For the tool, several objectives and requirements have been formulated which are presented in 4.3.1. The tool development is discussed in 4.3.2 and the tool assumptions are discussed in 4.3.3. These steps are presented in this chapter because they are the same for each case study and data source. The final description of the tool that is designed for the case and data of the case study follows in Chapter 5, where it is applied to the case study data.

4.3.1 Objective and requirements

The objective of the tool is to simulate the current and future electricity flow of a mixed business park.

The tool has several requirements that can be divided into three categories: technical, output and user requirements.

Technical requirements:

1. The tool shall offer the possibility to include renewable energy sources;
2. The tool shall offer the possibility to include site data;
3. The tool shall offer the possibility to include aggregated data from literature (such as user profiles for distinct economical processes);
4. The tool shall offer the possibility to study the exchange of energy with the boundaries of the system (import/export);
5. The tool shall offer the possibility to include buffer and storage options such as batteries, power-to-gas (electrolysis) and heat and cold storage;
6. The time resolution of the tool shall be sufficiently small to study the hourly electricity flow;
7. The tool shall be an integrated model to capture the interaction of different energy supplies and demands.
8. The tool shall offer the possibility to specify the demand of each sector (transport, buildings, industry) individually, to simulate a mixed business park.

Output requirements:

1. The tool shall report the annual energy mix and CO_2 emissions of the simulated configuration;
2. The tool shall report the required investment costs of the simulated configuration;
3. The tool shall report the exchange of energy with the boundaries of the system;
4. The tool shall report the peak and average electricity demand of the system.

User requirements:

1. The tool shall be free to use (no paid subscription needed);
2. The tool shall be operable on a standard laptop and PC with simulation run times of less than a minute;
3. The tool shall include a user-friendly interface.
4. The tool shall include comprehensive documentation for verification and validation of model outcomes.

4.3.2 Tool development

Using multiple review articles (Dagoumas & Koltsaklis, 2019; Priesmann, Nolting, & Praktiknjo, 2019; Ringkjøb, Haugan, & Solbrekke, 2018; Tozzi & Jo, 2017) and leads provided by my Antea supervisor Joris Knigge and TU Delft supervisor Michel Fremouw, four models have been evaluated: HOMER (Khalil et al., 2021), EnergyPLAN (Lund et al., 2021), the Energy Transition Model (Quintel, 2023) and urbs (Dorfner & Hamacher, 2022).

HOMER fulfils all technical and output requirements and has been used in a previous study of the energy management of mixed business parks (Maatman, 2022), but requires a paid subscription. This would significantly impair the possibility to replicate the method followed in this thesis and therefore the tool is not selected.

EnergyPLAN fulfils all requirements. The possibility of coupling the energy and transport sectors is a promising feature of EnergyPLAN (Ringkjøb et al., 2018), because the usage of electronic vehicle charging as a flexibility option on mixed business parks can be explored.

The Energy Transition Model of Quintel Intelligence is suitable for the design of a sustainable mixed business park but lacks sufficient documentation. Therefore, the effects of changing parameters on the outcome of the model cannot be studied. The ‘black box’ of underlying assumptions and logic therefore limits the options to verify and validate the results obtained by the model.

urbs fulfils all technical and output requirements but requires understanding of Python to operate. This makes it harder for consultants, government officials and entrepreneurs without proper knowledge of Python to use.

In conclusion, EnergyPLAN provides the best option for simulation of the business park. It covers all requirements stated above and is free to use. EnergyPLAN is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark and is open source. It is developed for the operation of the energy system at national scale (Lund et al., 2021) but has also been used on local scale for the simulation of regions, cities and a congregation of buildings (Østergaard, 2015). This congregation of buildings is comparable to a mixed business park.

To make the tool suitable for the use on a mixed business park and provide enough detail to study (the effects on) grid congestion, modifications were made. In the end, EnergyPLAN has formed the basis, but final execution of the complete analysis was performed using a combination of Python, MS Excel and EnergyPLAN. This is discussed in the next section. It should be noted that the analysis could also have been performed without Python, by making use of similar functionalities integrated into MS Excel. The runtime of the Python scripts (See Appendix D) was several seconds.

4.3.3 Tool assumptions

It is important to realise that the tool is not reality, but a representation of reality. The tool itself and the usage for this thesis comes with several assumptions to simplify the model and make it suitable for the application to a mixed business park. The model assumptions of EnergyPLAN are listed in the documentation of EnergyPLAN (Lund et al., 2021). The user assumptions for this thesis are the following.

- Not all roofs are suitable for PV panels. Furthermore, some roofs already have been fitted with panels. The total available panel area for new panels is 20% of the total roof area.
- Energy yield per square meter panel: 200 Wp/m^2 (based on consumer grade solar PV panels available at EnergieWonen, Soly and Solar Magazine). Datasheet available in Appendix.
- Electrical storage is proportional to the peak grid exchange (demand or supply). A peak exchange of 1 MW yields a 1 MWh battery with a power rating of 250 kW. This ratio of storage and capacity is common for RES integration and self-consumption enhancement (Killer, Farrokhseresht, & Paterakis, 2020; Maatman, 2022).
- RES generation:
    - The annual capacity factor for South oriented PV panels is 0.117 (JRC, 2023). This means that a 6 MWp installation yields 6166 MWh.
      The annual capacity factor for Eat-West oriented PV panels is 0.095 (JRC, 2023). This means that a 6 MWp installation yields 5007 MWh.
    - The capacity factor of wind energy is determined based on the simulation of wind energy. Inputs are the hourly wind speeds measured at 10 meters above ground at a meteorological site close to the business park and the power curve of the wind turbine. This value can be compared to the capacity factors of 3 operational onshore wind farms in the neighbourhood of the mixed business park: Windpark N33 (0.32-0.39) (RWE & Eurus Energy, 2023), Windpark Drentse Monden en Oostermoer (0.30-0.35) (RVO, 2019) and Windpark Fryslân (0.44) (Windpark Fryslân, 2023).
- The carbon intensity of the grid electricity consumed on the mixed business park is assumed constant at 356 gCO_2/kWh (Our World in Data, 2023). In reality, carbon intensity is dependent on the type of electricity generation (Miller, Novan, & Jenn, 2022). Because solar PV in The Netherlands peaks during midday, the carbon intensity dips. This coincides with offices hours.

Furthermore, during off peak hours (during the night), the high penetration of Dutch wind energy reduces the carbon intensity. By assuming a constant carbon intensity, the CO_2 emissions of grid electricity consumed on the mixed business park will be overestimated by 0-10% (Miller et al., 2022).

- LCOE per energy source (Department for Energy Security and Net Zero (UK GOV), 2023; EIA, 2023; IRENA, 2023; Pacific Northwest National Laboratories, 2023; PBL, 2023b; Trinomics, 2020).
  - Rooftop Solar PV: 0.072 €/kWh (PBL, 2023b).
  - Onshore wind: 0.05 €/kWh (IRENA; Trinomics; UK GOV), 0.057 €/kWh (PBL, 2023b).
  - Combined Cycle Gas Turbine (CCGT) and Open Cycle Gas Turbine (OCGT): 0.05-0.10 €/kWh (EIA; Trinomics), 0.14 €/kWh (UK GOV).
  - Coal: 0.08 €/kWh (EIA; Trinomics).
  - CHP: 0.08 €/kWh (EIA; Trinomics; PBL).
  - Battery storage: 0.11-0.14 €/kWh (EIA, PNNL).

  →For the Dutch electricity mix in 2021 (IEA, 2023), the assumed Levelised Cost of Electricity (LCOE) of grid electricity is 0.095€/kWh based on the fuel mix and LCOEs mentioned above. The LCOE is a metric for the cost of energy of a specific energy source, including investments, operations and decommissioning.
- Investment costs RES:
  - Wind energy (in the Netherlands): €1350/kW (PBL, 2023b)
  - Rooftop PV (in the Netherlands): €555/kWp (PBL, 2023b) - €1000/kWp (Groenpand; Energiezakelijk). €700/kWp is chosen for the analysis.
  - Storage: €100-200/kWh (Killer et al., 2020; Komorowska, Olczak, Hanc, & Kamiński, 2022). €150/kWh is chosen for the analysis.
- Connection costs:
  - Monthly peak exchange: €2/kW,
  - Annual connection capacity: €21.54/kW,
- Net Present Value (NPV):
  - Discount rate: 4%,
  - Capacity tariffs increase with 5%/year,
  - Grid electricity costs increase with 2%/year.

In Section 6.4.1, these assumptions will be evaluated.

4.4 Case Study Description: Heerenveen-Zuid

As mentioned in Chapter 2, the approach used in this thesis can be followed as a guideline to perform an energy transition on mixed business park. For this thesis project, the existing mixed business park Heerenveen-Zuid has been analysed. This section provides the main characteristics of the business park.

4.4.1 Location, size and companies

Heerenveen-Zuid mixed business park is in Heerenveen, Friesland. As the name suggests, the park is situated in the South of Heerenveen, a town with approximately 30 000 inhabitants. The total area of the perimeter of park is roughly 0.75 km^2.

A map of the park is provided in Figure 4.6. In this figure, all firms on the park have been indicated with a label. The green labels represent firms that have a large-scale connection to the grid, the red labels represent small-scale users. In total, 81 firms are present on the park.

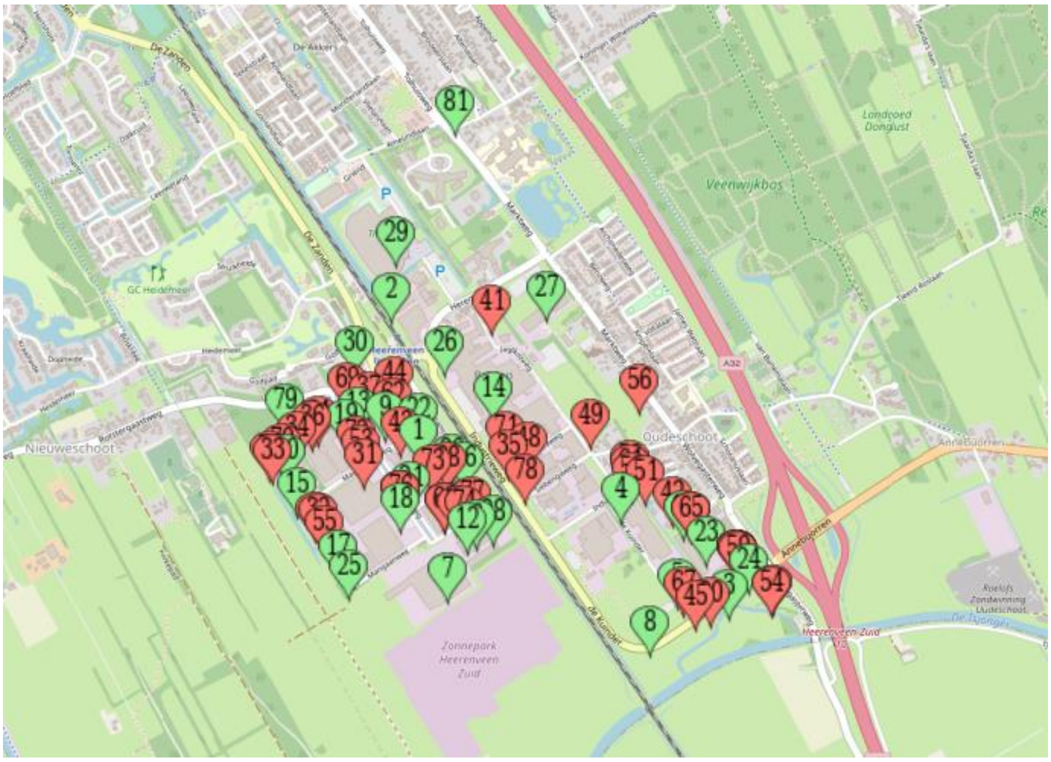

Figure 4.6 Map of the companies connected to distribution station Pim Mulier and part of Heerenveen-Zuid. Green are large scale users, red small-scale users.

Not all companies were part of the pilot project of Antea Group. The focus of the pilot project was on the large-scale users, also because these users have accurate and detailed data of the electricity consumption. In the end, 70% of the total annual electricity consumption of the park was captured in the pilot project.

The large-scale users can be grouped into categories that describe their electricity consumption. Based on the three categories proposed in subsection 4.1.4, the distribution is as follows:

Table 4.2 Grouping of companies into user profile categories.

Category	# of firms	% of annual electricity use
9-17 office hours	20	80
8-20 opening hours (including Saturday)	4	12
Continuous	4	8

Economic activities are diverse: food production, car retailers and maintenance, hotel and restaurants, logistics, bike manufacturing, etc. Because several companies have expressed concerns regarding their privacy, a complete list of the companies present in the pilot is not available. However, because the categories are known and more importantly, the electricity consumption is available, analysis and design of the energy system of the mixed business park is possible without private information of the participating companies.

4.4.2 Electricity Infrastructure

The mixed business park is connected to a single DSO distribution station: Pim Mulier. From the Pim Mulier station, multiple cables supply electricity to the area. Three of these cables have become congested. Figure 4.7 shows a schematic representation of the grid situation in Heerenveen and Figure 4.8 shows these cables on the map of Heerenveen-Zuid with the use of ArcGIS (ArcGIS, 2022). The purple cables are middle voltage cables and supply electricity to the large commercial consumers, the red cables are low voltage cables.

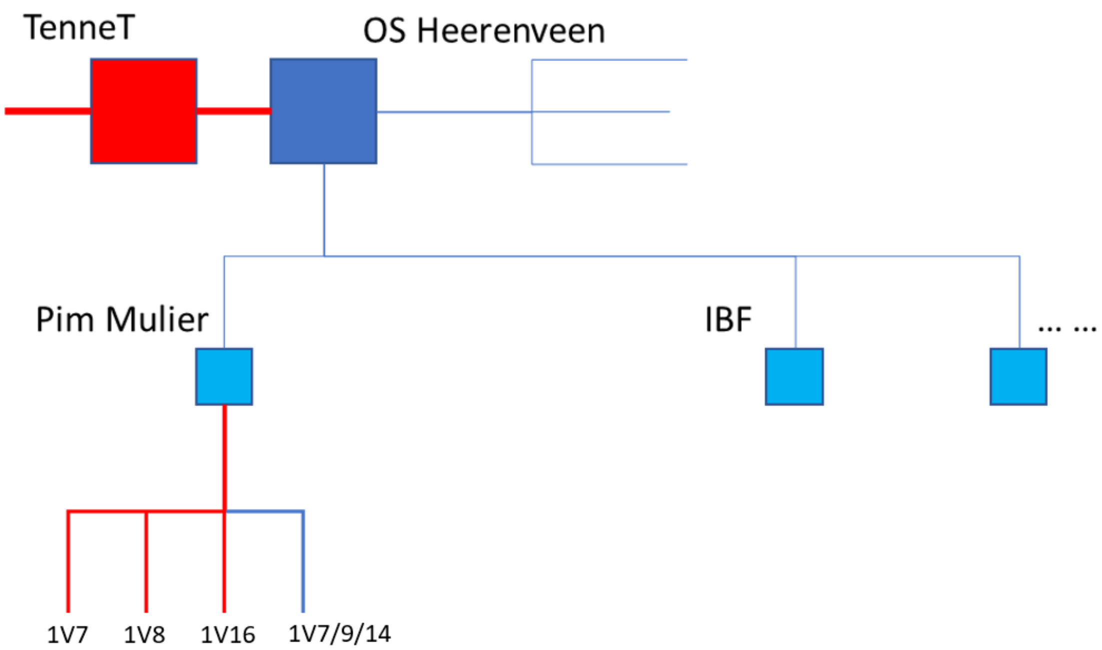

Figure 4.7 Schematic representation of the grid situation in Heerenveen.

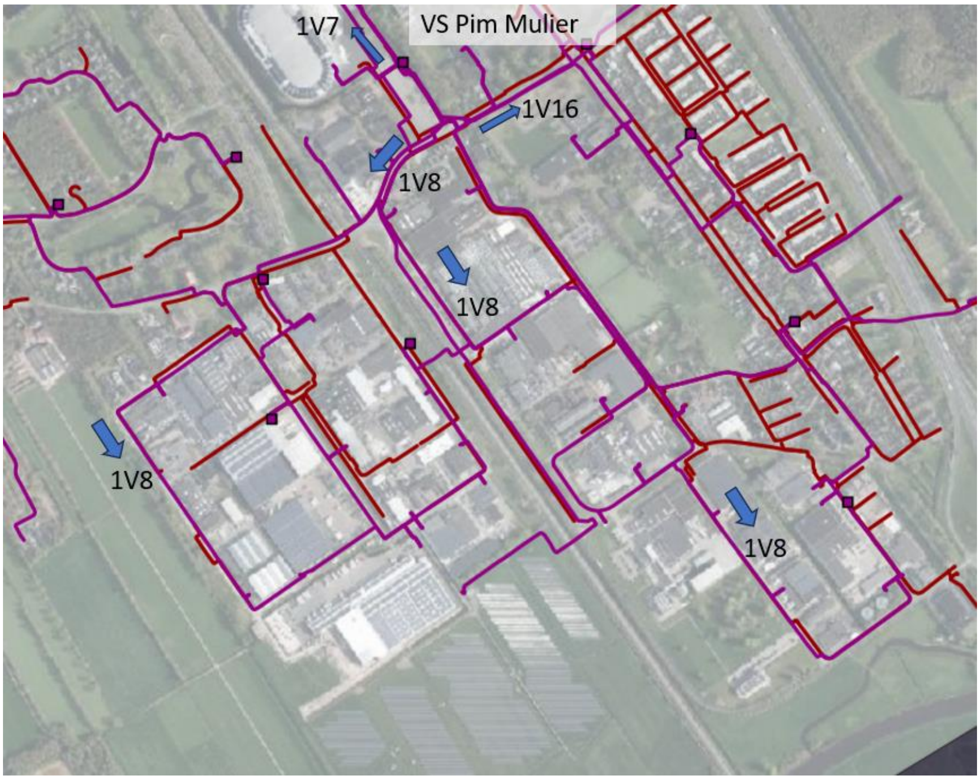

Figure 4.8 Satellite image showing the grid infrastructure on Heerenveen-Zuid. Created with ArcGIS.

TSO Tennet is faced with grid congestion problems due to supply peaks of RES, whereas the grid congestion on the cables connected to substation Pim Mulier are faced with grid congestion due to the demand of electricity. The analysis of the baseline case in Chapter 5 will show that this is indeed the case, as annual supply peaks are much lower than the demand peaks.

The DSO Liander has planned to increase the capacity of these cables, but this only temporarily resolves the transport congestion. Future increases in grid exchange, both supply and demand, could result in the same problem. Furthermore, the costs of increase the capacities of the cables and the substation are significant (Royal HaskoningDHV, 2022). Therefore, the municipality of Heerenveen started a pilot project. Together with the entrepreneurs on the park, the park management, the entrepreneurial organisation and Antea Group, a pilot project was initiated to reduce the grid congestion on the park.

4.4.3 Responsibilities of Antea Group

In the pilot, the responsibilities of Antea Group were the following:

1. Inform all stakeholders about the current situation and translate this to the implications for the entrepreneurs on the park.
2. Gain insight in the actual energy situation in terms of total volumes, transportation peaks, flexibility options and future demand scenarios.
3. Propose solutions aimed at the individual companies and at the park as a whole.

4.4.4 Current status of the case

After Step 3 of the previous subsection was performed, the individual users are investigating the optimal solutions for their situation. Antea Group is monitoring the process and is available as a sparring partner for the stakeholders.

4.4.5 Added value of this thesis to the case study.

The results of this thesis are of great value to the mixed business park because it proposes shared solutions for the park in terms of renewable energy generation. The integration of these RES may, as will the analysis of different configurations show, reduce the peaks of grid exchange on the mixed business park. Furthermore, it shows the potential of implementing storage or demand response to reduce grid congestion. Finally, this thesis provides a balanced optimal solution for the energy situation at Heerenveen-Zuid because the proposed solutions are evaluated on multiple criteria. This evaluation framework can also be used for other mixed business parks in Heerenveen, Friesland and other locations in the Netherlands.

5. Step 2: Analysis of current energy balance on mixed business park

This chapter describes the tool to analyse the electricity flows on the mixed business park and presents the results of the baseline electricity consumption. Based on the park introduction in 4.4, the options for RES are discussed.

The chapter is structured as follows. Section 5.1 describes the energy management tool that is used to analyse the electricity balance on the mixed business park and simulate RES configurations (Chapter 6). Section 5.2 then presents the analysis of electricity balance the mixed business park. This is followed by an investigation of the RES potential on the park in Section 5.3.

5.1 Energy management tool description

The tool uses a combination of EnergyPLAN, Python and Excel. EnergyPLAN is used for the distribution profiles of RES generation, Python is used to aggregate the data from different users and to run the configurations with battery storage and the configurations with flexibility, Excel and Python are used to analyse the datasets and create visuals.

The tool consists of five modules: data formatting, introduction of RES capacity, introduction of storage, introduction of flexibility and output generation. This is shown in Figure 8. Each module consists of several steps.

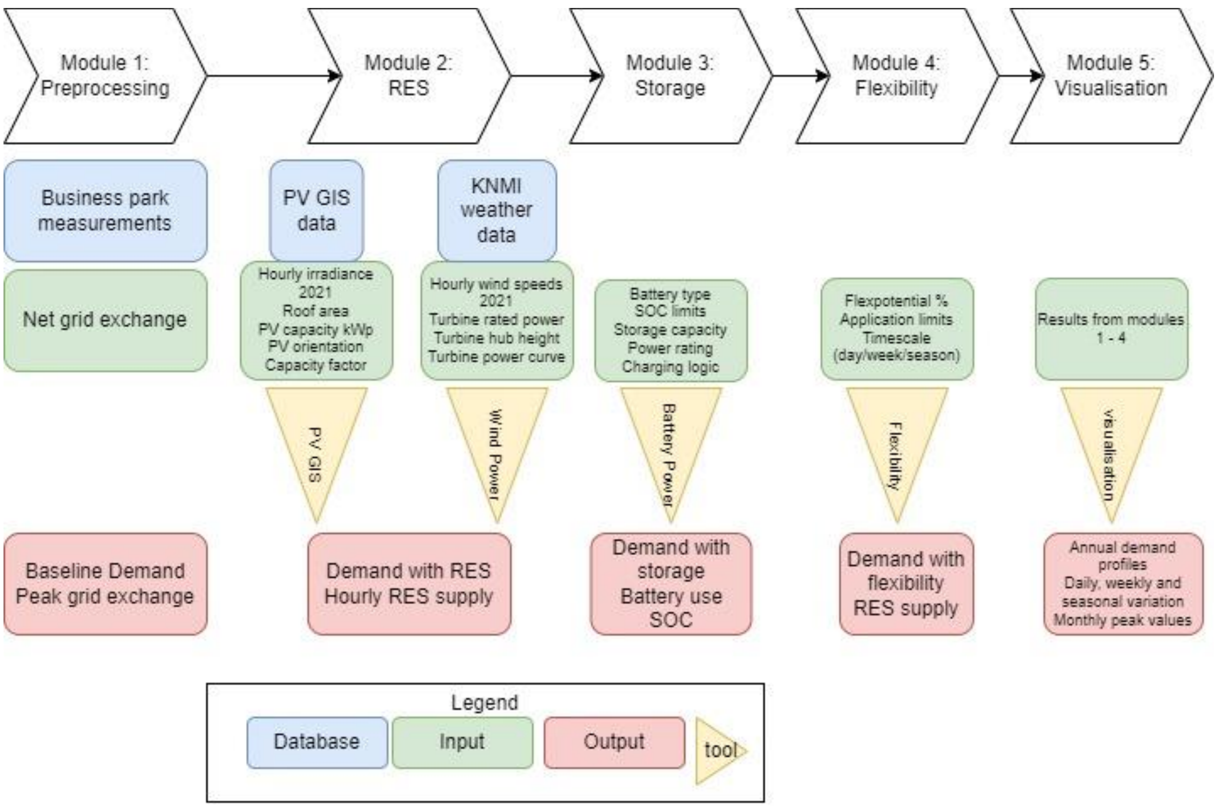

Figure 5.1 Structure of the mathematical model used to evaluate the RES configurations.

Table 5.1 Introduces all parameters that will be used in subsequent modules of the tool.

Tabel 5.1 Parameters for the modules of the tool.

Parameter	Unit	Symbol
Electrical power P	Watt	W
Rated power of solar PV panels	Watt Peak	Wp
Energy or storage capacity	Watt hour (= 3600 Joules)	Wh or J
Volume	Cubic meters	m^3
Area	Square meters	m^2
All monetary aspects (costs, revenues, etc.)	Euros	€
Surface roughness length	Meters	m
Wind speed	Meters per second	m/s
Hub height	Meters	m

Module 1: Data sourcing

To obtain the consumption data, different options exist as noted in Section 3.2.3:

1. Construction of user profile based on literature.
2. Construction of user profile based on interviews with the user.
3. Installation of a separate measurement unit at the user.
4. Calculated based on the data from the local grid operator.

Each option has its strengths and weaknesses:

Literature-based may be less time consuming but lacks detail. Furthermore, data is not easily accessible or does not fit the type of activity on the mixed business parks. Some efforts have been made to estimate the energy consumption based on floor level (Maes et al., 2011), but this is not accurate enough for business parks that are faced with grid congestion. Recently, a UK study developed average daily consumption profiles for several activity types on mixed business parks (Granell, Axon, Wallom, & Layberry, 2016). One drawback of the use of average daily profiles might be that this does provide correct monthly and annual peak demand or supply values.

Construction based on interviews is more consuming, but data quality is not guaranteed. The user might report inaccurate values about daily energy use. Because most non-residential users in the Netherlands receive monthly bills for their electricity use, insight in monthly consumption and peak exchanges with the grid is better compared to literature-based (Liander, 2023a).

Construction based on data provided by a separate measurement unit is the most detailed level of data. This can be time consuming because each connection must be fitted with a measurement unit. Luckily, 60% of small commercial and residential connections in the Netherlands voluntarily use a "smart meter" that register and communicate the daily use of electricity to the DSO (CBS, 2021a). For large users with a connection of more than 100 kW "telemetry meters" are obligated that store the consumption of electricity in 5 or 15-minute resolution (Joulz, 2020). Obtaining this information requires consent from each individual user, after which the data can be retrieved from the contracted measurement company. This is a very time-consuming process.

In case the three options above are unavailable, a final option is to go to the DSO. The DSO does not possess company consumption data but measures the flow of electricity in the infrastructure. If a business park is connected to a single cable or substation, the aggregated use of electricity on the park can be obtained at this location.

For the case study, the data provided consists of Excel files that contain electricity consumption data from 2021 with a 5-minute or 15-minute resolution. Every individual address has a separate file, which means that companies with multiple addresses have multiple data files. Also, some companies have more than one grid connection on a single address. This means that the data file consists of multiple columns. Because EnergyPLAN assumes leap years, 8784 (24*366) hourly values per year are needed. This means that an extra day is created at the end of the year with a representative consumption profile for that weekday.

Data preprocessing involved the following steps:

1. Store all data files in a single folder.
2. For all data files with multiple grid connections, create a merged (=summed) column.
3. For all data files with 5-minute resolution, take the average of every three 5-minute values to obtain 15-minute resolution.
4. Sum all consumption columns to obtain one single column containing 15-minute data.
5. Take the average of every four 15-minute values to obtain hourly values.

Some details are lost during the resizing of the data from 5 or 15- minute values to hourly values. In terms of total energy consumption, the use of average values ensures that there is not offset. However, in terms of peak values in consumption and supply differences occur. Comparison of original and hourly data files shows that the offset in daily, monthly and annual peak values is <1.8% for positive peak values and <3% for negative peak values.

Module 2: RES integration

For Solar PV and wind, hourly values must be generated.

For solar PV, the PVGIS tool of the European Commission Joint Research Centre (JRC) has been used (JRC, 2023).

1. Define location by zooming and clicking on the map.
2. Select year: 2021.
3. Choose mounting type: Fixed.
4. Choose orientation: for South, select "Optimise slope and azimuth". For East/West, first select 90 (East), then select "Optimise slope".
5. Choose PV technology: Crystalline silicon.
6. Define PV power in kWp: 6000 for South, 3000 for East/West.
7. System loss: 14% (default).
8. Repeat Steps 4-7 for -90 orientation: West.
9. This yields one dataset with 8784 values of South orientation 6 MWp PV and two datasets 3 MWp East and West, respectively. Summing East and West yields 6 MWp East/West.

For wind, no database of hourly data is available comparable to PVGIS. Therefore, the following procedure is used:

1. The KNMI hourly dataset of average wind speed at 10 m above ground in Leeuwarden from the year 2021 is exported (KNMI, 2023a). This KNMI weather station is chosen because it is the closest station that stores the complete historical set of wind speeds.
2. Using the local roughness length: $z_0 = 0.3$ m, this is translated to hub height of 100m using the logarithmic profile law in the equation below. $z_0 = 0.3$ m is derived from the course *Introduction to Wind Turbine Design* (Wieringa & Rijkoort, 1983; Zaayer, 2022).

$$V_{hub} = V_{measured} * \frac{\ln\left(\frac{h_{hub}}{z_0}\right)}{\ln\left(\frac{h_{measured}}{z_0}\right)}$$

In this equation, V_{hub} denotes the wind speed at hub height in m/s, $V_{measured}$ is the measured wind speed at the measurement height in m/s. h_{hub} is the hub height in m and $h_{measured}$ is the measurement height in m.

3. A simplified power curve is constructed based on a cut-in wind speed $V_{cut\text{-}in}$ of 3 m/s, rated wind speed of 12 m/s and cut-out wind speed of 25 m/s. This is comparable to a Siemens SWT 3.0-108 that is used in neighbouring wind parks with a rated power P_{rated} of 3 MW (RVO, 2019; RWE & Eurus Energy, 2023). The power curve is shown in Figure 7. The curve between cut-in and rated wind speed is given by the following expression:

   $$P(V_{hub}) = 0.016 \left(\frac{V_{hub}}{V_{cut-in}}\right)^3 * P_{rated}$$

   In this equation, all parameters are as mentioned above. $P(V_{hub})$ is the resulting power for that specific wind speed at hub height. The factor of 0.016 is found empirically.

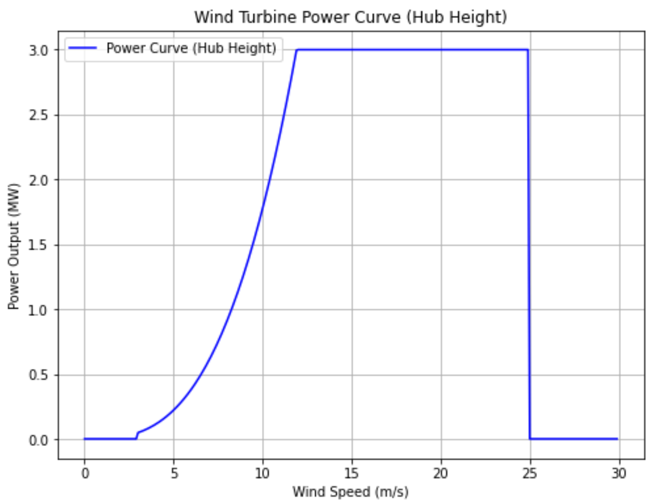

Figure 5.2 Power Curve of the simulated 3 MW turbine.

4. The hourly power outputs are found by the equation below.

   $$P\ (V_{hub}) = \frac{P(V_{hub})}{P_{rated}} * P_{rated}$$

5. Hourly power values are stored in a new file.
6. This yields a dataset with 8784 hourly values of the 3 MW turbine.

Finally, The RES yield files are combined with the hourly demand values of the mixed business park to obtain the new hourly demand of the business park. Positive demand means power is drawn from the grid; negative demand means power is supplied to the grid.

Module 3: Storage integration

The next step is to integrate the option of storage. The battery storage will be proportional to the RES capacity: 6 MWh and 1.5 MW charge and discharge (see Section 4.3.3). The battery type will be a Li-ion (see Section 4.3.3).

The battery can be programmed to the end-user's preferences. In this case, peak shaving and maximisation of self-consumption of RES have been tested. A visual representation of the battery storage logic is shown in Figure 5.3.

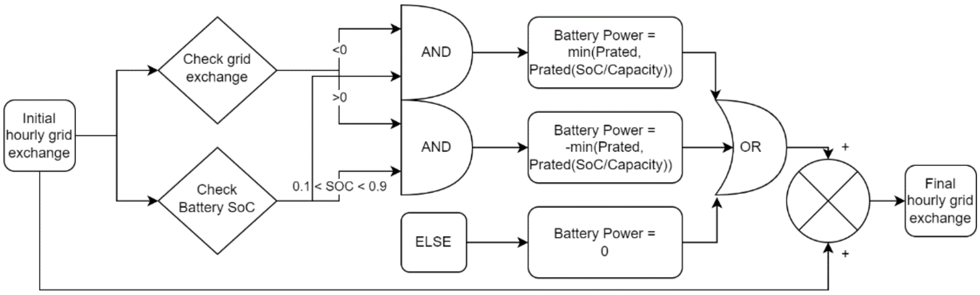

Figure 9.3 Flow diagram of battery charging logic.

In words, the battery is simulated as follows:

1. The capacity of the battery is set at 6 MWh and the power rating of the battery is 1.5 MW.
2. The battery charging limits are defined: for Li-ion, the state of charge (SOC) may vary between 10% and 90% to avoid excessive wear of the battery (Woody, Arbabzadeh, Lewis, Keoleian, & Stefanopoulou, 2020).
3. The charging and discharging moments are defined:
    a. The battery starts charging at demand < 0 kW so whenever there is a surplus of electricity and discharges at demand > 0 kW.
    b. The charging power may not violate the charging limits, so the charging or discharging power is the minimum of two values: the rated power and the remaining "space" left in the battery: Prated*(SOC/Capacity).
4. The power flowing **to** the battery is subtracted from the final demand in Module 3. The power flowing **from** the battery is added to the final demand in Module 3.
5. This yields a new list of 8784 hourly demand values.

Module 4: flexibility integration

The final addition to the configurations is the inclusion of flexibility of demand. A visual representation is shown in Figure 5.4.

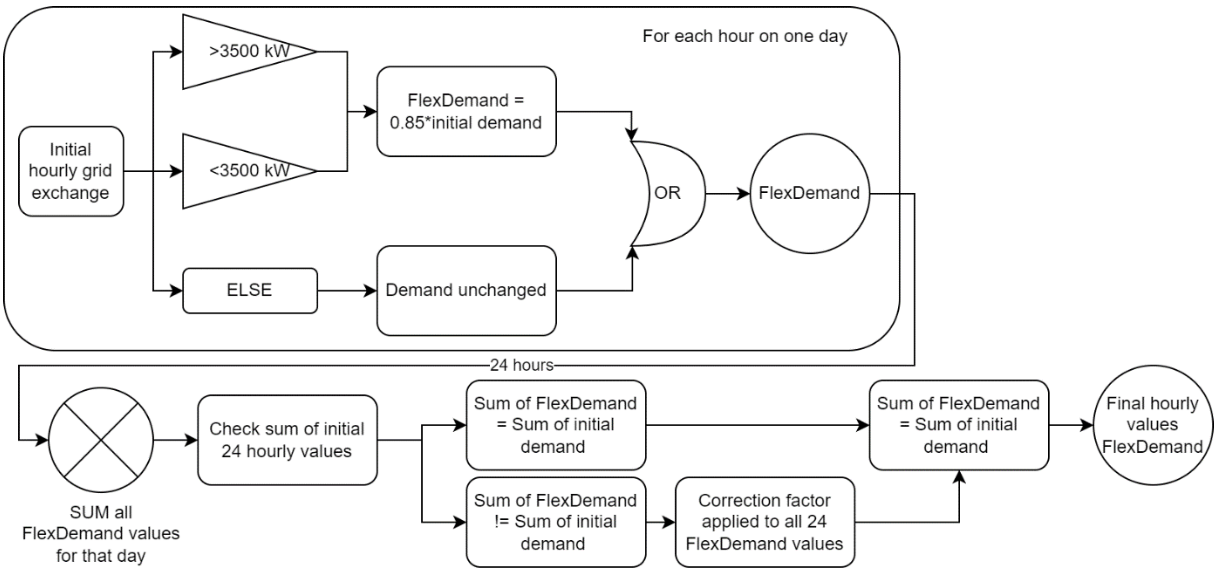

Figure 5.4 Flow diagram of flexibility integration.

In words, flexibility is simulated as follows.

1. The final hourly demand from Module 3 or 4, depending on the configuration, is loaded.
2. The flexibility as percentage of the initial hourly demand is defined comparable to the method used in (Nieta et al., 2018).
3. The daily sum of flexibility is zero. This means that the daily consumption of electricity remains equal to the initial hourly demand from Module 3 or 4.
4. The demand response rules are defined:
    a. When demand > 3500 kW, demand is decreased with a maximum of 15%. For example, an initial demand of 5000 kW is modified to 4250 kW.
    b. When demand < -3500 kW, demand is increased with a maximum of 15%. For example, an initial demand of -5000 kW is modified to -4250 kW.
    c. When -3500 kW < demand < 3500 kW, demand is unchanged.
5. Modified demand values are summed for each day and compared to daily summed initial demand. A correction factor is applied to ensure modified demand = initial demand for every individual day. The modified hourly demand values are then adjusted using this correction factor.
6. This yields a new dataset with 8784 hourly demand values.

Module 5: Output generation

In the final step, outputs must be generated that capture the elemental statistics and differences between the configurations. Table 1 summarises the main variables and the method to register them.

Table 5.2 Mathematical model output variables to be used in the evaluation of each configuration.

Variable	Unit	Method
Annual grid electricity consumption	kWh	Sum of positive exchange with grid
Annual RES generation	kWh	Sum of RES generation from Module 2
Annual CO_2 emissions	Mton	Sum of annual grid consumption * carbon intensity
Peak demand from grid connection	kW	Annual maximum value of positive and negative grid exchange
Self-consumption of RES	%	$\frac{Annual\ RES\ generation - Sum\ of\ negative\ exchange\ with\ grid}{Annual\ RES\ generation}$
Monthly peak values	kW	In Excel and Python, monthly peak positive and negative values are stored. These are compared in boxplots.
Weekly demand profiles for Weeks 3, 15, 26 and 40	-	Line plots showing the grid exchange for four weeks divided over four seasons.
Annual electricity costs	1000€	Sum (hourly grid exchange * NORDPOOL hourly day-ahead spot price)
Connection costs	1000€	Sum (|monthly peak|*Monthly peak price) + (Annual peak – baseline peak) *annual connection price
Investment costs	1000€	RES installed capacity in kW * Price per kW
LCOE	€/kWh	Weighted average LCOE of configuration based on $LCOE_{grid}$ and $LCOE_{RES}$

NPV after n years with discount rate r*	M€	$\sum_{j=1}^{n} \frac{income_j}{(1+r)^j}$

** The discount rate is a metric to assess the time value of money: earnings in the future are not the same worth as earning today.*

5.2 Analysis of electricity consumption data of the mixed business park

As a starting point, the annual consumption of the mixed business park Heerenveen-Zuid is analysed. This is considered as the baseline configuration. The baseline configuration is the configuration where no additional RES generation is realised, no flexibility or storage is implemented and no sharing of electricity between the different companies on the mixed business park is implemented.

5.2.1 Annual consumption

The annual consumption of electricity on the mixed business park is shown in Figure 8.

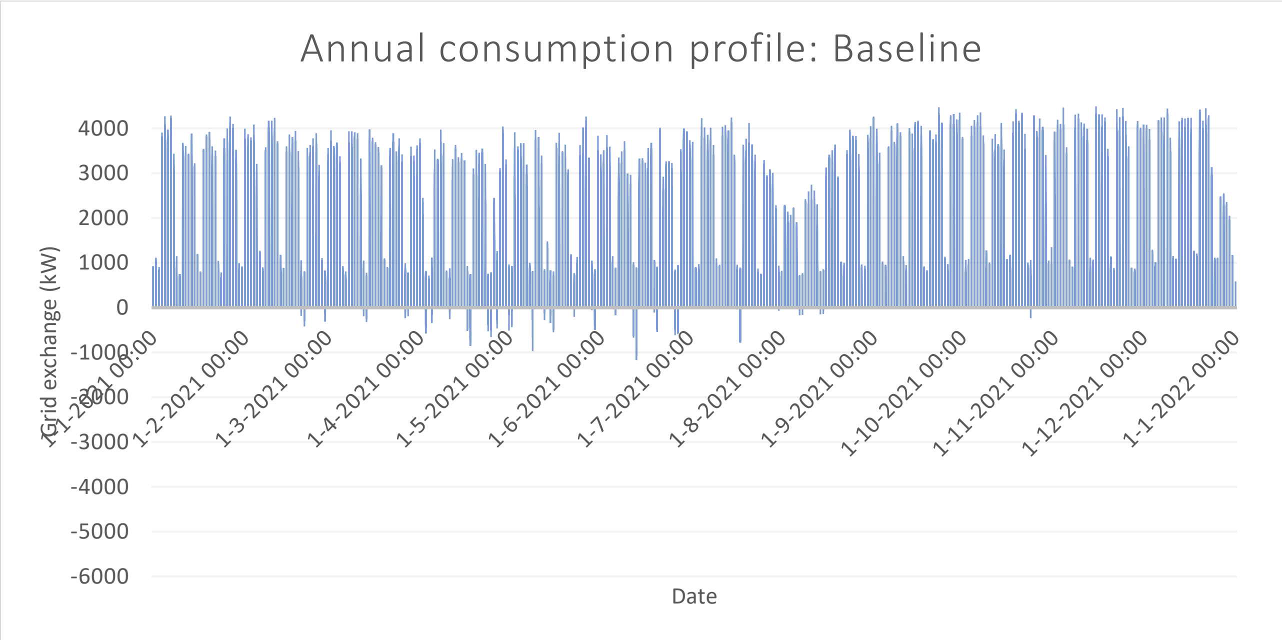

Figure 5.5 Annual grid exchange for the baseline configuration. Clear reductions in power demand are visible during Summer and Christmas holidays. Also, consumption during weekends is low. Baseload is slightly below 1000 kW.

The annual consumption profile shows that there is seasonal variation in the consumption of electricity. Electricity consumption is higher in autumn and winter than in spring and summer. Furthermore, during weekends and holidays the consumption is low. This is especially visible in a 3-week period in August when most construction companies and all schools are closed (Dutch: “bouwvak”) and around Christmas. The baseload of the mixed business park is roughly 1000 kW, while daily peak demand reaches 4000 kW regularly. The annual peak demand of electricity is 4491 kW.

Interestingly, the demand for electricity is negative on several occasions. This is because several companies employ rooftop solar PV. The peak net supply of solar PV to the grid is 1172kW.

Based on consumption data and visual estimation of satellite images of installed rooftop PV, the installed capacity of rooftop PV is 2000-2500 kWp (see also 4.4)

5.2.2 Weekly consumption

Zooming in on the data, four weeks of four different seasons have been analysed. The baseline weekly consumption profiles are shown in Figure 5.6.

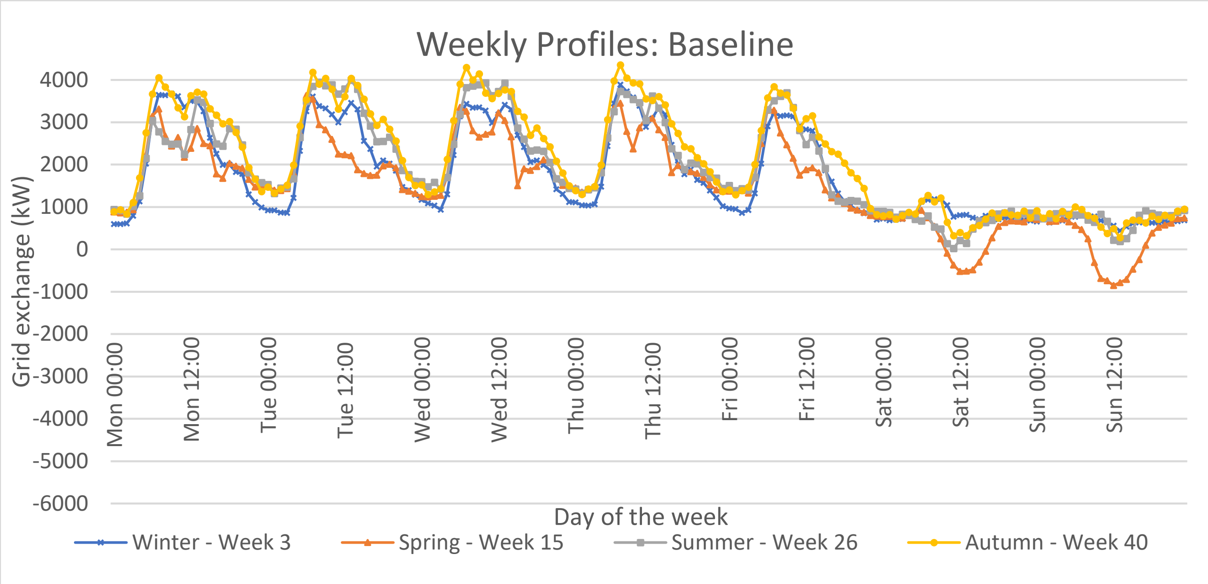

Figure 5.6 Weekly grid exchange for four weeks over the year. Clearly, consumption is lower on weekend days and most of the production takes place during office hours. Reductions in daytime peak demand in the Spring week during working hours is due to self-consumption of solar PV.

From Figure 5.6 it becomes clear that the mixed business park has a consumption profile that corresponds to a working week. The contribution of continuous processes towards the electricity demand is limited. During spring and summer, a reduction in demand is visible during midday. This is due to self-consumption of solar PV electricity. This is confirmed by weather reports from the Dutch Meteorological Institute (KNMI) (KNMI, 2023b). During weekends in Spring and Summer, the supply of solar PV is larger during midday than the aggregated demand, so a negative demand is observed during several hours on Saturday and Sunday. Finally, electricity demand on Friday is lower than on the other working days.

5.3 Possibilities of RES generation on the mixed business park

For the generation of renewable electricity on the mixed business park, solar PV and wind energy are the main candidates. In this section, a short study is discussed that yields the generation potential for these sources.

5.3.1 Rooftop Solar PV

On the mixed business park, approximately 2250 kWp of rooftop PV is present.

The next satellite image, Figure 5.7, shows the available rooftops for the installation of Solar PV panels highlighted using the Mapdevelopers Area Calculator Tool (Map Developers, 2024). The total roof area is 213 000 m^2.

Figure 5.7 Satellite image showing the available rooftops on Heerenveen-Zuid. Created with Map Developers.

From the satellite images, it is clear that several companies already use rooftop PV. Based on press releases and visual estimations, the total existing panel area is 11250 m^2, which translates to a capacity of 2.25 MWp (Ondernemend Friesland, 2024; Subvention, 2024; Velthoven, 2023).

The total available roof area is 213 000 m^2. Not all roofs will be suitable for PV panels and some roofs are already used, so it is assumed that the total available roof for new PV panels is 20% of the total, yielding 42600 m^2. By assuming a power density of 200 Wp/m$^2_{roof}$ and keeping some reserve to allow for inspection and maintenance paths between the panels, this yields 6 MWp of PV generation potential.

5.3.2 Wind energy

The benefit of a PV system is that it is easily scalable. For wind turbines, this is less the case. Turbines are available in different sizes, which provides some flexibility, but because spatial integration is often difficult, these options are limited. Figure 5.8 shows the location on the mixed business park that could accommodate a wind turbine with a tip height of 150m with a 100m safety perimeter.

Figure 5.8 Possible location for a 3 MW wind turbine including 100m safety perimeter.

This location is very suitable for several reasons.

1. The location is 800m from the nearest residential area, which significantly reduces the nuisance caused by noise and rotor blade shadows.
2. The location is on the south-west side of the mixed business park. Figure 5.9 shows the historical wind rose of the closest KNMI weather station (KNMI, 2024). This shows that not only most of the time the wind is coming from the third quadrant (between South and West), but also that the strongest winds are from this direction. This is beneficial for the energy yield of the turbine because the wind reaches the turbine undisturbed by the buildings on the park.
3. The location is close to a large solar farm. Cable pooling with the PV farm, or the sharing of a single connection cable, can be used to reduce the installation costs of the turbine and increase the effectiveness of use of the cable. The installation costs are reduced because a new connection to the grid does not have to be established. The effectiveness of use of the cable is increased because Solar PV and wind energy complement each other to provide a more continuous production of electricity (Li et al., 2023; Mertens, 2022; Widen, 2011).

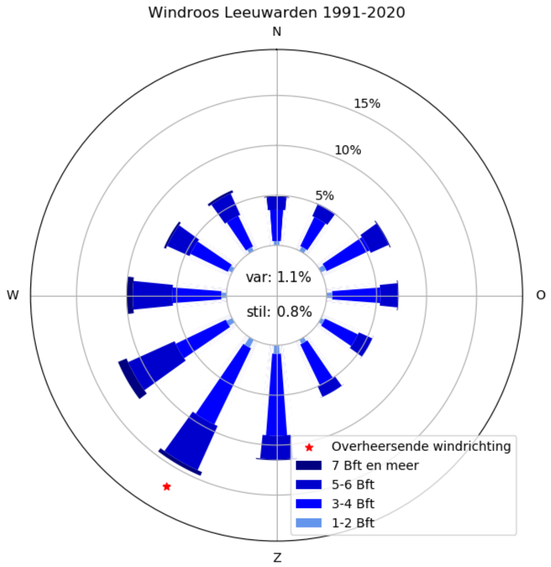

Figure 5.9 Historical wind rose for the closest KNMI weather station. Clearly, most of the wind is coming from the third quadrant between South and West (KNMI, 2024).

6. Step 3: Design of configurations for the energy transition

This chapter discusses the RES configurations and how they are integrated in the model of the mixed business park. It starts with the identification of the configurations based on the potential for RES as discussed in Section 5.3. Subsequently, these configurations are simulated and analysed in the tool, which provides annual and weekly electricity profiles. The outputs of all configurations are grouped and scored based on technical, social, environmental and economic criteria. This yields the final trade-off matrix, which determines the optimal configuration for Heerenveen-Zuid. Finally, the results are discussed in more detail and additional analyses are performed for the integration of heat storage and large battery sizes.

This chapter is structured as follows: Section 6.1 presents the RES configurations. This is followed by the results of the RES configurations from the tool in Section 6.2. The outputs of all configurations are scored and evaluated using MCDM in Section 6.3. Finally, Section 6.4 discusses the results of the configurations in more detail and presents the main findings.

6.1 Energy configuration identification

The discussion of energy management on mixed business parks from previous chapter forms the basis for the different energy configurations to be simulated on the mixed business park. Each configuration is a combination of RES generation, storage and demand flexibility. To avoid confusion, icons will be displayed that represent the different options: for PV, for wind, for storage and for flexibility.

6.1.1 Configuration A: Solar PV and Storage

For the first configuration, solar PV and storage will be combined on the mixed business park. Solar PV is the most accessible form of RES for entrepreneurs. The combination of Solar PV and storage adds the possibility for charging the battery during peak supply moment, or peak shaving, an important feature for the reduction of grid congestion. This goes for both the reduction of peak demand and peak supply. Furthermore, charging during RES supply and discharging during net demand increases the self-consumption of RES.

6.1.2 Configuration B: Solar PV and Wind

For the second configuration, a combination of wind and solar PV will be analysed. Based on the analysis of previous sections, this option could be beneficial because together these sources can provide a more continuous flow of renewable electricity to the park. This would reduce the need for storage.

6.1.3 Configuration C: Solar PV, Storage and Flexibility

The third configuration involves solar PV, storage and demand flexibility. Demand flexibility is incorporated into EnergyPLAN by defining daily, weekly and seasonal flexibility. In this case, only daily flexibility is used. This is because the energy yield of RES is weather based. Because current weather forecast models do not possess enough accuracy to predict the wind and solar PV energy yield for weeks in advance, the weekly and seasonal flexibility are not used.

6.1.4 Configuration D: Solar PV and Flexibility

The fourth configuration allows for comparison with A, namely of storage or flexibility in the case of high penetration of solar PV.

6.1.5 Configuration E: Wind and Flexibility

The fifth configuration is wind energy combined with flexibility. This allows for a review of the most suitable form of RES between Solar PV and wind with flexibility.

6.1.6 Configuration F: Solar PV, Wind and Storage

The sixth configuration adds battery storage to Solar PV and wind energy to optimise the self-consumption of RES.

6.1.7 Configuration G: Solar PV, Wind and Flexibility

The final configuration integrates flexibility. Instead of time shifting supply of electricity by storing it and releasing it during peak demand hours, the demand is time shifted in the flexibility configuration.

6.2 Results of the RES configurations

This section discusses the annual and weekly consumption profiles of the RES configurations. All graphs are shown in Appendix A. In this section, three configurations have been highlighted: A, F and G. These configurations provide a cross section of all configurations. With these three configurations, the comparison between solar only and a combination of solar and wind can be made; the introduction of storage or demand response can be studied and the difference between storage and flexibility can be identified.

The output values used to evaluate all configurations are reported in subsection 6.2.4 and the remaining consumption profiles can be found in Appendix A.

6.2.1 Annual consumption

In this subsection, the annual consumption profiles are discussed. This is important because it provides insight in the seasonal variability of demand and supply of RES and the annual effects of storage and flexibility.

6.2.1.1 Configuration A: Solar PV South and Storage

First, the configuration of Solar PV South with battery storage is discussed. This configuration is chosen because it shows the seasonal variability of Solar PV. It is shown in Figure 6.1.

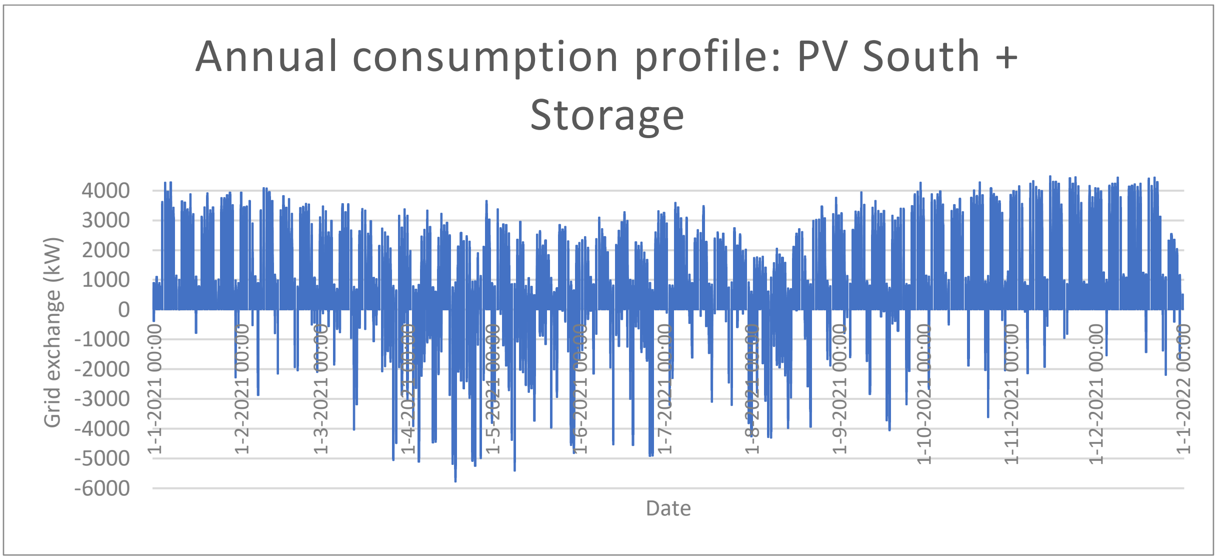

Figure 6.1 Annual grid exchange for Configuration A: 6 MWp PV in South orientation and a 6 MWh battery. Large feedback of electricity is observed in summer months, whereas electricity is taken from the grid during winter months. Peak supply of Solar PV determines annual peak exchange at -5787 kW.

The annual consumption profile shows that there is a large seasonal variability of PV supply. Between March and October, supply is often larger than demand, creating negative grid exchanges. In the baseline configuration, no net supply of RES to the grid was observed between November and February, but in this configuration, this is sometimes the case. Reduced consumption due to holidays in August yields even more oversupply of RES in that month. The weekly pattern that was clear in the baseline case can also be observed in this figure: demand peaks often occur in the morning when PV production is still low. This yields a pattern of five days with higher demand and then two days with lower demand. This creates 52 "dips" in the figure, representing the 52 weeks in the year.

The annual peak demand is not affected by the added RES supply compared to the baseline case, because it happens at 7am on the 15th of November, when Solar PV is unavailable. Annual peak supply, so negative grid exchange, however, increases dramatically to 5787 kW on the 18th of April at 12pm.

Zooming in on the operation of the battery, Figure 6.2 shows the average state of charge (SOC) of the battery for each week of the year.

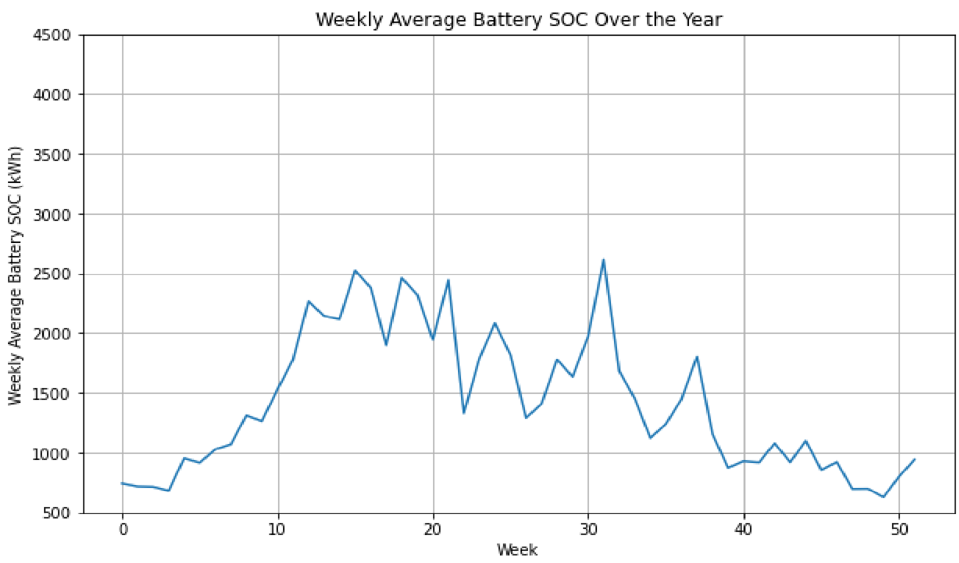

Figure 10.2 Weekly average battery state-of-charge for Configuration A (S).

Remember from Section 5.1 that the battery only charges when the grid exchange is negative, so in periods with low solar irradiance, the average SOC is low. On the contrary, during high solar PV injection and low demand, the average SOC is higher because the battery can become fully charged during the day. This is visible in Figure 6.2. In the winter months, the average SOC varies between 600 kWh and 1100 kWh, or 10% and 18%. Especially in Week 49, the battery starts empty and is not charged nor discharged for the full week. In contrast, during the summer months the SOC is much higher. This reflects the case that during the day, the battery is charged and during the evening/night, the battery is discharged. Also, because of lower demand during the summer holiday and high PV production, Week 31 has the highest average SOC of the year. The total annual volume of energy that is exchanged in the battery is 1577 MWh.

6.2.1.2 Configuration F: Solar PV South, Wind + Storage

The second configuration discussed is Configuration F: 3 MWp PV South, 3 MW Wind and 6 MWh Storage. This configuration can be compared to Configuration A to show the effect of interchanging 3 MWp of solar PV with wind energy.

First, Figure 6.3 shows the annual consumption profile.

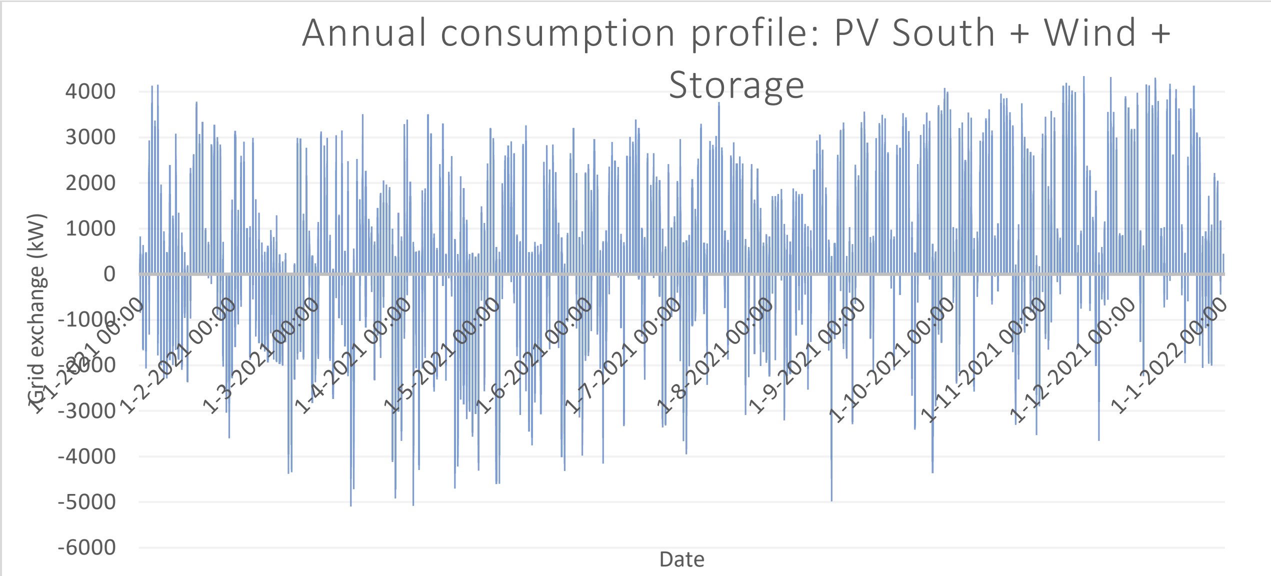

Figure 6.3 Annual grid exchange for Configuration F: 3 MWp Solar PV S, 3 MW wind and Storage. Positive and negative peaks are clearly reduced compared to Figure 6.1, partially due to a different composition of RES and due to flexibility measures. Peak grid exchange is -5097 kW on the 13th of March.

Compared to Figure 6.1, the distribution of negative peaks in grid exchange, which denotes a surplus of RES, is less concentrated in the summer months. Furthermore, the weekly pattern that was observed in Figures 6.1 and the baseline case Figure 5.5 is less pronounced, because weekday demand peaks that often occur in the morning are sometimes captured or reduced by wind energy production.

The annual peak demand is slightly affected by the added RES supply compared to the baseline case, because there is some wind energy. The annual peak demand is 4343 kW. Compared to the baseline, annual peak supply however increases dramatically to 5097 kW on the 13th of March at 11:00 hrs. Compared to Configuration A, annual peak supply is 12% lower.

Zooming in on the operation of the battery, Figure 6.4 shows the average weekly SOC of the battery for every week of the year.

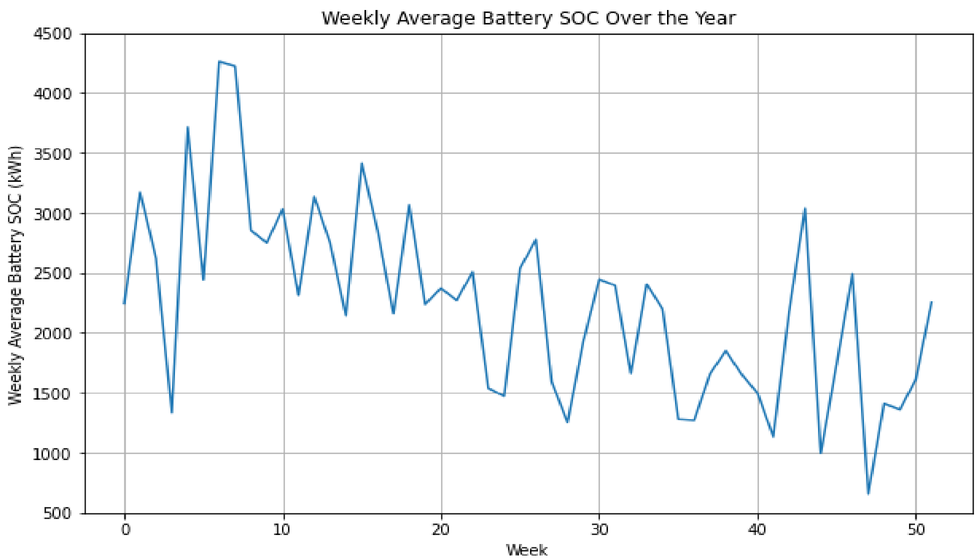

Figure 6.4 Weekly average battery state-of-charge for Configuration F (S).

Compared to Figure 6.2, the SOC is higher and rarely reaches the lowest limit of 600 kWh or 10%. This is because the lack of PV energy in winter months is compensated for by the wind energy that is generated. Particularly in February, Weeks 7 and 8, the average SOC is high due to high generation of wind energy. Compared to Configuration A, one can conclude that the battery plays a more active role because it is regularly charging and discharging throughout the year. The total annual volume of energy that is exchanged in the battery is 1710 MWh.

6.2.1.3 Configuration G: Solar PV East/West, Wind + Flexibility

The final annual consumption profile discussed here is the Configuration G with 3 MWp Solar PV East/West, 3 MW wind and 15% flexibility. This configuration is chosen because it shows the effect on the seasonal variability of combining RES, the differences of South and East/West PV production and the effect of flexibility. Figure 6.5 shows the annual consumption profile of the configuration.

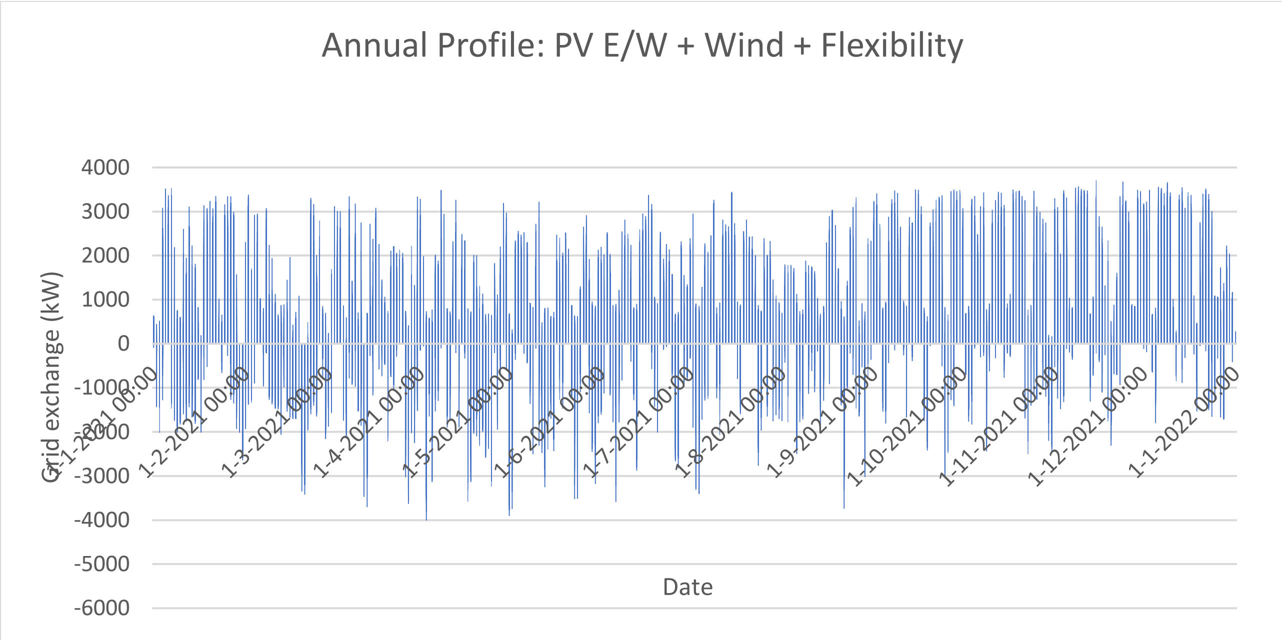

Figure 6.5 Annual grid exchange for Configuration G: 3 MWp Solar PV East/West, 3 MW wind and 15% flexibility. Positive and negative peaks are clearly reduced compared to Figure 9, partially due to a different composition of RES and partially due to flexibility measures. Peak grid exchange is -4012 kW.

The annual consumption profile shows that the combination of Solar PV and Wind yields a RES supply that is more evenly distributed over the year compared to only Solar PV in Configuration A. Furthermore, the introduction of flexibility significantly reduces both the negative and the positive peaks in grid exchange to 3706 kW and -4012 kW, respectively. The final thing that stands out is that in the last 3 months of the year, daily demand peaks are less 'suppressed' by RES generation because Solar PV is less available compared to the rest of the year. Therefore, during that time of the year, the users on the park do not have to shift their demand much.

6.2.2 Weekly results of the RES configurations

The second analysis considers four weeks divided over four seasons in the year. These weeks are carefully chosen to represent working weeks without holidays. This allows for comparison of weekdays vs. weekend days and the use of electricity in different seasons. Each figure shows Week 3 (Winter), Week 15 (Spring), Week 26 (Summer) and Week 40 (Autumn). Local time is adjusted to CET. X-axis labels are at 12am and 12pm. First, individual configurations are analysed. In addition to the 4-weeks comparison, one week is studied in more detail to show the dynamics of RES generation, electricity demand and storage. Finally, a comparison is made between different configurations for the Spring week.

6.2.2.1 Configuration A: Solar PV South + Storage

First, weekly profiles of Configuration A with 6 MWp Solar PV in South orientation in combination with battery storage are shown. This starts with four weeks with final demand are shown in Figure 6.6, followed by a closer look at the spring week.

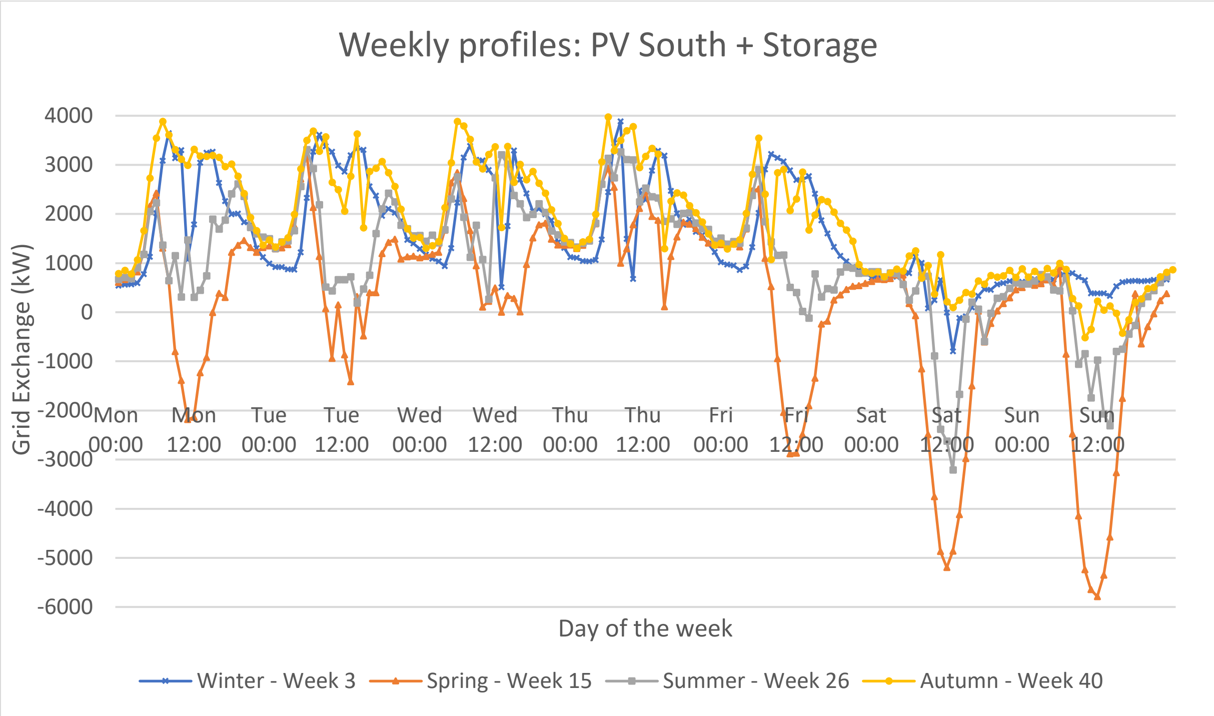

Figure 6.6 Weekly grid exchange profiles of Configuration A (S).

Figure 6.6 shows the seasonal variability of Solar PV supply. Demand peaks on weekdays are lower due to high self-consumption of RES, especially in Spring and Summer. On weekend days, RES oversupply creates negative grid exchanges. The 6 MWh battery is too small to store the oversupply: the total supply to the grid on Saturday the 17th of April is 39.4 MWh. More sophisticated charging logic is therefore required to make the battery suitable for peak-shaving, or other means of restriction such as curtailment must be adopted to reduce the stress on the grid connection.

The following Figure 6.7 shows the same spring week as in previous figure, but now the interaction of the battery on the grid exchange and the solar production is highlighted.

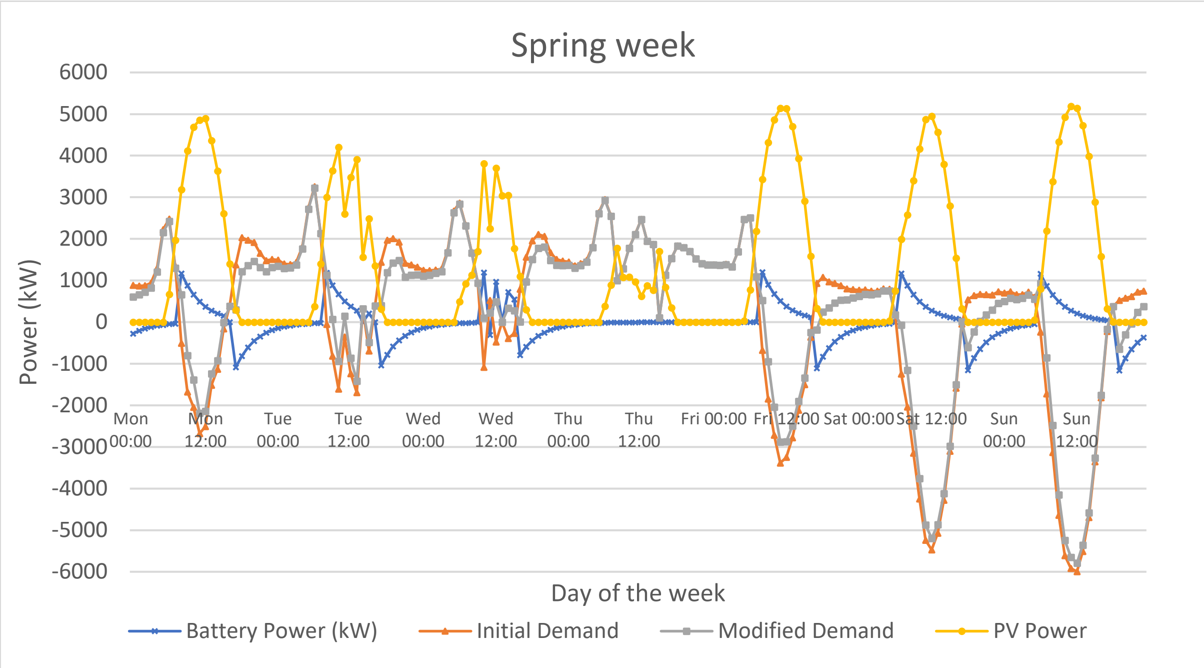

Figure 6.7 Detailed visualisation of the interaction between Solar PV production, grid electricity demand and battery power for Configuration A (S).

From Figure 6.7, the operation of the battery and the effect on the demand from the grid is clearly visible. The blue line represents the battery power (BP). BP > 0 means the battery is charging, BP < 0 means the battery is discharging. The modified demand (grey line) is the sum of the initial grid exchange before operation of the battery (orange line) and the battery power. The yellow line represents the production of the 6 MWp PV installation of this configuration. Three main aspects stand out:

1. During periods of positive demand, the battery discharges, which results in lower demand peaks from the grid for example on Monday, Tuesday and Friday evening.
2. During periods of negative grid exchange, the battery charges, which results in lower injection peaks of solar electricity at midday on Monday, Friday, Saturday and Sunday.
3. The battery stores excess PV energy and releases this energy later. In this way, self-consumption of PV electricity is enhanced. Comparing initial and modified demand of this week results in an increase in self-consumption of 12%.
4. The battery is not large enough to store all RES power: on Sunday, the amount of excess RES power is five times larger than the storage capacity of the battery.

6.2.2.2 Configuration F: Solar PV South, Wind and Storage

Secondly, the weekly analysis of Configuration F 3 MWp Solar PV South with 3 MW Wind and a 6 MWh battery is shown. First, four weeks with final demand are shown, followed by a closer look at the winter week.

Figure 6.8 shows the weekly profiles of the four weeks around the year.

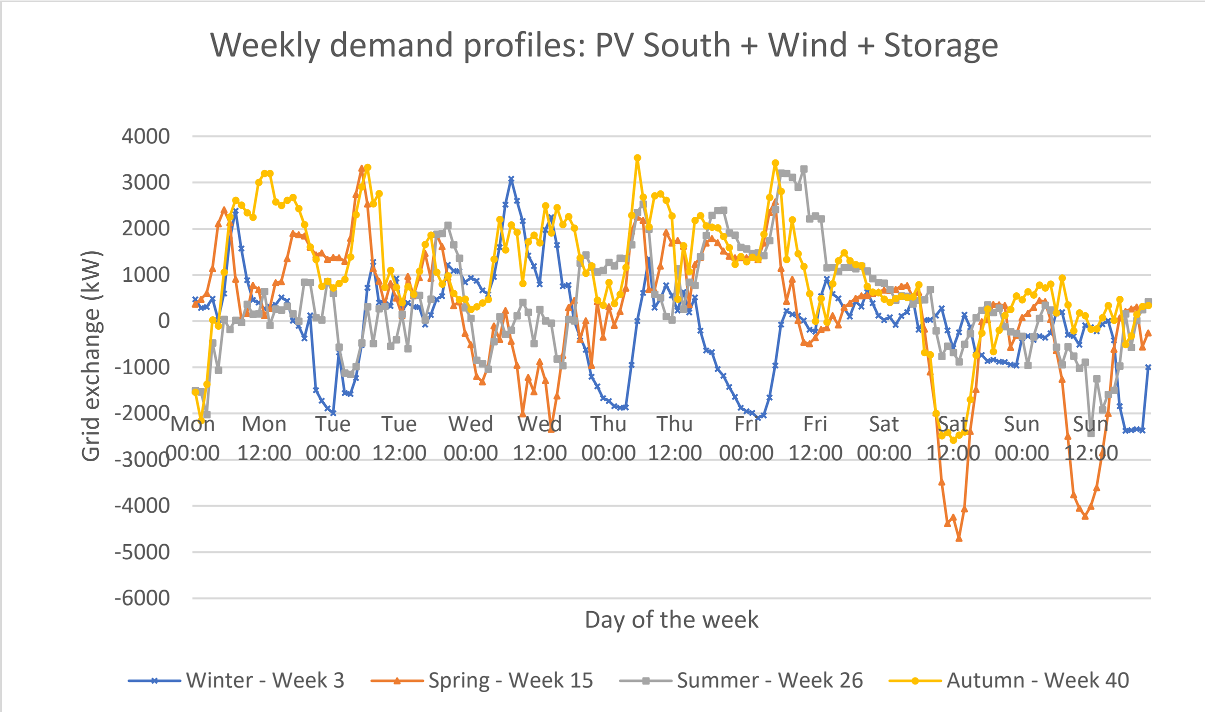

Figure 6.8 Weekly grid exchange profiles of Configuration F (S).

From Figure 6.8, several things stand out.

1. Compared to the weekly profiles of Configuration A, negative grid exchange due to excess RES generation are apparent in all weeks. Especially the winter week shows a high capacity of wind energy between Wednesday and Friday.
2. The grid exchange peaks are lower than for Configuration A because the combination of wind and solar provide more RES energy, also during peak demand hours. Moreover, the supply peaks are lower because solar PV and wind seldom provide their rated power simultaneously. This was also noted by (Mertens, 2022).

The following Figure 6.9 shows the same winter week as in previous figure, but now the interaction of the battery on the grid exchange and the solar and wind production is highlighted.

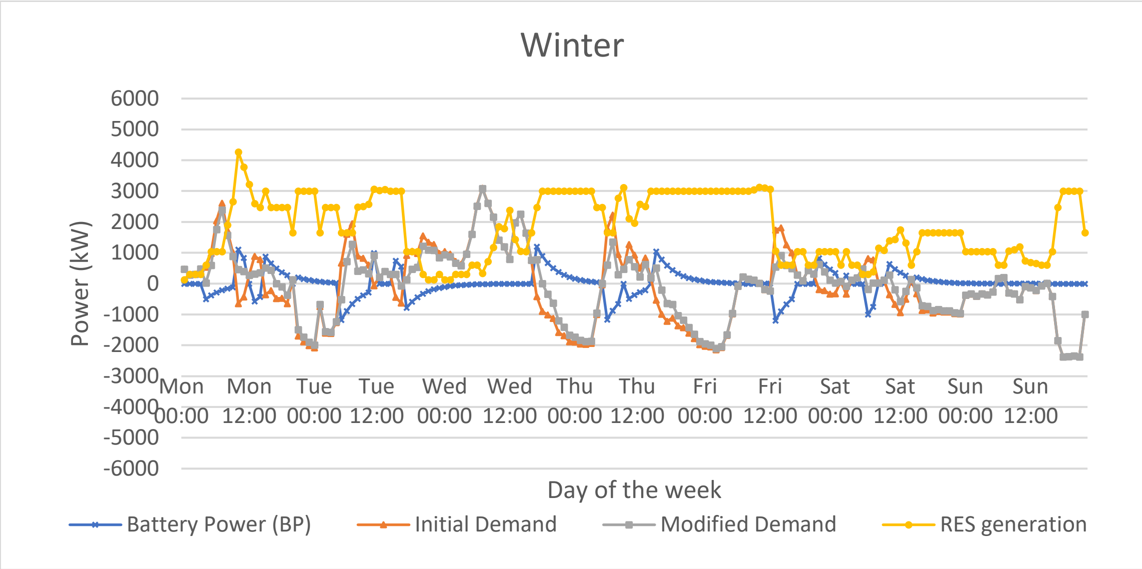

Figure 6.9 Detailed visualisation of the interaction between Solar PV production, grid electricity demand and battery power for Configuration F (S).

From Figure 6.9, several things stand out:

1. As noted in the annual analysis of this configuration, the supply of wind energy means the battery is active more than in the case without wind. The total amount of energy exchanges this week in the battery accumulates to 40 MWh, compared to 6.8 MWh in Configuration A winter week because of the negative grid exchanges caused by supply of RES.
2. High windspeeds cause the demand curve to be shifted down by 3 MW for almost the full duration between Wednesday and Friday 12:00. During this period, the battery is fully charged and only briefly discharges when the consumption of electricity on the park is high during the day on Thursday.
3. The battery charging logic caused jumps in the modified demand when the initial demand is close to zero. This is because when the battery is not close the SOC limits, it charges or discharges with rated power. This causes the modified demand to have opposite sign (+ or -) compared to the initial demand. This then triggers the battery to "reverse" the action in the previous hour. Because this triggers excessive wear in the battery, it should be avoided.

6.2.2.3 Configuration G: Solar PV East/West, Wind and Flexibility

Thirdly, the weekly profiles of the configuration involving 3 MWp Solar PV in East/West orientation, 3 MW wind and 15% flexibility is shown in Figure 6.10.

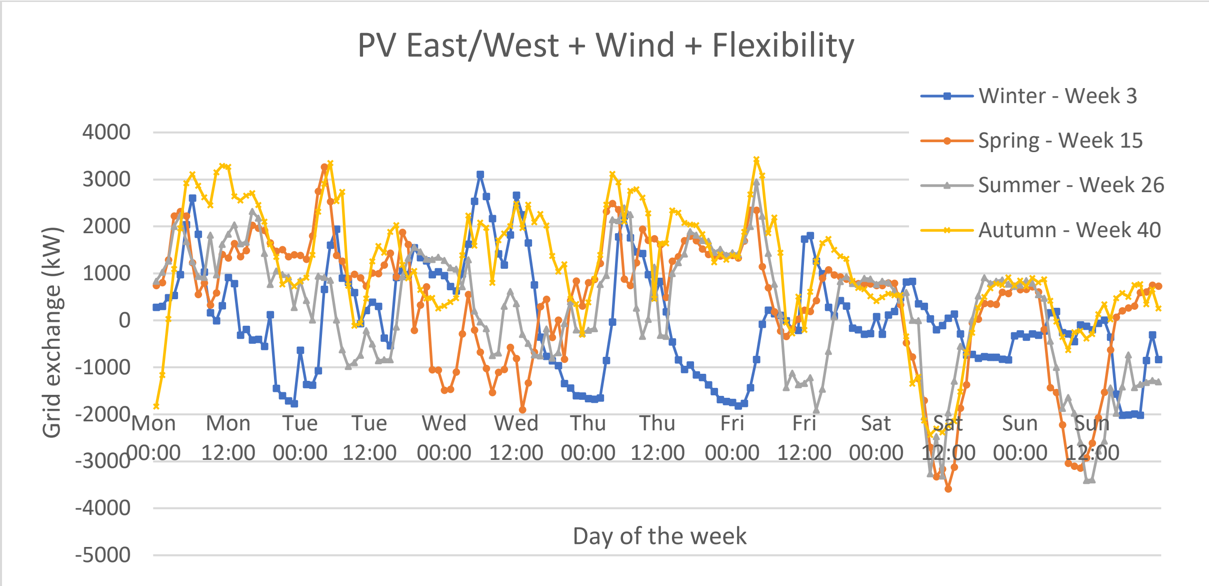

Figure 6.10 Weekly grid exchange for Configuration G: 3 MWp Solar PV East/West, 3 MW wind and 15% flexibility. Introduction of wind energy also yields RES supply during winter months. Demand peaks are reduced due to self-consumption of RES and flexibility.

From Figure 6.10 the added value of a combination of Solar PV and Wind is clearly visible. Because these RES are negatively correlated on all time scales (Widen, 2011), days of self-consumption and negative supply now also occur on winter days, even though the absolute installed power of wind is only 50% of the 6 MWp of the Solar PV South configuration. Furthermore, the total RES yield of the four weeks in Figure 6.10 is more than two times higher than in the Solar-only Configuration A: 971 MWh versus 425 MWh. In the winter week, high windspeeds result in the complete demand curve being shifted down by 3 MW between Wednesday and Friday, similarly to Configuration F in previous subsection Figure 6.8. Including flexibility further reduces the peak exchanges with the grid from an average daily peak exchange of 3775 kW to 3275 kW compared to PV E/W + Wind and no flexibility.

6.2.2.4 Spring week: comparison of Solar PV orientation, Wind and flexibility

This subsection considers the same Spring week in four different configurations: 1. A PV South + Storage, 2. A PV East/West + storage, 3. PV South + Wind, PV South + Wind + Flex. This allows for a comparison of South oriented panels vs. East/West oriented panels, PV-only or in combination with Wind and Flexibility of demand and supply or not. The resulting profiles are shown in Figure 6.11.

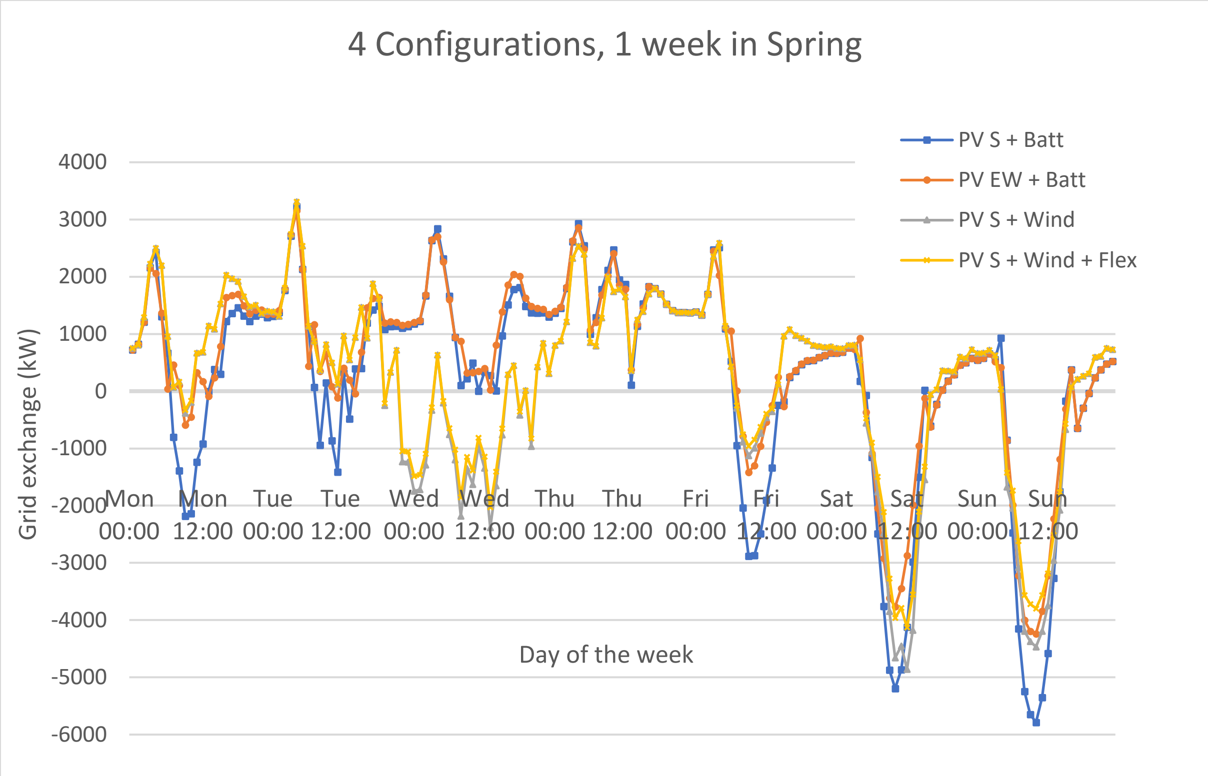

Figure 6.11 Comparison of two variations of Configuration A, the South Configuration B and the South Configuration of G.

From Figure 6.11, three main aspects stand out:

1. In terms of Solar PV orientation, the East/West orientation yields 22% less energy over the week than South. Furthermore, peak exchanges are 28% less. Self-consumption of South PV is 34% and East/West PV is 44%.
2. The addition of wind energy yields more energy for the same installed capacity, as was also noted in previous subsection, and RES self-consumption is higher in the case with a combination of PV and wind: 58%.
3. The integration of demand flexibility in the PV + Wind configuration only reduces the supply and demand peaks on the weekend days.

6.2.3 Monthly peak exchanges with the grid

This subsection discusses the monthly peak exchanges with the grid for all configurations. Figures 6.12 and 6.13 show the monthly positive peaks or demand per configuration and the monthly negative peaks or supply, respectively. The A, B, C, etc. denote the configuration.

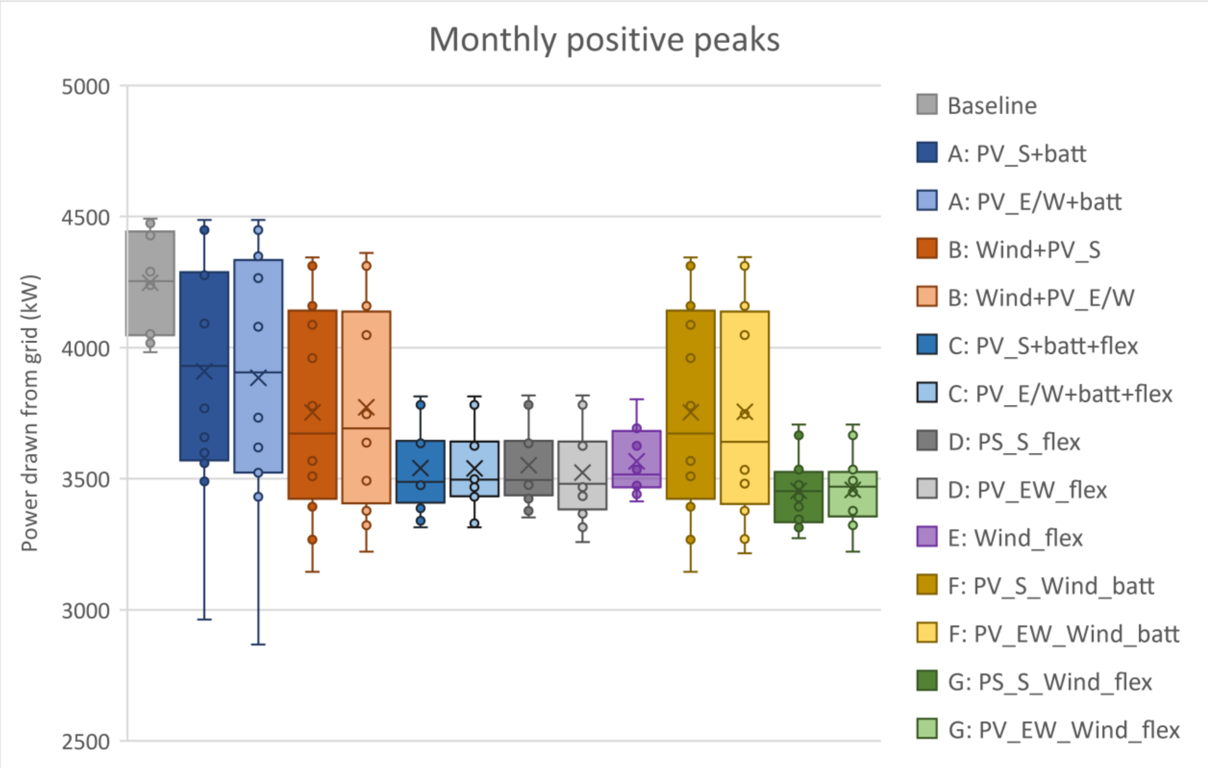

Figure 6.12 Positive peaks for grid exchange per configuration and PV orientation. x marks the average of each configuration.

From Figure 6.12, several things can be derived:

1. All configurations with RES supply reduce the average and median demand peaks from the grid. In the case of flexibility, these are reduced even more.
2. Comparing B and F: integration of battery storage does not yield significant changes in the peak demand values.
3. Apart from Configuration A, all configurations reduce the absolute (annual) peak demand of the business park due to self-consumption of RES or demand response.

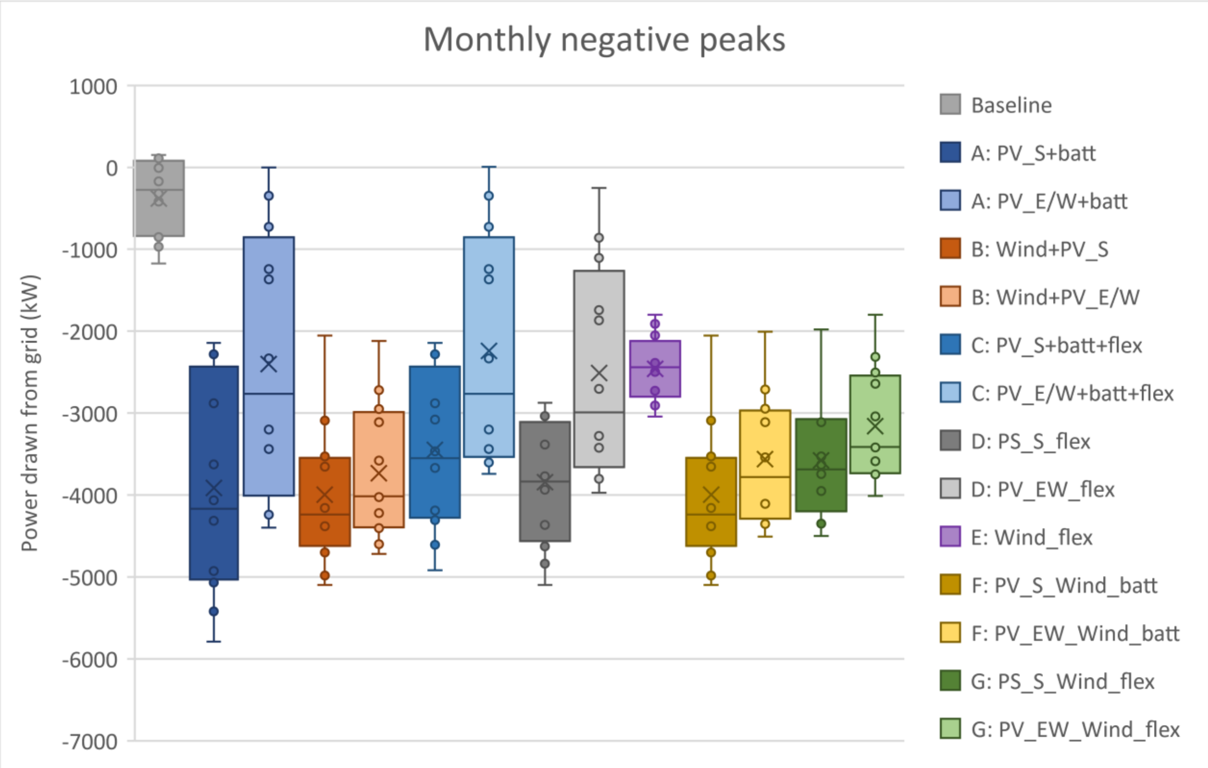

Figure 6.13 Positive peaks for grid exchange per configuration and PV orientation. x marks the average of each configuration.

From Figure 6.13, several things can be derived:

1. All configurations increase the supply peaks to the grid. Furthermore, all configurations involving Solar PV South have an annual supply peak that is higher than the demand peak of the baseline. This means the connection to the mixed business park must be increased to accommodate this.
2. East/West Solar PV places significantly less burden on the grid connection, because supply peaks are significantly lower than South Solar PV.
3. Battery storage manages to lower supply and demand peaks. However, because of the limited capacity of the battery, the differences between scenarios B and F are limited.
4. As means to lower grid congestion, integration of flexibility is more effective than the currently simulated battery. This can be seen by comparing A and D.
5. The larger the PV capacity, the larger the spread of peak supply values. This means that the connection required to accommodate the most negative peaks is less efficient: the heavy connection is only required a few days per year and will be overdesigned for the remaining days.

6.2.4 Configuration annual output comparison

Finally, the decision variables identified in Section 5.1 are shown for each configuration in Table 6.1. All configurations with Solar PV have two values per item: one for the South (S) orientation and one for the East/West (EW) orientation.

Table 6.1 Overview of annual results for all configurations. (S) and (EW) denote the results for the South and East/West PV orientation. In terms of performance, red numbers denote values that are worse compared to the baseline, green number denote values that are better than the baseline. Black values denote values that are very close (or equal) to the baseline.

Configuration			**A**	**B**	**C**	**D**	**E**	**F**	**G**
Variable	**Unit**	**Baseline**							
Annual grid electricity consumption	MWh	16020	11898 (S) 12308 (EW)	8422 (S) 8663 (EW)	12410 (S) 12654 (EW)	11712 (S) 12106 (EW)	10031	9302 (S) 9494 (EW)	83358 (S) 85696 (EW)
Annual RES generation	MWh	1976*	6277 (S) 5108 (EW)	10853 (S) 10269 (EW)	6277 (S) 5108 (EW)	6277 (S) 5108 (EW)	7715	10853 (S) 10269 (EW)	10853 (S) 10269 (EW)
Annual CO_2 emissions	tonne	5703	4046 (S) 4252 (EW)	2998 (S) 3084 (EW)	3979 (S) 4180 (EW)	4169 (S) 4310 (EW)	3571	2814 (S) 2920 (EW)	2968 (S) 3051 (EW)
Peak grid exchange	kW	+4491	-5787 (S) 4487 (EW)	-5291 (S) -4719 (EW)	-4919 (S) 3814 (EW)	-5095 (S) -3971 (EW)	+3803	-5096 (S) -4508 (EW)	-4498 (S) -4012 (EW)
Self-consumption of RES	%	97%	73% (S) 79% (EW)	71% (S) 74% (EW)	74% (S) 79% (EW)	66% (S) 72% (EW)	78%	74% (S) 76% (EW)	70% (S) 71% (EW)
Annual electricity costs	1000€	472	292 (S) 326 (EW)	214 (S) 231 (EW)	286 (S) 318 (EW)	287 (S) 319 (EW)	302	215 (S) 232 (EW)	212 (S) 228 (EW)
Grid connection costs	1000€	201	239 (S) 198 (EW)	222 (S) 206 (EW)	203 (S) 170 (EW)	210 (S) 175 (EW)	169	217 (S) 199 (EW)	191 (S) 175 (EW)
Investment Costs	1000€	-	5100	6150	5100	4200	4050	7050	6150
LCOE	€/kWh	0.095	0.12	0.078	0.12	0.088	0.078	0.11	0.078
NPV after 20 years**	1000€	-478	-2653 (S) -2549(EW)	-2173 (S) -2202 (EW)	-2003 (S) -1707 (EW)	-1260 (S) -952 (EW)	-381	-2989 (S) -2971 (EW)	-1651 (S) -1220 (EW)

**Calculated based on an estimated PV capacity of 2250 MWp.*

***Calculated based on 5% increasing connection costs and 2% increasing grid energy costs per year.*

Many aspects of Table 6.1 have been treated in previous sections: the effects of integrating Solar and Wind on total energy supply and self-consumption, the effects of peak exchange for Solar PV South vs. East/West configuration, the required connection to the grid that may require expansion depending on the configuration.

New information mainly considers the self-consumption and the economics of the configurations.

1. Self-consumption of RES ranges from 66% in Configuration D to 78% in Configuration E. This is because the peak supply of South PV in D around noon is so high that demand cannot adjust

enough and much energy is fed back to the grid. Furthermore, the functionality of the simulated battery is adequate: compared to similar configurations without battery, self-consumption is increased. This was also shown in more detail in Subsection 6.2.2.2.
2. Only Configuration E achieves a higher NPV after 20 years compared to the baseline. This is due to two aspects. First, energy yield of wind energy is much higher than solar PV. This reduces the energy consumption costs. Secondly, because all the monthly peak exchanges with the grid are lower, both the connection and the peak exchange costs are reduced. This offsets the slightly higher investment costs compared to Configuration D.
3. The integration of battery storage increases the investment costs significantly, but these costs are not offset by the returns in terms of lower connection costs and grid electricity costs.

6.3 Multi Criteria Decision Making: Choosing the optimal configuration for Heerenveen-Zuid

For the investigation of different pathways to integrating more RES and reducing grid congestion on mixed business parks, different configurations have been analysed and compared to the baseline case. These configurations consisted of different amounts and types of RES generation, storage and demand flexibility.

To choose the optimal configuration for the transition of a mixed business park, this thesis aims to go beyond a techno-economic analysis. In overview, the transition configurations will be evaluated on economic, technical, social and environmental performance. Criteria to evaluate these performances have been derived from literature (Antunes & Henriques, 2016; Arrizabalaga, Hernandez, & Portillo-Valdés, 2018; Höfer & Madlener, 2020; San Cristóbal, 2011; Witt, Dumeier, & Geldermann, 2020) and talks in the Energy Transition Advisory Group at Antea Group, especially with Søren Winkel and Joris Knigge. Alternatively, the stakeholders make up the criteria, based on a number of scenarios and their own objectives. This was done in Germany (Höfer & Madlener, 2020).

The criteria are weighted to form a weighted trade-off matrix. In this matrix, each configuration is scored for each criterion. The configuration with the highest score is the preferred option. To find a balance between engagement without asking too much time from the stakeholders, the criteria have been identified beforehand, but the criteria weights have been applied based on the Analytical Hierarchy Process (AHP). In AHP, each stakeholder ranks the criteria from most to least important, which yields the weights. Combining the rankings from the different stakeholders yields the final ranking.

6.3.1 Criteria identification and weighting

For each of the 4 categories, at least one criterion has to be present. The criteria form a mix of objective and subjective criteria and can be evaluated numerically, via literature study and via interviews with the stakeholders. Interestingly, several criteria do not fall exclusively in one of the four categories. One example is reduction of CO_2 emissions associated with grid electricity. This is an environmental criterion because it quantifies the environmental performance of the configuration. But at the same time, it could be an important criterion for entrepreneurs because it boosts their sustainable image, improving their social and economic performance. Therefore, the criteria are not grouped under the categories.

6.3.1.1 Levelised Cost of Energy

The Levelised Cost of Energy (LCOE) is used to evaluate the economic performance in the long run (Tezer, Yaman, & Yaman, 2017). This is comparable to the Cumulative Net Present Value to be discussed in subsection 7.1.9, but it is calculated differently. In this thesis, the LCOE is calculated based on the LCOEs as assumed in Chapter 5. It is a weighted average of the LCOE of each energy source, multiplied by its composition to the energy mix in the configuration.

6.3.1.2 Commercial readiness index:

The commercial readiness index (CRI) is a scale from 1 to 6 that describes the commercial use of a product or technology (Animah & Shafiee, 2018). At CRI 1, a product has not been evaluated both technically and commercially, whereas at CRI 6, a product readily receives financial support from banks. A graphical representation of the CRI and its relationship to the Technology Readiness Level as used by the European Commission (European Commission, 2014) is shown in Figure 6.14. The CRI of the chosen configuration depends both on the CRI of the individual components as well as the CRI of the configuration of components.

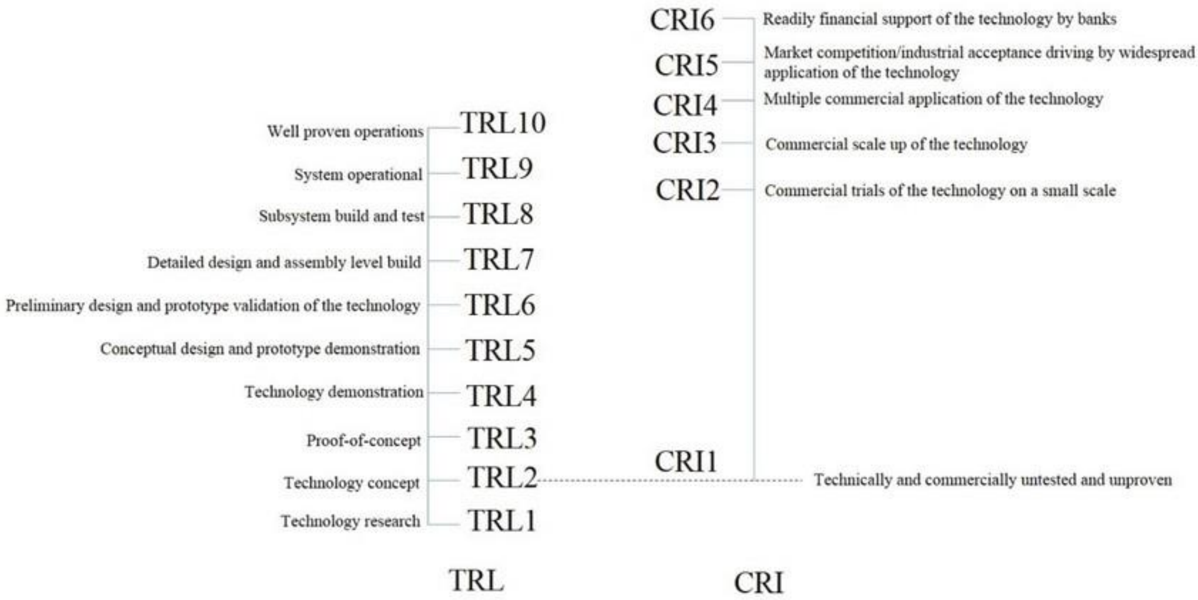

Figure 6.14 Technology Readiness Level and Commercial Readiness Index (Animah & Shafiee, 2018).

6.3.1.3 Reduction of grid congestion or grid relief

The reduction of grid congestion is especially important for the many mixed business parks in the Netherlands that are confronted with transport limitations and where capacity increasement by the DSO will take a long time. Reduction of grid congestion can be expressed in the reduction of peak electricity exchange (demand or supply) compared to the baseline configuration.

6.3.1.4 Level of self-consumption of RES

The level of self-consumption measures the ability of the configuration to supply the electricity needs of the mixed business park without interaction with the grid. The higher the energy autonomy, the better the mixed business park is protected from external factors such as black-outs, demand or supply curtailments and price fluctuations. Energy self-consumption is calculated with the equation below, comparable to the formula used in (Marańda, 2019):

$$Self\ consumption = \frac{total\ RES\ supply - Feedback\ to\ grid}{total\ RES\ supply} * 100$$

6.3.1.5 Reduction of CO_2 emissions

The reduction in CO_2 emissions measures the performance of the configuration in preventing global warming. This is a performance indicator of the energy transition. The more energy is supplied by renewable energy sources, the lower the CO_2 emissions are.

6.3.1.6 Ease of spatial integration

Spatial integration considers the area requirement, safety regulations and ease of spatial integration of the configuration. Rooftop solar panels requires less area than wind energy, but much more panels are needed to achieve the same energy output. Also, the PV panels will be distributed over the park, whereas a wind turbine will have a single connection to the grid. A single battery may require less area than several smaller batteries combined, but a suitable location must be present.

To evaluate the spatial integration, configurations are scored from 1 (very hard to integrate) to 5 (no adjustments needed to implement). Rooftop Solar PV requires no spatial integration. Storage requires a little bit of space because the batteries must be placed somewhere on the ground. Wind energy is the hardest aspect to integrate because a 3 MW wind turbine requires some open land surrounding the turbine. This is discussed in detail in the Guideline for Risk Zoning for Wind Turbines (DNV GL, 2020).

6.3.1.7 Investment costs

The investment costs form an important factor in the feasibility of the configuration. Data for the investment cost of RES generation has been derived from (PBL, 2023b).

6.3.1.8 Net Present Value of configuration

All RES configurations require a substantial investment. However, they might be profitable in the long run. First, replacing grid electricity with self-generated RES reduces the costs of importing electricity and excess RES generation can be sold to the grid. Next, changes in required connection capacity and monthly peak exchanges may be profitable in the case that they are reduced. The NPV after 20 years is calculated to investigate the profitability of each configuration compared to the baseline. 20 years is chosen because the RES configurations should easily reach this timespan.

6.3.2 Weighted Trade-Off

By conducting interviews with three stakeholders, the criteria weights have been assigned. This is shown in Table 6.3. Each expert ranked the criteria from most important (value 1) to least important (value 5 or 6, depending on the ranking). When the expert found it was too hard to separate two criteria, equal values were assigned. Summing the individual values results in the final ranking. In case the sum of individual values is equal, the criteria receive the same final rank and weight. This is the case to the criteria NPV and spatial integration (rank 2), investments and grid-relief (rank 3), and LCOE and self-consumption (rank 4).

Table 6.2 Criteria weights based on interviews with experts representing the DSO, the consultant and the provincial government (CONS, 2023; DSO, 2023; PROV, 2023)

Criterion	**DSO**	**Consultant**	**Province**	***Points***	**Final rank**	**Final weight**
CO_2 emissions	1	4	1	*5*	**1**	**1**
NPV	3	2	2	*7*	**2**	**0.9**
Spatial integration	2	1	4	*7*	**2**	**0.9**
Investments	3	2	5	*10*	**3**	**0.8**
Grid relief	4	3	3	*10*	**3**	**0.8**
LCOE	4	6	2	*12*	**4**	**0.7**
Self-consumption	5	4	3	*12*	**4**	**0.7**
CRI	6	5	6	*17*	**5**	**0.6**

The configurations will be scored using the following logic:

1. For criteria scores that are discrete (spatial integration and CRI) the scores are directly applied to the matrix.
2. For criteria scores that are continuous (LCOE, grid relief, self-consumption of RES, CO_2 reduction, investment costs) the best performing configuration receives a 5 and all other configurations are scored based on how close they are to this configuration using the following equation:

$$score = \left(1 - \left(\frac{value\ of\ current\ configuration}{value\ of\ best\ performing\ configuration} - 1\right)\right) * 5$$

   To illustrate this: Configuration F (S) has the lowest CO_2 emissions: 2814 kton. This yields a score of 5. Configuration D (EW) emits 4310 kton, which yields a score of 2.3.
3. For the NPV, the score is based on the following:
   a. NPV < -3000 → 0
   b. -3000 < NPV < -2000 → 1
   c. -2000 < NPV < -1000 → 2
   d. -1000 < NPV < 0 → 3
   e. 0 < NPV < 1000 → 4
   f. NPV > 1000 → 5

6.3.3 Trade-off Matrix

In this section, the results have been translated into scores per criterion. Using the predetermined weights, this yields the final scores as presented in Table 6.3.

Table 6.3 Scores for all configurations in weighted trade-off matrix. Best performing configuration per criterion receives a 5. Higher scores are better. Green final scores denote scores equal to or above the baseline, red values are lower than the baseline.

		Configuration													
Criterion	**Weight**	Baseline	A(S)	A(EW)	B(S)	B(EW)	C(S)	C(EW)	D(S)	D(EW)	E	F(S)	F (EW)	G (S)	G (EW)
LCOE	**0.7**	3.9	2.3	2.3	5.0	5.0	2.3	2.3	4.4	4.4	5.0	2.9	2.9	5.0	5.0
CRI	**0.6**	5.0	4.0	4.0	3.0	3.0	3.0	3.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0
Grid relief	**0.8**	4.1	2.4	4.1	3.0	3.8	3.5	5.0	3.3	4.8	5.0	3.3	4.1	4.1	4.7
Self-consumption	**0.7**	3.0	4.6	5.0	4.5	4.7	4.7	5.0	4.2	4.6	4.9	4.7	4.8	4.4	4.5
CO_2 emissions	**1.0**	-0.1	2.8	2.4	4.7	4.5	2.9	2.6	2.6	2.3	3.7	5.0	4.8	4.7	4.6
Spatial integration	**0.9**	5.0	4.0	4.0	3.0	3.0	4.0	4.0	5.0	5.0	3.0	2.0	2.0	3.0	3.0
Investments	**0.8**	5.0	3.7	3.7	2.4	2.4	3.7	3.7	4.8	4.8	5.0	1.3	1.3	2.4	2.4
NPV	**0.9**	3.0	1.0	1.0	1.0	1.0	1.0	2.0	2.0	3.0	3.0	1.0	1.0	2.0	2.0
Total		**22.2**	**19.4**	**20.7**	**21.1**	**21.7**	**19.9**	**21.8**	**23.2**	**25.3**	**25.2**	**18.8**	**20.3**	**22.2**	**22.6**

The trade-off matrix shows that of all the configurations, Configuration D, 6 MWp Solar PV in East/West orientation with 15% flexibility has the highest score. Closely followed by D (S); E and G. Configuration D stands out because it provides high self-consumption of RES, is easy to integrate on the business park because no land has to be used for the integration of flexibility and PV panels can be installed on the available roofs and the investment costs are lower than for configurations involving wind energy. It should be noted however that in terms of CO_2 reduction, the most important criterion, the configuration does not score very high.

All configurations with storage do not perform well. This is due to low scores for investments, LCOE and NPV that are only marginally compensated for with better performance on other criteria.

6.4 Analysis of results

In this section, the results presented in Section 5.2 for the baseline case and Section 6.3 for the RES configurations are discussed in more detail. First, the assumptions are evaluated on their quality. If it is likely that an assumption will change and that this change has negative consequences on the performance of the configurations, it is deemed unsafe. For example, increasing costs of PV systems. If the expected change of an assumption will increase the performance of the configurations, it is deemed safe. For example, increasing capacity factors for RES generation. All unsafe assumptions, or assumptions that have a large bandwidth (such as PV installation costs) will be evaluated. This is done in a sensitivity analysis. First, the analysis is performed on assumptions that are likely to change, then the sensitivity analysis is performed on the trade-off itself to check the robustness of the results.

6.4.1 Assumption evaluation

Before the configurations were simulated, several user assumptions had been established. In this subsection, every assumption is verified and validated. Furthermore, the effect of changing the assumptions on the outcome of the configurations is discussed.

Roof area: with the use of mapdevelopers.com and Google Maps, the total roof area has been estimated at approximately 210,000 m^2. The 20% coverage resulting in 6 MWp as used in the simulations is within **safe** boundaries. With a slightly higher coverage of 25%, which also leaves enough room for maintenance paths, 10 MWp can be reached.

PV yield per m^2: 220 W/m^2 is reported in commercially available datasheets. This is likely to increase in the future due to technological innovation. The assumption is **safe.**

Storage type: C4 li-ion used in scientific research. Future development of batteries may increase the roundtrip efficiency. The assumption is **safe.**

RES capacity factors:

- **Solar PV:** capacity factors for South and East/West configurations are comparable to values reported in back in 2016 (Pfenninger & Staffell, 2016). Technological improvements since then and in the future will increase the capacity factor due to reductions in conversion losses, improved low-irradiance yield and peak performance. Furthermore, climate change will result in more solar irradiation in The Netherlands, which increases the capacity factor even more (Sigmund, 2022). The assumption is **safe.**
- **Wind:** The capacity factor of the 3 MW wind turbine is 0.29, this is slightly below the operational capacity factors of neighbouring wind farms, except for Windpark Fryslân. Because the location of this park (in the IJsselmeer) is more favourable compared to the location under study, it may be assumed that the capacity factor will be closer to the other two parks. The assumption is therefore **safe.** Increasing the capacity factor will not influence the negative monthly peak values, because peak RES generation remains 3 MW and this is reached every month already at least once. Positive peak values might reduce slightly because at lower wind speeds, more electricity is generated. Annual energy yield will increase. This will lower the electricity costs and increase the NPV of the configurations. This will positively affect Configurations B, E and F.

Carbon intensity grid electricity: due to increased penetration of RES in the electricity mix, the carbon intensity of power is decreasing (IEA, 2023). Furthermore, the carbon intensity will vary more over the day, which will lead to an overestimation of CO_2 emissions on the mixed business park with a maximum of 10% (Miller et al., 2022). Therefore, the positive impact on CO_2 emission reduction of integrating RES on the mixed business park reduces. This also affects the scores for CO_2 emission reduction in the trade-off matrix. The effect on the scores is reduced however, because the scores are determined relatively to the configuration with the largest reduction. For now, the assumption is **safe**. In future studies, the most recent CO_2 intensity of grid electricity must be used.

LCOE of energy sources:

- **Solar PV:** due to maturation of the technology, the LCOE of solar PV is expected to decrease further. This is also reflected in the differences between previous scientific estimates (Bódis, Kougias, Jäger-Waldau, Taylor, & Szabó, 2019), who calculated the LCOE of rooftop PV between 0.12 and 0.15 €/kWp, and the 2024 prognosis of PBL at 0.057 €/kWp. The assumption is **safe**.
- **Wind:** high investment costs associated with offshore and large onshore farms pose an increasing risk for RES projects (Reed & Penn, 2023). This has led to an increase in LCOE of large offshore projects in the USA to 0.114$/kW (Jain, 2023). Fortunately, in the Netherlands risks are more associated with local policy considerations and acceptance (Angelopoulos et al., 2016). Also, the increase in LCOE that is seen in large projects is mainly due to upscaling of turbines and high costs for grid integration (Reed & Penn, 2023). This not the case for 3 MW onshore turbines. The assumption of the PBL value is therefore **safe.**
- **Fossil fuels:** the LCOE of fossil fuels has been very volatile in Europe lately due to geopolitical circumstances. Furthermore, the EU's Emission Trading Scheme (ETS) increases the LCOE of carbon intensive generation. The costs of emitting one tonne of CO_2 have risen from €20 to €80 between 2020 and 2023. It is therefore likely that the LCOE assumptions of OCGT And CCGT (natural gas), coal and oil will not be valid in future studies. The assumption is **unsafe.** This increases the LCOE of grid electricity, which negatively affects the baseline, and to lesser extent Configurations A, C and D.
- **Battery storage:** overall costs of electrical storage are falling rapidly and energy density and efficiencies are increasing rapidly (Ziegler & Trancik, 2021). For stationary applications, the prospects are even better. The LCOE assumed based on recent data is therefore **safe.**

CO_2 **emissions of RES generation are zero**. The CO_2 of manufacturing wind turbines and PV panels is offset by clean power production within 2 years (Dammeier et al., 2019) and 6 years (Yadav, Kumar, & Bajpai, 2023), respectively. This is easily reached during the lifetime of the installations (typically 20-30 years). The assumption is **safe.**

Investment costs RES:

- Wind energy: in 2021, the PBL estimated €1150/kW. The current value is therefore **safe.**
- Rooftop PV: a large bandwidth was observed. Evaluating both limits makes the results more robust.
- Storage: similar bandwidth as for Solar PV. Both limits must be evaluated.

Connection costs: will likely increase in the future. Therefore, in the calculation of the NPV, this has been accounted for.

NPV: The discount rate is always arbitrary and has a large influence on the results. Next to the 4% used, also 2% and 6% must be evaluated to see the sensitivity of the scores.

6.4.2 Sensitivity analysis: effects on final ranking of RES configurations

Two different types of sensitivity analysis have been performed: the first sensitivity analysis studies the effects of changing assumptions on the scores of the configurations. The second sensitivity analysis studies the effects of changing weights of the criteria.

6.4.2.1 Changing the assumptions

Because of the complexity of the model and the multitude of assumptions, a selection of aspects is evaluated. The focus is on the assumptions that are conservative or unsafe and on the assumptions that have large bandwidths. The following assumptions have been analysed:

- LCOE of fossil fuels: due to increasing CO_2 emission taxes and rising costs for fossil fuel in general, the LCOE of grid electricity will increase with 20% from 0.095 to 0.114 €/kWh.
- Investment costs of rooftop PV: both the lower limit of 555 €/kWp and the upper limit of 1000 €/kWp will be evaluated.
- Discount rate: 2% and 6%.

The bandwidth observed for storage investments has been evaluated but this did not influence the scores significantly and the options with storage remained ranked last and below the baseline.

Increasing the LCOE of grid electricity to 0.114€/kWh reduced the score of the baseline to 21.4 compared to 22.2. Other configurations showed less sensitivity to the changing LCOE, mainly because the highest ranking LCOE, now Configuration G, also saw an increase in LCOE from 0.078 to 0.088. Because the scores of the other configurations is determined based on the best performing configuration (see Section 6.3.2 scoring algorithm), this reduces the impact on the scores of the others.

Decreasing the investment costs of rooftop PV from 700€/kWp to 555€/kWp has an impact on the scores for the investment costs and on the NPV. Investment costs for Configuration D are now the lowest (3.3 m€) which cause all other scores to decrease because the investment costs of other configurations are decreasing with a smaller ratio due to the presence of wind or storage costs. The NPV scores of Configuration D increased from 2 to 3, the rest remained unchanged. This results in Configuration D both South and East/West to outrank the other configurations. Final scores for B, E and G remain above the baseline.

Increasing the investment costs of rooftop PV from 700€/kWp to 1000€/kWp has huge impacts on the scores for investment costs and the NPV. All configurations deploying Solar PV now face an NPV that is lower than -3 m€, giving it a 0 score. Also, because the investment costs of scenario E remain the same, the relative change is much larger than for the case when the costs were lowered. Aside from Configuration E, where the score remained unchanged and is higher than the baseline, only Configuration B (EW) yields a score that is on par with the baseline score (22.2). This shows that mix of RES reduces the sensitivity to price changes of a single technology. However, current trends suggest that the price of Solar PV will only decrease (Mandys, Chitnis, & Silva, 2023).

Changing the discount rate to 2% increases the scores of the NPV for Configurations D, E and G all with 1. Changing the discount rate to 6% decreases all the scores with 1 except for Configuration D which remained the same.

In conclusion, the best scoring configuration remains D (EW), followed by E, G (EW) and B (EW).

6.4.2.2 Changing the criteria weights

As can be seen from Table 6.3, the scores of several configuration are very close together. Because the weights of the criteria have been assigned through expert interviews, a different composition of experts could have yielded different weights which would impact the scores of the configurations.

First, single criteria have been changed while keeping the other weights constant. Then, a group of similar criteria has been changed. This is done because the Province expert noted that some of the criteria might be correlated (PROV, 2023). For example, a configuration which requires large investments, might also yield a lower NPV. Similarly, if most of the RES production is consumed directly, this could reduce the negative grid exchanges. Thus, self-consumption and grid-relief could be correlated as well.

All criteria have been changed one-at-a-time by increasing and decreasing the weights with 0.5. For all-but-one options, Configuration D (EW) kept the highest score. When the NPV weight was changed from 0.9 to 1.4, Configuration E had the highest score. This shows that the results of the trade-off matrix are not very sensitive to single criteria weight changes.

Two groups of criteria have been identified: (1) economic criteria LCOE, NPV and investment costs and (2) energy criteria CO_2 reduction, self-consumption and grid relief.

- Decreasing the weights of all economic criteria with 0.5 yields no change in best scoring configuration.
- Increasing the weights of all economic criteria yields Configuration E ranking the highest (32.2), followed by D (EW) (31.2).
- Decreasing the weights of all energy criteria with 0.5 yields no change in the best scoring configuration.
- Increasing the weights of all energy criteria with 0.5 yields no change in the best scoring configuration.

This confirms that the results from the trade-off are not very sensitive to criteria weight changes. The best scoring configuration is D (EW), followed by E and B (EW).

6.4.3 Integration of heat storage for excess renewable energy

The surplus of RES that is produced on the business park can be used further. In the current situation, it is fed back to the grid. The other option considers long term storage. For this, two options will be considered: conversion to heat for heat storage and conversion to gas storage. This is a simplification of the approach proposed in the Brains4Buildings for a mixed business park (Doomernik, Ludlage, Breukel, & Moor, 2022). It should be noted that the heat demand of the mixed business park is not part of the analysis and therefore key figures of average heat demand are used: non-residential buildings (all buildings on the mixed business park) are treated as residential buildings, where every 130 m^2 of utility building floor area is treated as one residential building (ECW, 2020). The average household consumes 40 GJ or 1200 m^3 natural gas annually for hot water and heating (Milieu Centraal, 2022). Using the total roof area from the Solar PV sizing (213,000 m^2) and assuming all buildings are single stories, this equates to 1640 households with a total annual heat demand of 65,538 GJ.

Taking the best performing Configuration, D, the negative grid exchange is 1418 MWh. Using a heat pump with a coefficient of performance of 3 (Daikin, 2023), this yields 15314.4 GJ of heat. This must be stored: the energy is generated during the Summer months but used during the Winter months. Depending on the chosen technology, round trip efficiencies range between 60% and 80% (Groot, 2020; Rabi, Radulovic, & Buick, 2023; Yang et al., 2021). Taking an average of 70%, the final heat supply equals 10,720 GJ, or 16% of the total heat demand. Assuming an average efficiency of gas boilers of 90% and a heat of combustion of 33 MJ/m^3, this saves 322,000 m^3 natural gas. The Levelised Costs of Heating (LCOH) depend on the type of storage, but are generally higher than gas-fired boilers (Yang et al., 2021). Figure 6.15 shows the LCOH for various options compared to gas-fired boilers. For projects where heat demand is much larger than supply, as is the case for Heerenveen-Zuid, the costs are near the higher limits (Yang et al., 2021).

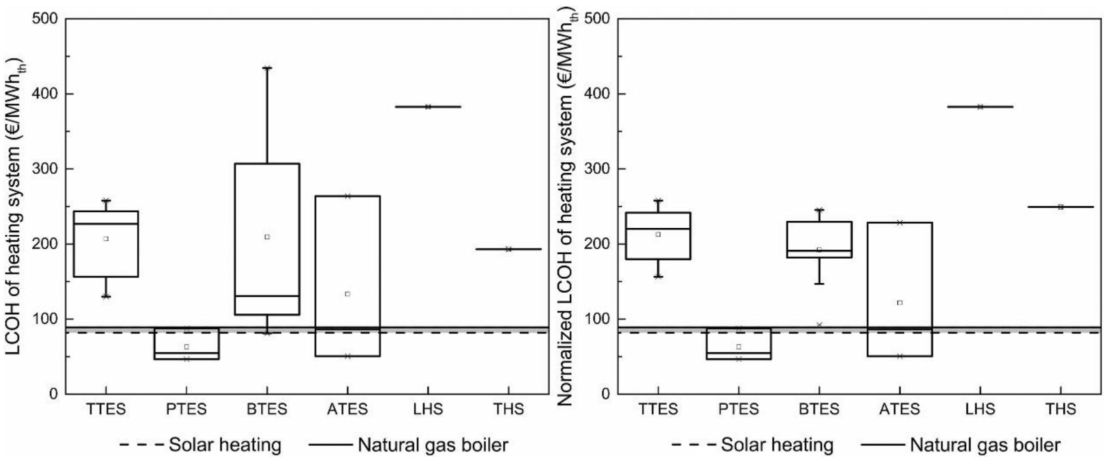

Figure 6.15 Economic comparison of various types of Seasonal Thermal Energy Storage compared to solar heating and natural gas boilers (Yang et al., 2021).

Please note that the LCOH of a natural gas boiler is **very** dependent on the price of natural gas. Since the Russian invasion of Ukraine, gas prices have soared and are currently 250%-350% higher compared to pre-invasion levels (Trading Economics, 2024). This means that the solid black line in Figure 6.15 that represents the LCOH of natural gas boilers will be much higher. The Dutch Environmental Assessment Agency (PBL) expects that the price of natural gas will remain approximately 300% higher compared to pre-invasion levels up to 2030 (PBL, 2023a). Therefore, multiple storage options can be economically feasible. Moreover, the security of supply is higher when the park can in part supply its own heat demand, which is valuable but not easily expressed in terms of economics.

A similar analysis for the configurations that have the largest excess RES production, B (S) and G (S), yields 2670 MWh. This would save approximately 600,000 m^3 of natural gas and supply 30% of the total annual heat demand.

Importantly, the rated power of the storage system must be dimensioned such that all the excess RES production can be captured. This favours the East/West solar PV in combination with wind energy because supply peaks are lower compared to PV-only and South PV orientation.

6.4.4 Increasing battery storage

The final section of the discussion investigates the effects of increasing the battery storage capacity. From the trade-off, battery storage configuration did not achieve high scores because high investment costs and low NPV are not compensated for by other performance criteria. To study this in more detail, Configuration A has been re simulated with 5 storage units: a total storage capacity of 30 MWh and a charging power of 6 MW.

Figure 6.16 shows the Spring week of Configuration A PV South.

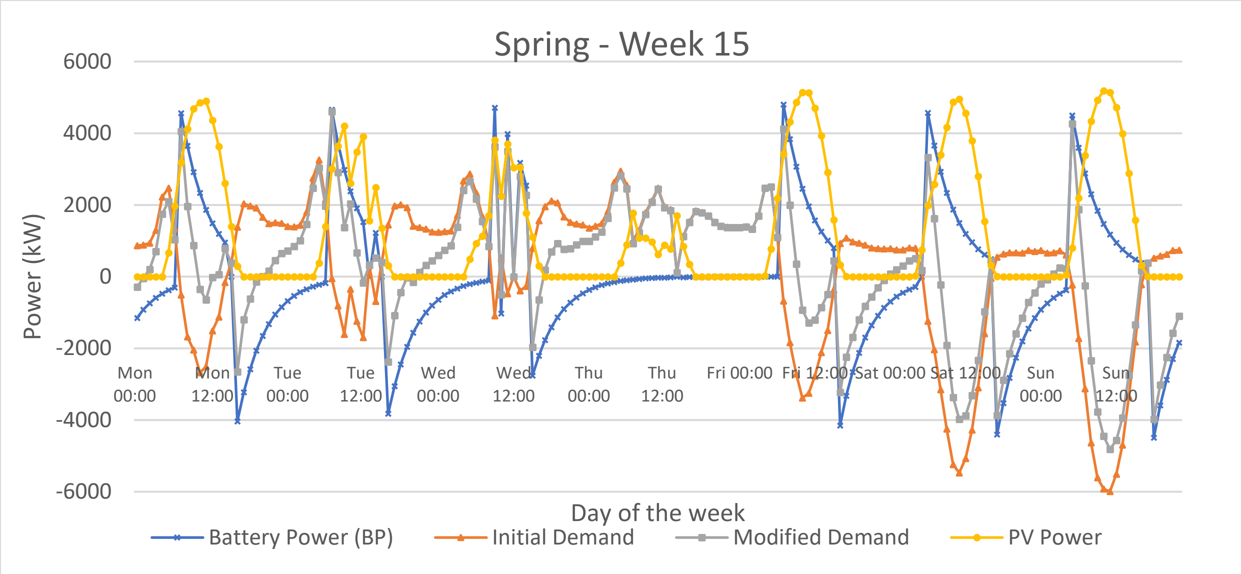

Figure 6.16 Detailed visualisation of the interaction between Solar PV production, grid electricity demand and battery power for Configuration A (S) with a battery that is five times bigger than the original configuration.

A comparison with Configuration A of Section 6.2.2.1 yields the following information:

- On days with large supply of RES, the 30 MWh battery effectively reduces peak supply to the grid: on Saturday and Sunday, peak grid exchanges are reduced with 27% and 20%, respectively, compared to 5% for the 6 MWh battery.
- Because the power rating scales with the storage capacity, the 30 MWh battery causes higher grid exchange peaks compared to the 6 MWh battery on Tuesday and Friday, effectively **increasing** grid congestion on these days.
- The self-consumption of Solar PV energy is increased: 75% of all PV energy is used, compared to 45% without battery and 54% with a 6 MWh battery.
- The charging strategy of the battery could be optimised to increase the self-consumption of solar PV. Currently, the charging strategy is based on grid exchange signals. Alternatively, basing the strategy on the actual or day ahead prediction of PV Power, such that the battery reaches rated charging power around noon (or the sunniest moment of the day).

In the trade-off matrix of Section 6.3.3, Configuration A with a 30 MWh battery would score 18.5 points, compared to 21.8 for Configuration A with a 6 MWh battery. Grid relief and self-consumption scores are higher, but LCOE, investment costs and NPV scores are lower. Grid relief and self-consumption scores are comparable to the Configuration A East/West PV panel orientation.

A different kind of battery to be considered is flow batteries. These batteries store the energy in liquids, instead of in electrochemical cells. This makes these batteries more suitable for cheap large capacity, low power storage (Sun & Zhang, 2022; Tolmachev, 2023). The costs of storage of these flow batteries are expected to decrease below €100/kWh, making them very competitive with Li-ion batteries (Komorowska et al., 2022; Sun & Zhang, 2022). The downside of flow batteries compared to Li-ion, is that they are less suitable for short term storage, which could be interesting if the batteries operate on a cost-optimising strategy (Komorowska et al., 2022).

In conclusion, increasing the storage capacity five times does not increase the performance of Configuration A with South PV panels. Minor improvements in grid relief and self-consumption of RES are outweighed by reducing economic performance. It can be concluded that using the current criteria weights, increasing the storage capacity is not beneficial. Please note that in the situation where storage costs are decreased and grid relief is much more important than direct economic performance, it could be beneficial to increase the storage capacity. For example, when the integration of large storage units could significantly increase the productivity of the mixed business park.

6.4.5 Main findings about RES configurations for Heerenveen-Zuid

First, for all configurations that involve PV panels in East/West orientation except B, the maximum grid exchange is reduced compared to the baseline case. This means that without compromising the stability or safety of the grid, a lot of RES generation can be integrated on the mixed business park. This means that the CO_2 emissions of the electricity consumption are reduced with 25% to 49% on the park. This is a good first step to reach one of the environmental goals of the Municipality of Heerenveen: 49% reduction of CO_2 emissions in 2030 (Gemeente Heerenveen, 2020). A similar analysis can be performed at the other two mixed business parks in Heerenveen, Haskerveen & Kanaal and International Business Park Fryslân.

Second, the results show that the investments required for the energy transition on the mixed business park are not offset by decreasing energy and connection costs paid by the users. However, the possibility of connecting more businesses to a previously "locked" grid yields economic benefits. Futhermore, the otherwise required investments of grid expansion are high as well: for each MW of additional grid capacity, 0.11 to 0.25 M€ is required (Royal HaskoningDHV, 2022). For projects below 50 MW, the costs are generally near the higher value of 0.25 M€/MW (Royal HaskoningDHV, 2022).

The sensitivity analysis performed on the assumptions and scoring criteria has shown that Configuration D (EW) is a robust optimal solution. The discussion of STES in 6.4.3 lead to the conclusion that storing excess RES supply is currently not economically feasible but might be interesting for other reasons or when natural gas prices increase. Increasing the battery storage capacity increase grid relief and self-consumption, but at the cost of economic performance. Wind energy is a very attractive option in terms of energy yield but will be harder to integrate due to current policies and perceptions in the Province of Fryslân.

In overview, the optimal solution for the energy transition on mixed business park Heerenveen-Zuid is to install 6 MWp of rooftop Solar PV panel in East/West orientation and combine this with demand response that requires a 15% flexibility on positive and negative grid exchanges above 3.5 MW.

7. Step 4: Implementation of optimal configuration for the energy transition

This chapter describes the implementation of the chosen configuration on the mixed business park. First, it discusses the implications for the stakeholders on the park. Second, the implementation strategy of the configuration is presented. Although the implications and the implementation are tailored towards the chosen Configuration D (EW), they are also suited for configurations that require other RES, more or less flexibility and storage.

7.1 Implications for stakeholders on the mixed business park for best scoring configurations.

For the stakeholders on the mixed business park, implementing Configuration D (EW) 6 MWp Solar PV in East/West orientation and 15% flexibility has several implications and opportunities. Per stakeholder, the most prominent opportunities and challenges are identified. The stakeholders are based on the stakeholder model provided in Section 4.2.

7.1.1 Users: businesses on the park

The users on the mixed business park benefit from a yearly economic profit of 0.17m€ compared to the baseline. Furthermore, their dependency on the grid reduces significantly because with a 76% self-consumption of Solar PV, their grid electricity use decreases with 25%. This reduces the CO_2 emissions and boosts their image to their own customers. Furthermore, because the peak exchanges with the grid are reduced, they can further electrify their production processes and new users can establish themselves at the business park. However, the 15% flexibility means that at 1474 hours per year, the users must change their demand with an average of 64 kW. This requires information from the DSO beforehand which hours (on the next day) so that the users are prepared. Also, it must be possible that production processes are run at lower power settings or that some processes are not executed simultaneously.

The challenges for the users are mainly associated with the large investments that are required for the configuration and the interruption of business operations during the implementation and transition phase. The integration of PV panels and flexibility constrains might lead to interruptions in power supply that impact production processes.

7.1.2 Societal organisations: park management

The main difference for the societal organisations on the mixed business park is that the energy management becomes centralised. They might choose to manage the system themselves, or outsource this (EIGEN, 2023). Societal organisations have an important role in bringing together the users on the park to organise the energy management centrally.

Integrating rooftop PV panels and demand response adds complexity to the management of the business park's infrastructure. Park management may face challenges in coordinating the installation, maintenance, and operation of these systems alongside existing utilities and services.

7.1.3 Knowledge institutions: universities and expertise centra

Knowledge institutions might benefit from the centralised system because the monitoring of energy management will be intensified. This allows for the extraction of data for scientific purposes. Research topics include the impact of RES and flexibility on technical aspects such as grid congestion and power quality, but also social-economic aspects such as the organisation of a Local Energy Market (see Section 2.1.4).

While the implementation of rooftop PV panels and demand response offers potential research avenues, there's a risk that the practical application within the mixed business park could be hindered by operational constraints or proprietary and privacy considerations (Doumen, Nguyen, & Kok, 2022). This limitation may restrict knowledge institutions' ability to conduct comprehensive studies or experiments on renewable energy integration and demand-side management strategies, thereby constraining their contribution to advancing sustainable energy solutions.

7.1.4 Governments: province and municipality

Government implications are multi-facetted. For one, the mixed business park can function as an example project that serves as an inspiration to other mixed business parks. Furthermore, because the grid congestion is relieved, the economy of the mixed business park can grow. However, more self-consumption will lower the taxes the users pay over the use of energy. It is beyond the scope of this analysis to investigate the net economic effects on the government economics. Most importantly, the CO_2 emissions reduction associated with the integration of 6 MWp provides a good first step in reaching the local and regional government targets.

Implementing rooftop PV panels and demand response requires adherence to regulatory frameworks and standards to ensure grid stability and safety. National, regional, and local governments may face challenges in developing and enforcing policies that balance the promotion of renewable energy adoption with the preservation of grid reliability. Failure to address regulatory compliance issues adequately could lead to grid instability, energy imbalances, and potential safety hazards, undermining the broader objectives of sustainable energy transition.

7.1.5 Companies: suppliers and consultants

Companies will benefit from the realisation of Configuration D because the realisation of the configuration will require the installation of 6 MWp of PV panels and the necessary monitoring system to manage the energy system. Furthermore, the operation of the configuration, especially the demand flexibility, will require some sort of management. If the park decides to outsource this, an ESCo may assume this role.

Suppliers of equipment, materials, and services related to rooftop PV panels and demand response systems may encounter supply chain disruptions, affecting the timely delivery of components or installation services. These disruptions may impact suppliers' reputations, financial performance, and ability to fulfil contractual obligations, jeopardising the successful implementation of renewable energy initiatives within the business park.

7.1.6 DSO

As a final important stakeholder that holds the middle between a government and a company stakeholder, the implications on the DSO are discussed. The major benefits for the DSO are twofold: (1) the configuration reduces grid congestion and (2) the monitoring of the energy system will provide the DSO with very accurate data of the electricity demand and supply. This can be applied to other similar mixed business parks in the region the DSO is active that are also faced with grid congestion.

Integrating rooftop PV panels and demand response into the electricity grid introduces challenges related to grid congestion and voltage stability. DSOs and must manage the variability of renewable energy generation and demand response activities to maintain grid reliability and quality of service. Without proper coordination and control mechanisms, increased penetration of decentralized generation and demand-side management could exacerbate grid congestion, voltage fluctuations, and power quality issues (Das et al., 2020; Doumen et al., 2022). Failure to address these risks may compromise the overall stability and resilience of the energy infrastructure, impacting the supply of electricity to the business park and surrounding areas.

7.2 Implementation strategy for Configuration D: stakeholders and deliverables

This section describes the implementation strategy for Configuration D (EW).

7.2.1 Feasibility study

The feasibility study encompasses a comprehensive examination of the financial, legal, and technical aspects of a proposed project to assess its viability and potential for success.

Financial feasibility involves analysing the project's costs and potential revenue streams, considering factors such as upfront investment, operational expenses, financing options, and projected returns on investment. Key factors to consider in the case of Heerenveen-Zuid are:

- Annual energy and connection costs paid by the users.
- Required investments for grid infrastructure fortification and expansion by the DSO.
- Investment costs of solar PV panels and monitoring systems for demand response.
- "Unlocked" economic potential if grid congestion is relieved and new companies can establish themselves at the park.

Legal feasibility entails evaluating regulatory compliance, permits, licenses, land rights, and any legal constraints that may affect project implementation. Key factors to consider in the case of Heerenveen-Zuid are:

- Permission for a shared (virtual) connection to the grid, such that consumption and RES production can be aggregated.
- Possibility for DSO to apply demand response during peak grid exchange hours (>3.5 MW).

Technical feasibility assesses the project's technical requirements, including engineering design, infrastructure needs, technology availability, resource assessments, and potential technical risks. Key factors to consider in the case of Heerenveen-Zuid are:

- Suitability of rooftops for PV panels.
- Remaining transport capacity during peak solar PV supply.
- Flexibility potential of production processes.

Together, these analyses provide stakeholders with a holistic understanding of the project's feasibility, enabling informed decision-making and risk management throughout the project lifecycle.

7.2.2 Financing decision

In the financing decision phase, the focus lies on identifying potential investors and revenue streams essential for project viability. This involves conducting thorough market research and financial analysis to pinpoint suitable financing sources, including private investors, financial institutions, and potential partners. Additionally, exploring options for subsidies, grants, or incentives offered by governments, utilities, or grid operators is crucial to offset upfront costs and enhance project economics. Understanding the intricacies of these subsidy programs, eligibility criteria, and application processes is essential for optimizing project financing and ensuring long-term financial sustainability. By carefully evaluating and leveraging available financing options, stakeholders can mitigate financial risks and enhance the overall feasibility and attractiveness of the project.

There are several subsidies and incentives in place in the Netherlands to promote the integration of RES in various settings, including mixed business parks. These subsidies aim to encourage the adoption of sustainable energy practices and reduce greenhouse gas emissions. Some examples for potential subsidies and incentives that may apply to mixed business parks are:

1. SDE++ (Stimulering Duurzame Energietransitie++) (RVO, 2023): This is a subsidy scheme aimed at stimulating the development of renewable energy projects and CO_2 reduction. It provides financial support for a wide range of renewable energy technologies, including solar, wind, biomass, geothermal, and more. Mixed business parks may be eligible to apply for this subsidy if they implement renewable energy projects.
2. Investment Allowance (Investeringsaftrek) (Belastingsdienst, 2024): Businesses investing in sustainable energy technologies, including those integrated into mixed business parks, may be eligible for investment allowances. These allowances provide tax relief for qualifying investments, effectively reducing the cost of implementing renewable energy solutions.
3. Innovation Subsidies: Various innovation subsidies are available to support research and development activities related to renewable energy technologies. Businesses developing innovative solutions for integrating RES into mixed business parks may be eligible for funding through these programs.
4. Local Municipality Grants: Some municipalities offer their own grants and incentives to businesses for implementing renewable energy projects. These grants may vary depending on the specific priorities and goals of the local government.
5. EU Funding Programs (European Commission, 2024; Murray, 2023): Businesses operating in the Netherlands can explore funding opportunities available through European Union (EU) programs aimed at promoting renewable energy and sustainability initiatives. These programs may provide grants, loans, or other financial support for RES projects in mixed business parks.
6. DSO funding (Liander, 2022): As part of grid congestion management, the DSO might incentivise mixed business parks to reduce peak grid exchanges and increase self-sufficiency of energy using RES. This could be in the form of lower connection tariffs or financial compensation for reducing demand during specified peak periods.

It's essential for businesses considering the integration of RES to thoroughly research the available subsidies and incentives, as well as any eligibility criteria and application procedures. Additionally, consulting with renewable energy experts or contacting relevant government agencies can provide valuable guidance and assistance in navigating the subsidy landscape. A comprehensive, recent overview of subsidies for the energy transition on mixed business parks has been presented (Vogelaar, 2023)

7.2.3 Distribution of ownership and responsibility

Establishing a clear distribution of ownership and responsibilities is crucial when implementing RES, storage solutions, and flexibility assets (Simonse, 2021). This involves assigning ownership for each component, such as solar panels or batteries, and allocating responsibilities among stakeholders like investors, operators, utilities, and regulatory bodies. This structure ensures efficient management and operation throughout the assets' lifecycle, fostering accountability, enabling effective decision-making, and contributing to sustainable integration into the grid.

7.2.4 Contracting suppliers of PV panels and monitoring systems

To implement the proposed solution effectively, it is imperative to identify suitable suppliers who can provide the necessary materials, equipment, or services required. This involves conducting thorough research and assessment to ensure that selected suppliers meet the project's requirements in terms of quality, reliability, and cost-effectiveness. Once potential suppliers are identified, the next step is to draft contracts that formalize the agreements between the parties involved. These contracts should outline the terms and conditions of the agreement, including but not limited to deliverables, payment schedules, warranties, and dispute resolution mechanisms. By formalizing agreements through well-drafted contracts, both parties can mitigate risks, clarify expectations, and establish a solid foundation for successful collaboration and project execution.

7.2.5 Operation, maintenance and end-of-life

Organizing the operation, maintenance, and end-of-life strategies of assets is essential for ensuring their long-term functionality, sustainability, and eventual decommissioning. This process involves developing comprehensive plans and protocols for the day-to-day operation and upkeep of the assets, including regular inspections, preventive maintenance schedules, and troubleshooting procedures to address any issues promptly and minimize downtime. Additionally, implementing effective end-of-life strategies entails planning for the eventual retirement or replacement of the assets, including considerations such as asset disposal, recycling, or repurposing to minimize environmental impact and maximize resource utilization. By systematically organizing these strategies, stakeholders can optimize asset performance, extend their lifespan, and responsibly manage their eventual retirement in alignment with regulatory requirements and sustainability goals.

8. Discussion

This chapter provides a discussion of four main aspects of this thesis. The first section discusses the research design. The second section discusses the results of the RES configurations that have been simulated. The third section discusses the added value of this research to the scientific field of energy transitions on mixed business parks and practical value for mixed business parks that are faced with similar problems as Heerenveen-Zuid. The final section discusses the limitations of this study and provide suggestions for future work.

8.1 Discussion of Research Design

The goal of this thesis was to analyse the energy management of an existing mixed business park and develop a guideline for the energy transition on mixed business parks. This section aims to evaluate the research design to reach this goal by highlighting the structure of the research, the data analysis and the sizing and integration of the RES configurations.

8.1.1 Discussion of research design

The literature study suggested a research design consisting of four steps to go from a status quo to a mixed business park that deploys higher shares of RES and reduces grid congestion (Rodin & Moser, 2021). In Chapter 4, commercial guidelines have been analysed and the 4-step approach was validated: most of the guidelines written for the target audience that is also the target audience of this thesis use four steps or phases. However, some modifications have been made compared to the content of each step as discussed by (Rodin & Moser, 2021), (Simonse, 2021) and (EIGEN, 2023). Most importantly, the moment of data collection was moved from the first to the second step. This is because the collection of data, in particularly actual consumption data, is a privacy-sensitive and time-consuming operation. Doing this in the first step risks obligations from the users because this would feel as a large commitment very early in the process.

Furthermore, by first performing the data analysis on the case study data and combining this with the park characteristics, an estimation of the RES potential was made. This was necessary because the grid congestion problem requires a thorough understanding of the electricity exchange peak values before configurations can be developed. Also, the maximum current grid exchange of 4491 kW was used to provide direction for the sizing of the renewables, storage and flexibility. For example, if the initial grid exchange of the park would be zero and the renewables were at rated power, a flexibility of 15% will ensure the grid exchange is approximately the same as this 4491 kW. In cases where the grid is less congested, the potential of RES could be determined already in Step 1 as part of the ambition setting. Tools such as the Energy Potential Scan developed by TNO or the PVB Toolkit can be used for this purpose (Nordkamp et al., 2021; TNO, 2021). This might also be used to get the stakeholders on the park enthusiastic, because it often shows that a lot of renewable energy could be generated.

8.1.2 Discussion of data analysis tool

As discussed, the tool to analyse the mixed business park is a representation of reality and the results are based on historical data. Because real life data has been used, some of the uncertainties are addressed and reduced, but the assumptions made to simplify the model can mean that Configuration D is not the most optimal path to better energy management with the integration of RES.

Furthermore, in this study only electricity as an energy carrier has been analysed on an hourly basis. However, heat demand cannot be complete neglected, especially when businesses plan to switch from natural gas fired boilers to heat pumps or when production processes are electrified.

Next, the model uses a combination of Excel, Python and EnergyPLAN to simulate the configurations. Initially, the idea was to use EnergyPLAN only, but this provided to many difficulties. Integrating the different aspects of the three applications into a single tool with a user interface could make the tool more suitable for people with fewer computational programming skills.

Finally, the grid of the mixed business park has been simplified considerably. The description of the grid in Section 4.4.2 showed multiple cables and a single substation. In the tool, the grid exchange of electricity has been simulated as a single connection to the substation. A more detailed analysis might be required depending on the problem description. This could be performed by recreation of the mixed business park in advanced software tools such as PowerFactory including preliminary locations and sizing of connection points for the rooftop PV panels and storage. Such an analysis has been conducted in a study on a simulated and simplified park (Neri et al., 2023), but not on a real case. One could opt for a physical adaption of the grid infrastructure to get everyone on the same line, but given current workloads at DSOs, this is not feasible. The other option is to establish a virtual grid, after making sure that the grid congestion is at the aggregated level and not on an individual transmission line. This way, the use of aggregated data is no problem.

To conclude, the usage of actual data in combination with RES generation for that same year has provided an accurate view of the electricity consumption on the mixed business park and the impact of different RES configurations. Further analysis should focus on the integration of heat demands and the simulation of the actual grid infrastructure.

8.1.3 Discussion of sizing and integration of RES, storage and flexibility

First, the sizing and integration of the renewables is discussed. The sizing and location of renewables was based on satellite images of the mixed business park. This is a good initial way of sizing, because this can be easily done without having to visit the park. Furthermore, to install 6 MWp of rooftop PV, a minimum area of 30.000 m^2 is required. This should be no problem on a total area of 213.000 m^2. Furthermore, the current policies of PV installation are aimed at maximising the use of rooftops first, before considering other locations (Provincie Fryslân, 2022). This is beneficial for the business park. However, the sizing and location of the wind turbine is more complicated. The chosen location has multiple advantages and in terms of location it seems feasible, although a more detailed study of the risk zoning might be required (DNV GL, 2020). Next, the current policies concerning new wind turbines in Friesland are stringent: either three or more older wind turbines must be phased out to make room for one newer, bigger turbine. Else, an exception to the environmental regulation or zoning plan must be made (Provincie Fryslân, 2022). Using ArcGIS, two solitary older turbines have been identified in the area surrounding the park and two near the park (ArcGIS, 2024). Replacing these older turbines with one newer turbine could be possible, but this means that the owners of the existing turbines must also benefit from this in one way or the other. Furthermore, the net added renewable power is slightly lower duo to the loss of generation of the older turbines.

Next, the functionality of the battery storage module has been evaluated. In weeks with high RES production, the battery managed to reduce the positive and negative grid exchanges, but in weeks with low RES production, the battery was largely inactive. The battery's main purpose was to enhance the self-consumption. This was achieved, as pointed out in subsection 6.2.2.1. A different approach to the modelling of the battery, including integration of the storage into an optimisation strategy could be explored. In this way, the inactivity of the battery could be reduced, for example by setting different charging and discharging thresholds in solar PV configurations in winter months. Also, different charging strategies, for example based on price signals instead of grid exchange signals can be investigated. It should be noted however that this could *increase* grid congestion if all batteries operate on a cost-minimising strategy (Cappellen, Rooijers, Vendrik, & Jongsma, 2023; Verzijlbergh et al., 2014). In Section 6.4.4, a simulation was performed using a battery system that is five times the size of the initial battery system. The analysis of the larger battery clearly demonstrated that a different charging logic is advisable if grid congestion is to be reduced. Also, charging based on PV power signals could be explored to increase self-consumption. In conclusion, the large battery yielded lower peak annual grid exchange, but only minor economic benefits in terms of total energy costs and connection costs. In terms of the trade-off matrix, the score was below the baseline scenario and the initial configuration.

Third, the flexibility integration is evaluated. The current problem of grid congestion in the Netherlands requires the government and DSOs to be creative as large parts of the Netherlands have become congested (NetBeheer Nederland, 2023a). In 2022, significant alterations have been made to the "netcode" or grid code to reduce grid congestion (Autoriteit Consument en Markt, 2022). The alterations strongly hint towards capacity subscription of users. This means that the DSO may impose limits on the use of the connection to the grid during certain hours (dynamic) or all the time (static). A pilot project of Liander, the DSO in Heerenveen-Zuid, considered dynamic capacity subscription during peak hours of a single large user on the mixed business Park Leeuwarden Schenkenschans (Liander, 2022). In this pilot, limiting the demand of a single user opened up connection capacity for eight other firms (Liander, 2022). In the research design of this thesis, a static approach has been used. The benefit of the static approach is that it is more straightforward to implement, especially when there are multiple users. One important aspect of the flexibility of this thesis is that the daily sum remains the same. This ensures that the total electricity consumption every day is the same as before applying the flexibility such that the users are not curtailed in their collective daily energy use, but only the time of use. Residential experiments and simulations have shown that applying flexibility is possible and might yield economic benefits, depending on the type of flexibility (Bjarghov, Farahmand, & Doorman, 2022). In this thesis, the impact of flexibility on the total costs of electricity is favourable, because the flexibility reduces the grid connection costs significantly. To illustrate this, the connection costs for Configuration A are 10% to 20% higher compared to Configuration C, which yields an annual benefit of €20,000 to €40,000.

8.2 Added value of this study

8.2.1 Scientific value

The scientific relevance of this thesis lies in its contribution to addressing significant research gaps identified in current literature as discussed in Chapter 2. Firstly, the coupling of process description to technical modelling of energy balance represents a critical aspect that has been underexplored. As highlighted by Butturi et al. (2019), many studies tend to focus solely on either process description or technical modelling, neglecting the interconnectedness between the two. By bridging this gap, the thesis enriches our understanding of energy dynamics within mixed business parks, offering a comprehensive perspective that incorporates both descriptive and analytical dimensions.

Secondly, the application of existing frameworks to case studies within the context of mixed business parks is an area where prior literature has been lacking. Susur et al. (2019) emphasize the importance of case studies in validating theoretical frameworks and assessing their applicability in real-world scenarios. By integrating established frameworks with empirical data from mixed business parks, this thesis contributes to filling this void, demonstrating the practical utility of theoretical constructs in informing decision-making processes and strategic planning related to energy transition. Consequently, the case study is now firmly embedded in scientific literature.

Finally, the results presented in this thesis offer novel insights into the energy balance and the potential for renewable energy generation within mixed business parks. By shedding new light on these aspects, the thesis extends the boundaries of existing knowledge, paving the way for further research and practical applications in the field of sustainable energy management. Through meticulous analysis and empirical investigation, the thesis not only addresses current gaps in scientific literature but also lays the foundation for future advancements in understanding and optimizing energy systems within mixed business park environments.

8.2.2 Value for practice and practitioners

The practical relevance of the results obtained in this thesis extends to various stakeholders involved in the operation and management of mixed business parks, including the local, regional and national governments, the businesses situated within the park, the DSO Liander, and the park management.

Firstly, for the municipality of Heerenveen, the findings offer valuable insights into crafting effective energy policies and strategies that align with sustainability goals (Gemeente Heerenveen, 2020). By understanding the energy dynamics and renewable energy potential within mixed business parks, the municipality can tailor regulations and incentives to encourage businesses to adopt greener practices, thus contributing to the overall energy transition objectives of the municipality (Gemeente Heerenveen, 2020, 2023).

At the regional level, the energy transition on mixed business parks aligns with broader sustainability objectives outlined in regional energy and climate strategies. The solar PV-only Configuration D aligns with current regional strategies for the implementation of RES (Provincie Fryslân, 2022). By promoting the adoption of renewable energy and energy-efficient practices among businesses, mixed business parks contribute to mitigating environmental impacts and fostering a cleaner and greener regional energy landscape. Furthermore, by serving as hubs for innovation, knowledge sharing, and capacity-building, mixed business parks drive economic growth, social prosperity, and sustainable development across the region. For Gelderland and Overijssel, this has already been assessed and quantified in more detail (Royal HaskoningDHV, 2022).

On the national level, the implementation of the energy transition on mixed business parks plays a vital role in advancing national sustainability goals and energy transition objectives as defined by the PBL and the National Government (PBL, 2023a; Rijksoverheid, 2019). By demonstrating the feasibility and scalability of renewable energy integration, mixed business parks contribute to achieving national targets for renewable energy deployment, emissions reduction, and energy security. Moreover, by promoting collaboration between industry, academia, and government, mixed business parks stimulate innovation, drive technological advancement, and enhance the competitiveness of the national economy in the transition to a low-carbon future.

Next, for the businesses operating within the mixed business park, the practical implications of the thesis results are significant. By uncovering opportunities for renewable energy generation and optimizing energy balance, businesses can not only reduce their carbon footprint but also lower energy and connection costs in the long term. A shared approach increases profits and self-consumption of solar energy (Ceglia et al., 2023). Moreover, the insights provided can inform decision-making regarding investments in renewable energy infrastructure and technologies, enabling businesses to align their operations with environmental sustainability while also enhancing their competitiveness in the market.

Additionally, the results of the thesis are of practical relevance to entities such as DSO Liander and park management. Liander can utilize the findings to better understand energy demand patterns within mixed business parks and optimize grid management strategies accordingly. Also, flexibility from the DSO and TSO side is seen as an instrumental aspect of the large-scale integration of RES (Das et al., 2020; Stawska et al., 2021). Moreover, park management can leverage the insights to facilitate the implementation of energy-efficient infrastructure and services within the park, fostering a conducive environment for sustainable business practices while enhancing the overall attractiveness of the park to potential tenants and investors. The practical implications of the thesis results extend beyond mere academic discourse, offering tangible benefits to key stakeholders involved in the sustainable development and management of mixed business parks.

To aid the development of energy transitions on mixed business parks, the following flow diagram, Figure 8.1, shows the procedure as derived from the steps in this thesis and other guidelines discussed in Sections 2.1.4 and 4.1.6 (EIGEN, 2023; Rodin & Moser, 2021; Simonse, 2021; TNO, 2021).

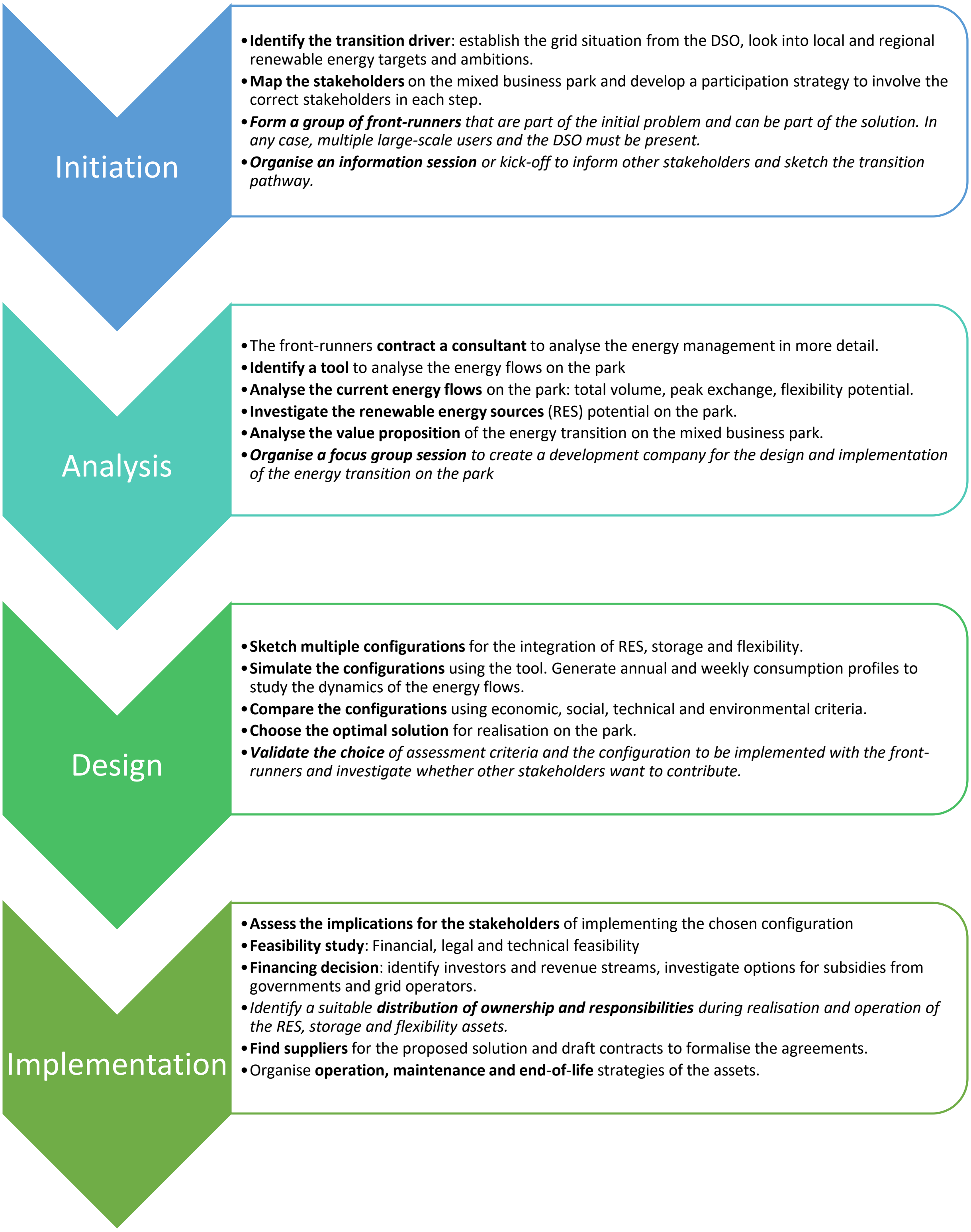

Figure 8.1 Process description for the energy transitions on mixed business parks. Intermediate steps that specifically consider stakeholder engagement are in italics.

Comparing Figure 8.1 to the approach outlined in Chapter 3, the main difference can be found in the intermediate steps that consider stakeholder engagement. The analysis of commercial guidelines and the execution of the Steps 1-4 as performed in Chapters 4, 5, 6 and 7 lead to the following conclusion. The critical link between integrating a technical energy simulation tool and a process description for the energy transition on mixed business parks lies in the stakeholders. Therefore, the process description suggests ways to engage the stakeholders. These intermediate steps are in *italics.*

For each phase, a different stakeholder is in the lead. During initiation, the initiative lies with the park management, entrepreneurial organisation and municipality. Among these stakeholders, a development company is founded. The development company hires a consultant to perform the analysis of the energy balance and design of the energy transition configurations. Based on the financing decision and the distribution of ownership and responsibilities in the fourth step, the development company outsources part of the work to market parties.

Finally, a system intermediary or transition broker can play an important role in the complete process (Cramer, 2020; Valladolid Calderon, 2021). Transition brokers, functioning as intermediaries with a neutral stance, play a pivotal role in facilitating processes of change at the regional level. Their impartial position allows them to create alliances, establish essential prerequisites, and spearhead impactful circular initiatives without arousing suspicions of self-interest. Transition brokers navigate between companies and other stakeholders, orchestrating the preparation, negotiation, and execution of circular agreements while facilitating the scaling up and eventual mainstreaming of these transitions (Cramer, 2020).

8.3 Limitations of this study and suggestions for future work

Throughout this thesis, several limitations have been described. These limitations come in two types: limitations because of the chosen scope of the thesis and limitations because of the research design simplifications and assumptions.

While this thesis makes significant progress in understanding energy management within mixed business parks, it is crucial to acknowledge its limitations to provide a comprehensive picture of the research landscape. Firstly, the treatment of energy management aspects remains incomplete. Despite discussing heat demand integration at a high level, incorporating excess RES to partially meet annual heat demand, the thesis overlooks critical elements such as leveraging residual heat and waste streams for industrial symbiosis. Recent studies underscore the importance of industrial symbiosis in enhancing energy efficiency and resource utilization within industrial ecosystems (Geng, Sarkis, & Bleischwitz, 2019). Furthermore, the integration of these broader aspects of energy management in modelling remains an important suggestion for future work (Demartini et al., 2022). Addressing these aspects could enrich the analysis by exploring additional avenues for sustainable energy utilization and fostering circular economy principles.

Secondly, the thesis primarily focuses on the direct economic benefits of energy configurations for park users: electricity bills and connection costs. This neglects broader considerations such as environmental and societal impacts. Recent research emphasizes the multifaceted nature of value propositions in sustainable energy systems, highlighting factors such as grid congestion mitigation, competitive advantages from renewable energy adoption, and reduction of emissions (EIGEN, 2023; F.G. Reis, Gonçalves, A.R. Lopes, & Henggeler Antunes, 2021). Incorporating these dimensions would provide a more holistic understanding of the value proposition of energy configurations within mixed business parks, aligning with broader sustainability goals and stakeholder interests.

Thirdly, the thesis acknowledges several simplifications and choices made in the research design, which could impact the robustness and applicability of the findings. For instance, the simplified treatment of the grid situation as a single connection may overlook critical nuances in grid congestion dynamics, necessitating a closer examination of hardware components and distribution network constraints. Recent advancements in grid optimization techniques emphasize the need for sophisticated approaches to grid management, considering factors such as distributed energy resources and demand response flexibility (Morstyn, Savelli, & Hepburn, 2021; Stawska et al., 2021; Zheng, Shafique, Luo, & Wang, 2024). Incorporating these considerations would enhance the accuracy and practical relevance of the analysis, offering more nuanced insights into energy management strategies within mixed business parks.

In conclusion, while the thesis contributes significantly to the understanding of energy transition dynamics within mixed business parks, its limitations underscore the complexity and evolving nature of sustainable energy management. In overview, future work could focus on the following aspects:

- The simulation of other types of (electrical) storage, for example flow batteries. This could significantly reduce the baseload electricity requirement. Baseload generation is one of the main challenges associated with electricity networks that have a high integration of Solar PV energy (Ordóñez, Fasquelle, Dollet, & Vossier, 2023)
- The integration of other types of flexibility, such as Vehicle to Grid (V2G). It is possible to include this option in EnergyPLAN (Lund et al., 2021), but that was determined to be outside the scope of this thesis.
- The effect of implementing the energy transition on mixed business parks throughout the country. These parks can function as decentralised energy generators and at the same time provide much needed flexibility and buffer capacity to the strained grid. The parks can function as a network that reduces grid congestion and the dependence on grid electricity on local and regional scale.

Addressing these limitations through further research and refinement of methodologies will not only enhance the academic rigor of future studies but also inform more effective policy and decision-making processes in the pursuit of sustainable energy transitions.

9. Conclusion and recommendations

9.1 Answering the research questions

To limit global warming, CO_2 emissions must be mitigated. Following the 2015 Paris Climate Agreement and subsequent EU and national policies, this means that the production of electricity must be transitioned from a fossil fuel-based sector to a sector that runs primarily on renewable energy sources (RES) such as wind and solar PV. However, the integration of RES comes with various challenges: intermittency of supply, location suitability, high investment costs and grid connectivity. The latter is currently slowing down the energy transition in the Netherlands, because newly installed RES capacity cannot be connected to the grid because the transport capacity limits are reached during peak demand and supply. This is called grid or transport congestion. For entrepreneurs on mixed business parks, this means that they cannot transition away from grid electricity by installing PV panels, electrify their vehicle fleet or production processes. Mixed business park Heerenveen-Zuid has been used as a case study.

The main research question consists of several aspects, which have been addressed in five sub questions.

1. *"Which steps are required to engage stakeholders in the energy transition on mixed business parks?"*

From the literature study and the analysis of commercial tooling for the energy transition on mixed business park, a 4-step approach to engage stakeholders is identified: initiation, analysis, design and realisation. The structure of this thesis represents the same approach and as such provides a complete walkthrough of this process. Figure 8.1 summarises the main aspects of each phase. Deviating from the literature study and analysis of commercial guidelines, the following aspects are highlighted:

- The data analysis has been moved from the first to the second step because of the commitment that is required from the users on the park for providing the data.
- Suggestions for stakeholder engagement have been identified for each step.
- Throughout the process, the inclusion of a system intermediary or transition broker is essential to stimulate the creation of a shared approach. These intermediaries orchestrate the stakeholders, such that each stakeholder finds its role in the transition.

2. *"What tools are available for the optimisation of energy management on mixed business parks?"*

The investigation of suitable tooling resulted in the conclusion that existing tooling was not fully capable of providing the necessary detail to study grid congestion. Therefore, the newly developed tool used to simulate the configurations was a combination of Excel, Python and EnergyPLAN. This provided an optimum between the complexity of the model and the required detail of the results. The tool consists of five modules: data sourcing, RES integration, storage integration, flexibility integration and output generation. The outline of the tool is presented in Figure 5.1 and a detailed description is provided in Section 5.1.

3. *"How can renewable energy configurations be simulated to increase the use of RES and reduce grid congestion on mixed business parks?"*

An investigation into the most suitable RES configuration on a mixed business park in Heerenveen has been performed. Seven different configurations of Solar PV, wind, storage and flexibility have been simulated. To provide a balanced result, eight criteria have been identified to score the configurations on environmental, social, economic and technical performance and criteria weights have been assigned to each of the eight criteria by interviews with experts for several stakeholders in the field of energy management on mixed business parks.

The optimal configuration for the mixed business park Heerenveen-Zuid is Configuration D. This configuration deploys 6 MWp in East/West orientation combined with 15% flexibility. This means that for the power that is exchanged with the grid, all hourly values with an absolute value (so both demand and supply grid exchange) above 3500 kW are reduced with a maximum of 15%. The daily sum of power remains the same as before the flexibility. Compared to the baseline, CO_2 emissions are reduced with 25%; grid congestion is reduced with 12%; the energy and connection costs decrease with 30% per year.

4. *"What are the effects and opportunities for the stakeholders on a mixed business park when renewable energy is implemented?"*

Integrating 6 MWp of Solar PV and 15% flexibility on an existing business park has the following main implications.

Users, primarily businesses on the park, experience economic benefits with a yearly profit increase of 0.18M€ compared to the baseline. They also reduce grid dependency by consuming 76% of their generated PV electricity. This reduces CO_2 emissions and enhances their image. However, flexibility demands, averaging 64 kW for 1474 hours annually, require adjustments in production processes and reliance on DSO-provided information. Some production processes cannot be executed during peak demand hours, whereas during peak supply hours, extra consumption is required.

Societal organizations, like park management, face centralizing energy management, which can be managed internally or outsourced. Integration of rooftop PV panels and demand response adds complexity, challenging coordination with existing utilities and services.

Companies, including suppliers and consultants, profit from system realization, requiring 6 MWp of PV panels and demand flexibility management. Supply chain disruptions may affect timely delivery of components, impacting implementation success.

DSOs benefit from reduced grid congestion and accurate energy system monitoring, aiding similar parks in the region. However, integrating rooftop PV panels and demand response poses challenges to grid stability and quality of service without proper coordination mechanisms.

Governments view the park as a model for sustainable development, inspiring similar projects. Reduced CO_2 emissions align with local and regional targets, but challenges exist in balancing renewable energy promotion with grid reliability regulations.

Knowledge institutions benefit from intensified energy management monitoring, aiding scientific data extraction. However, operational constraints and privacy considerations may impede practical application within the park, limiting comprehensive studies on renewable energy integration.

5. *"How does the implementation of the energy transition on mixed business parks contribute to the sustainability goals in the region and on national level?"*

The implementation of the energy transition on mixed business parks contributes significantly to sustainability goals at both the regional and national levels. At the regional level, mixed business parks serve as focal points for sustainable development initiatives, enabling the integration of RES and smart grid technologies to reduce carbon emissions and enhance energy efficiency. By promoting the adoption of renewable energy generation and energy-efficient practices among businesses operating within the park, the energy transition contributes to mitigating the environmental impact of industrial activities and fostering a cleaner and greener regional energy landscape. Moreover, by fostering collaboration between businesses, park management, and local authorities, the energy transition within mixed business parks facilitates knowledge sharing, innovation, and capacity-building, driving economic growth and social prosperity in the region.

On a national level, the implementation of the energy transition on mixed business parks aligns with broader sustainability objectives outlined in national energy and climate policies. By leveraging the synergies between industry, innovation, and sustainable energy, mixed business parks play a pivotal role in accelerating the transition to a low-carbon economy and achieving national targets for renewable energy deployment and emissions reduction. Moreover, by serving as showcases for sustainable energy solutions and best practices, mixed business parks demonstrate the feasibility and scalability of renewable energy integration, inspiring similar initiatives across the country. Furthermore, the energy transition on mixed business parks contributes to enhancing energy security, resilience, and competitiveness at the national level by diversifying energy sources, reducing dependence on fossil fuels, and promoting innovation and technological advancement in the energy sector.

In summary, the implementation of the energy transition on mixed business parks contributes significantly to sustainability goals at both the regional and national levels by fostering the adoption of renewable energy, enhancing energy efficiency, driving economic growth, and advancing innovation. By serving as hubs for sustainable development and collaboration, mixed business parks play a vital role in shaping a more sustainable and resilient energy future for the region and the nation.

For this thesis, the main research question was:

"How can renewable energy configurations be designed for and implemented on mixed business parks, to increase the use of renewable electricity and reduce grid congestion?"

The energy transition on mixed business parks encompasses production, storage, distribution, and demand management. These four aspects have been tested through various configurations of RES, storage, and demand flexibility on a case study park: Heerenveen-Zuid. These configurations include different orientations of solar PV and are evaluated based on nine criteria covering economic, technological, social, and environmental aspects. A stakeholder engagement framework is outlined, guiding the thesis structure, while a novel tool combining Excel, Python, and EnergyPLAN is introduced to analyse the configurations and address current limitations in studying grid congestion. Results show that a configuration with 6 MWp rooftop solar PV in East/West orientation and 15% demand flexibility performs best, reducing grid congestion by 12% and CO_2 emissions by 25%. Despite challenges in integration and investment costs, configurations combining wind and solar energy score highly in CO_2 reduction. The integration of solar PV and flexibility presents economic benefits, adaptation requirements, and serves as an example for various stakeholders. Additionally, the implementation of the energy transition in mixed business parks is emphasized for its role in achieving regional and national sustainability goals, aligning with broader energy and climate policies. Mixed business parks are seen as crucial drivers for renewable energy adoption, innovation, and economic growth, contributing significantly to shaping a sustainable energy future.

9.2 Recommendations for stakeholders in the energy transition of mixed business parks

9.2.1 Users on the parks

Businesses operating within mixed business parks have a significant opportunity to contribute to the energy transition by adopting sustainable energy practices and investing in renewable energy technologies. It is recommended for businesses to conduct energy audits to identify areas for energy efficiency improvements and explore opportunities for on-site renewable energy generation. Moreover, collaborating with neighbouring businesses to explore synergies in energy utilization and industrial symbiosis can lead to mutual benefits and cost savings. Additionally, engaging in demand response programs and implementing energy management systems can help businesses optimize energy consumption patterns and reduce operational costs while supporting the overall sustainability goals of the park.

9.2.2 Park management and entrepreneurial organisations

Park management and entrepreneurial organizations serve as crucial intermediaries between park stakeholders and external partners, facilitating collaboration and driving innovation within mixed business parks. It is recommended for park management and entrepreneurial organizations to proactively engage with park stakeholders to understand their energy management needs and priorities. Moreover, organizing knowledge-sharing events, workshops, and networking opportunities can increase collaboration and facilitate the exchange of best practices among park tenants. Additionally, advocating for supportive policies and incentives at the local and regional levels can create an enabling environment for the adoption of sustainable energy solutions within mixed business parks, driving long-term economic and environmental benefits.

9.2.3 Companies and suppliers

Companies and suppliers of RES and smart grid assets play a critical role in providing innovative solutions to support the energy transition within mixed business parks. It is recommended for these companies to continue investing in research and development to enhance the performance and cost-effectiveness of RES technologies and smart grid infrastructure. Moreover, fostering partnerships with park stakeholders and offering tailored solutions to address specific energy management challenges can create new business opportunities and drive market growth. Additionally, companies should prioritize providing comprehensive technical support, training, and maintenance services to ensure the reliable and efficient operation of RES and smart grid assets within mixed business parks.

9.2.4 Consultants

Consultants play a key role in advising park stakeholders on energy management strategies and facilitating the implementation of sustainable solutions. It is recommended for consultants to stay updated on the latest developments in renewable energy technologies, smart grid solutions, and energy management practices through continuous professional development and knowledge sharing. Moreover, consultants should adopt a comprehensive approach to energy management consulting, considering not only technical aspects but also economic, environmental, and social factors. Additionally, creating long-term partnerships with park stakeholders and providing tailored advisory services can help consultants add value and drive positive outcomes in the energy transition process within mixed business parks. Consultant are suited for the role of transition broker as detailed in Section 8.2.2.

9.2.5 TSO and DSOs

The TSO and the DSOs play a pivotal role in facilitating the integration of RES and smart grid assets within mixed business parks. It is imperative for TSOs and DSOs to collaborate closely with park stakeholders to assess grid capacity and identify opportunities for grid reinforcement where necessary. Moreover, investing in advanced grid management technologies and demand response mechanisms can help mitigate grid congestion and enhance system flexibility. Additionally, TSOs and DSOs should actively engage in regulatory dialogue to streamline grid connection processes and incentivize investments in grid infrastructure upgrades or flexibility integration to reduce grid congestion and support the energy transition within mixed business parks.

9.2.6 Province and Municipality

Governments at both the provincial and municipal levels play a crucial role in creating an enabling policy environment to support the energy transition within mixed business parks. It is recommended for governments to develop comprehensive energy transition strategies that encompass regulatory frameworks, financial incentives, and capacity-building initiatives. Furthermore, governments should prioritize investments in sustainable infrastructure and promote public-private partnerships to accelerate the deployment of renewable energy and smart grid technologies. Additionally, fostering collaboration between different levels of government, industry stakeholders, and research institutions can facilitate knowledge sharing and best practices exchange, driving innovation and sustainable development within mixed business parks.

9.2.7 Knowledge Institutes: universities and research consortia

This thesis significantly advances understanding of energy transition dynamics within mixed business parks, its limitations highlight the intricate and evolving nature of sustainable energy management. Future research could address several key aspects, including the simulation of alternative electrical storage types like flow batteries to alleviate baseload electricity requirements, integrating other flexibility options such as Vehicle to Grid (V2G), and assessing the broader impact of energy transition implementation on mixed business parks nationwide. These parks have the potential to serve as decentralized energy generators, offering flexibility and buffer capacity to alleviate grid strain, thus reducing grid congestion and local and regional dependence on grid electricity. Addressing these limitations through further research and methodological refinement not only strengthens academic inquiry but also informs more effective policymaking and decision-making processes in advancing sustainable energy transitions.

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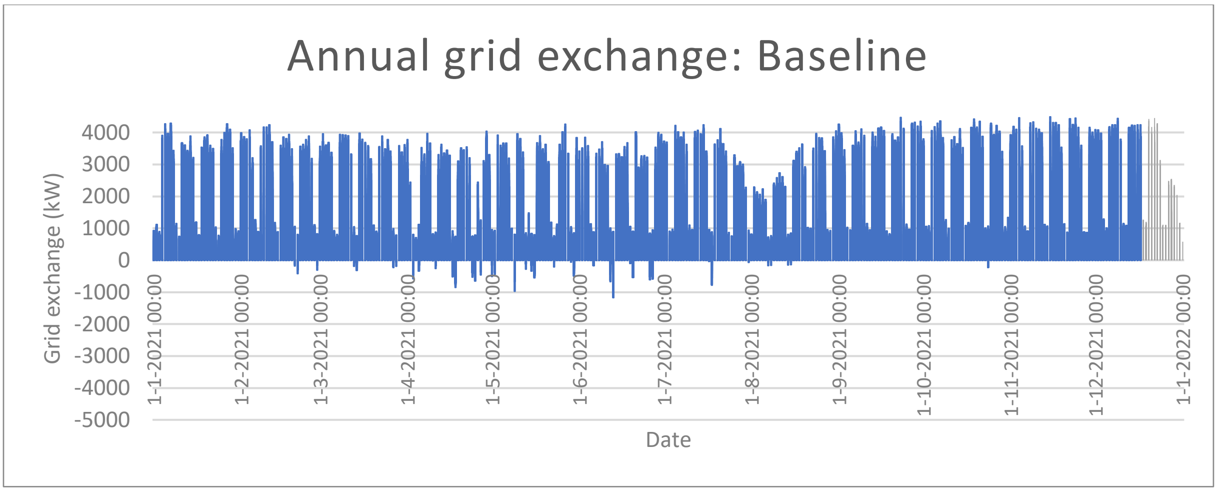
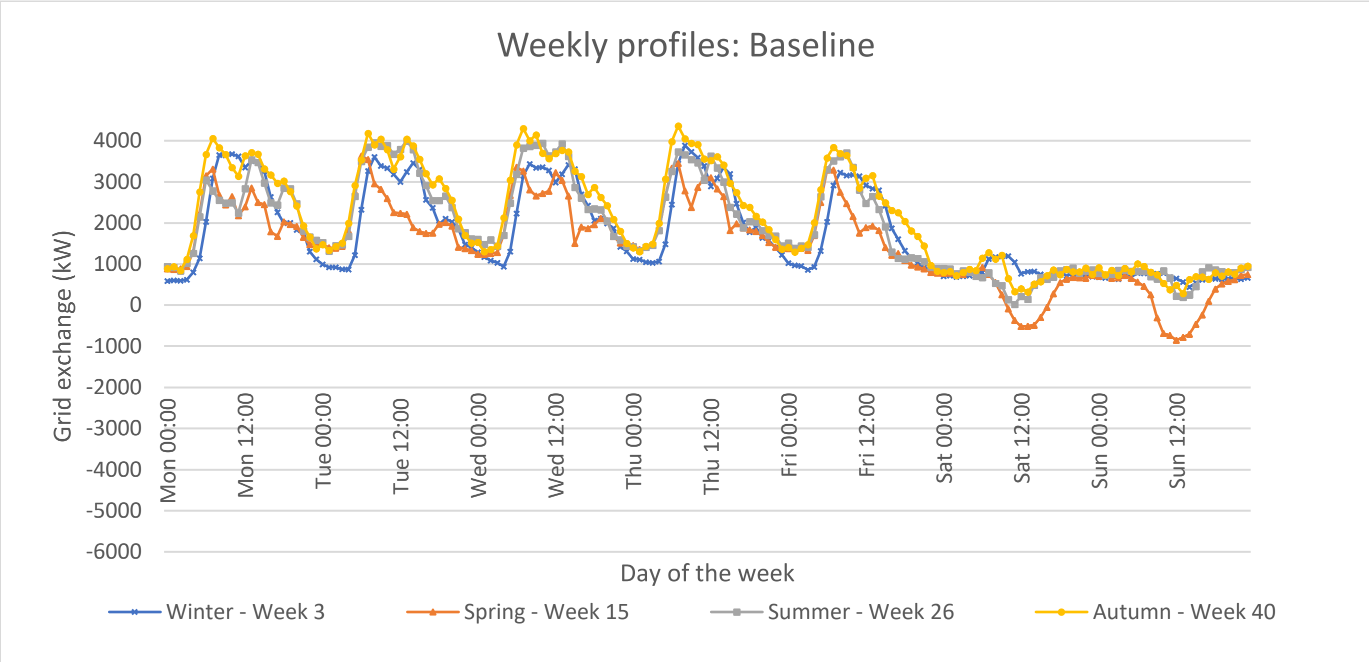
Appendix A: all graphs for baseline and RES configurations

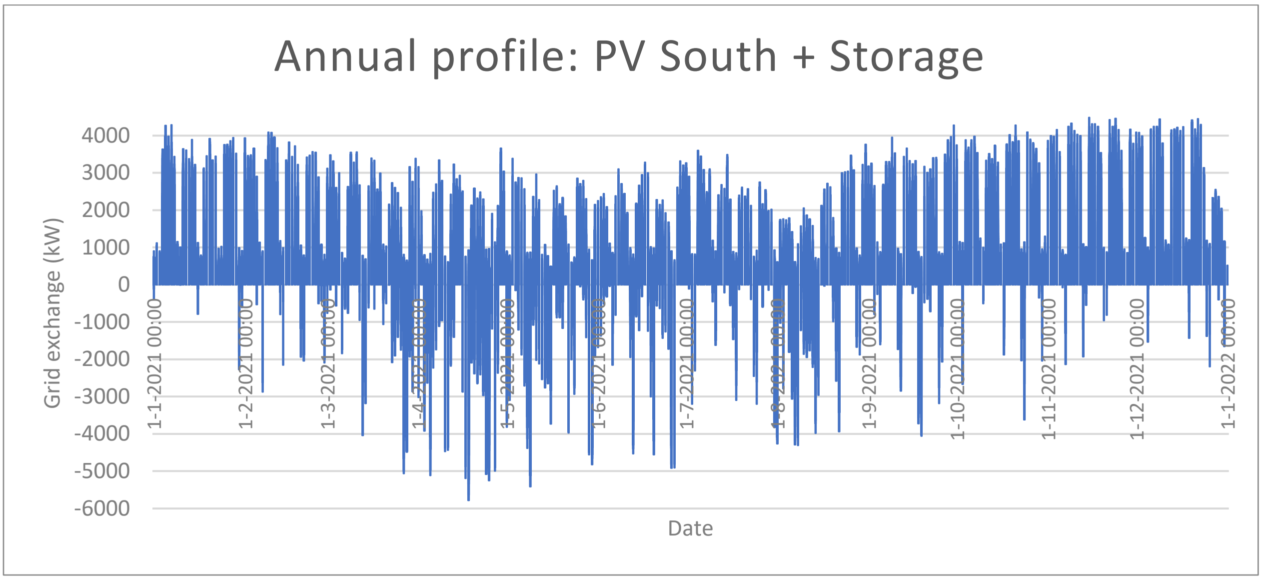
A.1 BASELINE

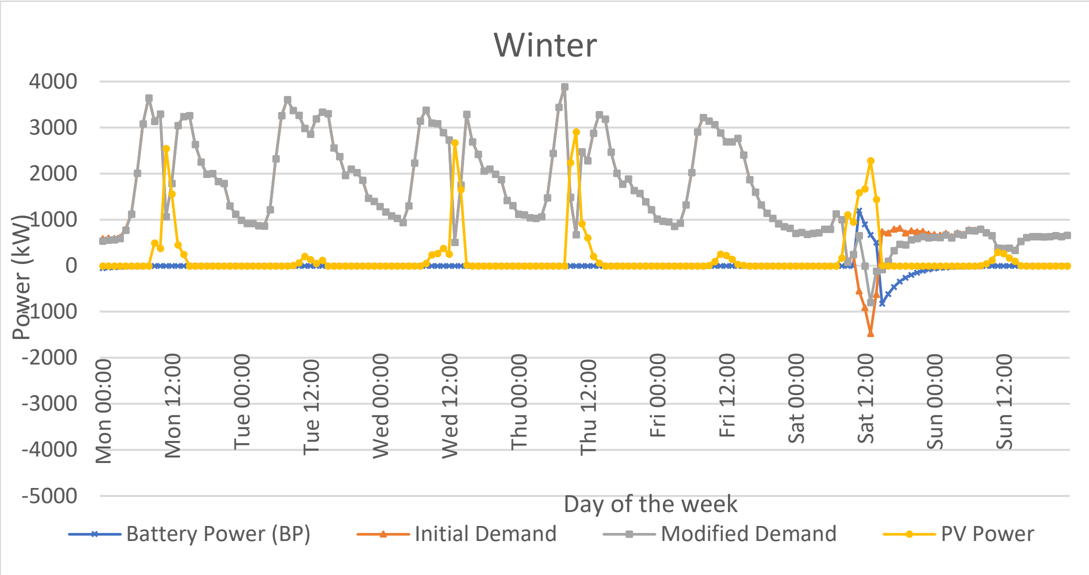


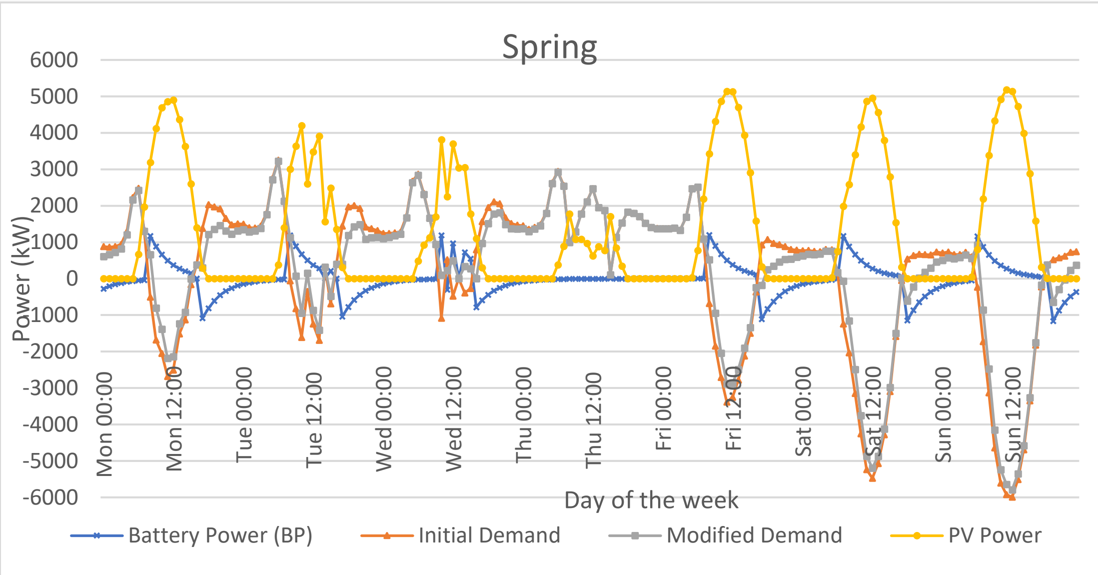


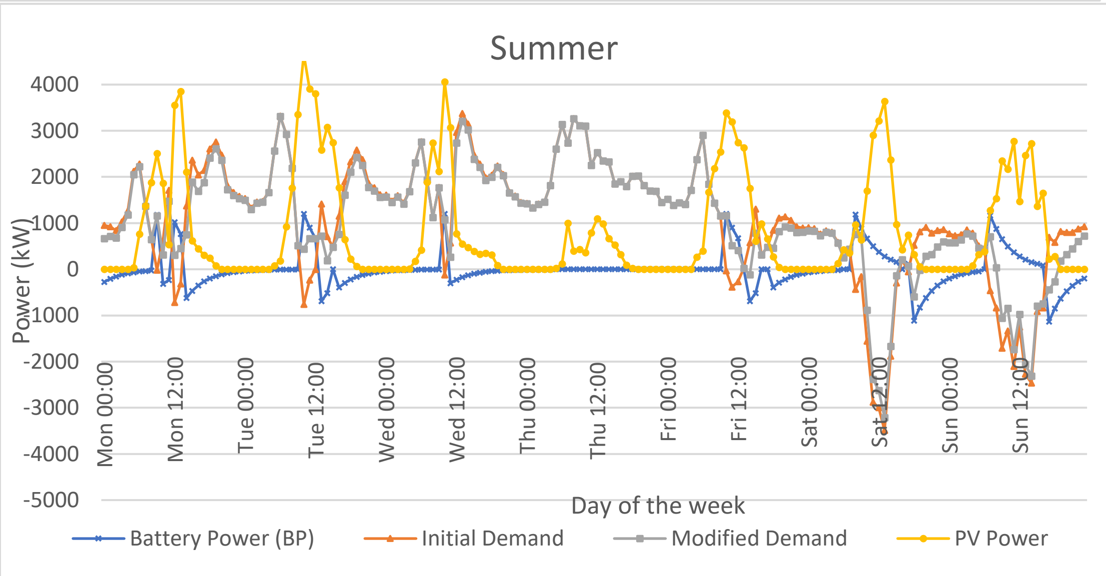
A.2 Configuration A: PV STORAGE

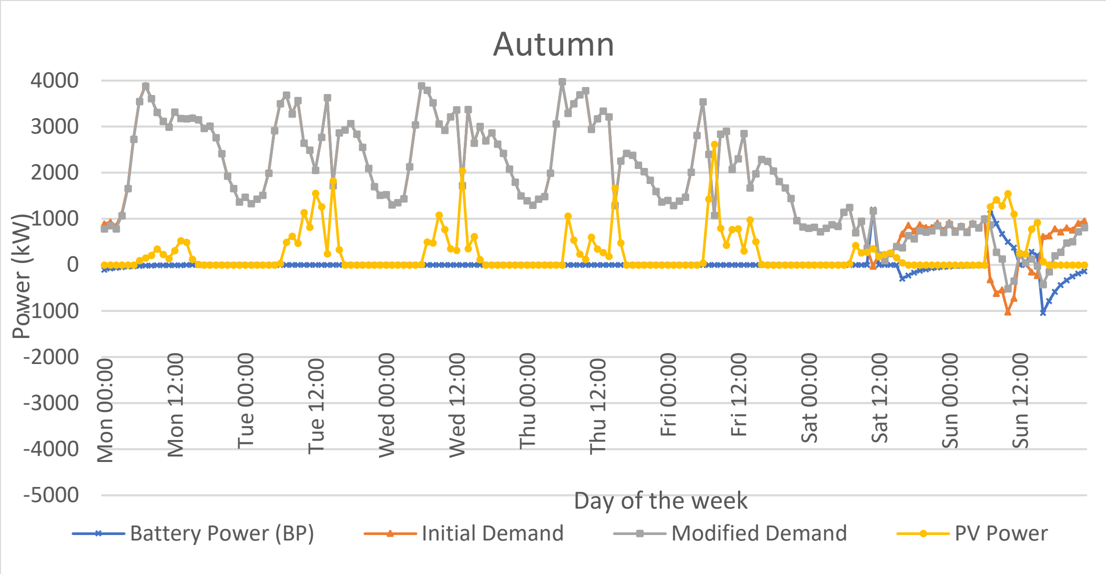
A.2.1 PV S STORAGE

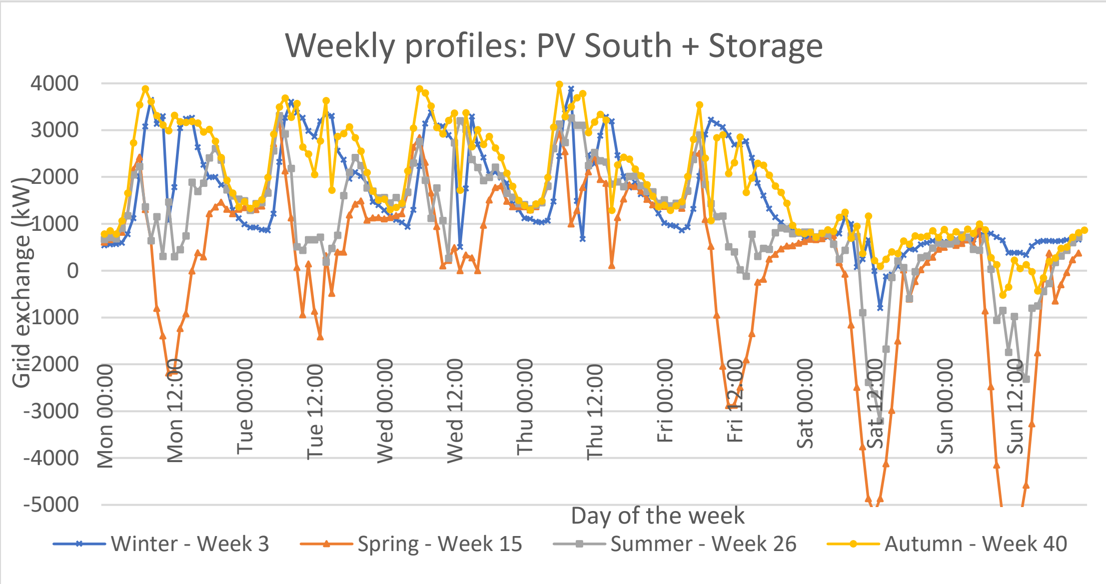



Winter
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
Power (kW)
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Battery Power (BP)
Initial Demand
Modified Demand
PV Power

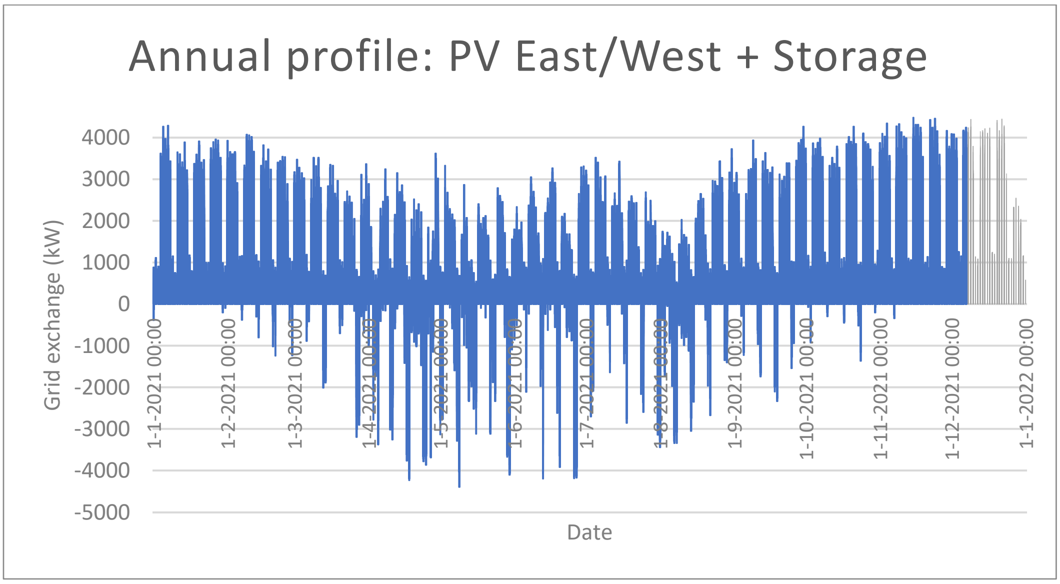

Spring
6000
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Power (kW)
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Battery Power (BP)
Initial Demand
Modified Demand
PV Power

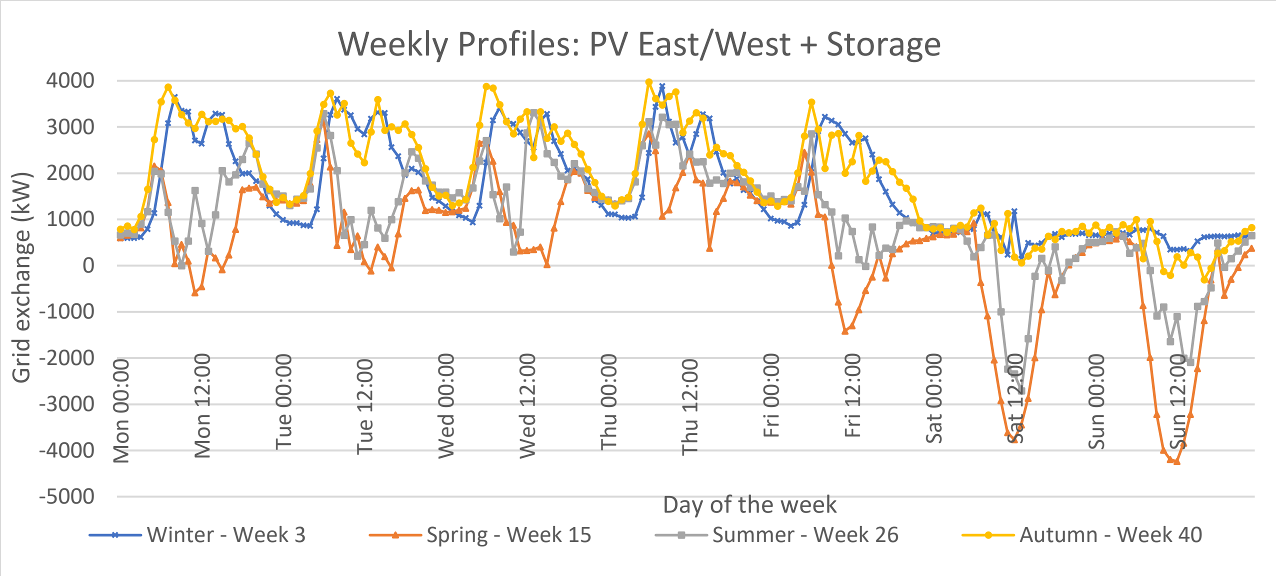

Summer
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
Power (kW)
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Battery Power (BP)
Initial Demand
Modified Demand
PV Power



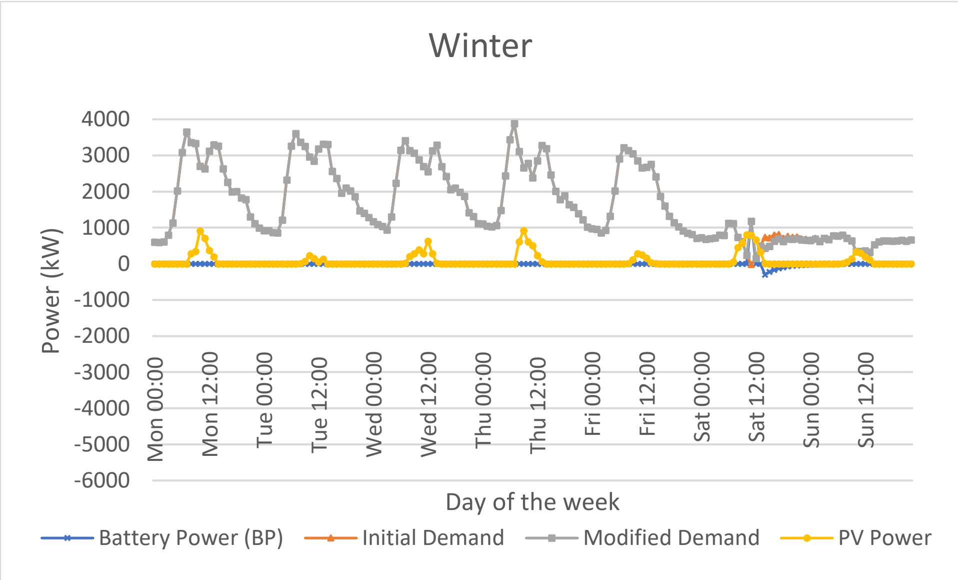


A.2.2 PV E/W STORAGE

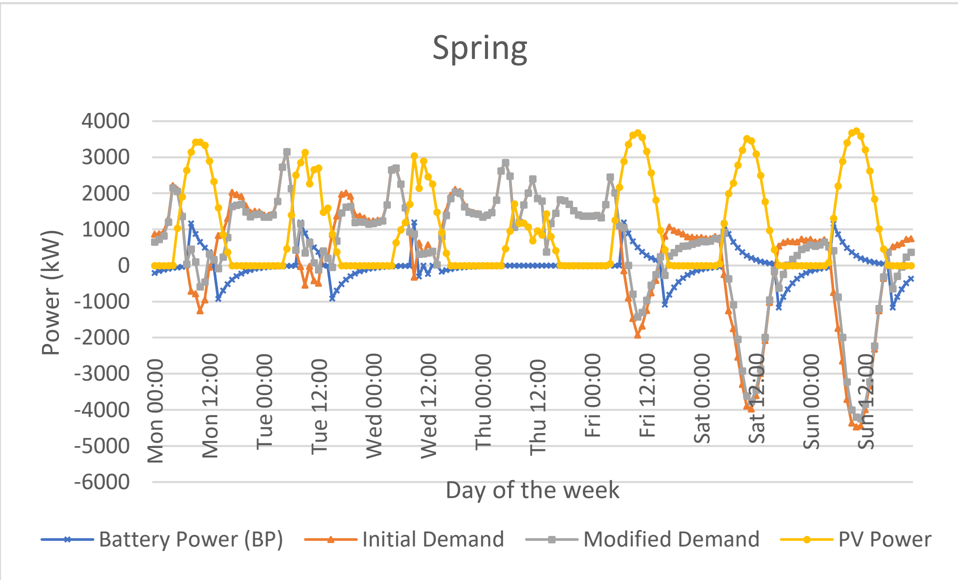




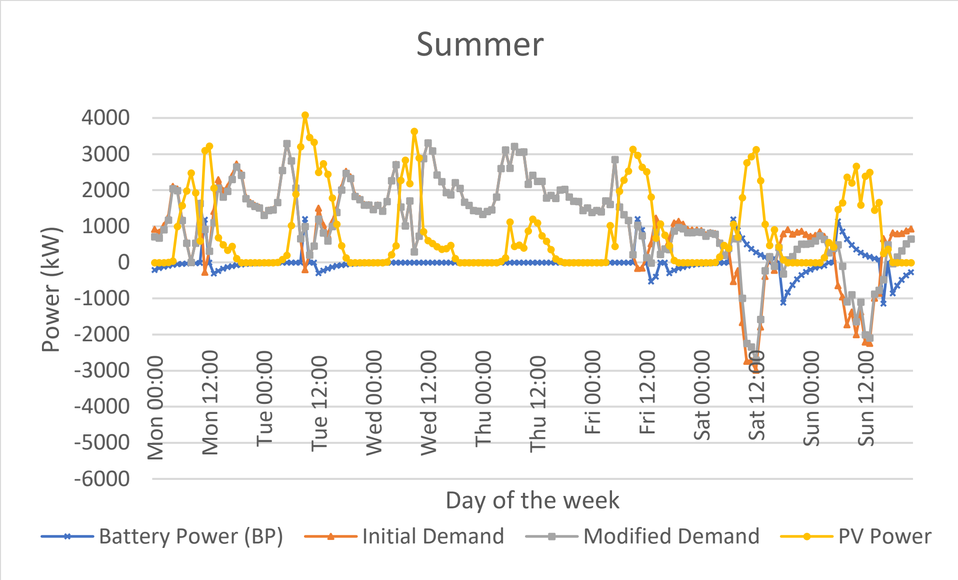
Weekly Profiles: PV East/West + Storage
Grid exchange (kW)
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Winter - Week 3
Spring - Week 15
Summer - Week 26
Autumn - Week 40

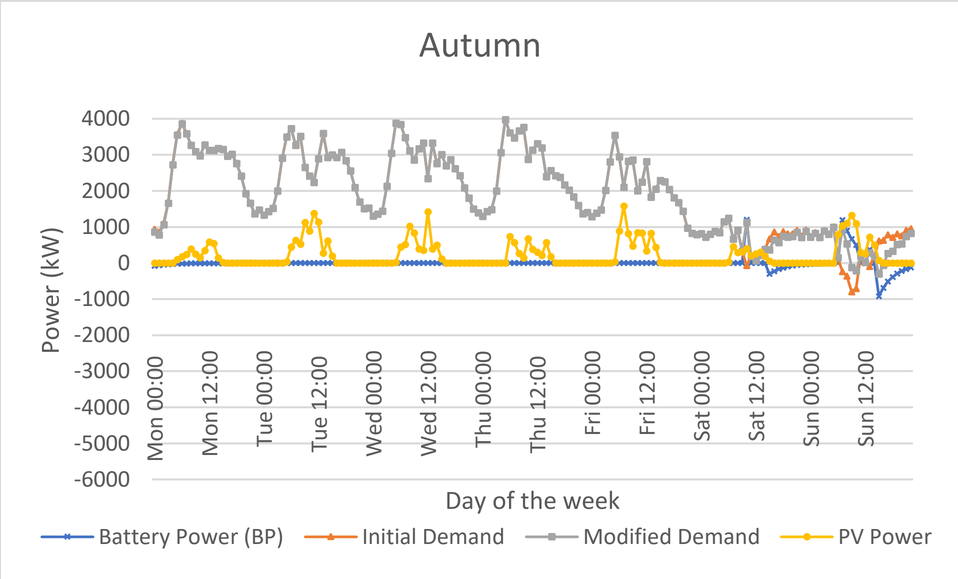


Winter
Power (kW)
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Battery Power (BP)
Initial Demand
Modified Demand
PV Power



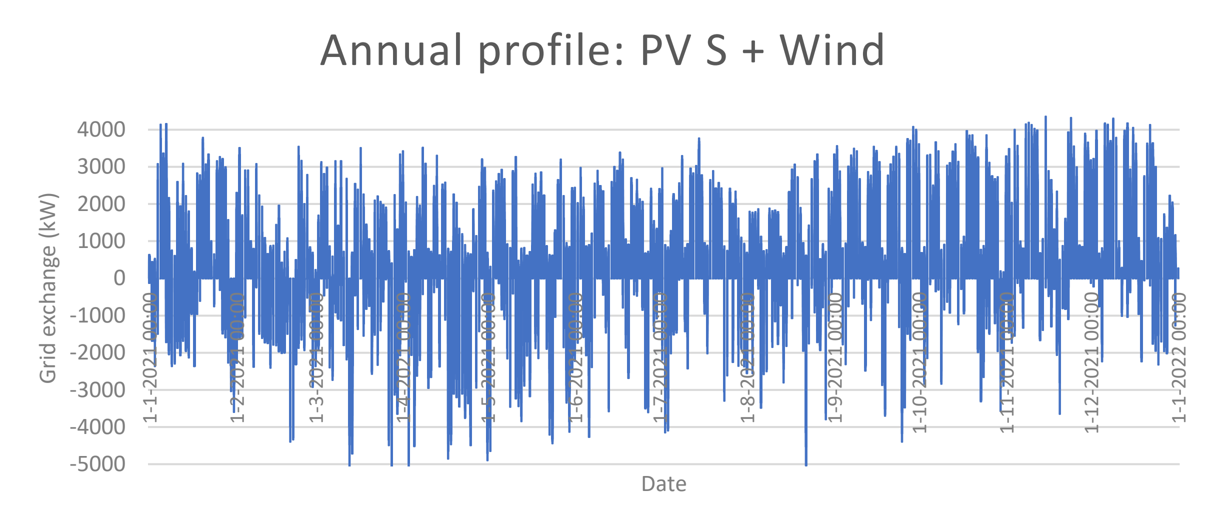
Spring
Power (kW)
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Battery Power (BP)
Initial Demand
Modified Demand
PV Power

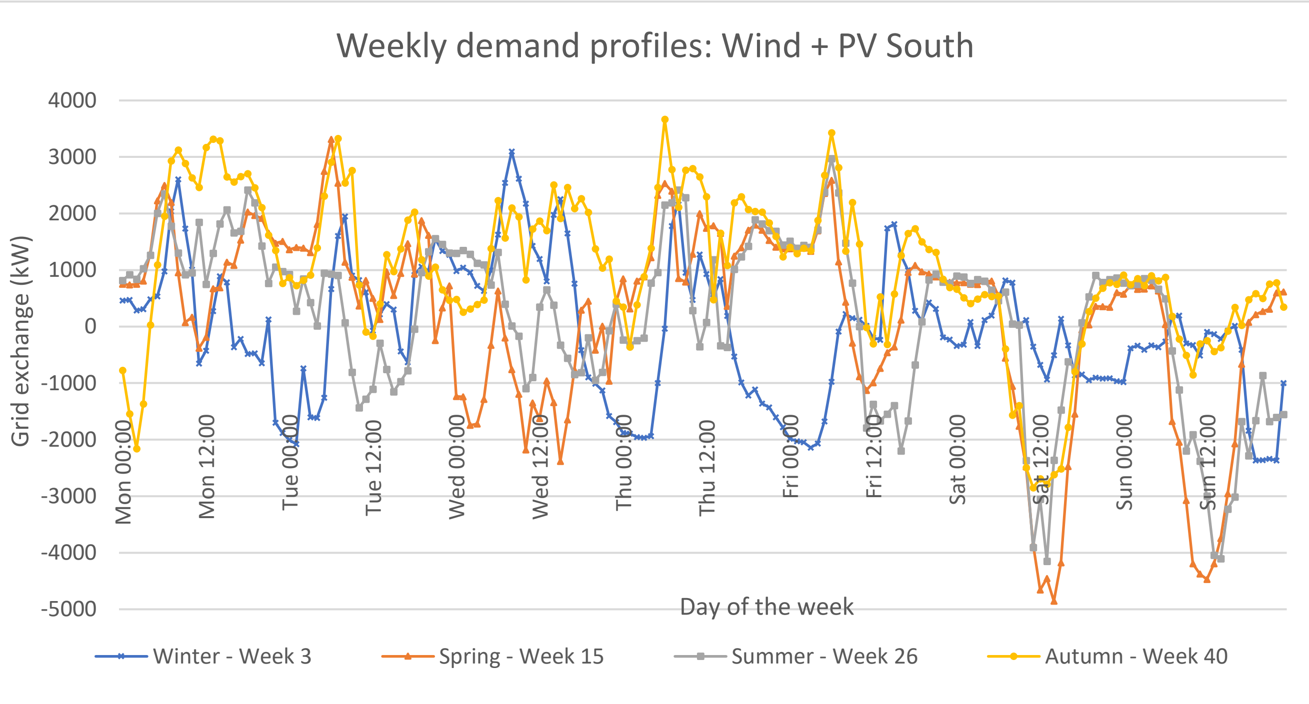

Summer
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Power (kW)
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Battery Power (BP)
Initial Demand
Modified Demand
PV Power


Autumn
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Power (kW)
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Battery Power (BP)
Initial Demand
Modified Demand
PV Power

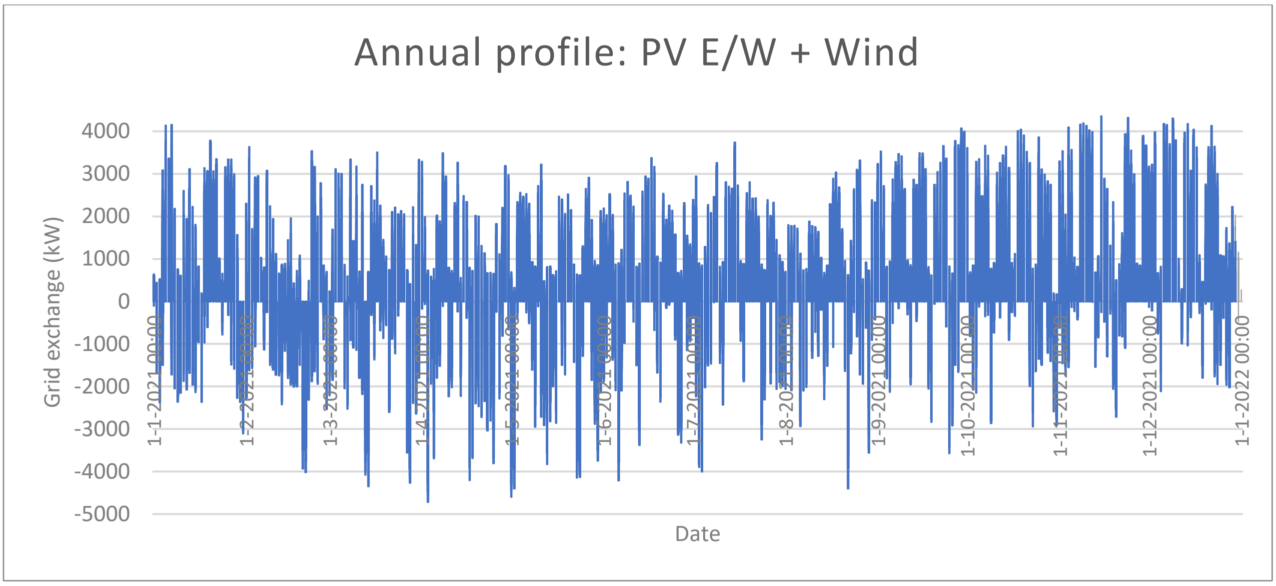
A.3 Configuration B: PV WIND

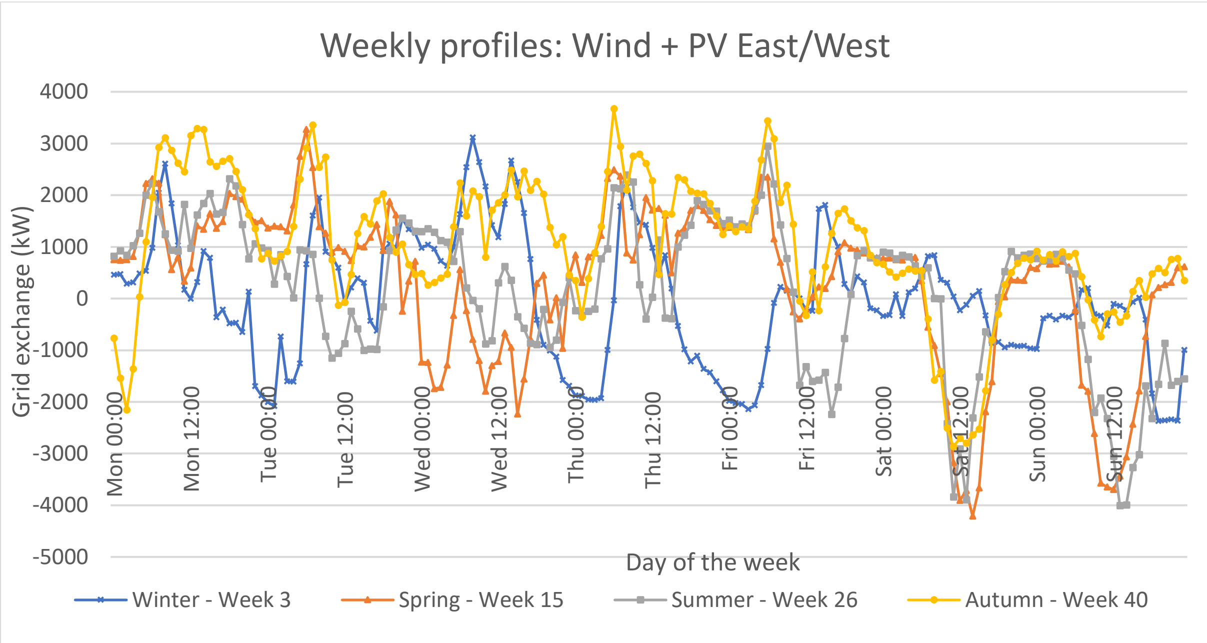
A.3.1 PV S WIND





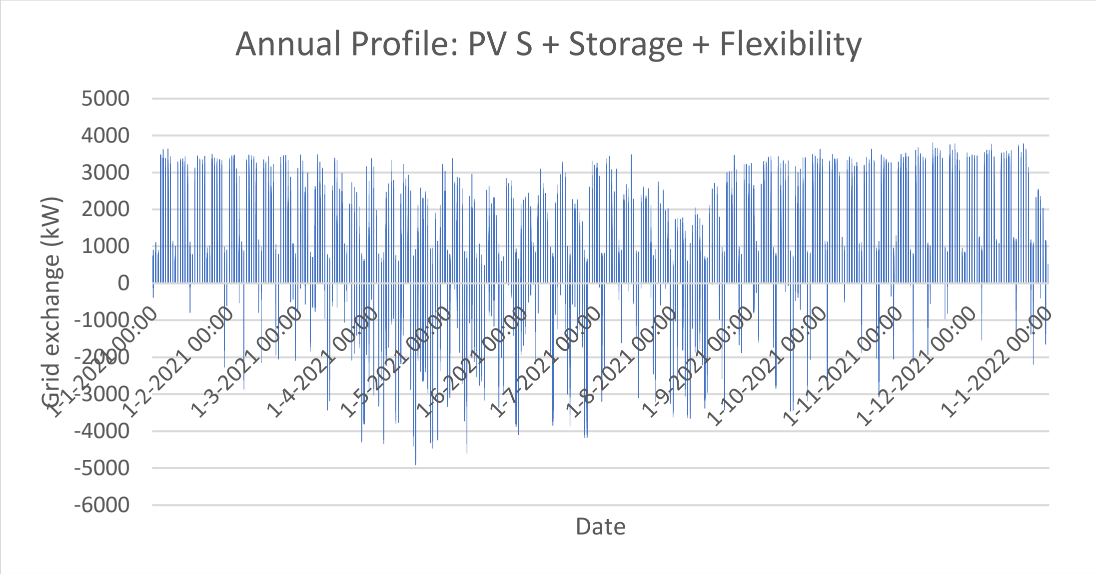
A.3.2 PV E/W WIND

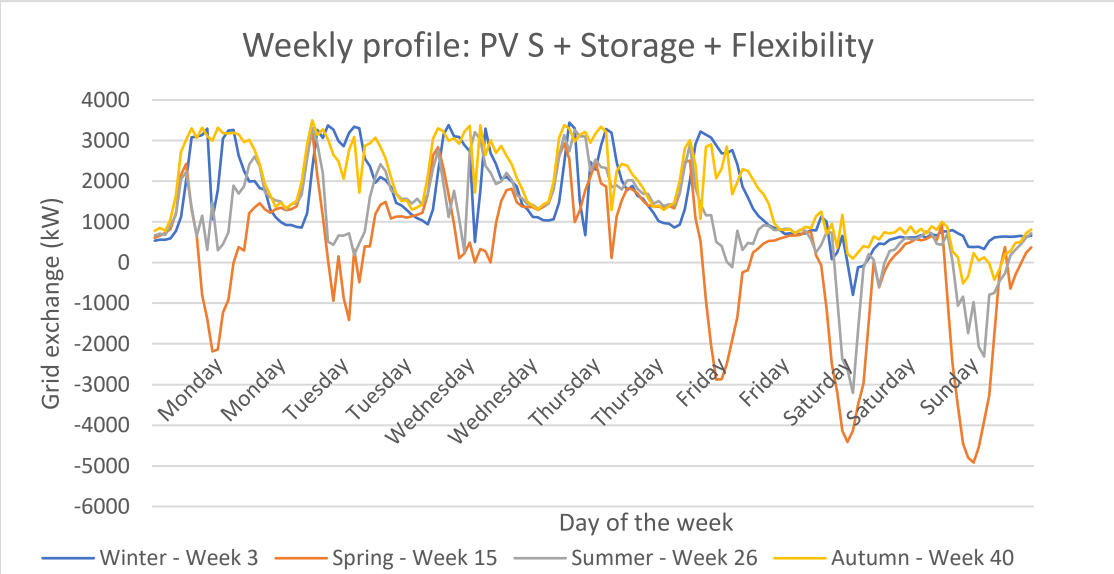




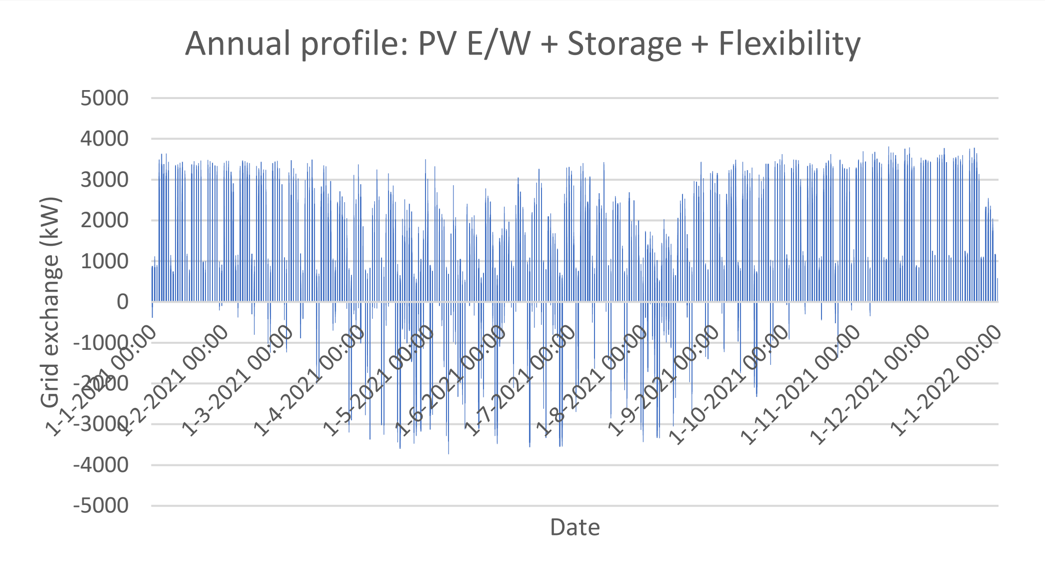
A.4 Configuration C: PV STORAGE FLEXIBILITY

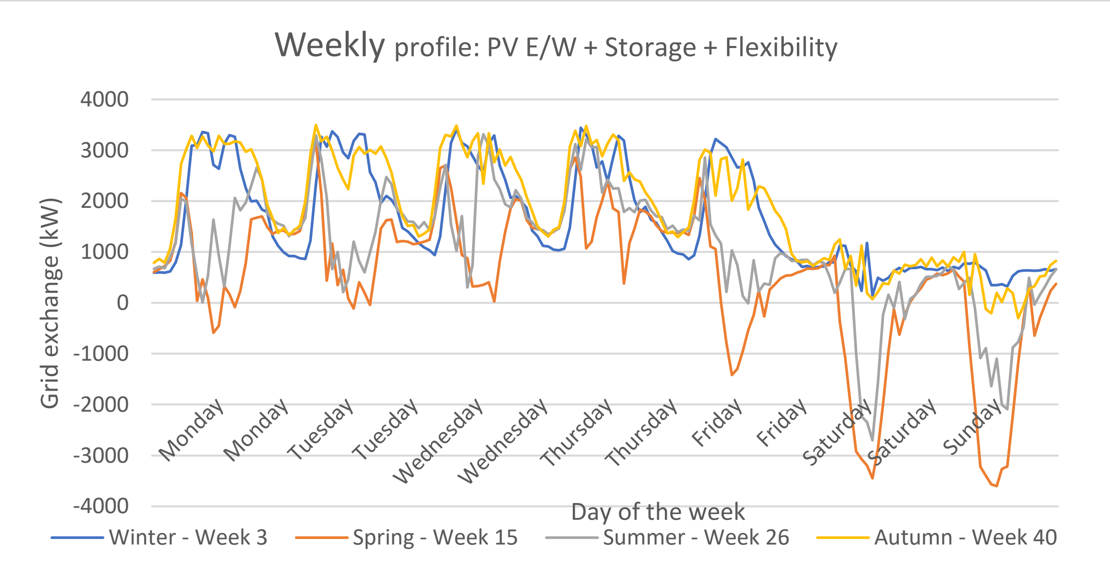
A.4.1 PV S STORAGE FLEXIBILITY





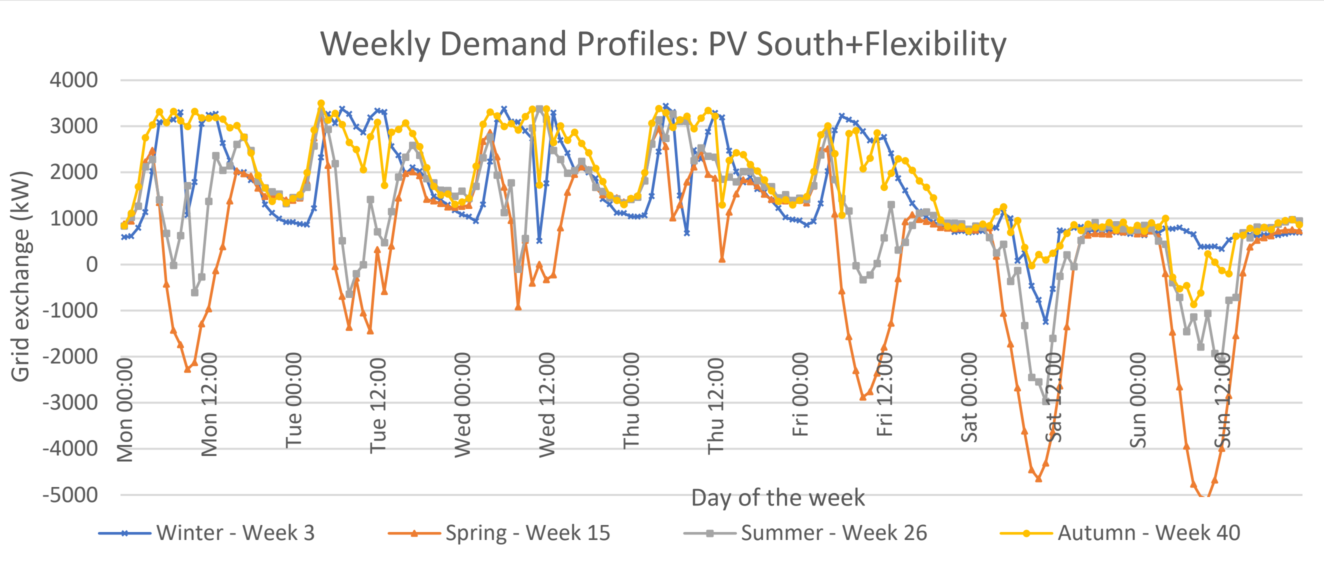
A.4.2 PV E/W STORAGE FLEXIBILITY



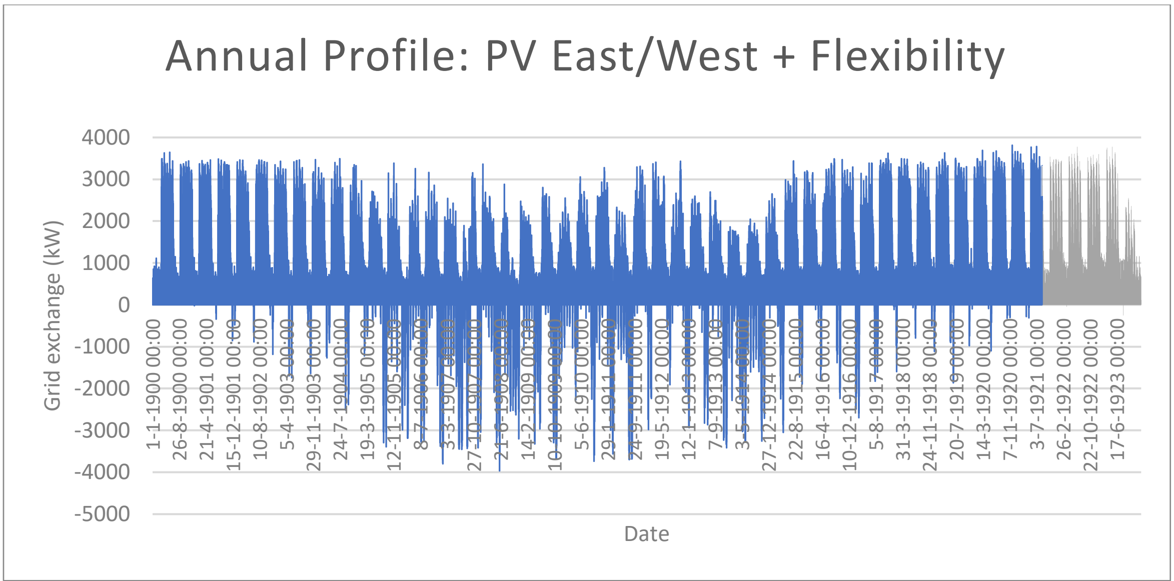


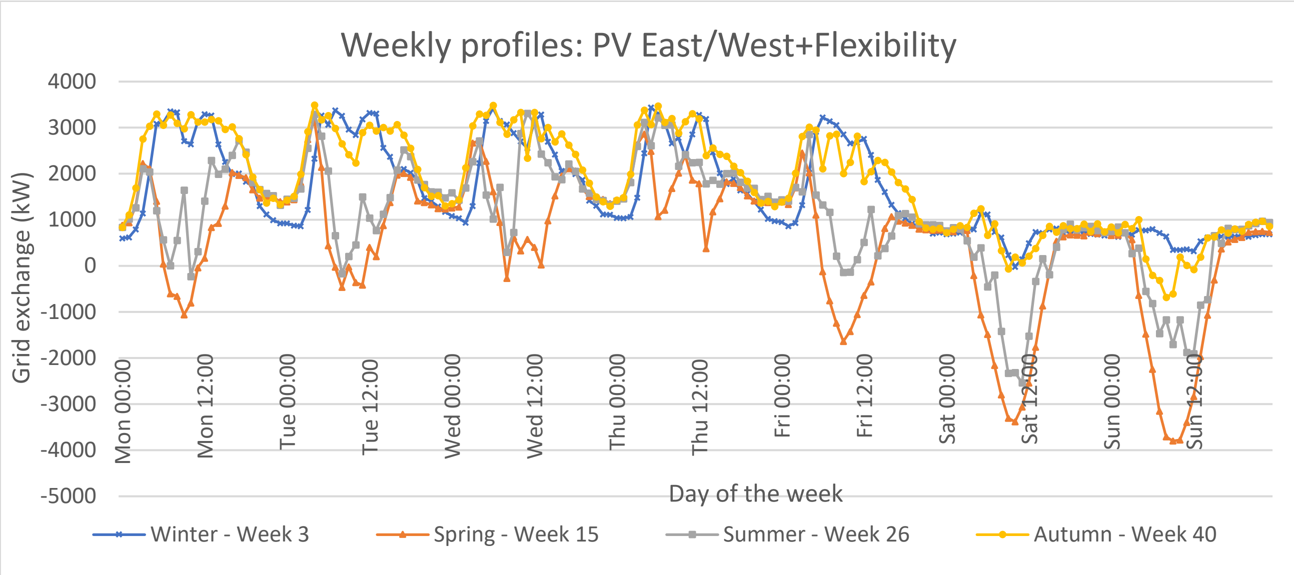
A.5 Configuration D: PV FLEXIBILITY

A.5.1 PV S FLEXIBILITY

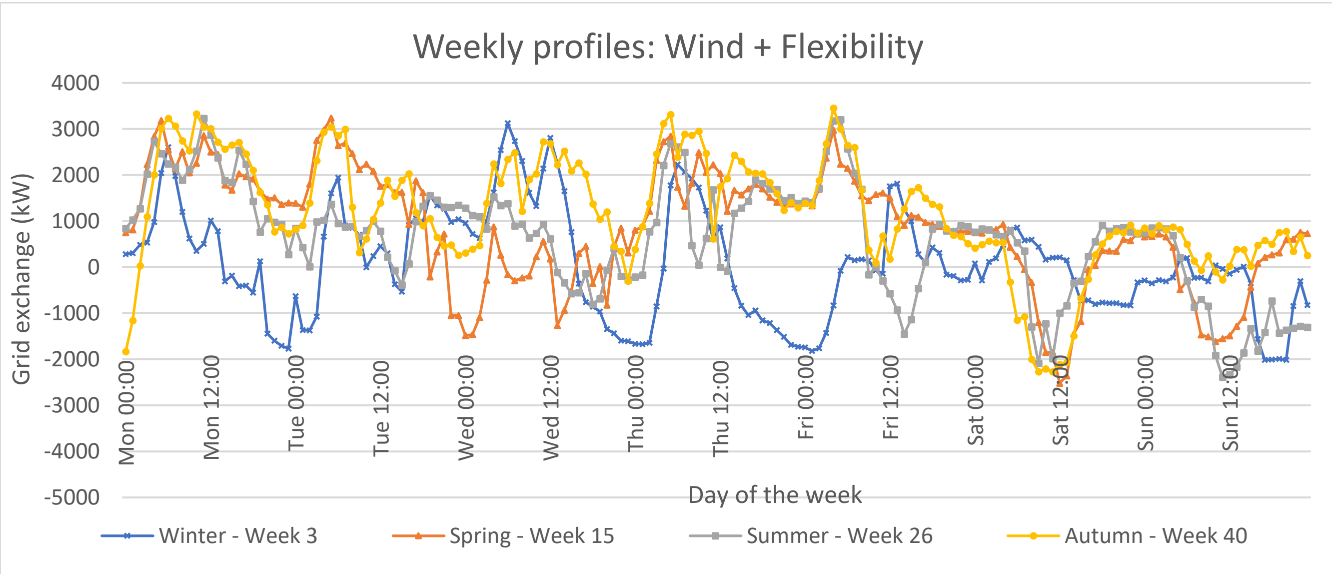


A.5.2 PV E/W FLEXIBILITY



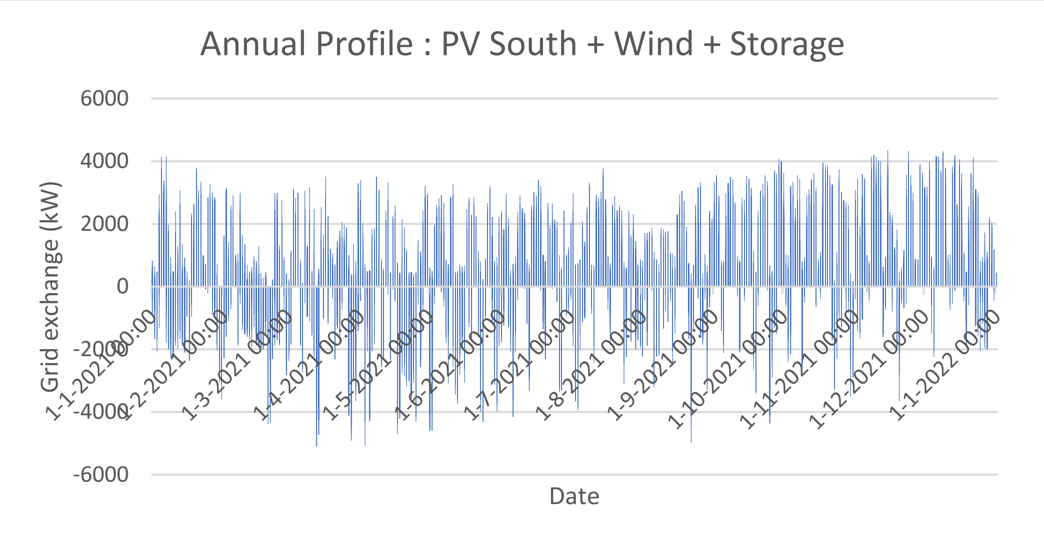


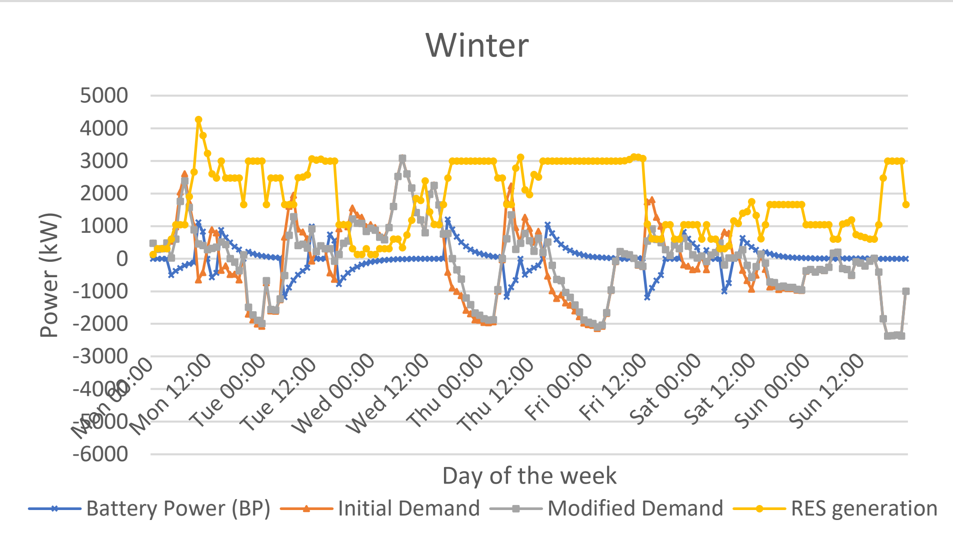
A.5 Configuration E: WIND FLEX

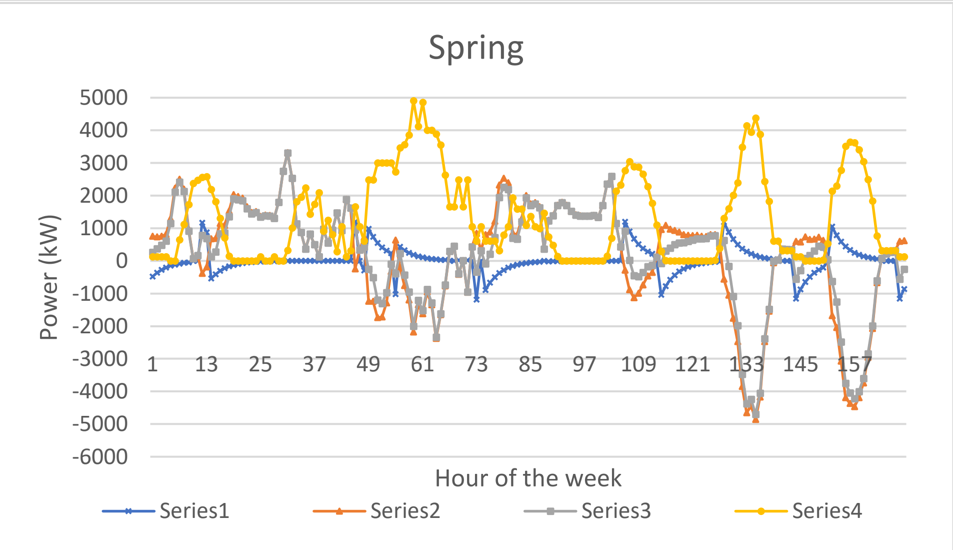


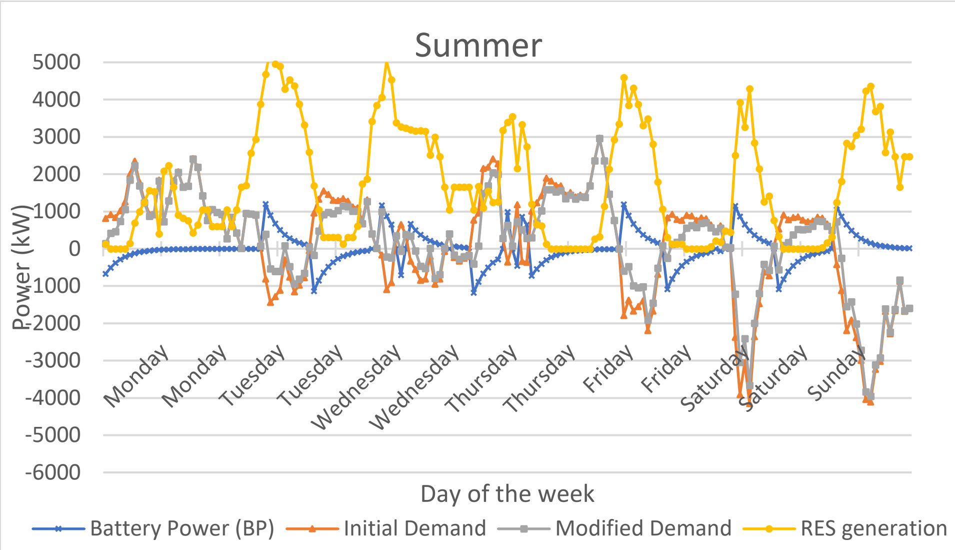
A.6 Configuration F: PV WIND STORAGE

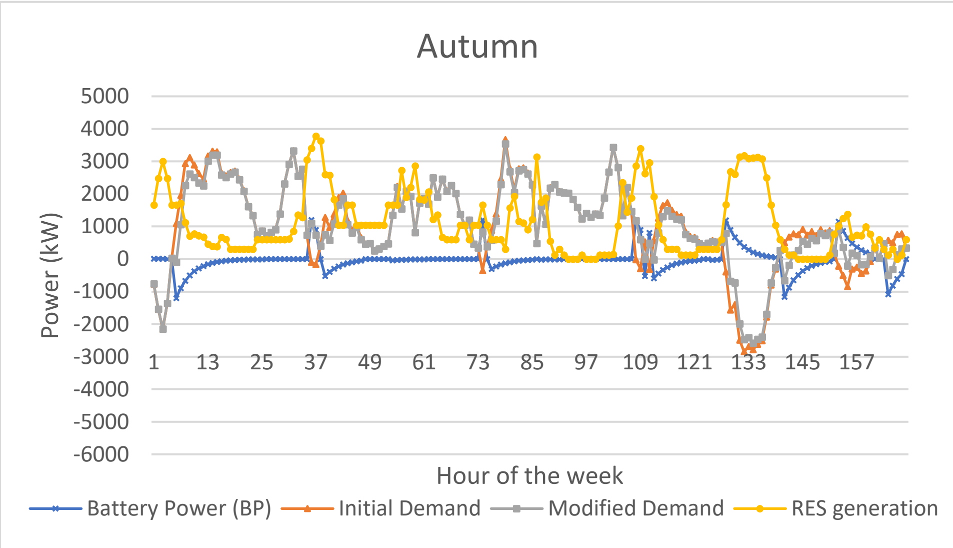
A.6.1 PV S WIND STORAGE

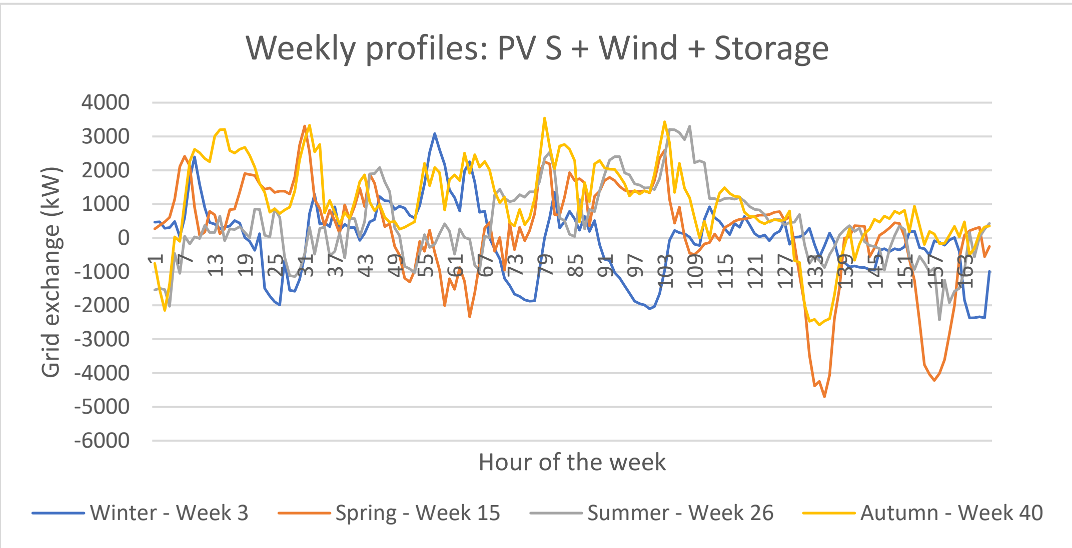




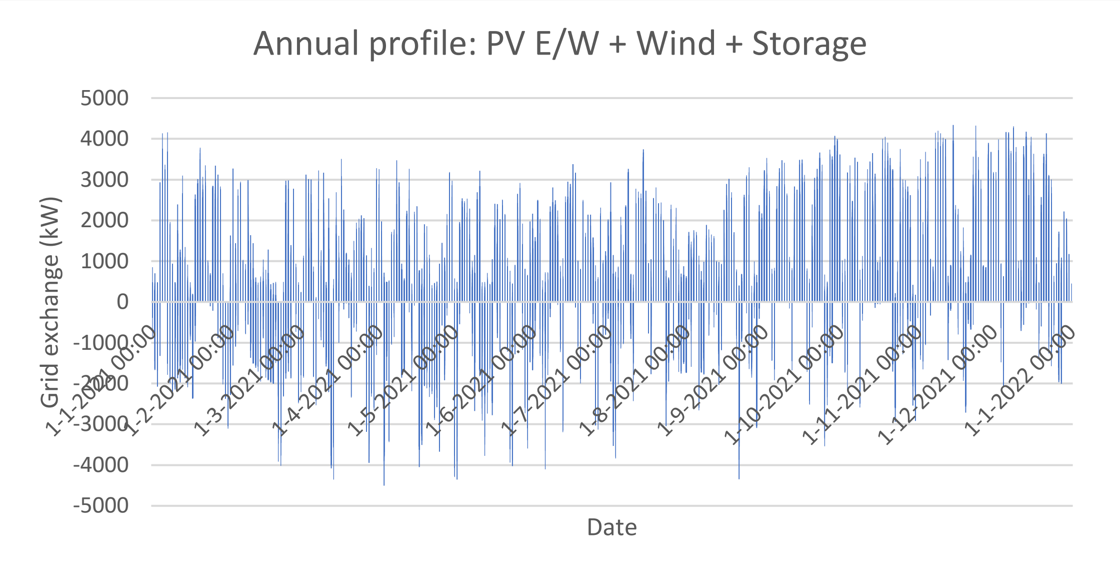


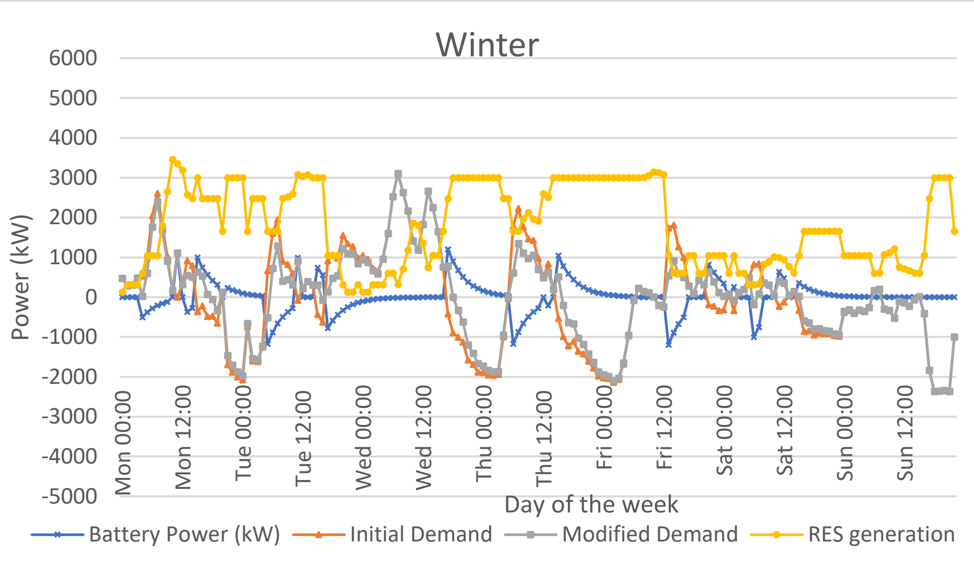

Summer
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Power (kW)
Monday
Monday
Tuesday
Tuesday
Wednesday
Wednesday
Thursday
Thursday
Friday
Friday
Saturday
Saturday
Sunday
Day of the week
Battery Power (BP)
Initial Demand
Modified Demand
RES generation

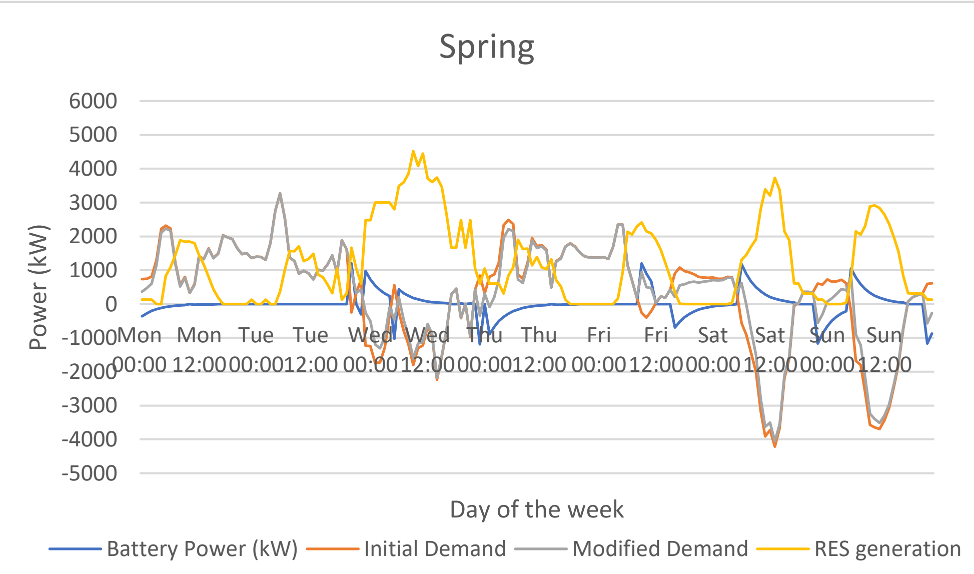

Autumn
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Power (kW)
1
13
25
37
49
61
73
85
97
109
121
133
145
157
Hour of the week
Battery Power (BP)
Initial Demand
Modified Demand
RES generation

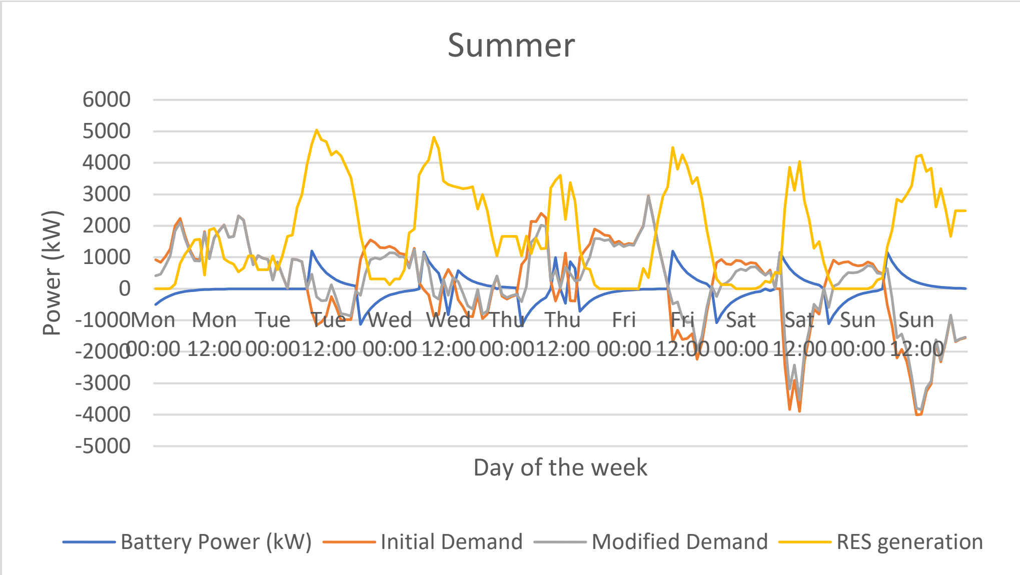

Weekly profiles: PV S + Wind + Storage
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Grid exchange (kW)
1
7
13
19
25
31
37
43
49
55
61
67
73
79
85
91
97
103
109
115
121
127
133
139
145
151
157
163
Hour of the week
Winter - Week 3
Spring - Week 15
Summer - Week 26
Autumn - Week 40

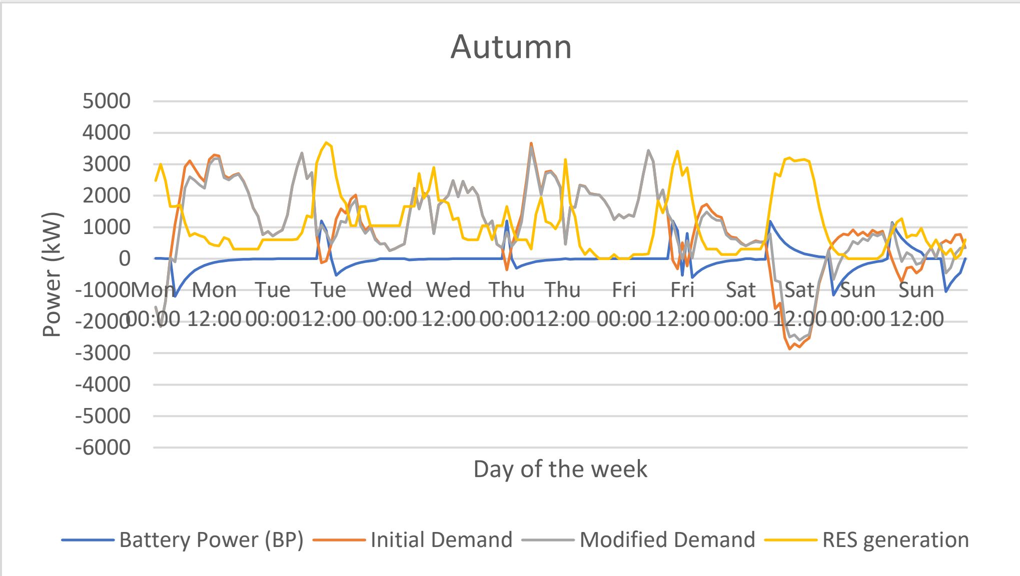
A.6.2 PV E/W WIND STORAGE

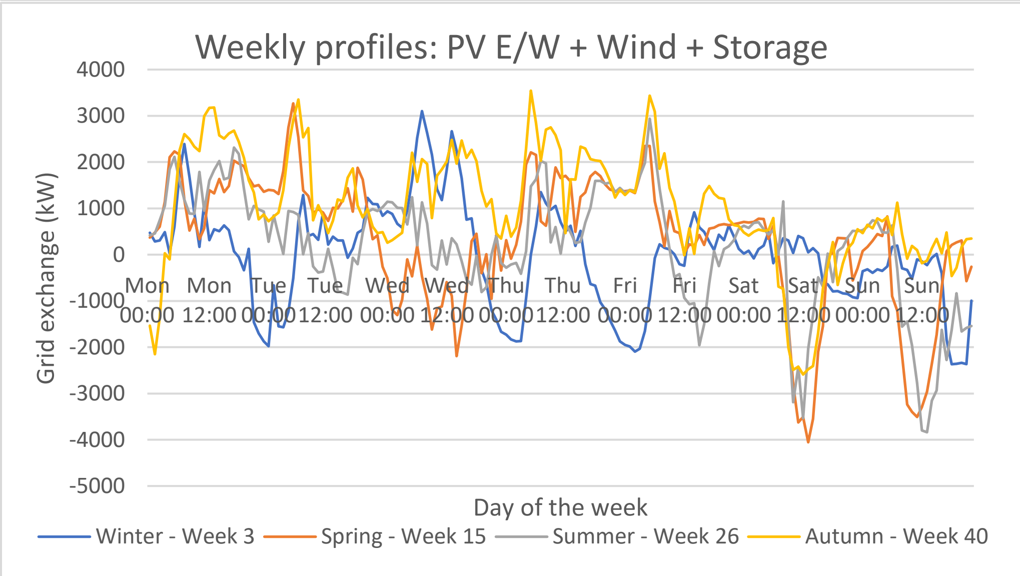






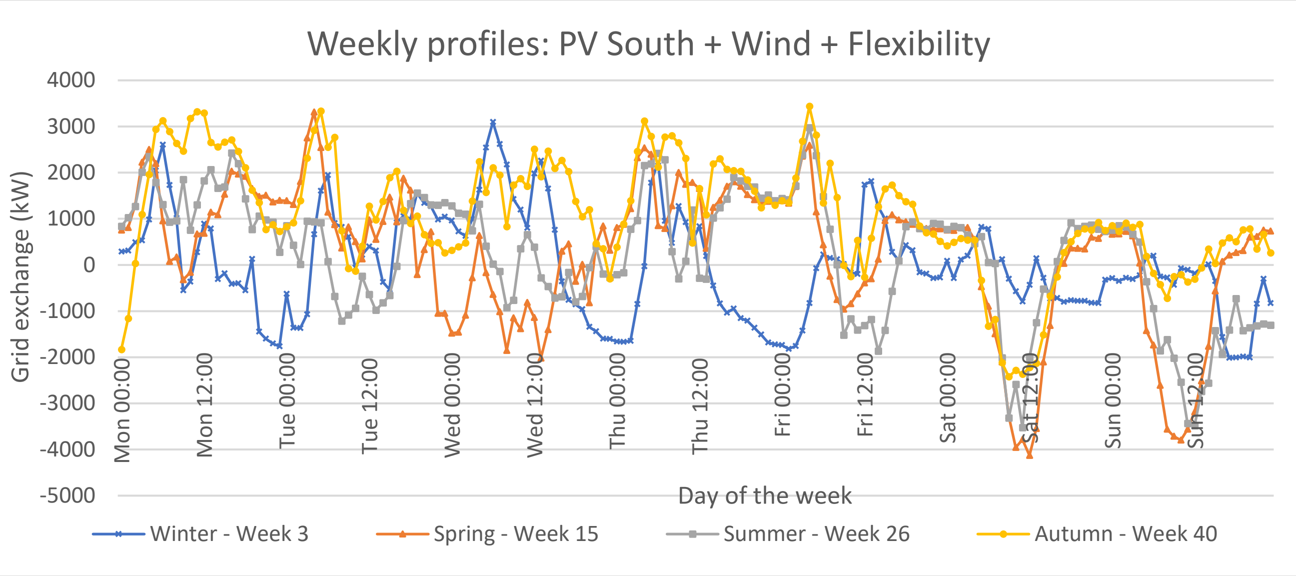

Summer
Power (kW)
6000
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Battery Power (kW)
Initial Demand
Modified Demand
RES generation


Autumn
Power (kW)
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Battery Power (BP)
Initial Demand
Modified Demand
RES generation

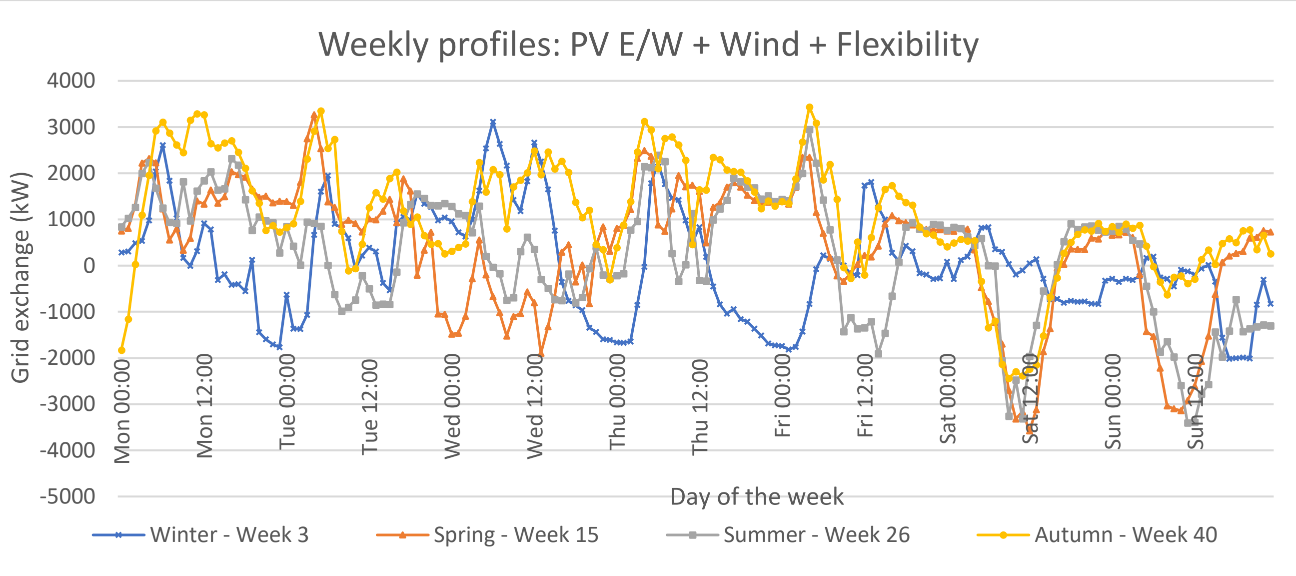

Weekly profiles: PV E/W + Wind + Storage
Grid exchange (kW)
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
Mon 00:00
Mon 12:00
Tue 00:00
Tue 12:00
Wed 00:00
Wed 12:00
Thu 00:00
Thu 12:00
Fri 00:00
Fri 12:00
Sat 00:00
Sat 12:00
Sun 00:00
Sun 12:00
Day of the week
Winter - Week 3
Spring - Week 15
Summer - Week 26
Autumn - Week 40

A.7 Configuration G: PV WIND FLEXIBILITY

A.7.1 PV S WIND FLEXIBILITY



A.7.2 PV E/W WIND FLEXIBILITY



Appendix B: interview protocol and informed consent

B.1 Interview protocol

B.1.1 Introducing mail

“Dear …,

Let me quickly introduce myself. I am Jeroen Janissen, master student Sustainable Energy Technology at the TU Delft. Currently, I am writing my master’s thesis about the energy transition on mixed business parks. I have a specific focus on the electricity demand and how to solve grid congestion with the use of renewable energy sources. As part of my thesis, I am interviewing professionals that are important stakeholders surrounding the electricity management of mixed business parks.

To increase the use of renewable energy and reduce grid congestion, I have developed several scenarios. These scenarios include different forms of renewable energy, storage and demand flexibility. I would like to compare these scenarios on four main categories: social, economic, technological and environmental. For this, I would like to ask for your opinion for both the identification of criteria and the weighting of these criteria.

The interview will take place online and takes approximately 30 minutes.

Please let me know when you are available.

Kind regards,

"Beste …,

Laat ik mezelf kort voorstellen. Ik ben Jeroen Janissen, masterstudent Sustainable Energy Technology aan de TU Delft. Momenteel schrijf ik mijn masterscriptie over de energietransitie op gemengde bedrijventerreinen. Ik heb een specifieke focus op de vraag naar elektriciteit en hoe de congestie van het elektriciteitsnet kan worden opgelost met het gebruik van hernieuwbare energiebronnen. Als onderdeel van mijn scriptie interview ik professionals die belangrijke stakeholders zijn rondom het elektriciteitsbeheer van gemengde bedrijventerreinen.

Om het gebruik van hernieuwbare energie te vergroten en de congestie op het elektriciteitsnet te verminderen, heb ik verschillende scenario's ontwikkeld. Deze scenario's omvatten verschillende vormen van hernieuwbare energie, opslag en vraagflexibiliteit. Ik zou deze scenario's willen vergelijken op vier hoofdcategorieën: sociaal, economisch, technologisch en milieu. Hiervoor zou ik graag uw mening willen vragen over zowel de identificatie van de beoordelingscriteria als de weging van deze criteria.

Het interview vindt online plaats en duurt ongeveer 30 minuten.

Ik hoor graag wanneer dit schikt.

Met vriendelijke groet,

Jeroen Janissen

B.1.2 Interview planning

0-5 min: personal introduction, introduction of thesis topic

5-10 min: description of scenarios

10-15 min: description of criteria

15-20 min: identification of missing criteria

20-25 min: ranking criteria (AHP)

25-30 min: finalising interview

B.1.3 Content

Start meeting

Thank the interviewee for his/her time.

Explain the thesis project and the goal of the interview.

– Transition of mixed business parks to include more renewables and reduce grid congestion

– Evaluate different configurations of renewables based on multiple criteria.

Explain the structure of the interview and expected duration.

Start transcribing

Informed consent signed? If yes, proceed otherwise ask if they have read the informed

consent and if they agree with the conditions explained in the document.

– Inform about the interview transcript.

– Explain what will be publicly available.

– Mention that if the interviewee does not want to answer a question that it is accepted.

Part I: General questions

1. Aan welke organisatie(s) bent u verbonden en welke positie vervult u daar?

2. Bent u bekend met het begrip netcongestie?

Ja *Kunt u een korte definitie geven?*

Nee *Korte uitleg geven (vergelijking met file op de weg)*

3. bent u bekend met het begrip multi-criteria analyse?

Ja *Kunt u een korte definitie geven*

Nee *Korte uitleg van verschillende MCA-methoden*

Binnen deze studie werken we met een gewogen Multi Criteria Analyse. De gewichten van de criteria worden bepaald aan de hand van Analytical Hierarchy Process: rangschikken van meest belangrijk naar minst belangrijk.

Part II: RES configurations and analysis

Schetsen van 3 configuraties:

- Zon PV en opslag
- Zon PV, wind en opslag
- Zon PV, opslag en flexibiliteit

Uitleg van variabelen die gemonitord worden per configuratie: CO_2, piekvermogens, kosten, energie-uitwisseling met het net.

Uitleg van de criteria om de configuraties te toetsen:

- Investeringskosten en de LCOE. Deze bepalen de financiële haalbaarheid van het project en wat de toekomstige baten zijn.
- Vermindering congestie door lagere pieken: Waardoor meer bedrijven zich kunnen vestigen en bestaande bedrijven verder kunnen elektrificeren. Door vermeden netverzwaring kunnen ook financiële risico's afgedekt worden.
- Energie autonomie: zelfvoorzienend worden verminderd afhankelijkheid van netbeheerder.
- CRI: dit bepaalt of een voorgestelde oplossing nog in de ontwikkelingsfase, testfase of operationele fase is.
- Vermindering van CO_2 emissies: door de afname van elektriciteit uit het net, vermindert de CO_2 uitstoot.
- Ruimtelijke inpassing: hoeveel ruimte vraagt de oplossing? bezwaren van omwonenden, aantrekkelijkheid van het gebied, regelgeving.
- Attractiviteit: als u de configuratie een rapportcijfer zou geven, wat zou dat dan zijn?

Part III: Missing criteria and ranking

4. Mist u nog criteria in deze lijst?

Ja *Uitleg criterium en waarom belangrijk. Onderzoeker noteert dit criterium.*

Nee *Door naar volgende vraag*

5. U mag nu de 9 oorspronkelijke criteria en uw eigen ingebrachte criteria rangschikken. Begin hierbij met de belangrijkste en dan naar de minst belangrijke.

Part IV: Concluding

6. Benoemen dat dit alle inhoudelijke vragen waren en dan vragen of ze mij nog iets willen

meegeven wat niet aanbod kwam in het interview. → Schiet je nog iets te binnen wat

niet aanbod kwam tijdens het interview?

7. Heeft u suggestie voor mensen die nog meer waardevol zijn om te interviewen?

8. Heeft u relevante bronnen die ik kan gebruiken?

Part V: Finishing the interview

- Bedanken voor de deelname.
- Waar kan het uiteindelijke verslag gevonden worden?
- Delen van informatie over het interview.

B.2 Informed consent

Master thesis project at the Delft University of Technology

You are being invited to participate in a thesis project with the title: Improving energy at mixed business parks: a guideline for consultants, government officials and entrepreneurs. This thesis project is being done by Jeroen Janissen from the TU Delft in collaboration with Antea Group.

The purpose of this research study is to investigate how the implementation of renewable energy configurations can be designed for and be implemented on mixed business parks.
The data will be used for master thesis research which will be published in the repository of the TU Delft. In addition, an academic publication can be done based on the master thesis. We will be asking you to participate in a one-on-one semi-structured interview which help to gain insight into the evaluation of renewable energy configurations
The interview will be transcribed and summarised. The summary of the interview will be shared with you, and you will have the opportunity to omit any information in the summary. The summary will be used for analysis. Anonymity will be maintained by displaying only an overview of the types of companies the interviewees are related to and the general analysis of the information gathered. There will be no direct information related to the interviewee in the final product. This work may lead to an academic article. The transcript will be preserved for up to two years under the responsibility of Jaco Quist to support such potential article, only accessible to the research team.
Should such publication take place, you will remain anonymous, and all privacy measures presented in this document will be enforced.
Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain anonymous. Anonymity is preserved by not including any personal information in the interview summary. We will minimize any risks by keeping the data in a TU Delft approved storage, and the data will only be accessible to the research team (Principal investigator (Me); First supervisor (Jaco Quist); Second supervisor (Michiel Fremouw)).
By signing this form, you confirm that you have read and understood the information provided and agree to participate in the study voluntarily.

Corresponding researcher:
Name: Jeroen Janissen

Responsible researcher (First supervisor):
Name: Dr. Jaco Quist

Second supervisor:
Name: Michiel Fremouw

Name: ________________
Date: ___/___/________

Signature:

____

Appendix C interview summaries

C.1 DSO Expert

The expert is senior partner energy transition at a DSO. She supports, advises and influences stakeholders in the regional energy strategies, Cluster Energy Strategy for industry and the build environment and the charging infrastructure for electric vehicles. Her focus is to bridge the gap between policy and private stakeholders and between external stakeholders and the internal organisation and processes. Grid congestion is an acute problem in the Netherlands, especially in Noord-Brabant en Limburg, where both the demand of electricity and the supply of excess RES production are straining the grid. MCDM is the process of evaluating the possible options against several, often competing interests. Because the stakeholders are so diverse, a proper execution of MCDM is essential. This will not only increase the acceptance of a solution, but also ensures long term support.

Ranking of criteria:

1. Reduction of CO_2 emissions,
2. Spatial integration,
3. NPV and investments,
4. Grid-relief and LCOE,
5. Self-consumption,
6. CRI.

The expert notes that NPV and investments are hard to separate from each other because they could be correlated or connected. No criteria are missing.

C.2 Consultant Expert

The expert is Strategic Consultant at a consultancy firm. He advises governments and private clients about the energy transition. The focus is on bringing stakeholders together and facilitating knowledge exchange between parties. Guiding the process of an energy transition project is very challenging, because the interests of the different stakeholders are often not aligned. In that sense, grid congestion can also be seen as a misalignment between the supervisor of the DSOs on the one side and the DSOs and commercial and industrial users on the other side. The supervisor aims at the lowest infrastructure costs for the delivery of power, effectively creating a tight market. Therefore, the DSOs limited their investments, which is now causing problems. Grid congestion is the problem that is caused by the transport capacity not suited to the fast electrification of industry and unforeseen investments in renewables. For the energy transition, Multi-Criteria Decision Making (MCMD) is important because different stakeholders will have different priorities. A proper MCDM may create acceptance across the stakeholders.

Ranking of criteria:

1. Spatial integration,
2. NPV and investments,
3. grid relief,
4. Reduction of CO_2 emissions and self-consumption,
5. CRI,
6. LCOE.

NPV and investments and reduction of CO_2 emissions and self-consumption are difficult to separate. Therefore, same ranking. No criteria are missing from the list.

C.3 Provincial Expert

The expert is transition broker at a Dutch Province. He acts as an intermediary between government and large industrial users, or between large industrial users in an industrial cluster. He tries to stimulate exchanges of resources, energy and waste stream, for example residual heat. Grid congestion is caused by the DSOs that did not anticipate to the fast electrification, combined with economic growth and a rapid decline in RES costs, which stimulated many businesses to deploy for example rooftop PV. Therefore, industrial users are forced to be creative. I try to assist them. In large energy transition projects, MCDM is not something that is thought of explicitly, in fact, it is the default way to go. Because of the diverse stakeholders, each decision is based on a trade-off of differing preferences and wishes.

Ranking of criteria:

1. Reduction of CO_2 emissions,
2. NPV and LCOE,
3. Grid-relief and self-consumption
4. Spatial integration
5. Investments
6. CRI

NPV and LCOE hard to separate, the expert mentions that they are correlated or causally connected. The same goes for grid-relief and self-consumption: high values self-consumption might lead to lower negative grid exchange peaks. List of criteria is complete.

Appendix D python scripts

D.1 Wind energy simulation

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt

# Load the CSV file with header
csv_file = "C:\\Python_for_data_analysis\\windspeed_ms_10m.csv"
df = pd.read_csv(csv_file)

# Extract wind speed data from the 'windspeed' column
wind_speed_data = df['windspeed']

# Turbine parameters
rated_power = 3 # in MW
cut_in_speed = 3 # in m/s
rated_speed = 12 # in m/s
cut_out_speed = 25 # in m/s
hub_height = 100 # in meters
roughness_length = 0.03 # in meters
measured_height = 10 # in meters

# Convert wind speeds to hub height using logarithmic wind profile
def convert_to_hub_height(wind_speed, measured_height, hub_height, roughness_length):
    return wind_speed * (np.log(hub_height / roughness_length) / np.log(measured_height / roughness_length))

# Apply the conversion to the wind speed data
df['Wind Speed Hub Height'] = wind_speed_data.apply(lambda x: convert_to_hub_height(x, measured_height, hub_height, roughness_length))

# Power curve for the simulated wind turbine
def power_curve(wind_speed):
    # Adjusted power curve based on the provided information
    if wind_speed < cut_in_speed or wind_speed >= cut_out_speed:
        return 0
    elif cut_in_speed <= wind_speed < rated_speed:
        return 0.016 * (wind_speed / cut_in_speed)**3 * rated_power
    elif rated_speed <= wind_speed < cut_out_speed:
        return rated_power
    else:
        return 0

# Apply the power curve to the dataset adjusted for hub height
df['Power Output'] = df['Wind Speed Hub Height'].apply(lambda x: power_curve(x))

# Convert 'Power Output' from MW to kW
df['Power Output kW'] = df['Power Output'] * 1000
```

```
# Save the results to the same CSV file
output_csv = "power_output_simulation_with_hub_height.csv"
df.to_csv(output_csv, index=False)

# Save the results to a new CSV file
output_csv = "power_output_simulation_with_hub_height.csv"
df.to_csv(output_csv, index=False)

# Calculate annual energy yield in MWh
annual_energy_yield_mwh = df['Power Output'].sum()  # Assuming 'Power Output' is in MW

# Calculate annual capacity factor
hours_in_a_year = 24 * 366
annual_capacity_factor = annual_energy_yield_mwh / (hours_in_a_year * rated_power)

# Print the results
print(f"Annual Energy Yield: {annual_energy_yield_mwh:.2f} MWh")
print(f"Annual Capacity Factor: {annual_capacity_factor:.4f}")

# Plot the adjusted power curve for visualization
wind_speed_range = np.arange(0, 30, 0.1)
power_curve_values = [power_curve(ws) for ws in wind_speed_range]

plt.figure(figsize=(8, 6))
plt.plot(wind_speed_range, power_curve_values, label='Power Curve', color='blue')
plt.xlabel('Wind Speed (m/s)')
plt.ylabel('Power Output (MW)')
plt.title('Wind Turbine Power Curve')
plt.legend()
plt.grid(True)
plt.show()

# Plot histogram of wind speed at hub height
plt.figure(figsize=(12, 6))
plt.hist(df['Wind Speed Hub Height'], bins=30, color='skyblue', edgecolor='black')
plt.xlabel('Wind Speed at Hub Height (m/s)')
plt.ylabel('Frequency')
plt.title('Histogram of Wind Speed at Hub Height')
plt.grid(True)
plt.show()

# Plot histogram of power output
plt.figure(figsize=(12, 6))
plt.hist(df['Power Output'], bins=30, color='lightgreen', edgecolor='black')
plt.xlabel('Power Output (MW)')
plt.ylabel('Frequency')
```

```
plt.title('Histogram of Power Output')
plt.grid(True)
plt.show()


print(f"Simulation completed. Results saved to {output_csv}")
```

D.2 Battery simulation

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

# Load electricity demand data from a CSV file, reading only the first
8784 rows (assuming a leap year with 366 days)
data =
pd.read_csv("C:\\Python_for_data_analysis\\Demand_files\\Wind_3MW_PV
_3MWp_EW.csv", nrows=8784, header=0, names=['demand'])

# Battery parameters
power_rating_kw = 1500 # Power rating in kW
storage_capacity_kwh = 6000 # Storage capacity in kWh

# Initialize battery state of charge (SOC)
battery_soc = storage_capacity_kwh

# Define charging and discharging thresholds
charging_threshold = 0.9  # Charge when SOC drops below 90% capacity
discharging_threshold = 0.1  # Discharge when SOC exceeds 10% capacity

# Initialize variables to store the modified demand data and battery
charge
modified_demand = data['demand'].copy()
battery_charge = []

# Initialize variables to track monthly peak values
monthly_peak_positive_demand = [0] * 12
monthly_peak_negative_demand = [0] * 12

# Initialize lists to store monthly peak values
months = ['Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug',
'Sep', 'Oct', 'Nov', 'Dec']
monthly_peak_data = []

# Create lists to store weekly average SOC
weekly_avg_soc = []
week_soc = []
week_count = 0

# Create a list to store the selected weeks
selected_weeks = [242, 2426, 4274, 6626]  # Adjust these as needed
```

```
# Create a list to store demand profiles for the selected weeks along
with battery SOC
demand_profiles_with_soc = [[] for _ in selected_weeks]
soc_profiles = [[] for _ in selected_weeks]

# Iterate through each hour of the year
for index, demand in enumerate(data['demand']):
    # Calculate the battery's power for the current hour
    battery_power = 0

   # Adjust charging logic based on demand
    if demand < 0 and battery_soc / storage_capacity_kwh <
charging_threshold:
        battery_power = min(power_rating_kw, (charging_threshold -
battery_soc / storage_capacity_kwh) * power_rating_kw)

    # Adjust discharging logic based on demand
    if demand > 500 and battery_soc / storage_capacity_kwh >
discharging_threshold:
        battery_power = -min(power_rating_kw, (battery_soc /
storage_capacity_kwh - discharging_threshold) * power_rating_kw)

    # Update battery SOC
    battery_soc = max(0, min(storage_capacity_kwh, battery_soc +
battery_power))
    battery_charge.append(battery_soc)  # Store battery charge at each
hour

    # Adjust demand by battery discharge
    modified_demand[index] = demand + battery_power

    # Update monthly peak values
    month = index // 744  # Assuming 31 days for January, 29 days for
February, and so on
    if modified_demand[index] > monthly_peak_positive_demand[month]:
        monthly_peak_positive_demand[month] = modified_demand[index]
    if modified_demand[index] < monthly_peak_negative_demand[month]:
        monthly_peak_negative_demand[month] = modified_demand[index]

    # Calculate weekly average SOC
    week_soc.append(battery_soc)

    if (index + 1) % 168 == 0:  # Assuming 168 hours in a week
        weekly_avg_soc.append(sum(week_soc) / len(week_soc))
        week_soc = []

    # Store demand profiles and battery SOC for the selected weeks
    for i, week_index in enumerate(selected_weeks):
        if index == week_index:

demand_profiles_with_soc[i].append(modified_demand[index])  # Demand
```

```
profile
            soc_profiles[i].append(battery_soc)     # Battery SOC


# Initialize lists to store daily peak values (both positive and
negative)
daily_peak_positive_demand = [0] * 7
daily_peak_negative_demand = [0] * 7

# Initialize a counter to keep track of the current day
current_day = 0

# Initialize lists to store weekly averages of daily peaks and
corresponding week numbers
weekly_avg_daily_peaks = []
week_numbers = []

# Iterate through each hour of the year
for index, demand in enumerate(modified_demand):
    # Calculate daily peak values (positive and negative) for the
current day
    if demand > daily_peak_positive_demand[current_day]:
        daily_peak_positive_demand[current_day] = demand
    if demand < daily_peak_negative_demand[current_day]:
        daily_peak_negative_demand[current_day] = demand

    # Check if a new day has started
    if (index + 1) % 24 == 0:   # Assuming 24 hours in a day
        current_day += 1
        if current_day == 7:
            # Calculate the weekly average of daily peaks and reset
daily peak values
            weekly_avg_positive = sum(daily_peak_positive_demand) / 7
            weekly_avg_negative = sum(daily_peak_negative_demand) / 7
            weekly_avg_daily_peaks.append((weekly_avg_positive,
weekly_avg_negative))
            week_numbers.append(len(weekly_avg_daily_peaks))
            daily_peak_positive_demand = [0] * 7
            daily_peak_negative_demand = [0] * 7
            current_day = 0

# Create a DataFrame to store the weekly averages of daily peak values
along with week numbers
weekly_peak_data = pd.DataFrame({'Week Number': week_numbers,
                                 'Avg Positive Daily Peak (kW)':
[avg[0] for avg in weekly_avg_daily_peaks],
                                 'Avg Negative Daily Peak (kW)':
[avg[1] for avg in weekly_avg_daily_peaks]})

# Save the DataFrame to a new CSV file
weekly_peak_data.to_csv('weekly_average_peaks_PV_EW_Wind_battery.csv
', index=False)
```

```
# Create a new DataFrame with modified demand data
modified_data = data.copy()
modified_data['demand'] = modified_demand

# Save the modified demand data to a new Excel file
output_excel_file = 'PV_EW_Wind_with_battery.xlsx'
modified_data.to_excel(output_excel_file, index=False)

# Add a column to the Excel file with hourly power values of the battery in a new sheet
with pd.ExcelWriter(output_excel_file, engine='openpyxl', mode='a') as writer:
    # Convert battery_charge to power values (kW)
    battery_power_values = [((charge - battery_charge[i - 1]) if i > 0 else 0) for i, charge in enumerate(battery_charge)]

    # Add a new sheet 'BatteryPower' with battery power values, initial demand, and modified demand
    battery_power_df = pd.DataFrame({'Battery Power (kW)': battery_power_values,
                                     'Initial Demand': data['demand'],
                                     'Modified Demand': modified_data['demand']})
    battery_power_df.to_excel(writer, sheet_name='BatteryPower', index=False)

# Manually specify starting points for each week
week_starts = [242, 2426, 4274, 6626]  # Replace with the row indices where each week starts

# Create a Pandas Excel writer using XlsxWriter as the engine.
excel_writer = pd.ExcelWriter('C:\\Python_for_data_analysis\\Weekly profiles\\PV_EW_Wind_battery.xlsx', engine='xlsxwriter')

# Write each dataframe to a new column in the Excel file.
for i, week_start in enumerate(week_starts):
    week_data = modified_data['demand'].iloc[week_start:week_start + 7 * 24]
    header = f'Week{i + 1} Demand (kW)'
    week_data.to_excel(excel_writer, sheet_name='ModifiedWeeks', startcol=i, index=False, header=header)

# Add a new sheet 'BatteryPower' with battery power values, initial demand, and modified demand
battery_power_df = pd.DataFrame({'Battery Power (kW)': battery_power_values,
                                 'Initial Demand': data['demand'],
                                 'Modified Demand': modified_data['demand']})
```

```
battery_power_df.to_excel(excel_writer,    sheet_name='BatteryPower',
index=False)

# Close the Pandas Excel writer and output the Excel file.
excel_writer.save()

print(f"Excel file '{output_excel_file}' saved successfully.")


# Print monthly peak positive and peak negative values
for month in range(12):
    monthly_peak_data.append([months[month],
                              monthly_peak_positive_demand[month],
                              monthly_peak_negative_demand[month]])

# Create a DataFrame for monthly peak values
monthly_peak_df = pd.DataFrame(monthly_peak_data, columns=['Month',
'Positive Peak (kW)', 'Negative Peak (kW)'])

# Specify the path for the Excel file
output_monthly_peak_file =
'C:\\Python_for_data_analysis\\Monthly_Peak_Values\\PV_EW_Wind_batt.
xlsx'

# Save the DataFrame to an Excel file
monthly_peak_df.to_excel(output_monthly_peak_file, index=False)

# Calculate the amount of electricity flowing to and from the battery
over the whole year
electricity_to_battery = sum(max(0, charge - battery_charge[i - 1])
for i, charge in enumerate(battery_charge) if i > 0)
electricity_from_battery = sum(max(0, battery_charge[i - 1] - charge)
for i, charge in enumerate(battery_charge) if i > 0)

print("Electricity to Battery (kWh):", electricity_to_battery)
print("Electricity from Battery (kWh):", electricity_from_battery)

# Create a plot of battery charge over the full year
plt.figure(figsize=(10, 6))
plt.plot(battery_charge)
plt.xlabel('Hour of the Year')
plt.ylabel('Battery Charge (kWh)')
plt.title('Battery Charge Over the Full Year')
plt.grid(True)

# Create a plot showing weekly average SOC
plt.figure(figsize=(10, 6))
plt.plot(weekly_avg_soc)
plt.xlabel('Week')
plt.ylabel('Weekly Average Battery SOC (kWh)')
plt.title('Weekly Average Battery SOC Over the Year')
plt.ylim(500,4500)
```

```
plt.grid(True)

plt.show()
```

D.3 Flexibility simulation

```
import pandas as pd

# Read the CSV file into a DataFrame
df =
pd.read_excel("C:\\Python_for_data_analysis\\PV_EW_with_battery.xlsx
")

# Assuming your CSV file has a column named 'demand'
demand_column = 'demand'

# Create a datetime column based on the assumption
df['datetime'] = pd.date_range(start="2020-01-01 00:00", end="2020-
12-31 23:00", freq="H")

# Variables for calculating average adjusted power
total_adjusted_power = 0
affected_hourly_values = 0

# Apply demand response rules
for index, row in df.iterrows():
    initial_value = row[demand_column]

    # Check if the initial value is greater than 3500
    if initial_value > 3500:
        # Reduce the demand by a maximum of 15%
        adjusted_value = max(initial_value * 0.85, 0)
        total_adjusted_power += adjusted_value
        affected_hourly_values += 1
    # Check if the initial value is less than -3500
    elif initial_value < -3500:
        # Increase the demand by a maximum of 15%
        adjusted_value = min(initial_value * 0.85, 0)
        total_adjusted_power += adjusted_value
        affected_hourly_values += 1
    else:
        # No adjustment needed
        adjusted_value = initial_value

    # Update the DataFrame with the adjusted value
    df.at[index, demand_column] = adjusted_value

# Ensure daily sum constraint
daily_sum_constraint =
df.groupby(df['datetime'].dt.date)[demand_column].sum()
for date in daily_sum_constraint.index:
    # Calculate the adjustment factor to maintain the daily sum
constraint
```

```
    adjustment_factor = daily_sum_constraint[date] / df[df['datetime'].dt.date == date][demand_column].sum()

    # Apply the adjustment factor to the daily values
    df.loc[df['datetime'].dt.date == date, demand_column] *= adjustment_factor

# Save the modified DataFrame to a new Excel file
df.to_excel('C:\\Python_for_data_analysis\\Annual_flex\\PV_EW_batt_flex.xlsx', index=False)

# Calculate and print the average adjusted power
average_adjusted_power = total_adjusted_power / affected_hourly_values if affected_hourly_values > 0 else 0
print(f"Average adjusted power applied to affected hours: {average_adjusted_power:.2f} kW")

# Print monthly peak positive and peak negative values
monthly_peaks = df.groupby([df['datetime'].dt.year, df['datetime'].dt.month])[demand_column].agg(['max', 'min'])

# Create a new DataFrame for monthly peaks
monthly_peaks_df = pd.DataFrame({
    'Month': [f"{month_name} {year}" for year, month_name in monthly_peaks.index],
    'Positive Peak (kW)': monthly_peaks['max'].values,
    'Negative Peak (kW)': monthly_peaks['min'].values
})

# Save monthly peaks to a new Excel file
monthly_peaks_df.to_excel('C:\\Python_for_data_analysis\\Monthly_Peak_Values\\PV_EW_batt_flex.xlsx', index=False)

# Manually specify starting points for each season
winter_start = 242  # Replace with the row index where winter starts
spring_start = 2426  # Replace with the row index where spring starts
summer_start = 4274  # Replace with the row index where summer starts
autumn_start = 6626  # Replace with the row index where autumn starts

# Save demand data of 1 week in 4 different seasons to a separate CSV file
winter_data = df.iloc[winter_start:winter_start+7*24]
spring_data = df.iloc[spring_start:spring_start+7*24]
summer_data = df.iloc[summer_start:summer_start+7*24]
autumn_data = df.iloc[autumn_start:autumn_start+7*24]

# Create a Pandas Excel writer using XlsxWriter as the engine.
excel_writer = pd.ExcelWriter('C:\\Python_for_data_analysis\\Weekly profiles\\PV_EW_batt_flex.xlsx', engine='xlsxwriter')

# Write each dataframe to a new column in the Excel file.
winter_data.to_excel(excel_writer, sheet_name='Sheet1', startcol=1,
```

```
index=False, header=False)
spring_data.to_excel(excel_writer, sheet_name='Sheet1', startcol=2,
index=False, header=False)
summer_data.to_excel(excel_writer, sheet_name='Sheet1', startcol=3,
index=False, header=False)
autumn_data.to_excel(excel_writer, sheet_name='Sheet1', startcol=4,
index=False, header=False)

# Close the Pandas Excel writer and output the Excel file.
excel_writer.save()

# Calculate daily positive and negative peaks
daily_peaks =
df.groupby(df['datetime'].dt.date)[demand_column].agg(['max',
'min'])

# Create a new DataFrame for daily peaks
daily_peaks_df = pd.DataFrame({
    'Day': range(1, 367),  # Assuming a non-leap year with 366 days
    'Positive Peak (kW)': daily_peaks['max'].values,
    'Negative Peak (kW)': daily_peaks['min'].values
})

# Save daily peaks to a new Excel file
daily_peaks_df.to_excel('C:\\Python_for_data_analysis\\Daily_Peak_Va
lues\\PV_EW_batt_flex_daily_peaks.xlsx', index=False)

print("Simulation completed")
```

Appendix E: Dutch version of Process Description for the energy transition on mixed business park (Nederlandse versie Figuur 8.1)

This Appendix contains a translated version of Figure 8.1 from the report. This Figure is translated to Dutch to provide a version for use by stakeholders in the energy transition of Dutch mixed business parks. For a detailed description of the figure, the reader is referred to Section 8.2. The figure is to be used in combination with the report.

Initiatie

- **Identificeer de transitiedriver:** stel de netsituatie vast vanuit de DSO, kijk naar lokale en regionale doelstellingen en ambities op het gebied van hernieuwbare energie.
- **Breng de stakeholders in** kaart op het gemengde bedrijventerrein en ontwikkel een participatiestrategie om bij elke stap de juiste stakeholders te betrekken.
- ***Vorm een groep koplopers*** *die deel uitmaken van het initiële probleem en deel kunnen uitmaken van de oplossing. Er moeten in ieder geval meerdere grootverbruikers en de DSO aanwezig zijn.*
- ***Organiseer een informatiesessie*** *of kick-off om andere belanghebbenden te informeren en het transitietraject te schetsen.*

Analyse

- De koplopers **contracteren een adviseur** om de energiehuishouding nader te analyseren.
- **Identificeer een simulatiemodel** om de energiestromen op het park te analyseren
- **Analyseer de huidige energiestromen** op het park: totaalvolume, piekuitwisseling, flexibiliteitspotentieel.
- **Onderzoek het potentieel** van hernieuwbare energiebronnen op het park.
- **Analyseer de waardepropositie** van de energietransitie op het gemengde bedrijventerrein.
- ***Organiseer een focusgroepsessie*** *om een ontwikkelingsbedrijf op te richten voor het ontwerp en de uitvoering van de energietransitie op het park*

Ontwerp

- **Schets meerdere configuraties** voor de integratie van RES, opslag en flexibiliteit.
- **Simuleer de configuraties** met behulp van het simulatiemodel. Genereer jaarlijkse en wekelijkse verbruiksprofielen om de dynamiek van de energiestromen te bestuderen.
- **Vergelijk de configuraties** aan de hand van economische, sociale, technische en ecologische criteria.
- **Kies de optimale oplossing** voor realisatie op het park.
- ***Valideer de keuze*** *voor de beoordelingscriteria en de te implementeren configuratie met de koplopers en onderzoek of andere stakeholders willen bijdragen.*

Implementatie

- **Beoordeel de implicaties** voor de belanghebbenden als de gekozen configuratie geïmplementeerd wordt.
- **Haalbaarheidsstudie:** financiële, juridische en technische haalbaarheid
- **Financieringsbeslissing:** identificeer investeerders en inkomstenstromen, onderzoek mogelijkheden voor subsidies van overheden en netbeheerders.
- *Identificeer een passende* ***verdeling van eigendom en verantwoordelijkheden*** *tijdens de realisatie en exploitatie van de duurzame energie-, opslag- en flexibiliteitsactiva.*
- **Zoek leveranciers** voor de voorgestelde oplossing en stel contracten op om de afspraken te formaliseren.
- Organiseer de **exploitatie, het onderhoud en de end-of-life**-strategieën van de activa.