Chair of Economic- and Business Management

Master's Thesis

Determination of the economic value of energy flexibility with a regional model approach

Jonathan Lunzer, BSc

October 2022

Scope of the Thesis

Mr. Jonathan Lunzer is given the topic

Determination of the economic value of energy flexibility with a regional model approach

to work on in a master's thesis.

In the first section of the master's thesis, the theoretical foundations for dealing with the topic described are to be worked out. For this purpose, the development of the energy sector, in particular the provision of electrical energy, as well as the development and application of storage technologies are to be elaborated. An essential part of the work is the development of a time series-based model to calculate the economic efficiency of storage investments at different penetration levels of renewable energies. In order to work on the topic, knowledge about energy scenarios, model developments, and economic feasibility calculations for the evaluation of investment options must be obtained from the relevant literature.

The focus of the practical part is the development of a model to calculate the electrical power flexibility needs of a model region. The model must be adaptable and applicable to different demographic and geographic variations. Furthermore, different penetration depths of renewable energies and several compositions, consisting of photovoltaic and wind energy, are to be calculated in the model. During this procedure, the findings regarding the economic viability of the different simulations are to be evaluated and interpreted, and an outlook on future developments is to be given.

Leoben, March 2022

Univ.-Prof. Dr. Wolfgang Posch

Lehrstuhl für Wirtschafts- und Betriebswissenschaften

MONTANUNIVERSITÄT LEOBEN
www.unileoben.ac.at

EIDESSTATTLICHE ERKLÄRUNG

Ich erkläre an Eides statt, dass ich diese Arbeit selbständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt, und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

Ich erkläre, dass ich die Richtlinien des Senats der Montanuniversität Leoben zu "Gute wissenschaftliche Praxis" gelesen, verstanden und befolgt habe.

Weiters erkläre ich, dass die elektronische und gedruckte Version der eingereichten wissenschaftlichen Abschlussarbeit formal und inhaltlich identisch sind.

Datum 12.10.2022

Unterschrift Verfasser/in
Jonathan Lunzer

Principle of equality

This paper has refrained from using gender-specific formulations. It is explicitly stated that formulations within this thesis are meant to treat all genders equally.

Acknowledgement

This thesis is of very special meaning to me, as it provided an extraordinary opportunity for me to combine scientific work with insights and experiences from actual business cases. As this project was carried out as a joint venture between AFRY Management Consulting GmbH Austria and the Department of Business Administration and Economics at the Montanuniversität Leoben, I was given the possibility to learn from both sides.

First, I would like to express my gratitude to Univ.-Prof. Dipl.-Ing. Dr.mont. Wolfgang Posch, who accredited this project in the beginning and provided me with the fundamental knowledge needed to investigate such an interesting field of energy markets and flexibilities. My warmest thanks goes to my supervisor Dipl.-Ing. Alexandra Groiß, BSc who gave guidance in any respect throughout all phases of this project. Thank you for your patience and endurance.

Furthermore, this project would have never been as insightful, interactive, and hands-on without the influence of my colleagues and supervisors at AFRY. I want to thank Dr. Wolfgang Pospischil and Dipl.-Ing. Horst Dulle for the easy-going organizational process throughout the duration of this project. A special thanks belongs to Dipl.-Ing. Thomas Steinberger who supported me whenever I needed a sparring partner for complex modeling questions or just offered me an additional meeting slot even when his calendar seemed already very dense. Thanks for giving me the chance to both feel as a full member of the team while providing me with enough time to finish my thesis.

I want to send greetings and a big thanks to visiting professor Dr. David Daniels, who was the first impulse for me to focus on the topic of flexibilities by supervising me while writing a white paper on value and cost elements in future power systems at the Chalmers University of Technology Göteborg.

As these past months have been quite turbulent for me, I would also like to highlight my biggest supporters alongside this journey. At the forefront, my parents Christian and Petra, who have had an open ear in every situation possible. My three sisters Nicole, Marie-Christine, and Natalie, who I consolidated quite often to either ask for advice or just to catch-up and let my thoughts dangle a bit. A big thanks goes out to my friends Fabian, Alex, Jakob, Thomas, Anna and many more, who have been intensively involved during my studies, guided me through ups and downs and have always been ready with fun and games.

Abstract

In fast-transforming energy systems renewable technologies and innovative digital solutions play a major role to tackle the issue of climate change. Due to the increasing renewable capacities in energy systems, the need for flexibilities is emerging. Intelligent system management and increased utilization of flexibility are at the core of transitioning to a sustainable future energy system.

This thesis looks into the interplay between the need, potential and the value of flexibility in regional and decentralized electric power systems. It investigates the effects of different penetration levels of solar photovoltaics and wind power capacities within a regional system as more and more storage technologies are added.

An evaluation framework is created based on a systematic three-step-approach starting with (1) the evaluation of flexibility needs on a local level followed by (2) the identification of local flexibility solutions and (3) the economic assessment of the effects on local energy systems and end-users. The framework provides a generic process, applicable to regions with different demographics and thus bears the ability to be adjusted to any given region. This strategy shall close the gap between the nation-wide analysis of flexibilities and the household-specific approaches to further improve the overall functioning of an interconnected energy system with increasing bi-directional flows on the lower grid levels.

Bringing the data to the model, the framework suggests computing scenarios with the underlying demand profiles, the renewable energy generation data and integrates the techno-economic parameters for the flexibility options available in the region. Three different scenarios are being investigated – solar PV-dominated, wind power-dominated, and a mixed renewables (solar PV and wind) -dominated system. At the core of this evaluation, a calculation model was created to determine the differences between these scenarios regarding flexibility need, how this need can be met by storage technologies (Li-Ion batteries), and what the economics of these scenarios mean to the investors of flexible assets. The power grid is used only at times of local shortage or already fully utilized flexibilities in order to give priority to local optimization.

The results across all scenarios showed a weak economic performance. The investment costs of batteries have the strongest influence on the outcome across all considered factors. The results prove that there is potential to exploit for Li-Ion battery storages, but investments are unprofitable at current levels of capital expenditures, lacking suitable market conditions to leverage their potential e.g., in local flexibility markets. Solely increasing the capacity of renewables lead to an enormous volatile and unstable system where the need for grid infrastructure skyrockets. As a consequence, measures must be taken to cushion those effects. Storage technologies provide the possibility to stabilize the system, while providing additional features to elevate the value of flexibility.

Kurzfassung

In einem sich schnell wandelnden Energiesystem spielen erneuerbare Technologien und innovative digitale Lösungen eine wichtige Rolle, um dem Problem des Klimawandels entgegenzutreten. Aufgrund der zunehmenden Kapazitäten an erneuerbaren Energien entsteht ein steigender Bedarf an lokaler Flexibilität. Intelligentes Management der Systeme und die Nutzung von Flexibilität sind der Schlüssel zur Energiewende.

Diese Arbeit befasst sich mit den Korrelationen zwischen dem Bedarf, dem Potenzial und dem Wert von Flexibilität in regionalen und dezentralen elektrischen Energiesystemen. Sie untersucht die Auswirkungen unterschiedlicher Durchdringungsgrade von Photovoltaik- und Windkraftkapazitäten innerhalb eines regionalen Systems, während dem System gleichzeitig Speicherkapazitäten hinzugefügt werden.

Es wird eine Methodik geschaffen, die auf einem systematischen dreistufigen Ansatz beruht: (1) Bewertung des lokalen Flexibilitätsbedarfs, (2) Identifizierung lokaler Flexibilitätslösungen und (3) deren ökonomische Auswirkungen auf lokale Energiesysteme. Die Methodik bietet einen generischen Prozess, der auf Regionen mit unterschiedlichen demografischen Gegebenheiten anwendbar ist und somit an jede Region angepasst werden kann. Diese Strategie soll die Lücke zwischen der länderspezifischen Analyse von Flexibilitäten und den haushaltsspezifischen Ansätzen schließen, um das Funktionieren eines vernetzten Energiesystems mit erhöhten, bilateralen Lastflüssen in den unteren Netzebenen zu verbessern.

Die Methodik berücksichtigt unter anderem die zugrunde liegenden Standardlastprofile, die Erzeugungsdaten von erneuerbaren Energien und integriert die technisch-wirtschaftlichen Parameter für die, in der Region verfügbaren, Flexibilitätsoptionen. Es werden drei verschiedene Szenarien untersucht - ein photovoltaik-dominiertes, ein wind-dominiertes und ein kombiniertes System (Photovoltaik und Windkraft). Als Kernstück der Bewertung wurde ein Berechnungsmodell erstellt, um die Unterschiede zwischen diesen Szenarien hinsichtlich des Flexibilitätsbedarfs zu ermitteln, wie dieser Bedarf durch Speichertechnologien (Li-Ion-Batterien) gedeckt werden kann, und wie sich die Wirtschaftlichkeit der Investitionen innerhalb dieser Szenarien entwickelt. Das elektrische Netz wird dabei nur in Zeitpunkten lokaler Unterdeckung oder ausgelasteter Flexibilitäten herangezogen, um einer lokalen Optimierung Vorrang zu geben.

Alle Szenarien zeigten eine schwache wirtschaftliche Profitabilität. Die Investitionskosten der Batterien haben den stärksten Einfluss auf das Ergebnis aller betrachteten Faktoren. Die Ergebnisse zeigen, dass es ein Potenzial für Li-Ion-Batteriespeicher gibt, dass dieses jedoch bei aktuellen Investitionskosten unrentabel bleibt, solange es an geeigneten Marktbedingungen fehlt, um das Potenzial zu nutzen z.B. Flexibilitätsmärkte für lokale Speicher. Die Erhöhung der Kapazität der erneuerbaren Energien führt zu einem enorm volatilen und instabilen System, in dem der Bedarf an Netzinfrastruktur in die Höhe schießt. Als Konsequenz müssen Maßnahmen ergriffen werden, um diese Auswirkungen abzufedern. Speichertechnologien bieten die Möglichkeit, das System zu stabilisieren und gleichzeitig den Wert der Flexibilität zu erhöhen.

Table of contents

List of figures

List of tables

List of equations

List of abbreviations

aFRR	Automatic Frequency Restoration Reserve
APS	Announced Pledges Scenario
$AvCost_{Batt}$	Avoided costs through stored energy annually
$Batt_{Li\text{-}Ion}$	Number of Li-Ion batteries in the region
BES	Battery Electric Storage
BDEW	Bundesverband der Energie- und Wasserwirtschaft e.V.
C	Amount of fully dis-/charged battery cycles per year
CAES	Compressed Air Energy Storage
Cap_{PV}	Total capacity of solar PV in the region
Cap_{Wind}	Total capacity of wind power in the region
Cap_{RES}	Total capacity of iRES-e in the region
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
$Cost_{Grid,\ day}$	Energy supply costs from grid (daytime) annually
$Cost_{Grid,\ night}$	Energy supply costs from grid (nighttime) annually
$Cost_{inv,Batt}$	Capital expenditures of a Li-Ion battery system
DIN	Deutsches Institut für Normung
DNV AS	Det Norske Veritas Group
DoD	Depth of Discharge
DSM	Demand-Side Management
DSO	Distribution System Operator
E-Mobility	Electromobility
E_{Batt}	Usable battery capacity
$E_{Charged,a}$	Amount of energy charged annually
$E_{Charged,a,day}$	Amount of energy charged annually (daytime)
$E_{Charged,a,night}$	Amount of energy charged annually (nighttime)
$E_{Discharged,a}$	Amount of energy discharged annually
$E_{Discharged,a,day}$	Amount of energy discharged annually (daytime)
$E_{Discharged,a,night}$	Amount of energy discharged annually (nighttime)
$E_{Feed\text{-}In}$	Amount of energy fed into the grid
$E_{Grid,day}$	Amount of energy obtained from grid (daytime)
$E_{Grid,night}$	Amount of energy obtained from grid (nighttime)
$E_{Grid,day,h}$	Energy delivered from/into the grid at daytime per hour
$E_{Grid,night,h}$	Energy delivered from/into the grid at nighttime per hour

$E_{HH,yrly}$	Average annual energy demand per household
EN	European Norm
E_{PV}	Energy generated from solar PV per hour
ETH	Eidgenössische Technische Hochschule Zürich
EU	European Union
E_{Wind}	Energy generated from wind power per hour
F_{PV}	PV factor
F_{Wind}	Wind factor
FCR	Frequency Containment Reserve
FN_{D+}	Annual sum of positive daily flexibility need
FN_{W+}	Annual sum of positive weekly flexibility need
FN_{M+}	Annual sum of positive monthly flexibility need
FN_{Y+}	Annual sum of positive yearly flexibility need
h	Hour
IEA	International Energy Agency
iRES-e	Electricity generated by intermittent Renewable Energy Sources
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt Hour
kWp	Kilowatt Peak
LCOE	Levelized Cost Of Energy
$LCOE_{PV}$	Levelized cost of energy for solar PV
$LCOE_{Wind}$	Levelized cost of energy for wind power
L_{HH}	Load per household per hour
Li	Lithium
$L_{Residual}$	Residual load per hour
mFRR	Manual Frequency Restoration Reserve
min	Minute
MW	Megawatt
MWh	Megawatt Hour
MWp	Megawatt Peak
MPI	Modified Profitability Index
N_{HH}	Number of households
NPV	Net Present Value
NZE	Net Zero Emissions by 2050 Scenario
PHS	Pumped Hydro Storage
$P_{Batt,max}$	Maximum battery power
P_{Charge}	Charging power

$P_{Discharge}$	Discharging power
$P_{el,day}$	Residential electricity price (daytime)
$P_{el,night}$	Residential electricity price (nighttime)
$P_{Grid+,max}$	Maximum power supply from grid
$P_{feed\text{-}in}$	Feed-in tariff
$P_{Grid-,max}$	Maximum power delivery into the grid
r	Discount rate of storage investments
R^+	Number of hours with residual load >0 annually
R^-	Number of hours with residual load <0 annually
RES	Renewable Energy Sources
RES-e	Electricity generated by Renewable Energy Sources
$Rev_{Feed\text{-}In}$	Feed-in revenue annually
RR	Replacement Reserve
SDGs	Sustainable Development Goals
SMEs	Small and Mid-sized Enterprises
STEPS	Stated Policies Scenario
St_{LVL}	Storage level
$t_{discharge}$	Discharge time
TSO	Transmission System Operator
TWh	Terawatt Hour

1 Introduction

The first chapter of this master thesis explains the initial situation and complications that led to, and will be addressed throughout, the thesis. It further follows the research questions derived from the objectives to contribute to the target, which will be described in detail in the upcoming chapters. Additionally, it will be shown, how the methodological process in this thesis is carried out. To conclude with the organizational aspects, the thesis structure will be explained.

1.1 Situation and complication

In a fast-transforming energy system, as we see it currently around the globe, renewable technologies and innovative digital solutions play a major role to tackle the issue of climate change. Due to the increasing renewable capacities, the need for balancing mechanisms is emerging. Intelligent system management and increased utilization of flexibility will most likely be crucial to enable the transition towards a sustainable power system in the future.

Power systems around the world can be different in many ways, but they all serve a similar purpose. Differences in generation technologies, interconnection with other power systems, served load profiles, and regulatory environments can all lead to different market and policy structures, but either way the goal remains the same: providing end-users with electricity where and when it is needed, reliably and at a reasonable cost.

Where power markets have been deregulated, market products and services provide economic signals to investors and grid element operators to build and operate these elements in such a way that the overall grid mission is accomplished. The heterogeneity of power systems has led to a similar heterogeneity of market products, due to the fact that the optimal way to manage one system may not be appropriate for another.

As today’s energy systems are largely built on assets reaching close to a century in lifetime, naming transmission and distribution networks as well as generators, they are challenged by the enormously fast-developing renewable energy technology sector. The high volatility of renewable generation leads to wide-spread intermittency challenges for the power system, where the need and potential for flexibility service providers are added to the discussion. What has been described as differences between power systems globally can also be seen on a regional level. Breaking down the geographical boundaries suddenly opens new questions and complications but might lead to new economical possibilities regarding the flexibility of a future, decentralized power system.

It is not easy for operators – utilities, industrial companies as well as households – and investors to calculate the value of building flexible assets and providing flexibility services to the grid. This might be possible on a high-level approach or within very broad system boundaries (e.g., country level). For end-users this evaluation is difficult, due to the fact that it is connected to a number of external influences like regulatory measures, grid services and not yet established regional flexibility markets. Hence, this thesis evaluates this given issue for end-users and tries to determine the economic and societal impact on end-users as well as the system and its stakeholders like operators and generators.

1.2 Target and research issue

This thesis aims to tackle the interplay between the need, potential and the value of flexibility in regional and decentralized electric power systems. Following on the complications described beforehand, this thesis is about to establish a process to identify the chances that come alongside with the energy transition and flexibility markets for regional players, investors, and municipalities.

Scientific research from universities and other institutions as well as representative associations of market players provide frameworks and approaches to validate the need and potential for flexibility in a continental context or on country level. An evaluation of the literature will be carried out qualitatively, comparing them to each other and mapping advantages and disadvantages to identify relevant information for this thesis. Further the characteristics of flexibility shall be taken to establish a reliable base for the following study. Elaborating on the results of the theoretical evaluation, this thesis tries to develop a framework and subsequently an evaluation model to determine the value of electric flexibility within regional boundaries integrating an analysis of economic key-figures as well as societal impact on end-users.

The framework shall provide a generic process, suitable to be applied on different regions. Due to this, it is crucial to create an input mask, which includes parameters, that can be altered for different future use cases. In addition, a comparison of existing energy scenarios will be done, to depict different renewable energy penetration rates and flexibility capacities (e.g., batteries) within a region, as well as their respective economic evolution. Through that, synthetic data sets shall be created for the sake of comparability. The analysis shall be answering the following questions:

- Is the developed framework suitable to evaluate the value of flexibility in regional power systems?
- What are the effects of different penetration levels of renewable energy sources (RES) within a regional system on flexibility needs?
- What are the differences between a solar photovoltaics (PV)-dominated system, a wind-dominated system and those of a mixed system (solar PV plus wind generation)?

1.3 Methodology

The theoretical approach to contribute to the target of this thesis will be described in the following.

To conduct a reliable study, it is crucial to find proven literature and scientific research in the field of interest. Therefore, comprehensive theoretical research using a systematic review method was carried out. The research for the theory regarding the goal of the study, focusses on the flexibility market, technical feasibility studies of flexibility systems, frameworks to assess flexibility needs in current and future energy systems, national and regional renewable energy developments as well as future outlooks and scenarios. The research follows a specific framework for literature reviewing (see Figure 1):

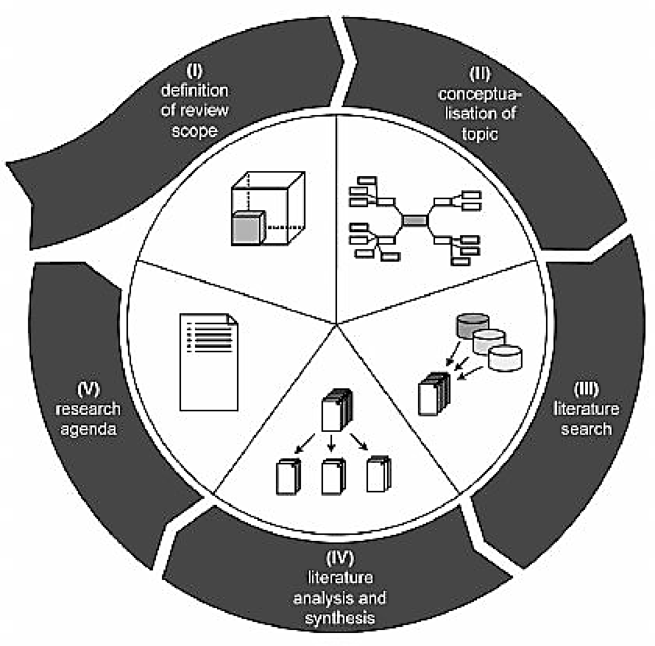


Figure 1: Framework for literature reviewing[1]

Derived from the conducted research and the identified existing frameworks which are investigating flexibility needs, their utilization and the determination of needed capacities, frameworks are chosen to disclose possibly missing aspects to apply them on regional electric power systems and to figure out a holistic approach for the practical part. Parts of the frameworks identified during the research are being used for the evaluation of flexibility needs and potential in regional systems. This process aims to identify the aspects of established frameworks usable for the development of the regional approach.

To develop a framework that works for regional electric power systems the previously explained aspects are being complemented by measures relevant on a regional basis to conclude to an approach for the economic evaluation of flexibility within a decentralized and regional system. This approach shall be tested in the practical part of the thesis where a simulation is carried out to test whether the approach can be used to evaluate flexibility potential and need, on a regional basis.

For the practical part of the thesis, it is important to set system boundaries and input parameters for further application of the developed framework. The inputs are built on research, predefined load profiles and chosen scenarios to be analyzed. Further, an analysis will be carried out regarding the various scenarios deriving economic key-figures and measures to evaluate the socio-economic impact on end-users.

---

[1] Source: Mueller-Bloch, C.; Kranz, J. (2015), p. 3.

1.4 Thesis structure

The thesis is structured to gradually fulfill the aim of answering the research issue as defined in Chapter 1.2. Figure 2 is giving an overview of the overall structure of the thesis:

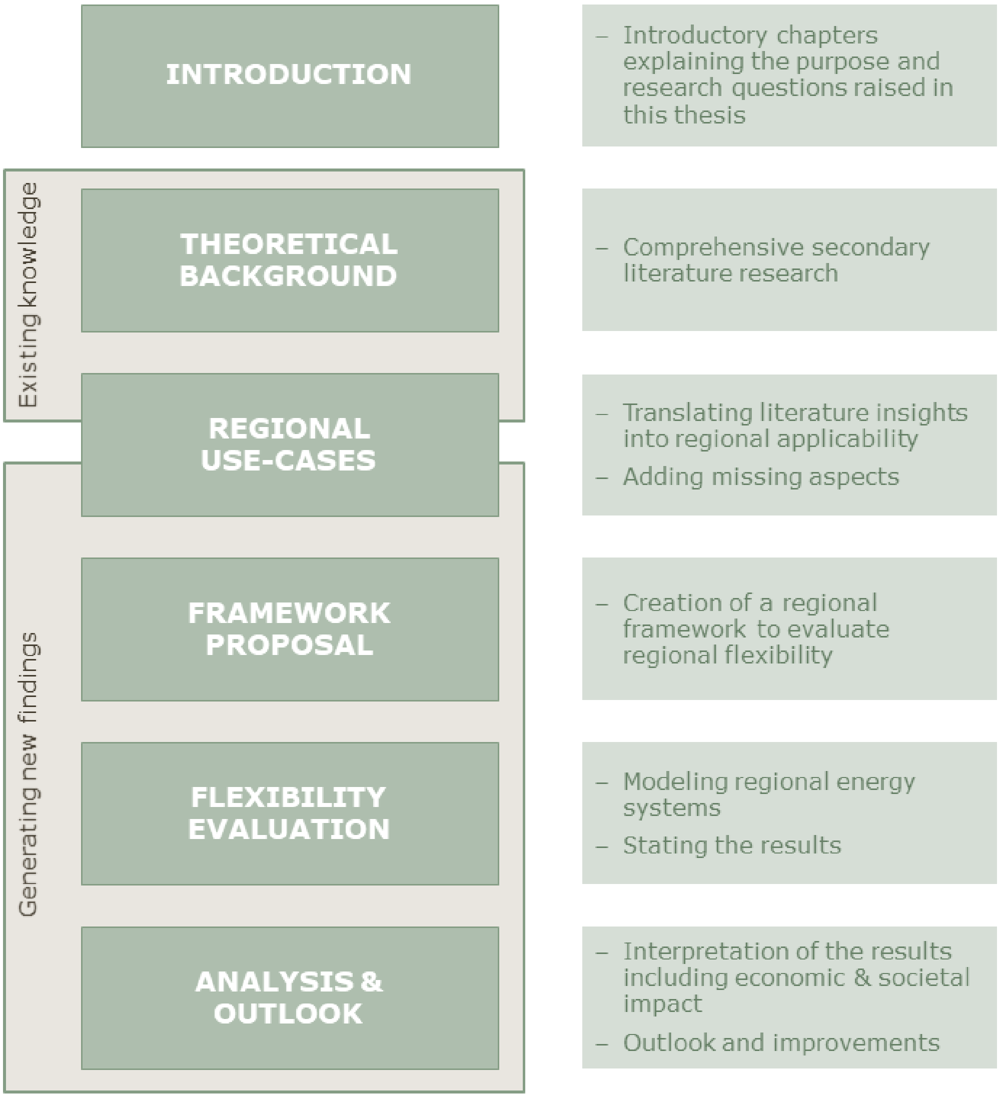


Figure 2: Thesis structure[2]

---

[2] Source: Own illustration

2 Theoretical background

A quick look into the past shows that power systems have already changed a lot over time and have to continue this track, given the fact that there are some bold targets set by political leaders in numerous countries around the world. The council of the European Union (EU) for example agreed to set the target for renewable energy sources (RES) in the overall energy mix to 40% by 2030.[3] Even in times, where the world's economies suffered by the challenges induced by the Covid-19 pandemic, the steep curve of renewable energy developments from solar PV and wind continued to rise. Solar PV and wind are currently the cheapest and cleanest available sources for electricity generation to add to the system in most countries.[4] Nevertheless, it also brings massive challenges to the entire supply chain of RES developments on various dimensions: political & regulatory dimension (policies and support schemes), technical dimension (conversion systems, grid continuity), economical & financial dimension (investment costs, costs for logistics), managerial dimension (inadequate communication, roles of grid operators, coordination between government entities).[5]

Carbon-free electricity, produced by solar PV and wind, is immensely intermittent due to rather quick possible changes in weather patterns and its quality and distribution differ widely across time and space. With this underlying heterogeneity of the resources, it has been observed, that the design of technology-specific RES support schemes has a major impact on market and environmental values solar PV and wind. To integrate large amounts of energy produced by those intermittent sources in a cost-effective manner, sufficient flexibility must be created to leverage these mixed valuations.[6;7]

To give a quantified context to the development of future electricity supply scenarios, Figure 3 shows how the different technologies will develop from 2020 data to 2030. There are three different scenarios calculated by the International Energy Agency (IEA):

---

[3] Cf. European commission, https://www.consilium.europa.eu/en/press/press-releases/2022/06/27/fit-for-55-council-agrees-on-higher-targets-for-renewables-and-energy-efficiency/, (Zugriff: 24.09.2022).

[4] Cf. International Energy Agency (2021), p. 15.

[5] Cf. Jelti, F. et al. (2021), p. 8 f.

[6] Cf. Abrell, J. et al. (2021), p. 2.

[7] Cf. Abrell, J. et al. (2019), p. 2.

- Net Zero Emissions by 2050 Scenario (NZE): This landmark scenario published by the IEA suggests an achievable roadmap to stabilize temperature levels at 1.5°C as well as the achievement of various sustainable development goals (SDGs).[8]
- Announced Pledges Scenario (APS): In this scenario, the emissions curve will be bent down globally, if all countries which have pledged to achieve their net zero targets will implement these targets in full scale and in time.[9]
- Stated Policies Scenario (STEPS): In this scenario, measures from governments that have been put in place already and specific policy initiatives that are still in the development phase are considered.[10]

Figure 3: Change in electricity generation by source and scenario, 2020 to 2030[11]

The trends shown by the IEA scenarios in Figure 3 underline what has been stated earlier: The growth of renewables will continue in all scenarios and is led by solar PV and wind. According to the IEA, China's policies are consistent with their targets for 2030, facing a relatively small gap for implementation. Therefore, the projected increase in the APS needs to be carried out mainly in other parts of the world, given the largest implementation gaps in the United States, Australia, the European Union and Canada. The share of electricity supplied globally by solar PV and wind in 2030 rises from below 10% in 2020 to 23% (STEPS), 27% (APS) and 40% (NZE), while increases of other renewable energy sources (e.g. bioenergy, hydro and geothermal) are far less outstanding.[12]

---

[8] Cf. International Energy Agency (2021), p. 15.
[9] Cf. International Energy Agency (2021), p. 16.
[10] Cf. International Energy Agency (2021), p. 16.
[11] Source: International Energy Agency (2021), p. 199.
[12] Cf. International Energy Agency (2021), p. 199.

2.1 Flexibility in energy systems

In scientific research, definitions for flexibility in energy systems can vary a lot, but still roughly describe the same phenomena. The term is often used in the context of renewable energies and volatile energy systems. As already stressed above, power systems are transforming with an enormous speed with political targets underlying. This also drives the need for flexible assets.

There are some frequently used terms in the context of flexibilities that are to be defined below. Whenever one of these terms is used in this work, the definitions in Table 1 give the context to a common understanding.

Table 1: Description of frequently used terms in the context of flexibility[13]

Term	Definition
Flexibility	Flexibility is the possibility of prompt changes of the fed-in or purchased power at a defined grid node of the power system by an external specification. The specifications can be made externally via aggregators, defined interfaces, or other system requirements.
Flexibility supply	The capability of a generator, consumer, or storage to reduce or increase electric power if required.
Flexibility demand	Equals flexibility need; The need to increase or decrease electrical power for different requirements.
Short-term flexibility need	Equals daily flexibility need; Flexibility required to compensate for hourly changes within a day.
Mid-term flexibility need	Equals weekly flexibility need respectively monthly flexibility need; Flexibility required to compensate for daily changes within a week respectively flexibility required to compensate for weekly changes within a month.
Long-term flexibility need	Equals yearly flexibility need; Flexibility required to compensate for monthly changes within a year.
Technical potential	Flexibility supply considering the physical, technical, and topological system boundaries.
Actual potential	Technical flexibility potential, considering the economic and practical (political or regulatory) restrictions.
Positive flexible power	Increase of electrical power at generators or reduction of electrical power demand.
Negative flexible power	Reduction of electrical power at generators or increase of electrical power demand.
Maximum possible retrieval duration	Maximum time span from the complete change of generation or consumption to the deactivation of flexibility.
Activation time	Time period from the receipt of a flexibility call to the complete change in generation or consumption.

---

[13] Cf. Esterl, T., Resch, G., Von Roon, S., et al. (2022), p. 8 f.

Regeneration time	Time period after deactivation of a flexibility until reactivation is possible.
Residual load	Difference between load and volatile, renewable power supply (solar PV, wind, or both)

Flexibility is considered as the possibility of prompt changes in the power output – regarding both, positive and negative changes. The reduction of electric power output respectively the increase of demand can be described as negative flexibility. Positive flexibility is meant by the increase of electric power output respectively the reduction of demand. Flexibility supply can be provided by various technologies such as generators, consumers, or storage facilities. While the time from the receipt of a flexibility activation request to the actual delivery is stated as activation time, the regeneration time is needed to get the flexible assets back online after it was deployed.[14]

Flexibility will be at the core of operating our future energy systems. It can be provided both from the demand-side and the supply side, but also through storage facilities. Because such flexibilities have influence on the markets and electricity grids, the analysis of flexibility encompasses main parts of the energy system. If regulatory adjustments, both on a national and international level, are being implemented, it is important to consider the interdependencies of different flexibility providing entities, especially those who demand flexibility.[15]

2.2 Drivers for flexibility need and potential

Thermal power plants (e.g., coal-, oil-, or gas-fired power plants), which are able to generate electricity whenever it is economically attractive, wind and solar PV power plants produce extremely variable. The generation of those renewable sources is heavily dependent on natural weather conditions, a certain time of the day, season, and location.[16]

Differences in generation technologies, interconnection with other power systems, served load profiles, and regulatory environments can all lead to different market and governance structures for different power systems; but nevertheless, the goal remains to provide end-users with electricity where and when it is needed, reliably and at a reasonable cost. Where power markets have been deregulated, market products and services provide economic signals to investors and grid element operators to build and/or operate these elements in such a way that the overall grid mission is accomplished. The heterogeneity of power systems has led to a similar heterogeneity of market products because the optimal way to manage one system may not be appropriate for another.[17;18]

---

[14] Cf. Esterl, T., Resch, G., Von Roon, S., et al. (2022), p. 7 f.

[15] Cf. Esterl, T., Resch, G., Von Roon, S., et al. (2022), p. 7.

[16] Cf. Zerrahn, A., Schill, W., Kemfert, C. (2018), p. 1.

[17] Cf. Salihu, M., Delplanque, L., https://blogs.worldbank.org/ppps/energy-service-delivery-will-change-next-decade-and-public-private-cooperation-will-be-key, (Zugriff: 27.09.2022).

[18] Cf. Westphal, K. et al. (2022), p. 7 ff.

The market signals and other mechanisms for managing a power system can blur the distinction between those necessary characteristics of a grid that enable it to achieve its fundamental mission and the means by which those characteristics are maintained in a specific system. As an example, the given work considers inertia. The definition of inertia can be described as the tendency of an object in motion to remain in motion. Inertia is an integral feature of traditional electric power systems that generate electricity using mainly thermal generators with spinning masses. A system with many of these generators has high inertia and is able to slow the frequency changes that result when rapid changes in supply or demand bring the system momentarily out of balance. More system inertia, ceteris paribus, provides more time to respond to these imbalances and maintains the frequency of the system within an acceptable range. Inertia is therefore a valuable feature of a grid. But inertia, per se, is rarely compensated for in power markets. In most traditional power systems inertia is an inherent feature of a generator; as one adds more generation, one also gets more system inertia, as it were, for free. But as power systems begin to switch away from fossil-fueled thermal generation and use more non-inertial renewable generation, such as wind and solar PV, the amount of spinning mass in the system will inevitably decrease as a result and system inertia will decline. Unless other action is taken, it will become harder to maintain the frequency in such a system and the grid may become more unstable. One obvious market-based solution would be to provide an economic incentive for providing inertia, yet inertia is not the only way to ensure the maintenance of system frequency. If market incentives focus on encouraging system inertia, one could lose focus on what is valuable about inertia, which is its contribution to grid stability.[19;20]

From the example of inertia in traditional power systems, as stated in the previous chapter, it can be derived that flexibility in all its facets can be (and assumingly has to be) substantial to system stabilizing, an economically feasible and attractive source of power that guarantees the system to work properly and deliver its purpose as it was described earlier: delivering electric power where and when it is needed, reliably, at a reasonable cost to consumers, and, increasingly, in a sustainable way.

Taking a closer look to the power system in the EU, especially to the more developed markets, there are a few flexibility demand options to be considered: energy market, reserves, and balancing power, as well as redispatch, distribution grid and short-term portfolio optimization, which will be explained in the following and have their origin from the following stated source, if not explicitly declared otherwise:[21]

---

[19] Cf. Denholm, P. et al. (2020), p. 1 f.

[20] Cf. Denholm, P. et al. (2020), p. 18 ff.

[21] Cf. Esterl, T., Resch, G., Von Roon, S., et al. (2022), p. 8.

- **Energy Market**: In addition to the technical framework conditions, the flexibility in the energy markets is determined by the demand and the volatile generation from RES or its temporal change. The amount of residual load, the difference between load and volatile RES generation, characterizes the flexibility demand that various flexibility options are available to meet, both on the generation and consumption side and in term of energy storage. Typically, hourly or 15-Minutes products are traded in energy markets. This is closest to the day-ahead spot market whereas activation time is less critical than for other flexibility demand options described in the following.
- **Reserves and balancing power**: Reserves are used to balance short-term imbalances between load and generation (≤ 15 min). The flexibility requirements are very precisely defined and depend on the type of control reserve. There are four different types of reserves in place in the European grid (not all of them are operable in every country): frequency containment reserve (FCR), automatic frequency restoration reserve (aFRR), manual frequency restoration reserve (mFRR) and replacement reserve (RR). Currently, the typical products are four hours, but there are plans to reduce the duration to 15 minutes. In addition, the reserves have very high requirements for actual availability as well as for the activation duration of the flexibilities, which differ between the four types of reserves.
- **Redispatch**: Measures in the form of redispatch can be called by the transmission system operator (TSO) from the time of market clearing until the actual time of delivery, as even short-term changes can lead to congestion.
- **Distribution grid**: The distribution system operator (DSO), who operates the distribution grid, uses flexibility for voltage regulation and to evade bottlenecks. The voltage maintenance requirements are defined by national or European norms (e.g., DIN EN 50160), according to which voltage levels at any node in the grid has to be within a certain width. Ten minutes are used as typical period to define the voltage quality. Critical network situations may also necessitate the use of longer time intervals.
- **Short-term portfolio optimization:** The flexibility requirements for short-term portfolio optimization are diverse and less precisely defined than, for example, reserve products. The typical requirement is a balancing of schedules in 15-minute intervals. On the one hand, fast flexibilities are needed to quickly compensate for the short-term deviations, such as deviations which occur at short notice within a quarter of an hour. On the other hand, these deviations can also last longer, which means that additional flexibilities are needed to supply or release energy over a longer period of time. The typical period is 15 minutes, as this is the so-called imbalance settlement period, over which the schedules are settled, or 60 minutes, as this period currently has the highest liquidity on the intraday market.

2.3 Outline of frameworks addressing flexibility demand

There is quite some research carried out already on the topic of flexibility in energy markets in general. Flexibility is tackled form different angles. It is assessed by technical feasibility studies to show whether our future power system with high shares of RES deployed has the need for highly reactive technologies to ramp-up and down quickly to balance loads.[22] But also, through scenario analysis, trying to examine the effect of large shares of RES on the economic costs and CO_2 emissions.[23] Studies that attempt to quantify the net revenue of flexible resources in a specific market helped to gain a more concrete understanding of the scope flexibility is facing in coming years.[24]

With those examples in mind, the next section will describe different frameworks evaluating flexibility and explain methodologies from different perspectives. As far as this research shows, there is no consensus about how to deal with the challenge of flexibility need in future energy systems, so the spotlighted studies and frameworks are chosen to state different opinions and a variety of aspects.

2.3.1 Mainstreaming RES – Flexibility portfolios

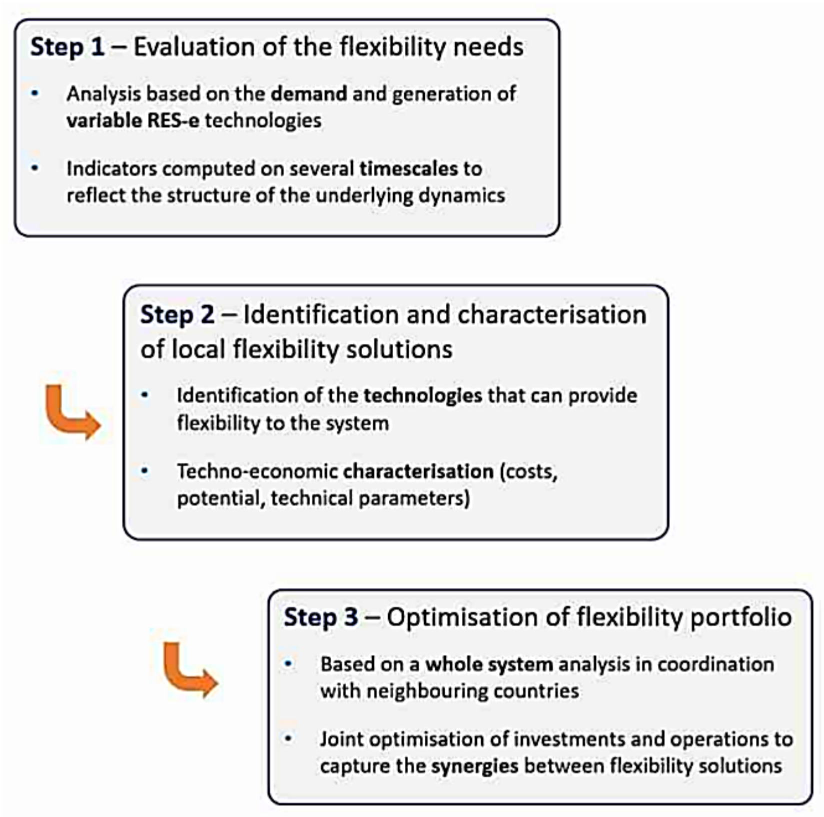
The EUROPEAN COMMISSION ordered a study on flexibility and RES, which has been made public in 2017. Chapter 2.3.1 is meant to give a summary based on afore mentioned study. Therefore, if not stated differently, the information presented in this chapter has its origin in the following stated source.[25]

The reasoning for the EUROPEAN COMMISSION to carry out this study together with partner institutions is, to provide member states with assistance to tackle the EU-wide topic of increased RES-e technologies added to the power system and the underlying flexibility need created by this increase. The objectives are to create a framework that could be applied on national level to further contribute to a stable and reliant energy system within Europe, where all member states are considered, and no one is left behind with country-specific circumstances. It also provides an EU-wide analysis, where the methodology is used to model the overall benefits for the EU and the member states. This analysis is carried out in three different options. The options basically differ from each other in terms of flexibility solutions, improvements and other assumptions that are set as boundaries for the model.

The recommended methodology to define flexibility portfolios follows a three-step-approach which is shown in Figure 4.

---

[22] Cf. European commission, Directorate-General for Energy (2019), p. 1 ff.
[23] Cf. Abrell, J. et al. (2021), p. 2.
[24] Cf. Goutte, S., Vassilopoulos, P. (2018), p. 1 ff.
[25] Cf. European commission, Directorate-General for Energy (2019), p. 1 ff.



Step 1 – Evaluation of the flexibility needs

- Analysis based on the **demand** and generation of **variable RES-e** technologies
- Indicators computed on several **timescales** to reflect the structure of the underlying dynamics

Step 2 – Identification and characterisation of local flexibility solutions

- Identification of the **technologies** that can provide flexibility to the system
- Techno-economic **characterisation** (costs, potential, technical parameters)

Step 3 – Optimisation of flexibility portfolio

- Based on a **whole system** analysis in coordination with neighbouring countries
- Joint optimisation of investments and operations to capture the **synergies** between flexibility solutions

Figure 4: Recommended framework to establish flexibility portfolios[26]

Step 1 – Evaluation of flexibility demand

Several effects influence the flexibility needs on different timeframes, when investigating a system dominated by a large share of RES-e sources:

- Flexibility needs on an hourly level are mainly driven by the imbalances caused by the difficulties in forecasting RES-e supply profiles.
- Flexibility needs on a daily level are mainly driven by the generation profile of solar PV within a day and the daily pattern of the load.
- Flexibility needs on a weekly level are mainly influenced by wind regimes and by the variations between load patterns on weekdays versus weekends
- Flexibility needs on a yearly level are mostly driven by the fact that solar PV generation and wind generation have alternating generation patterns seasonally. Solar PV generation is higher in summer, while wind generation has the tendency to be higher during wintertime. There is also an effect following different demand patterns as well as the load-temperature sensitivity (heavily dependent on the heating/cooling specifications within a country).

As ‘flexibility’ has been defined earlier in Table 1, this study provides a different definition, still addressing the same issue: “Flexibility is defined as the ability of the power system to cope with the variability of the residual load curve at all times. Hence, flexibility needs can be characterized by analyzing the residual load curve.”[27]

---

[26] Source: European commission, Directorate-General for Energy (2019), p. 6.

[27] European commission, Directorate-General for Energy (2019), p. 21.

The way, this study suggests computing the different types of flexibility will be explained in the following paragraphs:

- **Daily flexibility needs:** Flexibility wouldn't be required if the residual load were to be flat across the 24 hours of a day. In this case no dispatchable units would be needed and baseload generation could meet the demand easily. The study defined the daily need for flexibility by calculating the difference between the residual load and a conceptual flat residual load – the daily averaged residual load. Here are the steps to compute this metric:
    1. Compute the difference between generation (from iRES-e and must-run plants) and the demand to receive the residual load for the whole year with an hourly resolution
    2. Compute the daily averaged residual load
    3. To meet the definition made above, the residual load needs to be subtracted from its daily average resulting in a volume of flexibility need measured in terawatt hours (TWh) per day (illustrated by the green area pictured in Figure 5)
    4. To receive the total sum of daily flexibility need over a year, the obtained 365 values just need to be summed up expressed in TWh per year

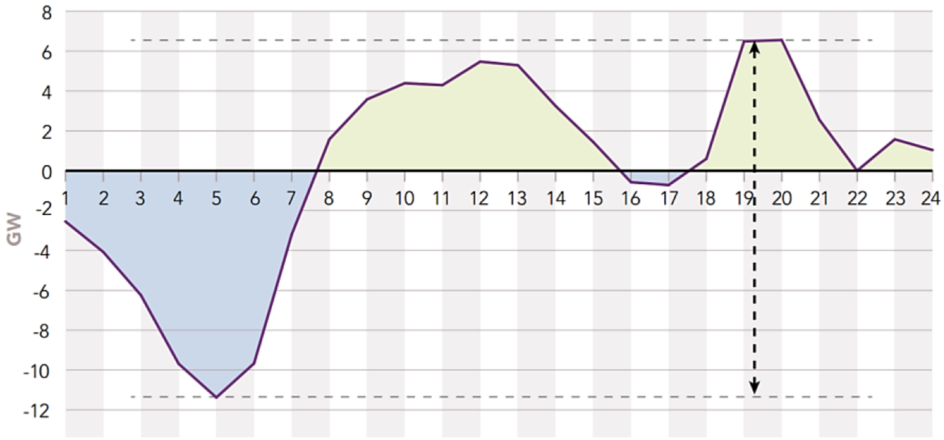


Figure 5: Daily needs of flexibility illustrated for a given day[28]

- **Weekly flexibility needs:** On a weekly basis, the procedure is quite similar to the daily one with some minor adjustments to exclude daily phenomena which have been taken into account already:
    1. Compute the difference between generation (electricity generated by intermittent renewable energy sources (iRES-e) and must-run plants) and the demand to receive the residual load for the whole year with a daily resolution
    2. Compute the weekly averaged residual load
    3. Next, the residual load (in daily resolution) needs to be subtracted from its weekly average resulting in a volume of flexibility need measured in terawatt hours (TWh) per week (illustrated by the green area pictured in Figure 6)
    4. To receive the total sum of weekly flexibility need over a year, the obtained 52 values just need to be summed up expressed in TWh per year

---

[28] Source: European commission, Directorate-General for Energy (2019), p. 22.

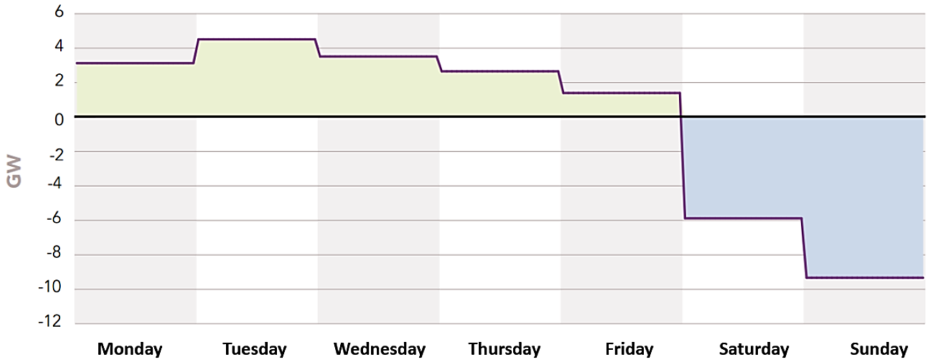


Figure 6: Weekly needs of flexibility illustrated for a certain week[29]

- **Annual flexibility needs:** Alike the weekly flexibility demand assessment, the annual flexibility needs are computed by undergoing the same procedure with the important difference of using a monthly time resolution.

Step 2 – Identifying local solutions for flexibility

In step two of the study, the contributors tried to summarize the important flexibility solutions that should be taken into account in order to meet the flexibility requirements induced by the large amount of RES-e capacity. It's intuitive, that step 1 and step 2 of the study will be diverse for each and every member state, when running through the methodology. The portfolio of flexibility solutions optimized for one country might not at all fit for another. This is due to the fact that the geography is different to deploy pumped hydro storage (PHS) or compressed air energy storage (CAES). The geographical situation also influences the potential (and costs) for interconnectors between neighboring countries. Costs to build-up or deploy those flexibility solutions could also be widely spread across the different countries.

It is recommended by the study to include the following types of flexibility solutions in the process of consideration and extended by a list of techno-economic characteristics to be assessed to determine their full potential tackling the flexibility needs:

- **Flexible generation technologies**: Conventionally speaking, these technologies are the flexible asset stabilizing the power grid for decades already. Within this group thermal power plants are considered (open- (OCGTs) as well as combined-cycle gas turbines (CCGTs), hydro power plants and reciprocating engines. Associated with those technologies they all have the inherent ability to ramp-up power output and down again adapting to the flexibility needs claimed by the grid operators, accompanied with additional services like frequency control, black start and voltage control. The downside of those technologies is that their operation comes with relatively high costs. In order to provide flexibility services, some countries already retrofitted some of their outdated thermal generators. Retrofitting increases their ramping speed, efficiency and lowers the minimum stable level of generation. The authors of the study suggest a list of considerable techno-economic parameters:

---

[29] Source: European commission, Directorate-General for Energy (2019), p. 22.

  - investment costs
  - operational costs
  - fuel costs
  - CO_2 intensity
  - efficiency)
- **Storage**: Storage facilities have a wide range of use cases in the context of flexibility. First of all, they can serve as arbitrage mechanism, storing energy at a certain point of time and, depending on the discharge time, delivering it back to the grid while demand is high. In the same manner, it can also leverage the economics of either the storage facility itself, or in combination with a power plant (e.g. solar PV), both by feeding in at high prices and storing at low prices. Additionally, storage can provide black start services, manage congestions, and regulate voltage levels. The costs for batteries, aside from other storage technologies, are coming down significantly every year what possibly drives the market penetration of batteries with a significant rate in the upcoming years. For storage, the following considerable techno-economic parameters are stated in the study to be considered:
  - investment costs
  - operational costs
  - efficiency
  - discharge time
  - potential (in Megawatt (MW))
- **Demand-response**: Demand-response, also named demand-side management (DSM), is applied by technologies or devices on the demand-side, which are able to modify their consumption as a response to external incentives. It can be deployed by industrial, residential, or other sectors. To what extend DSM can play a role for flexibility services within member states is heavily dependent on the scale of industry, the number of electric vehicles in the transportation sector, or on the development status of devices in the residential sector. The DSM correlated techno-economic parameters identified by the study are:
  - investment costs
  - operational costs
  - activation costs
  - max. load shifting duration and interval
  - min. break time
  - potential (in MW)
- **Interconnectors:** Interconnectors are identified as being crucial for the European energy system to complete the EU-wide market and enable cross-country electricity transfer to exploit and harvest the complementarities of adjacent systems (in this case electricity systems of neighboring countries). Interaction of this kind is most valuable in case of widely differing generation mixes and load profiles of neighboring systems. This is, amongst others, a major advantage in terms of generation patterns from wind power. While solar energy is generated via a strong day/night pattern, wind is not. This makes interconnectors enormously valuable in times of high wind generation in a specific

country. Considerable techno-economic parameters for interconnectors were identified as:

  - investment costs
  - operational costs
  - losses
  - potential (in MW)

- **System-friendly iRES-e:** Technologies such as wind and solar PV are considered as system-friendly if they are deployed in non-generic manner. The orientation of PV panels can be changed to east/west instead of aiming south ways. Another possibility are wind turbines that are able to operate at lower wind speeds. Underlying techno-economic parameters were found considerable for system-friendly iRES-e as:
  - investment costs
  - operational costs
  - capacity factor
  - potential (in MW)

Step 3 –Flexibility portfolio optimization

In this final step, the study suggests fusing together the knowledge gained in step 1-2, to finally conclude with the optimized composition of flexibility solutions given by the assessment. To capture all attributes outlined above, the following characteristics need to be inserted into the model:

- **Hourly time resolution**: Running the model on an hourly basis, is the least necessary resolution to capture the dynamics in a simulated system properly. Ramping times, demand-response and variable generation is unraveled in far smaller time frames in reality thus modeling will be more accurate by using at least hourly data.
- **Annual time horizon**: Seasonal effects of the RES-e generation patterns or from heating/cooling sector can only be captured by expanding the modeling to at least one year. Using anker-days or anker-weeks will create misleading output and should therefore be avoided in such an analysis.
- **Regional modeling**: A key-aspect that is tackled by the model is the interconnectivity of energy systems – in this case between countries. If cross-border flows are not considered, the model would possibly overestimate costs for investments to meet the demand.
- **Investments and operations jointly optimized**: A pure simulation model could suggest optimization measures to a given bunch of investments but disregard the trade-off between other flexibility options identified through the assessment.

To provide the analysis with robust input data, it is recommended by the study to take more than just one baseline historical year for wind generation and solar PV into account. Using multiple weather scenarios ensures that the resulting energy system is resilient against challenging weather conditions.

2.3.2 The value of flexible power plants in European day-ahead and intraday power markets

French researchers have carried out this study to quantify the revenues that can be captured by flexible assets on the German and French power markets. Chapter 2.3.2 is based on this study. Therefore, if not stated differently, the information presented in this chapter has its origin in the following stated source.[30]

The growth of intermittent RES-e generation in the system as well as the direction of intraday power markets moving closer to real time, is at the core of this study. The envisaged target is to estimate the empirical and future value, measured in net revenue of a CCGT power plant fired with natural gas. Gas turbines are able to adjust their power output within minutes, hence, they can participate on the day-ahead and intraday bidding to profit from short-term changes of prices. Quantifying the 'value of flexibility' by investigating the possible net revenues of the CCGT through the 15-minute auctions (one day-ahead of delivery) and the hourly day-ahead auctions, the authors identified a premium for the capability of the asset to ramp-up faster.

Generally speaking, the paper states two measures to determine the value of flexibility:

1. **Immediacy** – This characteristic is valued by approaching real-time markets and increased dynamics for the urgency of delivery. The value of immediacy is linked to forecast errors and revealed during the intraday process.
2. **Ramping capability** – Sources of flexibility supply such as CCGTs with quite fast inherent ramping capabilities can generate revenue through auctions (15min, 30min products) that are currently, at least in some European countries, aiming towards 5min-products.

In a next step, those flexibility components are being analyzed by modeling the different prices from hourly and quarter-hourly auctions to better understand how flexibility revenues fluctuate with an increased number of jumps and high volatility. Building on the timeframes of the auctions, the time-series used for the model are in hourly or quarter-hourly resolution.

A major issue of balancing power markets is the problem of the so called 'forecast error'. Acknowledging that electricity generated from intermittent renewable energy sources is on the rise, more volatility will be added to the system. Forecasting of weather patterns is a complex process and afflicted with uncertainty. In the context of power markets, the forecast error describes the difference between the day-ahead forecast and the actual demand as it is illustrated by Figure 7.

---

[30] Cf. Goutte, S., Vassilopoulos, P. (2018), p. 1 ff.

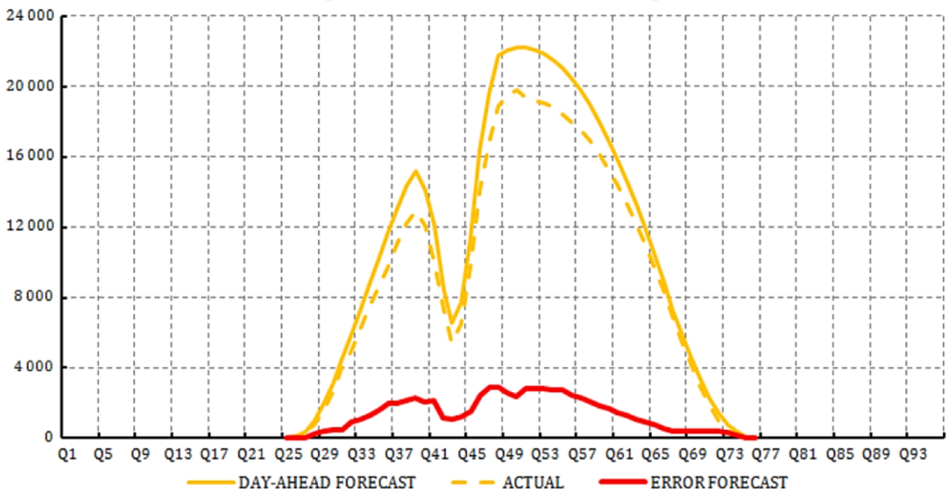


Figure 7: Solar forecast[31]

With increased iRES-e, it can also be seen, that the volumes traded on the day-ahead and intraday markets increased over the years. Looking at Figure 8, the picture states clear, that capacity within the system with sufficient ramping dynamics is needed to be added to the system at a constant rate for years to come. Accompanying the data from the study with a different, more recent source, proofs that the trend has been continuing its path as Figure 9 shows. Fixed price limits for day-ahead markets[32] on the one hand, and rather loose limits for the intraday markets[33], give this development an additional push forward.

---

[31] Source: Goutte, S., Vassilopoulos, P. (2018), p. 13.

[32] -500 €/MWh, +3.000 €/MWh; price range for bids on the day-ahead market

[33] -9.999 €/MWh, +9.999 €/MWh, price range for bids on the intraday market

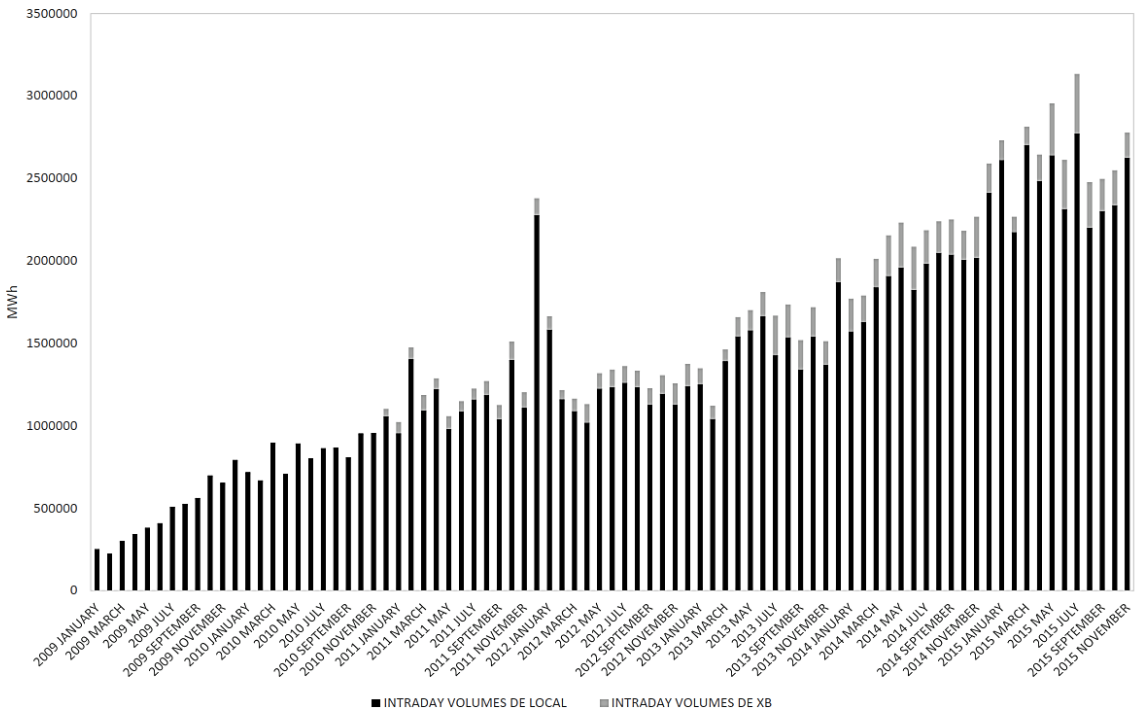


Figure 8: Evolution of Intraday trading volumes in Germany between 2009 and 2015 based on trade volumes at EPEX SPOT[34]

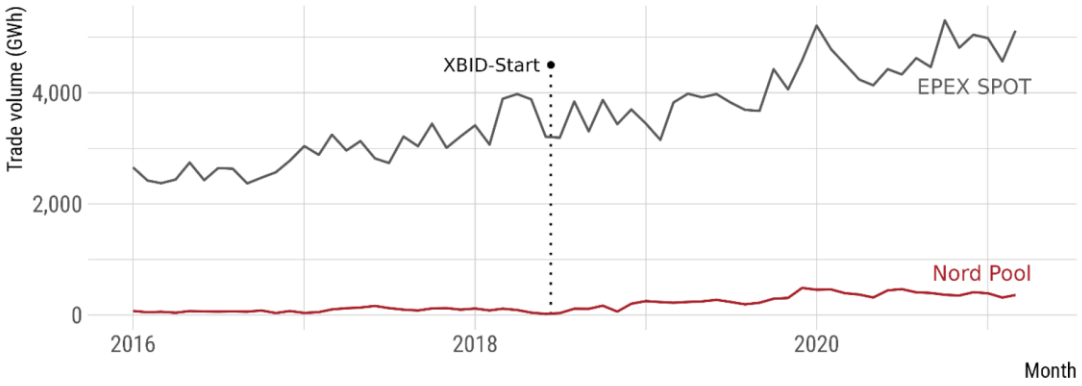


Figure 9: Trade volume of the electricity exchanges (EPEX SPOT, Nord Pool) in GER/LUX intraday trading between 2016 and 2021[35]

Description of the modeling approach

As pointed out in the introduction to this paper, the authors focused on a CCGT power plant to constitute the flexible asset. Some assumptions where made, prior to the calculation to define what the capabilities of the flexible assets are.

The increment of the flexibility is a 'perfect megawatt' produced by the CCGT. The perfect MW is meant to meet the volatility in day-ahead and intraday prices as it is able to ramp-up and down by following the dynamics of the price. It is not accounted for any technical constraints of the CCGT such as minimum running or down times, efficiency

---

[34] Source: Goutte, S., Vassilopoulos, P. (2018), p. 8.

[35] Source: Monopolkommission (2021), p. 12.

variations or ramping speeds, nor that the CCGT could have influence on the market clearing price.

Via the actual modeling, it is depicted over time whether the price level exceeds the variable costs of the power plant. If so, the difference between the market clearing price - auction price at a specific time increment A_t - and the variable costs at the same time increment VC_t is considered as the margin within that specific timestep (see Equation 1). If not, the CCGT will remain stationary without generating energy or profit (see Equation 2).

Equation 1: Case of auction price exceeding the variable costs[36]

$$A_t > VC_t\,; Margin = A_t - VC_t$$

Equation 2: Case of variable costs exceeding the auction price[37]

$$A_t < VC_t\,; Margin = 0$$

The calculation is carried out for both the day-ahead market and the intraday market. Each of them is run through by the model for continuous trading and auctions considering both hourly and quarter-hourly time resolution.

2.3.3 The economic and climate value of flexibility in green energy markets

Researchers from ZEW LEIBNITZ CENTRE FOR EUROPEAN ECONOMIC RESEARCH and the DEPARTMENT OF MANAGEMENT, TECHNOLOGY AND ECONOMICS AT THE ETH ZURICH conducted a study that examines the economic and CO_2-related effects of enhanced flexibility across time, space, and a regulatory dimension. Chapter 2.3.3 is based on this study. Therefore, if not stated differently, the information presented in this chapter has its origin in the following stated source.[38]

At the core of this study some will find a three-dimensional approach assessing flexibility need and potential within an interconnected power system, such as the EU, in ‘time’, ‘space’ and ‘regulation’ or translated into more technical words: spatial flexibility (cross-country flows and cross-market electricity trade), temporal flexibility (energy storage) and regulatory flexibility (tradeable green quotas). The authors entitle their framework as empirical-quantitative as it brings together the synergies of an in-depth quantitative analysis together with research on market data. Where data was missing, they worked with assumptions via geographic proximity. This basically means that the missing values were imputed from neighboring countries. The chosen approach enables the empirical-quantitative framework to assess flexibility from various perspectives, what meets the complexity of the topic. Not only storage technologies (time) and cross-market trade (space) is being analyzed, also policy and support schemes are tackled. It analyses the differing effects of RES support policies being implemented on a national level versus coordinated, EU-wide enactment and a system of tradable renewable energy quotas.

---

[36] Goutte, S., Vassilopoulos, P. (2018), p. 15.

[37] Goutte, S., Vassilopoulos, P. (2018), p. 15.

[38] Cf. Abrell, J. et al. (2021), p. 1 ff.

Averaging each hour of a day throughout a year results in the illustration shown in Figure 10. The appearance may be deceptive, but at no point in time the generation from RES meets the demand quite close. Not even by adding up solar PV and wind, even though it is way better also in terms of balance. Not only the demand could not be met, but the heavy need for load-shifting remains. Solar PV generates the commonly known day-to-night imbalance, but also the production curve from wind energy is not quite fitting, given the averagely high production during off-peak hours. Overall, a good illustration of the potential to enhance temporal flexibility.

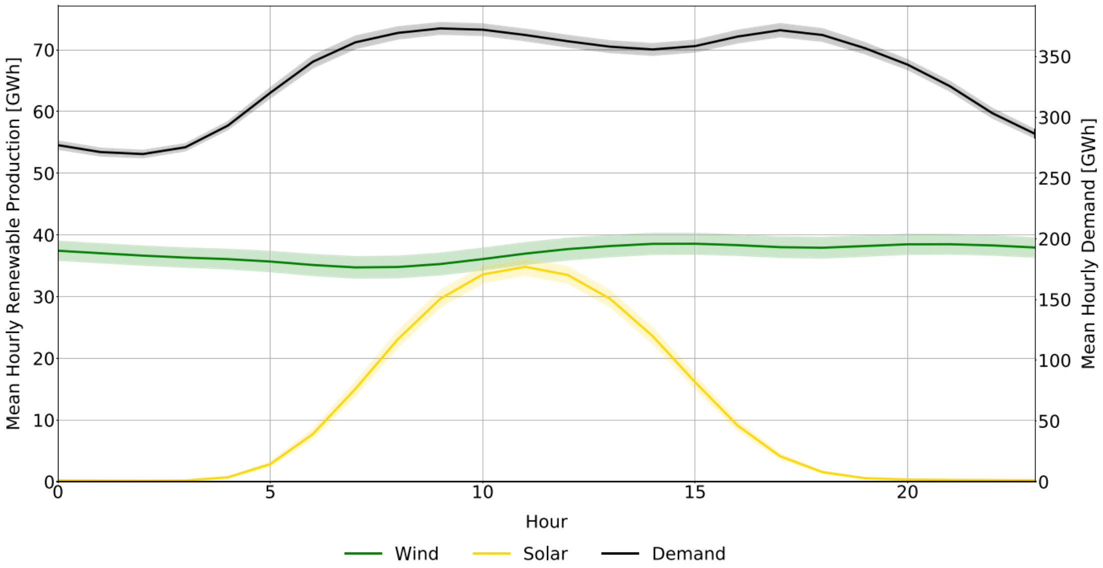


Figure 10: Hourly profiles of demand and electricity generation from solar PV and wind over an average day in Europe[39]

Spatial flexibility can be met by offering trade between countries to pool different availability profiles for RES. It further enables conventional power generation capacities. A correlation analysis between solar PV & wind generation and demand was conducted across several EU member states shown in Figure 11 to Figure 16. The generation data for solar PV and wind power are taken and averaged throughout the year 2017. High correlations can be seen in Figure 11 and Figure 14 between solar PV generation and demand patterns. Despite a few outliers in the demand-demand correlation, it can be stated that solar PV is not quite promising to provide flexibility in the interconnected system – of course, when looking at those aspects only. From Figure 16 and Figure 15, it can be understood that the flexibility potential is substantial by fusing solar and wind together and yet provide more capacities for cross-country trade.

---

[39] Source: Abrell, J. et al. (2021), p. 3.

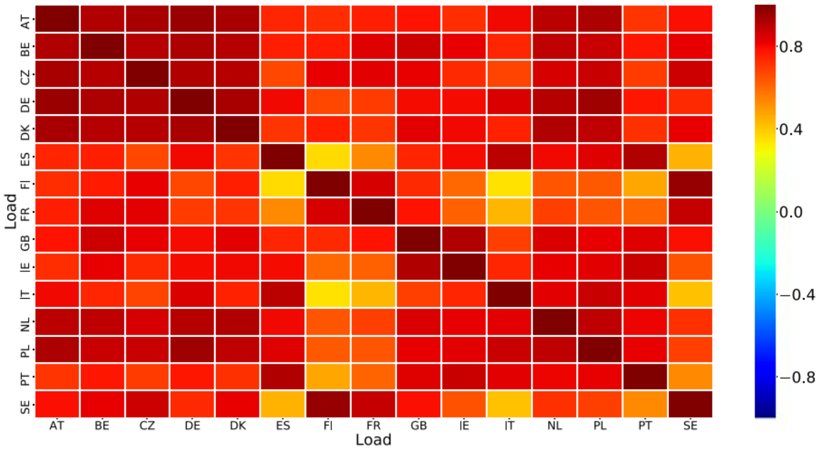


Figure 11: Heat map of cross-country correlation: demand vs demand[40]

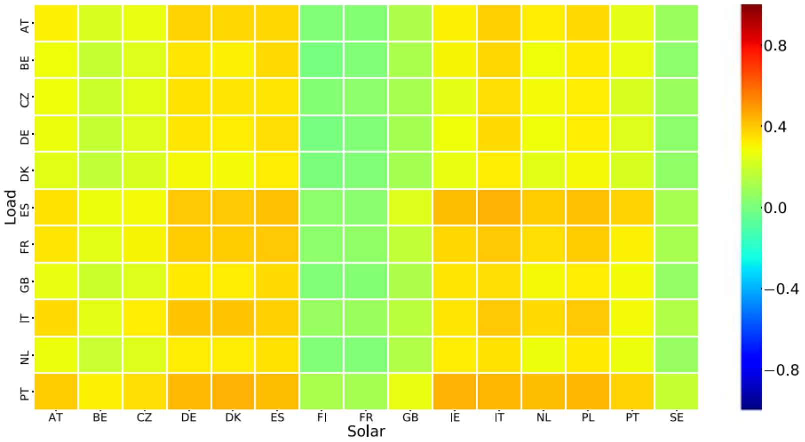


Figure 12: Heat map of cross-country correlation: Solar PV vs demand[41]

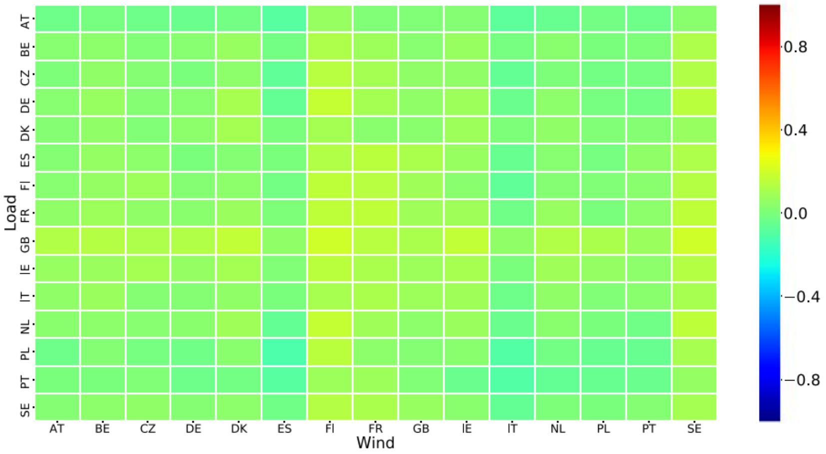


Figure 13: Heat map of cross-country correlation: Wind vs demand[42]

---

[40] Source: Abrell, J. et al. (2021), p. 4.
[41] Source: Abrell, J. et al. (2021), p. 4.
[42] Source: Abrell, J. et al. (2021), p. 4.

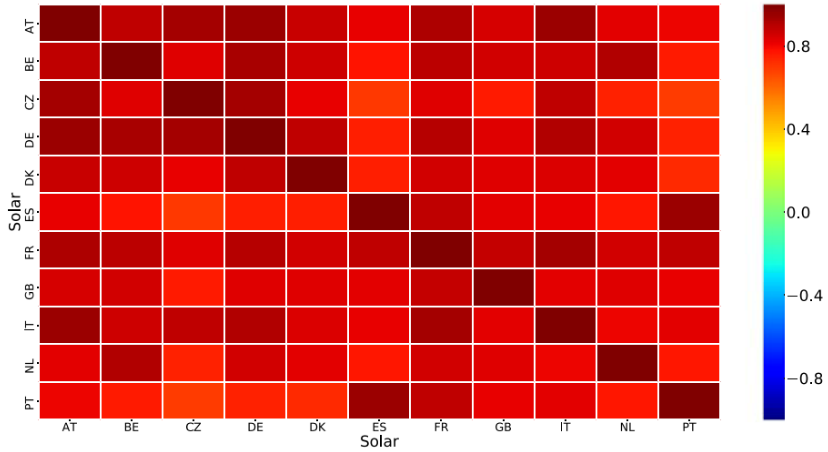


Figure 14: Heat map of cross-country correlation: Solar vs Solar[43]

Figure 15: Heat map of cross-country correlation: Wind vs Wind[44]

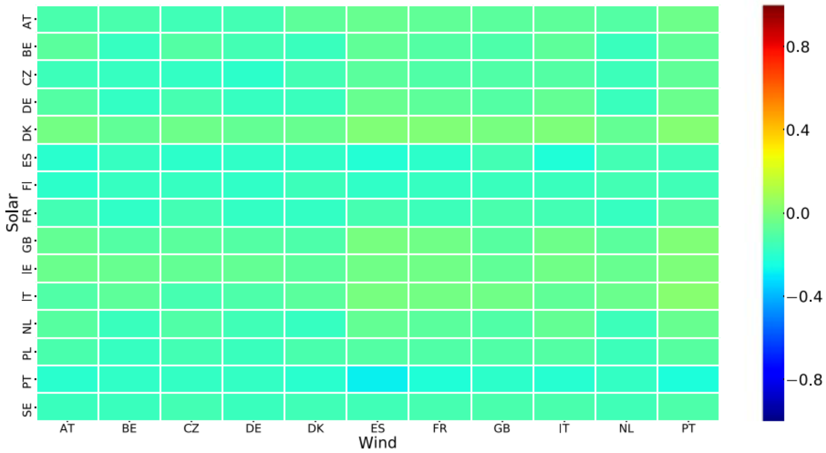


Figure 16: Heat maps of cross-country correlation: Solar vs Wind[45]

---

[43] Source: Abrell, J. et al. (2021), p. 4.
[44] Source: Abrell, J. et al. (2021), p. 4.
[45] Source: Abrell, J. et al. (2021), p. 4.

The natural resources differ from country to country and are available in mixed qualities. This accounts for investment costs as well. Figure 17 plots wind and solar resource quality across European member states to point out the immense potential in some countries versus their marginal investment costs. The maximum generation potential in this case refers to the quantity of generation that can be built within a country by using up all suitable locations. The investment costs may be understood as the costs for an additional increment of one Megawatt hour (MWh) added on top of existing capacities. The scatter states in rather direct manner, that trade across country borders would be beneficial to exploit the potential of renewable energies built-up where they are most profitable.

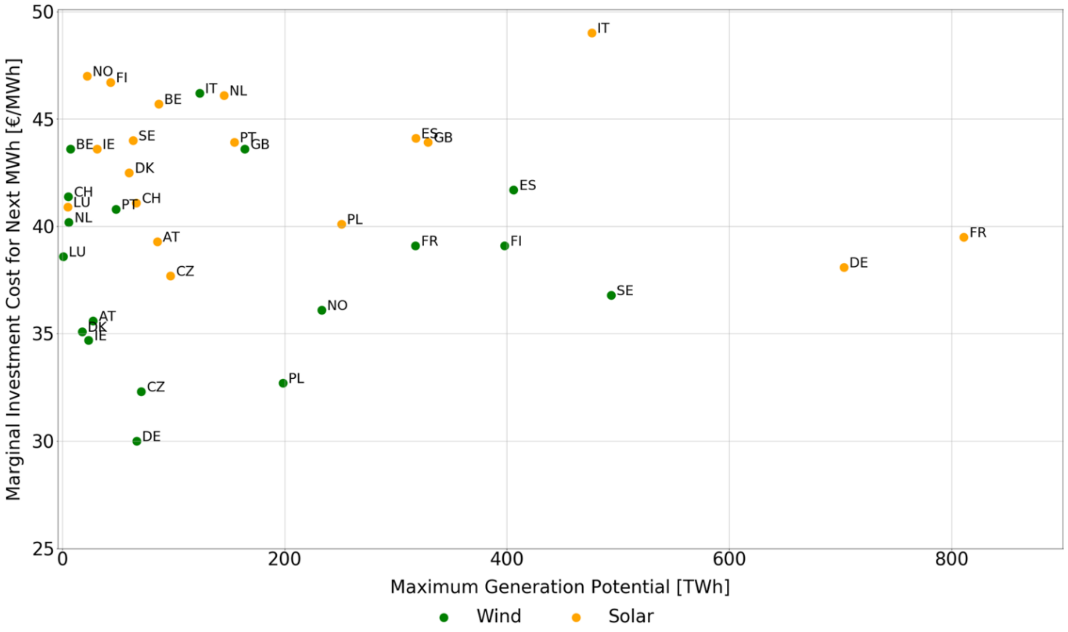


Figure 17: RES quality by EU country: Marginal investment costs of expanding RE generation and maximum RE generation potential[46]

Description of the modeling approach

The model approach is based on the principle of the social planner's problem. Generally speaking, it tries to maximize consumer welfare while meeting set technological constraints.[47] Applied to the flexibility study, it aims for minimizing costs while increasing high shares of iRES-e in total electricity generation. The model is based on hourly time steps and therefore computed over 8760 increments to include seasonal changes and the availability of renewables across an entire year. Model regions were connected, but transfer capabilities limited for trading. Besides that, the model captures curtailment of iRES-e for grid shortages, iRES-e investments, and storage technologies. In total 18 European countries were covered with underlying data from 2017. Further, the framework enables to examine whether the additional flexibility in the EU power systems impacts CO_2 emission levels.

---

[46] Source: Abrell, J. et al. (2021), p. 4.

[47] Cf. Williamson, S. (1999), p. 6 f.

Conceptual framework

The whole concept is based on a specific terminology for variables for certain technologies or other relevant measures considered by the framework. The following list provides explanation to the terminology:

$i \in I$	dispatchable technologies
$r \in R$	generation from iRES-e
$s \in S$	storage technologies
$t \in T$	time period
$c \in C$	regions

The mathematic interrelations across the variables used to evaluate flexibility within this study will be stated and explained in following paragraphs. If not explicitly highlighted differently, those formulas are based on ABRELL, J. ET AL. (2021).[48]

According to the formulated social planner's approach, price-inelastic demand must be supplied at the lowest cost C^{tot} possible to meet the target for electricity generated from RES-e and additionally constraints B. This context is formally stated in Equation 3:

Equation 3: Formal mathematic statement to define the model approach

$$\min_{Q} C^{tot}(Q) \quad s.t. \quad B(Q),$$

with Q being a vector covering the quantity variables to be considered. Those variables include conventional hourly generation X, trade T, yearly renewable generation G, storage level S, energy release form storage P, energy injection into storage J and curtailment C.

The sum of investment costs for newly added RES-e capacity C^{inv} and the cost for electricity generation C^{gen} gives the total costs C^{tot} (see Equation 4):

Equation 4: Sum of total costs

$$C^{tot} = C^{gen} + C^{inv}$$

Power generated by conventional plants X_{ict} is considered as such, that the model prevents the generation from exceeding available capacity in each time step (see Equation 5):

Equation 5: Generation and investment conventional

$$\alpha_{ict}\bar{k}_{ic} \geq X_{ict}\,, \quad \forall i, c, t\,,$$

Where α_{ict} preconceives any sort of down-time of generation due to maintenance and $\bar{\mathrm{k}}_{\mathrm{ic}}$ designates the installed capacity in region c, technology i and time t. For renewable generation the term G_{rc} is used for additionally added quantities per year to add-up existing capacity of RES-e generation $\bar{\mathrm{r}}_{\mathrm{rc}}^{\mathrm{tot}}$ per year. The sum of both cannot be higher than the feasible potential π_{rc} for each region c and technology r (see Equation 6):

---

[48] Cf. Abrell, J. et al. (2021), pp. 8-11.

Equation 6: Generation and investment RES

$$\pi_{rc} \geq \bar{r}_{rc}^{tot} + G_{rc}\,, \quad \forall r, c$$

For the sake of system stability, the planner is able to curtail generated electricity to ensure balancing of the grid. The curtailed energy C_{rct} is capped to the total amount of RES-e being produced at that time multiplied by α_{rct}, a factor considering resource availability (see Equation 7):

Equation 7: Curtailment

$$\alpha_{rct} * (\bar{r}_{rc}^{tot} + G_{rc}) \geq C_{rct}, \quad \forall r, c, t$$

Trade volume $T_{cc't}$ from one region c to another region c' at a certain time t, is limited by the net transfer capacity $v_{cc't}$ between two regions. This correlation is stated in Equation 8:

Equation 8: Trade volume

$$v_{cc't} \geq T_{cc't}, \quad \forall c, c', t \quad \mathit{and} \quad c \neq c'$$

Adding storage, three measures have to be considered: the capacity of the storage itself $\bar{\mathrm{k}}_{\mathrm{sc}}^{\mathrm{S}}$, the capacity to inject energy $\bar{\mathrm{k}}_{\mathrm{sc}}^{\mathrm{J}}$ and the capacity to release it back $\bar{\mathrm{k}}_{\mathrm{sc}}^{\mathrm{P}}$. The quantity variables J_{sct}, S_{sct}, and P_{sct} associated with those constraints thus cannot exceed those levels at all times t according to Equation 9:

Equation 9: Electricity storage

$$\bar{k}_{sc}^{J} \geq J_{sct}, \quad \forall s, c, t$$
$$\bar{k}_{sc}^{S} \geq S_{sct}, \quad \forall s, c, t$$
$$\bar{k}_{sc}^{R} \geq P_{sct}, \quad \forall s, c, t$$

Storage technologies must be modelled with time consistency between every time step t. To ensure that, a law of motion is applied which explains that a time t, the storage level S_{ct} depends on the storage level of the previous time step t – 1, the injected and released energy (and, in case of hydro reservoirs, the natural water inflows φ_{sct}). This law reads in Equation 10 as:

Equation 10: Law of motion for storage

$$S_{sc(t-1)} + \eta_{sc} * J_{sct} - P_{sct} + \varphi_{sct} = S_{sct}, \quad \forall s, c, t\,,$$

with η_{sc} being the roundtrip efficiency capturing losses within the storing cycle.

The framework defines a renewable energy policy, that incorporates targets for the quantity of iRES-e developments in both:

1. all modeled regions within the study
2. one specific region

The mathematic scheme of this policy target is illustrated by Equation 11 and Equation 12:

Equation 11: RES policy target for one region

$$\sum_{r}\left(\bar{r}_{r,c}^{tot} + G_{r,c} - \sum_{t} C_{rct}\right) = \tau_c, \quad \forall c$$

Equation 12: RES policy target for all regions

$$\sum_{r,c}\left(\bar{r}_{r,c}^{tot} + G_{r,c} - \sum_{t} C_{rct}\right) = \tau$$

Measuring economic benefits

The actual economic benefits calculated by the model take all values from the explained conceptual framework into account to conclude to a concrete set of economic benefits. Those benefits are measure by sectoral surplus W_c in each of the regions considered. Benefits gained from trade Γ_c between the regions is calculated as the subtraction of export minus import. Storage profits Φ_c were gained when energy is stored in at low prices and released at higher prices – as is the process of arbitrage trading. The difference of obtained green permits as a result from high shares of RES-e production in a region and permits that a region has to hold given by the quota policy, is considered to be the income from permit trade Π_c. In terms of congestion management between regions, the model relies on empirical assumptions, because of the unclear rules of procedure of transmission system operators (TSOs). It is assumed, that the profits Ξ_c are split between neighboring countries. The sum of economic benefits per region W_c resulting from those calculations can be described as the sum of storage profits Φ_c, congestion rents Ξ_c, gains from trade Γ_c and income from trading permits Π_c lessen total costs C^{tot} (see Equation 13):

Equation 13: Economic benefits by sectoral surplus

$$W_c = \Gamma_c + \Phi_c + \Xi_c + \Pi_c - C^{tot}, \quad \forall c$$

2.4 Qualitative values of flexibility

Alongside with all those quantitative (technical and economical) characteristics of flexible assets, flexibility services and challenges that evolve with comprehensive deployment of iRES-e capacities mentioned by the frameworks described in Chapter 2.3, there are additional characteristics of rather qualitative origin. Qualitative values of flexibility in a more macroeconomic understanding may have influence on a wider group of involved parties, the public or public investments, country-specific independencies and many more aspects. A selection of such values that are explicitly important to the society are listed within the following paragraphs.

2.4.1 Realization of RES targets

The example of Austria shows, that accompanying targets on European level, the domestic government can nevertheless lead the way and set an even bolder goal: to reach 100% electricity production from renewables by 2030. As we have seen above, this brings challenges in various types. The frameworks explained in Chapter 2.3 suggest different pathways to meet system flexibility, but despite the specific execution method – it might be a set of options – the value that comes along with this integration of flexibility services, is the actual enabling of building a sustainable energy system that may be running entirely on green energy in the not-so-distant future. To reach climate-neutrality, this extensive cutting of CO_2 emissions induced by the electricity transformation is urgently needed. Flexibility thus can contribute to solving the emissions issue.[49]

2.4.2 Reduction of grid expansion needs

Investments in cables and grid lines are heavily capital intensive, thus building new infrastructure undergoes a complex process until its realization. The transmission system operators (TSOs) as well as distribution grid operators (DSOs) are constantly working on the improvement and reliability of grids in projects that have duration of, in some cases, several decades. Some could be tempted to say, that the processes within those projects are inefficient or even outdated. As our electricity systems are changing at a very high speed, it may occur that the anticipated benefits of a newly commissioned grid element could not defend the underlying investment. To cope with the ever-growing capacities of intermittent renewable energy sources being added to the grid, system flexibility could counterbalance congestions in many incidents. This may lead to non-justifiable grid investments that may be spared. As grid investments and infrastructure projects are developed and performed by TSOs or DSOs, which are mainly state-owned companies, the incurred costs are covered by some sort of payback mechanism. The qualitative value of flexible assets in this case can be measured by the reduction of public spendings for infrastructure.[50]

2.4.3 Achieving energy independency

Global supply chains are complex, interlinked, and interdependent processes. Considering the energy sector, this interlinkage can be found as well, but due to the various resource types, the delivery channels are mostly independent form each other. This accounts for oil, gas, but especially for electricity. In fact, consumers today need a combination of energy resources such as gas for heating, electricity for powering devices at home and a third source of energy for transportation. The point of this is, that in a transforming scenario, where the future energy system will be built strongly on renewable sources, the supply chain has to be rethought as the IEA pictures in Figure 18 and Figure 19. The path of suppliers to consumer will change and accordingly the infrastructure and the way energy is handled will adapt to that. Some established infrastructure will not be fundamentally different from future infrastructure, while gaseous resources and liquids will remain a major player in the future to store and puffer energy or even turn some processes around: as gases (e.g. natural gas) have been transformed into electricity, electricity might be utilized to be transformed into gases (e.g. hydrogen). This offers

---

[49] Cf. Suna, D., Totschnig, G., et al. (2022), p. 1 f.

[50] Cf. Migliavacca, G., Rossi, M. et al. (2021), p. 2.

various options to store and provide flexibility to the system. As flexibility is more and more being considered and valued as a strong contributor to establish system stability, it is a main driver to succeed with establishing energy independency for countries with low or zero fossil resources vis-à-vis fossil fuel exporting countries.[51]

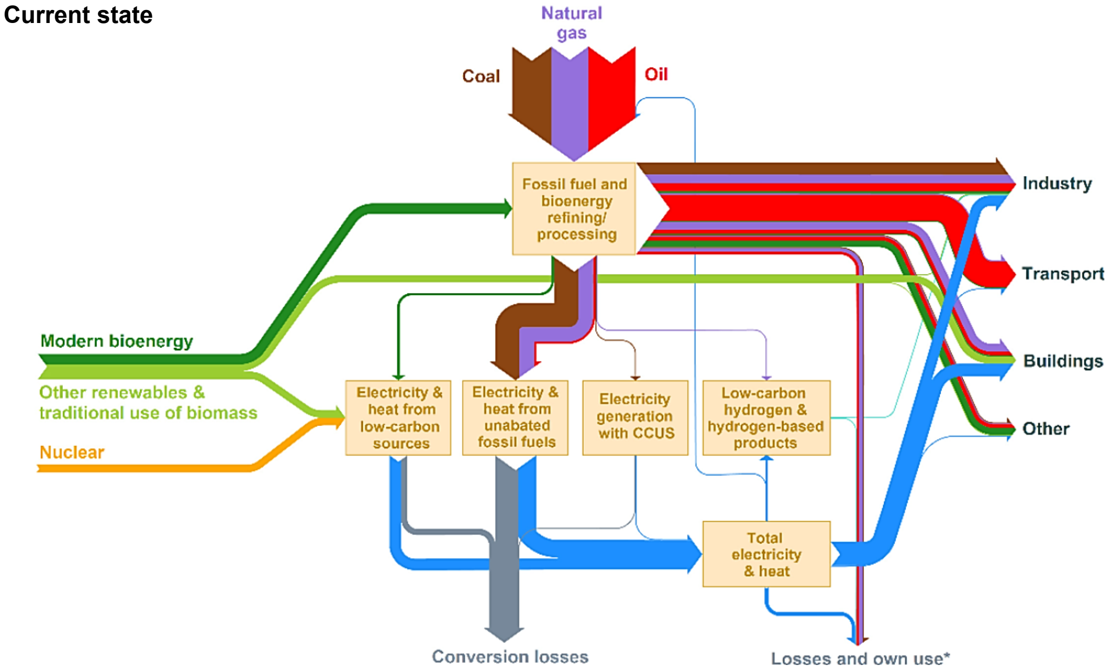


Figure 18: Current global energy system[52]

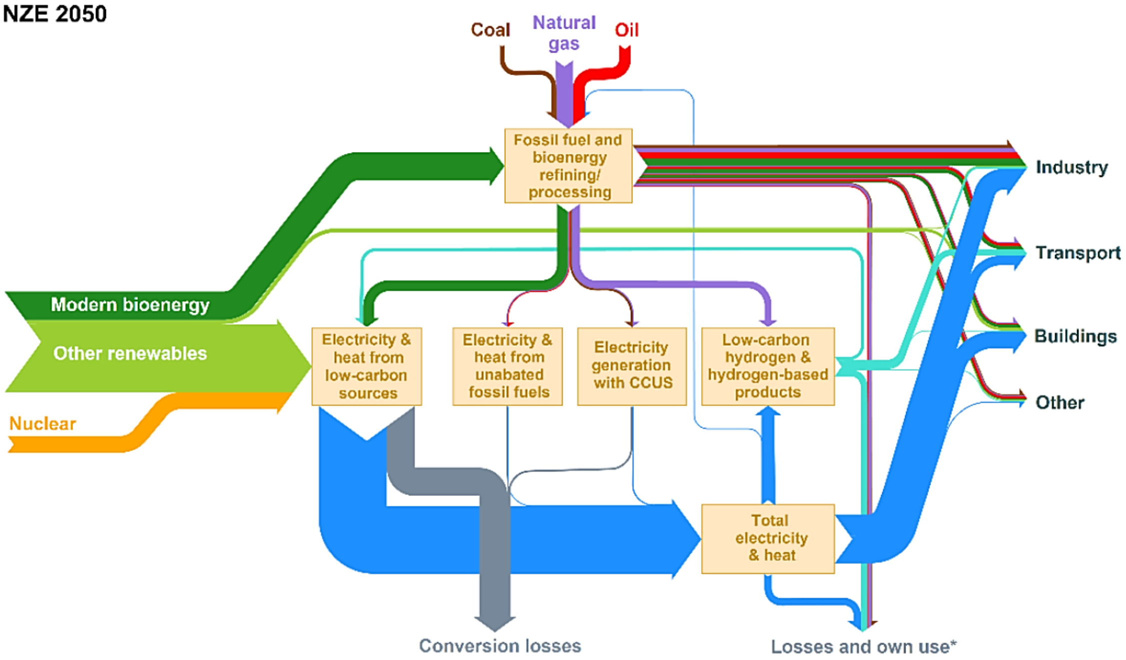


Figure 19: Global energy system in the NZE Scenario by 2050[53]

---

[51] Cf. International Energy Agency (2021), p. 250.
[52] Source: International Energy Agency (2021), p. 251.
[53] Source: International Energy Agency (2021), p. 251.

3 Regional framework for flexibility evaluation

This thesis is focusing on the evaluation of regional flexibility needs, potential business cases and the effects locally installed flexible assets have or could have on the public sector, especially the necessity of grid connection. Building on the results of comprehensive literature research and its description of flexibility related characteristics, this thesis seeks to develop a framework and to determine the value of power flexibility within regional boundaries. The framework is intended to provide a generic process, applicable to regions with different circumstances and demographics. For this reason, it is crucial to create a template that provides the ability to be adjusted to yet to be defined parameters.

As a first, very important, step it must be defined what 'regional' stands for, as this is not unified in the literature. Despite some other definitions, this piece of work considers a region to be a scalable demographic and geographic territory. The size of the region can be adjusted by the number of households, heavy industry, and small- and mid-sized enterprises (SMEs). The region can be covering a village or be scaled-up to a county or province. Every region has differing possibilities in terms of RES-e capacities, considering the geographical effects of solar radiation and wind speeds.

3.1 Dimensions of regional flexibility

The comprehensive literature research, carried out earlier in this thesis showed, that a very simplistic, but still holistic view on flexibility in power markets is provided when looking at three dimensions of flexibility in general. Those dimensions are designed to describe cross-country flexibilities across markets and grid lines, but there is a lot in this perception to learn from for regional areas. Following the research from ABRELL, J., ET AL. (2021), the next paragraphs try to explain those suggested dimensions on a regional level:[54]

3.1.1 Space

The scene around spatial flexibility is renewed for a regional area comparing it to cross-national flexibility systems. Interconnectors provide capacities for transporting and balancing electricity over longer distance. Not only does it help to balance congestions as a consequence of forecast errors caused by dramatic incidents in weather patterns, but the interlinkage between markets also increases trade volume at the electricity exchanges and provide the market with the ability to balance shortages while asset optimization is possible. Most of this is not required or yet not possible on a regional level. Nevertheless, there are other implications joining the discussion. Local flexibility, in the context of space, tackles the topic of interconnectivity of households, industry, and

---

[54] Cf. Abrell, J. et al. (2021), p. 2 ff.

other consumers. The question for a future energy system is, whether local balancing on a way smaller scale can have impact on the need for grid developments across longer distances. There is already research that tries to answer this question of flexibility impact on grid infrastructure on the existing, continental European energy system. With this thesis, the effects of reducing grid requirements through local balancing shall be evaluated.[55]

3.1.2 Time

The time dimension addresses all kinds of effects various technologies may have on the energy system. The major issue here is that in an iRES-e-dominated system, there is quite some mismatching of demand and supply curves, especially when looking on daily curves. This can be understood as a challenge, but also as potential. At the forefront, the divergence may be addressed by any kind of storage technologies. The characteristics decide whether technologies are suitable for flexibility services or not. This also depends strongly on what the local system requires the most. Ramping-up quickly, may be a strong advantage, but pooling of natural resources and storing energy over time might even be more critical to the system. Nevertheless, the in the course of this thesis suggested framework to evaluate flexibility needs, shall be able to answer this question later on.

3.1.3 Regulatory

Regulatory influence on the development of technologies can be acknowledged by looking back on the developments in RES-e or electric vehicles or other technologies to be boosted towards a sustainably working society. One example is given in Figure 20 for wind energy developments in Austria. Through subsidy schemes installed in 2002 a boom was triggered. But as fast as numbers grew back then, the rush was over after 2006, when the public funded subsidies were cut down. Similar effects can be seen later in the years of 2017 to 2021. Using this figurative example, the impact of subsidies on investment in a particular technology can be established beyond doubt.[56]

Figure 17 and its description in Chapter 2.3.3 already stated the differences across countries in terms of their investment costs for technologies such as wind power and solar PV. Thus, some countries need to provide way more subsidies than others. Taking this issue to the local level, it might not seem to be big of a deal. But not only RES-e developers on a big scale are concerned about public funding. For households as well as industry companies, subsidies affect the economics of their investments and may drive decisions as such. Addressing flexibility options on a local level, capacities and the availability of load management is reliant on private engagement. Incentives and well-established procedures enforced by public entities and regulators could drive developments in opportune areas to leverage local effects. The regional framework formulated in the following aims to evaluate those effects on a regional level.[57]

---

[55] Cf. Migliavacca, G., Rossi, M. et al. (2021), p. 2.

[56] Cf. IG Windkraft, https://www.igwindkraft.at/?xmlval_ID_KEY[0]=1045, (Zugriff: 04.10.2022).

[57] Cf. Migliavacca, G., Rossi, M. et al. (2021), p. 2.

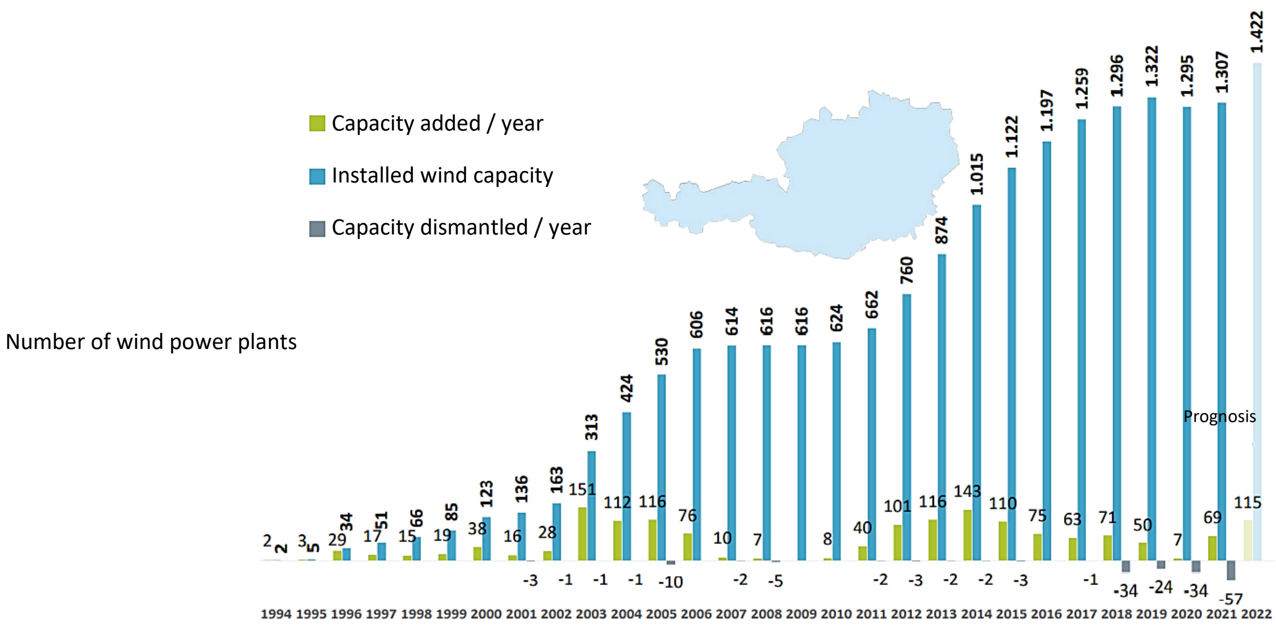


Figure 20: Development of windmills by numbers and year in Austria[58]

3.2 Adaptation of cross-country approaches for regional purposes

As far as the here conducted research shows, there are frameworks developed for continental assessment of flexibility needs, such as the European Union, considering its benefits of leveraging different weather patterns across countries via transmission.[59] Other frameworks are focusing more on trade and the exploitation of the market mechanisms to provide flexibility to the grid whilst optimizing the economics of assets.[60] On the opposite side, there are some techno-economic calculations thought through for households and smaller RES-e and storage investments.[61] All of those are guiding the process towards a sustainably powered electricity system.

As it was outlined before, this thesis tries to close the gap between the nation-wide analysis of flexibilities and the household-specific approaches. Nation-wide or on a continental scope, market mechanisms and large to very large power plants as well as storage facilities on big scale are considered within the analysis. On the household approach, the focus is clearly on the people themselves, optimizing their spending and costs of powering a household or in some cases additionally an electric car. By establishing a regional approach, it shall be possible for municipalities, larger groups of people in any kind of communities or also quite decentralized, more rural areas, to evaluate their potential to not only develop the best fitting energy system for the locals, but also considering aspects to improve the overall functioning of an interconnected energy system.

---

[58] Source: IG Windkraft (2022), p. 9.

[59] Cf. European commission, Directorate-General for Energy (2019), p. 1 ff.

[60] Cf. Goutte, S., Vassilopoulos, P. (2018), p. 1 ff.

[61] Cf. Abrell, J. et al. (2021), p. 1 ff.

3.2.1 Methodology to design a regional framework

As we have learned from the literature, the evaluation of flexibility needs is most practical via a systematic step-by-step approach. One way to establish a portfolio of flexibility solutions is suggested by the EUROPEAN COMMISSION[62] pictured in Figure 4. While this approach considers the wide scope of all European countries, same adaptions could be necessary to reformulate the structure meeting the requirements of a regional framework. Building on the fundament provided by the EU COMMISSION, the following (see Figure 21) approach is suggested to use within this thesis:

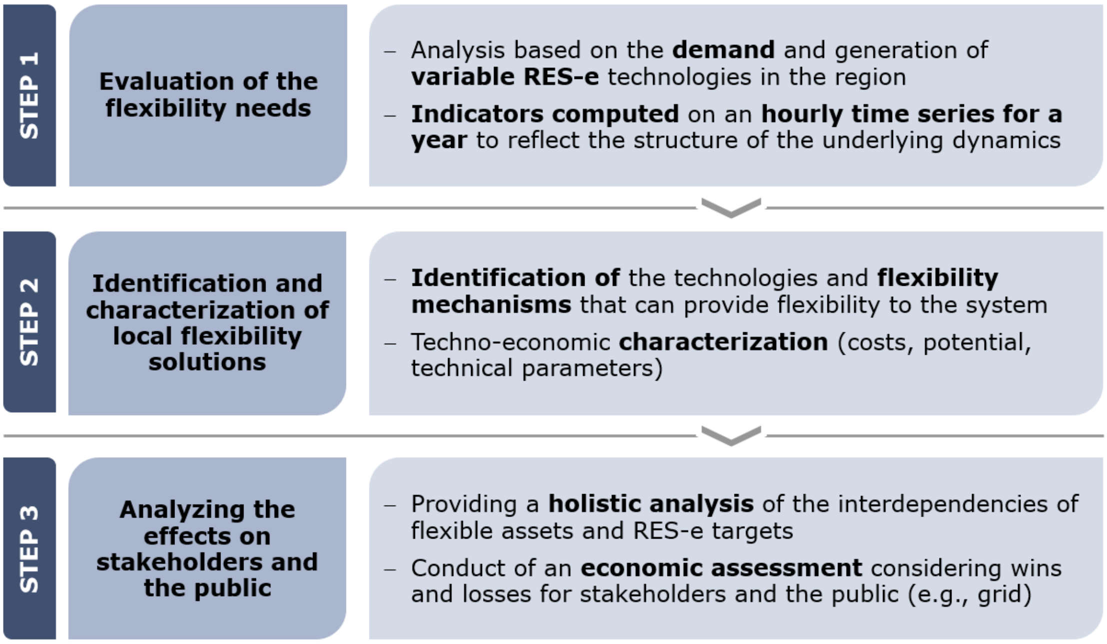


Figure 21: Framework for the evaluation of regional flexibility[63]

<u>Step 1: Evaluation of the flexibility needs</u>

The first step to evaluate flexibility is to identify reliable data sources. There are characteristics (e.g., solar PV generation) that need to be provided as time-series in a certain resolution. Others, like demographic input about the region, can be stated in form of static numbers. Depending on the location of the region on the planet, a number of sources could be addressed, such as research institutes, national statistics, governmental reports, data from TSOs/DSOs (if publicly available). Those characteristics and the required resolution in time are listed in Table 2.[64]

---

[62] Cf. European commission, Directorate-General for Energy (2019), p. 19.
[63] Source: Own illustration based on European commission, Directorate-General for Energy (2019), p. 19.
[64] Cf. European commission, Directorate-General for Energy (2019), p. 25 ff.

Table 2: List of characteristics

Characteristic	Time resolution
Demand profiles of: - Households - Heavy Industry - SMEs	hourly
Solar PV generation	hourly
Wind generation	hourly
Run-of-river hydro power generation	hourly
Quantity of households	static
Quantity of heavy industries	static
Quantity of SMEs	static

Using those measures, a first modeling can be computed on the evaluation of flexibility needs. For the actual determination of the flexibility needs on a regional level, the approach described in Chapter 2.3.1 is acknowledged fitting, with some adjustment. According to an Austrian research team, adding a dimension of 'monthly flexibility needs' is useful to close the gap between a weekly analysis and the annual. Monthly evaluation improves the results considering a broader spectrum of weather patterns.[65] Flexibility needs are then computed by the model on a daily, weekly, monthly, and annual basis.

Step 2: Identification and characterization of local flexibility solutions

Local flexibility solutions differ from the one's available for a broader system. For this reason, the following section states those flexibility options that are possibly available for local energy systems. As it was said in the introduction of Chapter 3, the regional approach aims to be a generic approach, that can be applied on any kind of energy system within a country and as such, no technological options shall be excluded even though, not all of them are applicable everywhere.

This list provides a number of flexibility options to be considered when assessing energy systems on a regional level, trying to meet the modelled flexibility needs. The options listed below are a selected choice from the following stated sources, if not explicitly stated differently:[66;67;68]

---

[65] Cf. Suna, D., Totschnig, G., et al. (2022), p. 5.

[66] Cf. European commission, Directorate-General for Energy (2019), pp. 27-31.

[67] Cf. Abrell, J. et al. (2021), p. 7 f.

[68] Cf. Suna, D., Totschnig, G., et al. (2022), p. 4.

- **Flexible generation technologies**: such as thermal power plants or combined heat and power plants, which can be fired by various fuels (natural gas, waste, biomass.
- **Storage**: as versatile technology with extremely different compositions and scientific principles has a wide range of applications as flexibility provider. A few rather popular and widespread technologies are listed below, with no claim to represent all fitting technologies, but being the ones most commonly deployed.
    - Pumped hydro storage plants
    - Lithium-Ion batteries
    - Compressed air energy storage
- **Demand-response**: as an overarching synonym for technologies or systems which are able to modify their consumption/demand according to external incentives. For the provision of flexibility solutions in local energy systems, those options are considered useful:
    - Load management via Power-to-Heat (P2H), using heat pumps and electric boilers in centralized as well as decentralized buildings
    - Electromobility (E-Mobility)
- **Curtailment**: providing flexibility in a rather inefficient way, curtailing energy that cannot be handled by the grid to assure stability and voltage quality for consumers.
- **Power-to-Gas (Hydrogen)**: Electrolysis and its ability to consume excess electricity created by RES-e can provide flexibility in a more economic and grid-supporting way than curtailment.
- **Bilateral/multilateral trading**: between two or more entities (e.g. households) provides flexibility by smoothing-out local congestion and providing a business case to the two parties involved. This is dependent on the national regulatory conditions.
- **System-friendly RES-e technologies:** built-up to shift generation profiles from solar PV by installing the panels in different angle and orientation to the sun.

To provide a comprehensive data set of flexibility options for the modeling, some techno-economic parameters of those options listed above must be defined or found in literature. Those parameters include:

- Investment costs
- Costs according to maintenance and operation
- Actual potential (according to the definition in Table 1)
- Fuel costs (not applicable to all options)
- CO_2 intensity (not applicable to all options)
- Efficiency of the technology (not applicable to all options)

Other constraints like ramping rates, availability, discharge time, minimum and maximum of stable generation, off- and running-times as well as environmental constraints are very technology specific and have to be evaluated for each flexibility option separately.[69;70]

---

[69] Cf. Esterl, T., Resch, G., Von Roon, S., et al. (2022), p. 8.

[70] Cf. European commission, Directorate-General for Energy (2019), pp. 27-31.

Step 3: Analyzing the effects on stakeholders and the public

Bringing the data to the model, the framework to evaluate flexibility on a regional basis suggests computing scenarios with the underlying demand profiles, the RES-e generation data and integrate the techno-economic parameters for the flexibility options available in the region defined. Averaged weather patterns across a number of weather years may smooth out the fluctuation characteristic within a year. To cover hiccups and outliers within the evaluation of flexibility, single weather years are suggested.

A qualitative analysis of the effects on stakeholders and the public can be carried out through using the outputs from the calculations. Evaluating the impact of specific flexibility options isolated, may provide insights into which direction the investments from stakeholders and public entities of a defined region should lead.

3.3 Additional factors and implications for a regional flexibility system

Differences between regional and national energy systems could be broken down via grid levels. The transmission system operator is responsible for operating the highest voltage level (380 Kilovolt (kV) /220kV) and as such providing interconnection across countries. The distribution system operators take over all voltage levels below to transform and distribute electricity to end-consumers. Consumers on lower grid levels such as households will have to contribute to cope with the surging flexibility demand. Therefore, concepts for flexible tariffs for consumers as well as the regulatory framework for implementing regional bilateral or multilateral trading concepts have been discussed and implemented. The exact effects of those policy measures on grid utilization are yet to be investigated.[71]

Grid connection is needed to balance energy systems and provide consumers with electricity. Another aspect of this thesis will be the evaluation of the effects on the ‘grid necessity’ on a local level. It is not within the scope to simulate any grid flows, but grid connection between stakeholder in the system is considered as given. As an assumption for the evaluation of the local system, shifting loads from one household to another is possible and not considered as a grid service, while positive residual loads (consuming energy from the grid) caused by high demand that cannot be covered by RES-e generation, are considered as a grid service. The same accounts for negative residual loads resulting in grid delivery or curtailment.

The regional framework and the calculation carried out by this thesis in Chapter 4 tries to evaluate the effects of different RES-e scenarios and storage technologies on the grid, local flexibility needs and the economics of residential storage investments.

---

[71] Cf. Österreichs Energie (2020), p. 4 ff.

4 Economic evaluation of regional energy flexibility

This section challenges the regional framework formulated above as well as the aggregated knowledge from the literature. Through this, the thesis tries to contribute to the evaluation of flexibility in regional power system through a scenario and sensitivity analysis. It is not the claim of this work to come up with a detailed modeling of all kinds of technologies and measuring the interoperability between single participants in the system across time. The scope of this thesis includes a holistic evaluation of a regional system, its flexibility needs in different iRES-e scenarios, investments in storage technologies and their economic feasibility. Following this evaluation, some implications and insights are to be created to determine the value of flexibility in an economic and societal dimension.

4.1 Inputs and data

The first step in the process to evaluate flexibility, is collecting some data. Consumer demand profiles, data-series for solar PV and wind power generation on hourly resolution, but also demographic input must be clarified to model scenarios. The evaluation in this thesis focuses on an exemplary region of a specific size, that can be adjusted for bigger or smaller regions for future developments of this framework.

4.1.1 System boundaries and conditions

As the framework in Chapter 3.2.1 suggests there are basically three clusters of demand centers in a region: households, industry and small- and mid-sized enterprises. The approach is adapted for this case to solely consider demand profiles of households. It has been decided to focus on households only, because the demand profiles of industries are highly different between regions. This work shall not be biased by any kind of extreme situation but deliver an estimation that gives a feeling for the need and potential of regional and decentralized systems. The system boundaries for the considered case of this thesis were set for a small city in Austria with 3000 households.

4.1.2 Definition of different scenarios

Considering the suggestions from literature to evaluate flexibility built on the assessment of residual load, which refers to the subtraction of iRES-e from the demand. Run-of-river hydro, solar PV and wind power are meant by iRES-e as it can be seen in Chapter 3.2.1. As run-of-river power plants require specific geographic circumstances and natural resources that are not available in certain areas, it will not be taken into account in this evaluation. Three scenarios are defined to investigate in the course of this thesis:

- **Scenario 1 - Solar PV-dominated system**: The demand from households in this scenario is solely met by solar PV generation or delivered from the grid. Energy from the grid is formulated as a positive residual load throughout the whole evaluation. It shall be an indicative analysis to investigate the effects of solar PV-dominated electricity supply patterns on flexibility needs.
- **Scenario 2 - Wind power-dominated system**: The demand from households in this scenario is solely met by wind power generation or delivered from the grid. Energy from the grid is formulated as a positive residual load throughout the whole evaluation. It shall be an indicative analysis to investigate the effects of wind power-dominated electricity supply patterns on flexibility needs.
- **Scenario 3 - Combined wind & solar PV powered system**: This scenario provides generation from wind and solar PV to meet the demand from households. As above, if demand exceeds the amount of RES-e generated, the residual load is positive and requires electricity from the grid. The analysis focusses on the effects solar PV patterns have on wind generation profiles and whether it improves or worsen to flexibility needs within a regional system.

4.1.3 Data sets and technology characteristics

To assure that the modeling in Chapter 4.2 concludes to reproductive and accurate results, data must be researched carefully. The data that is used within this thesis is taken from publicly accessible sources and represent the most recent available data sets. The following chapters will describe the chosen data and its sources, including demand time-series and RES-generation time-series given on an hourly basis. Further characteristics of storage technologies, various residential electricity price tariffs and levelized cost of energy for solar PV and wind are needed for the calculations. All of those categories will be explained in the following:

- **Demand time-series**: The source for the demand time-series for households are taken from BUNDESVERBAND DER ENERGIE- UND WASSERWIRTSCHAFT E.V., (BDEW) which are commonly used by utilities to depict the demand from their customers and compute forecasting. The demand-series offered by the source are spread across the different consumer groups. In this case 'standard load profile H0' is taken what states the standard profile for households with an average yearly consumption of 1000 Kilowatt hours (kWh). Those profiles are split into three time categories and additionally separately calculated for Saturdays (see Figure 22) , Sundays (see Figure 23) and working days (see Figure 24). The exact values can be found in the Appendix.[72]

---

[72] Cf. BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., https://www.bdew.de/energie/standardlastprofile-strom/, (Zugriff: 05.10.2022).

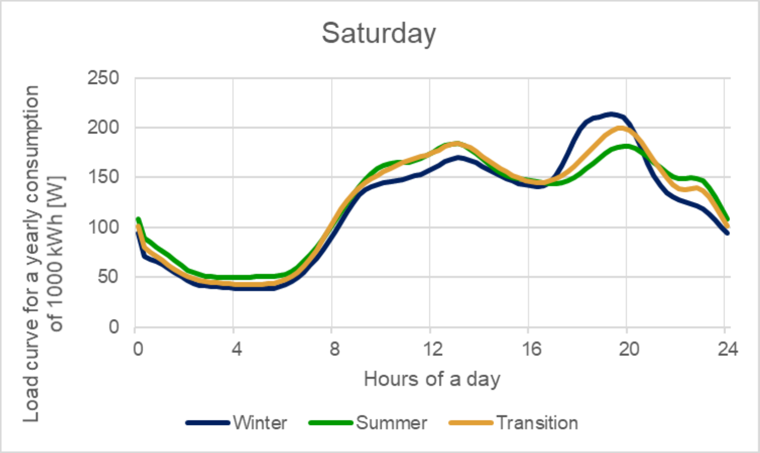


Figure 22: Load curves for households on Saturdays[73]

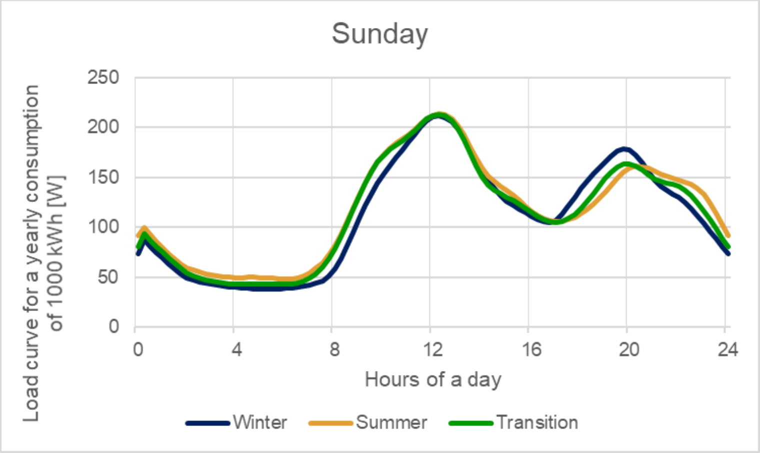


Figure 23: Load curves for households on Sundays[74]

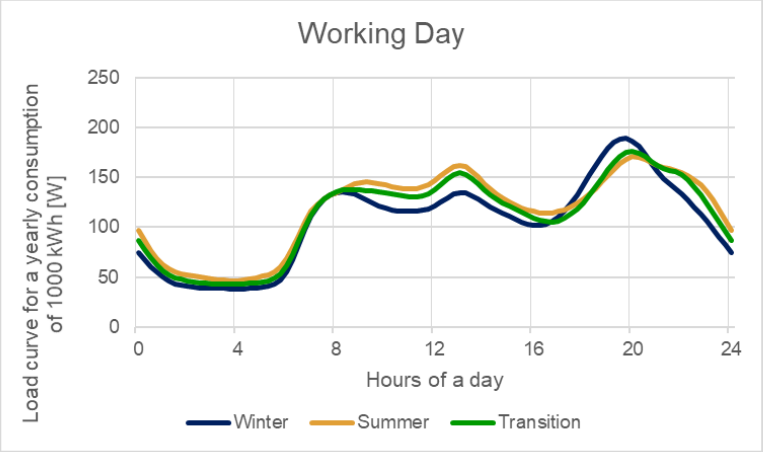


Figure 24: Load curves for households on working days[75]

---

[73] Source: Own illustration based on Fünfgeld, C., Tiedemann, R. (2000), p. 8 ff.
[74] Source: Own illustration based on Fünfgeld, C., Tiedemann, R. (2000), p. 8 ff.
[75] Source: Own illustration based on Fünfgeld, C., Tiedemann, R. (2000), p. 8 ff.

- **Solar PV generation data**: The European Commission developed a tool to provide solar PV generation data for any latitude and longitude on earth. The access to the data base is open source and has a set of inputs that can be pre-qualified for the data excerpt. Inputs defined for the solar PV generation profiles are stated in Table 3:

  Table 3: Inputs for the solar PV data set

Characteristic	Input
Latitude	46.893
Longitude	15.521
Slope	40 degree (optimum)
Azimuth	-4 degree (optimum)
Nominal Power of PV system	1 Kilowatt peak (kWp)
System losses	14%
Year	2020

  The downloaded data set from the EU SCIENCE HUB with the inputs from above provides an hourly time-series of electricity generation in Watts relative to the nominal power of the chosen PV system.[76] For the flexibility evaluation on a regional level, the data form only one year is used and not averaged across several weather years to include every uncertainty in the analysis. Averaging more years would smoothen the data and might reduce noise and fluctuations impacting the results. This data will further be prepared for the modeling and extended with the capacity defined for the scenarios. As this analysis builds on the aggregation of small-sized solar PV plants designed for one household or a small community, 5 kWp (five Kilowatts at peak performance) is defined to be the standard solar PV plant.

- **Wind power generation data**: The case of wind power generation has to be treated a bit differently. Wind speeds are very much dependent on the surface structure and the hub height of a power plant. Within the research for this thesis, it was not able to find a data set on an hourly level that provides generation of wind power to scale it to built-up plants as it was doable for solar PV. Nevertheless, other researchers tried to assess wind power across Europe and calculated an average load factor on an hourly basis using a power curve for the different wind farms in a country, e.g., Austria. With this average load factor it is possible to compute the amount of generated electricity from wind by defining the installed capacity in a region. As it is not that easy to build a wind farm in someone's backyard, the approach for wind is a bit different than for solar PV. The capacity of one wind power plant built in the model is defined as 3 MW.[77]

---

[76] Cf. EU Science Hub, https://re.jrc.ec.europa.eu/pvg_tools/en/, (Zugriff: 05.10.2022).

[77] Cf. Gonzalez Aparicio, I., Zucker A., et al. (2016), p. 14 ff.

- **Storage technologies**: The model set-up for this thesis considers Lithium (Li)-Ion battery storage as available technology to store electricity temporarily and release it back again, when needed. As this model aims to simplify the process to not exceed the computation efforts of the thesis, Li-Ion batteries for households are dimensioned according to an up-to-date market research. This research includes 16 different battery electric storage (BES) systems which are available in 2022. Those BES systems were averaged in terms of power and duration of discharge concluding with an average battery with the following specifications (see Table 4):

Table 4: Specifications for an average Li-Ion battery storage system

Specification	
Capacity	10,3 kWh
Charge-/Discharge power	6,1 kW
Discharge time	1,7 Hours (h)
Price	994 €/kWh

The appendix holds the detailed data according to the research for Li-Ion batteries. Table 4 states the specifications for the ‘standard battery’ proxy used for the modeling process, where the average was built across the 16 battery packs form different manufacturers and similar sizes. The capacity stated above is the actual usable capacity already considering the duration of discharge of the investigated battery technologies.

- **Tariffs**: This section describes the various tariffs that are used to model the economic value of flexibility investments. The defined system for this thesis is a regional, decentralized area with a specific size as defined earlier. To evaluate flexibility within the system, but also effects on the connected grid as well as the economics of investments into flexible assets, it is needed to define who pays what and how much the price is for electricity distributed within the system boundaries but also beyond. There are three different types of tariffs needed:
    - **Tarif for grid supply (daytime)**: This is the price, households would pay for every kilowatt hour of electricity supplied by the grid during daytime, starting at 6 AM and lasting until 10 PM. It can be considered as the generic residential electricity price. This price (see Table 5) was taken from projections conducted by DNV AS – a Norwegian energy company - for the year 2022.[78]
    - **Tarif for grid supply (nighttime)**: This is the price, households would pay for every kilowatt hour of electricity supplied by the grid during nighttime, starting at 10 PM and lasting until 6 AM. The scenarios provided by DNV AS do not include a separate price for night hours. Hence, another source was researched to define the price during night hours. The following stated source suggests tariffs during nighttime in

---

[78] Cf. DNV AS, eto.dnv.com/forecast-data, (Zugriff: 05.10.2022), p. 1 ff.

Austria to be 0,04 €/kWh lower than daytime prices. In order to this, the price set for daytime was adjusted by that means.[79]

- **Feed-in tariff**: The feed-in tariff is the amount of revenue per kilowatt hour created by a household for feeding electricity into the grid at any given time of the year. It does not matter, whether the electricity is provided by a battery or RES-e plant. The level of the feed-in tariff suggested for this thesis has been defined by benchmarking feed-in tariffs in Austria. Table 5 gives an overview of tariffs used in this thesis.[80]

Table 5: Tariffs for electricity

Tariff	
Grid supply (daytime)	0,24 €/kWh
Grid supply (nighttime)	0,20 €/kWh
Feed-in tariff	0,09 €/kWh

- **Additional aspects**:
    - **Discount rate of investments**: According to research carried out by GARCIA-GUSANO, D. ET AL. (2016)”, the discount rate for investments in renewable energy sources shall not exceed 5%. Following this, the discount rate for the economic assessment of the flexibility evaluation will be set at 5%.[81]
    - **Average demand per household**: The average yearly electricity demand per household in Austria amounts to 4863 kWh. This is calculated by STATISTIK AUSTRIA and used in the modeling to scale the demand from the time-series stated above to a representative amount.[82]
    - **Levelized cost of energy**: To account for the investment costs of solar PV and wind power plants, levelized cost of energy (LCOE) must be considered. The levelized cost of energy is a measure of the average net present costs of an electricity generating power plant over its lifetime. Therefore, those costs are to be considered in the modeling. As data was already taken from DNV AS research, this source will also be consulted for the LCOE (see Table 6 for more detail).[83]

---

[79] Cf. Selectra SAS, https://stromliste.at/strompreis/tarifarten/unterbrechbar/nachtstrom#:~:text=In%20%C3%96sterreich%20ist%20der%20Nachtstrom,Strombedarfs%20werden%20durch%20Wasserkraft%20generiert., (Zugriff: 05.10.2022).

[80] Cf. Energie Steiermark AG, https://www.e-steiermark.com/fileadmin/user_upload/downloads/Kundeninformation_und_Preisblatt_SteirerStrom_Sonne.pdf, (Zugriff: 05.10.2022).

[81] Cf. García-Gusano, D., Espegren, K., et al. (2016), p. 1 f.

[82] Cf. STATISTIK AUSTRIA (2021), p. 1 ff.

[83] Cf. DNV AS, eto.dnv.com/forecast-data, (Zugriff: 05.10.2022), p. 1 ff.

Table 6: Levelized cost of energy per source

LCOE from source	
Solar PV	4,52 €/kWh
Onshore wind	6,83 €/kWh

4.2 Modeling flexibility demand

As it was already introduced in Chapter 3, this thesis is about to evaluate flexibility needs in a scenario analysis. This means, that a region of certain size is synthesized and set into boundaries wherein three different scenarios are being investigated – solar PV-dominated, wind power-dominated, and a mixed RES-e (solar PV and wind) -dominated system. At the core of this evaluation, a calculation model was created to determine the differences between those scenarios regarding flexibility need, how this need can be met by storage technologies, in this thesis Li-Ion batteries, and what the economics of these scenarios mean to the investors of flexible assets in that system.

The operation of this region shall not be considered as an island, not interfering with the neighboring regions, but as part of a broader energy system being connected via grid connection trying to maximize local, decentralized consumption of electricity produced via renewable energies. Enhancing the regional utilization of RES-e and battery electric storage, the model calculates the possible electricity flows within the region via an approach that aggregates technologies in the region to four major groups that interact with each other:

1. **Renewable energy sources**: Solar PV and wind power plants that, shall solely, power the region and thus play an essential role in this evaluation. It has already been stated in Chapter 4.1 , how households, solar PV and wind farms are defined. Additionally, it is important to highlight that the small-scale RES-e and wind penetration must be seen as one aggregated power plant that operates at the same input data given in Chapter 4.1.3.
2. **Storage**: For reasons of data availability and simplicity, Li-Ion battery storage systems are considered as available for the regional system modelled in this thesis. The Li-Ion BES installed in the modelled region are being aggregated to one large battery, operating with the specifications of a number of small-scale batteries for households.
3. **Electricity grid**: The public electricity grid is given to be available for the regional system to interact with, but electricity delivery into the grid (feed-in of excess RES-e production) or supply to meet the demand is considered as non-preferable. The regional system shall be modelled at the best possible rate of internal electricity flows.
4. **Consumer**: The consumer is modelled as a household with a certain standard load profile. It is possible for the household to by supplied with electricity by RES-e generation, store electricity in its own battery storage or feed-in excess electricity into the grid in hours where the battery is fully charged.

The interactions in terms of physical electricity flows between those four groups are illustrated in Figure 25:

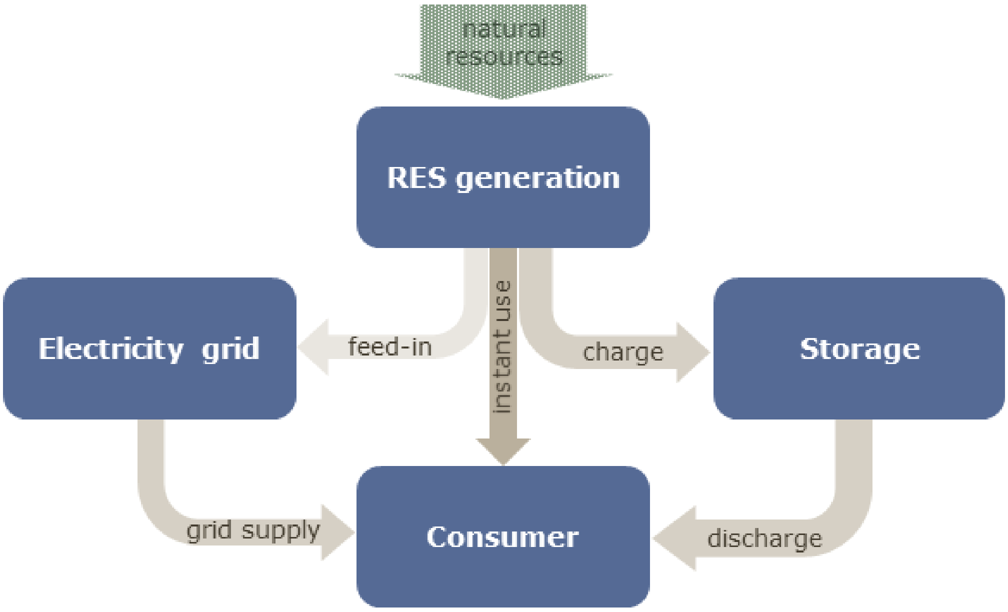


Figure 25: Flow chart for electricity in a regional power system[84]

4.2.1 Calculation logic of the model

Bringing the data to the model, a mix of the mathematical approaches of the EUROPEAN COMMISSION, DIRECTORATE-GENERAL FOR ENERGY (2019), GARCIA-GUSANO, D. ET AL. (2016) AND ABRELL, J. ET AL. (2021) is used to formulate a logic to result in the economic evaluation of local flexibility needs. Therefore, this logic will be explained in the following section, which is split in a more technical part, explaining how electricity flows are being modelled across time and an economic part, elaborating on the effects of the modeling, and translating Kilowatt hours (kWh) into a monetary value (€).

As a first step, some metrics are to be defined upfront and used in this nomenclature through the whole model. See Table 7 for the full list of metrics needed for the calculation of the regional flexibility model.

Table 7: Modeling metric nomenclature

Metric	Symbol	Unit
Load per household per hour	L_{HH}	kW
Residual load per hour	$L_{Residual}$	kW
Energy generated from solar PV per hour	E_{PV}	kWh
Energy generated from wind power per hour	E_{Wind}	kWh
Energy delivered from/into the grid at daytime per hour[85]	$E_{Grid,Day,h}$	kWh

---

[84] Source: Own illustration

[85] Daytime: 6AM-10PM

Energy delivered form/into the grid at night-time per hour[86]	$E_{Grid,Night,h}$	kWh
Storage level	St_{LVL}	kWh
Charging power	P_{Charge}	kW
Discharging power	$P_{Discharge}$	kW
Annual sum of positive daily flexibility need	FN_{D+}	MWh
Annual sum of positive weekly flexibility need	FN_{W+}	MWh
Annual sum of positive monthly flexibility need	FN_{M+}	MWh
Annual sum of positive yearly flexibility need	FN_{Y+}	MWh
Maximum power supply from grid	$P_{Grid+, max}$	MW
Maximum power delivery into the grid	$P_{Grid-, max}$	MW
Amount of fully dis-/charged battery cycles per year	C	-
Number of hours with residual load >0 annually	R^+	-
Number of hours with residual load <0 annually	R^-	-
Energy supply costs from grid (daytime) annually	$Cost_{Grid, day}$	€
Energy supply costs from grid (nighttime) annually	$Cost_{Grid, night}$	€
Feed-in revenue annually	$Rev_{Feed-In}$	€
Avoided costs through stored energy annually	$AvCost_{Batt}$	€
Number of households	N_{HH}	-
PV factor[87]	F_{PV}	-
Wind factor[88]	F_{Wind}	-
Total capacity of solar PV in the region	Cap_{PV}	MWp
Total capacity of wind power in the region	Cap_{Wind}	MW
Total capacity of RES-e in the region	Cap_{RES}	MW
Levelized cost of energy for solar PV	$LCOE_{PV}$	€ / kWh
Levelized cost of energy for wind power	$LCOE_{Wind}$	€ / kWh
Residential electricity price (daytime)	$P_{el,day}$	€ / kWh
Residential electricity price (nighttime)	$P_{el,night}$	€ / kWh
Feed-in tariff	$P_{feed-in}$	€ / kWh

---

[86] Night-time: 10PM-6AM

[87] Penetration of households with installed solar PV of 5 kWp; e.g., PV factor of 1 accounts for 100% of all households having 5kWp solar PV installed

[88] Penetration of the regional power system with a standard 3 MW wind turbine; e.g., Wind factor of 1 accounts for 15 MW wind power

Number of Li-Ion batteries in the region	$Batt_{Li\text{-}Ion}$	-
Maximum battery power	$P_{Batt,max}$	kW
Discharge time	$t_{discharge}$	h
Usable battery capacity	E_{Batt}	kWh
CAPEX of a Li-Ion battery system	$Cost_{inv,Batt}$	€ / kWh
Discount rate of storage investments	r	%
Average annual energy demand per household	$E_{HH,yrly}$	kWh
Amount of energy charged annually	$E_{Charged,a}$	MWh
Amount of energy charged annually (daytime)	$E_{Charged,a,day}$	MWh
Amount of energy charged annually (nighttime)	$E_{Charged,a,night}$	MWh
Amount of energy discharged annually	$E_{Discharged,a}$	MWh
Amount of energy discharged annually (daytime)	$E_{Discharged,a,day}$	MWh
Amount of energy discharged annually (nighttime)	$E_{Discharged,a,night}$	MWh
Amount of energy obtained from grid (daytime)	$E_{Grid,Day}$	MWh
Amount of energy obtained from grid (nighttime)	$E_{Grid,Night}$	MWh
Amount of energy fed into the grid	$E_{Feed\text{-}In}$	MWh
Net present value of a storage investment	NPV	€
Modified profitability index of a storage investment	MPI	%

Electricity flow calculation model

The electricity flow follows a clear path as it is defined as follows:

1. Electricity demand form households must be met by RES-e generation at zero costs, as there is no price for self-generated energy from RES-e in the region.
2. If demand exceeds RES-e generation in a certain hour, electricity is being discharged from the battery. In case of an empty battery, electricity is supplied form the grid to the applicable price (day/night). This calculation specification is stated in Equation 14 below.

Equation 14: Case of positive residual load

$$L_{HH} - E_{RES} \in \mathbb{R}^{+} \text{ and } St_{LVL} < (L_{HH} - E_{RES})\,;$$
$$L_{Residual} = L_{HH} - E_{RES} = E_{Grid} \in \mathbb{R}^{+}$$

3. On the opposite, if RES-e generation exceeds demand and the storage capacity is below maximum, electricity is obligatory stored in the battery using its maximum power for charging until capacity maximum is reached (see Equation 15).

Equation 15: Case of no residual load

$$L_{HH} - E_{RES} \in \mathbb{R}^{-} \; and \; St_{LVL} < E_{Batt} \, ; L_{Residual} = 0$$

4. In hours where there is a surplus production of energy when demand is already covered and the battery is fully charged, electricity is fed into the grid to the given feed-in tariff (see Equation 16).

Equation 16: Case of negative residual load

$$L_{HH} - E_{RES} \in \mathbb{R}^{-} \; and \; St_{LVL} = E_{Batt} \, ; L_{Residual} = E_{Grid} \in \mathbb{R}^{-}$$

These formulas are applied on the hourly data-series for a year to compute the residual load in every time step according to the RES-e generation. Summing up some preliminary results of the calculation explained previously, the model concludes also to the yearly values of metrics stated in Table 8:

Table 8: Yearly measures resulting from modeling

Metric	Symbol	Unit
Amount of energy charged into the battery annually	$E_{Charged,a}$	kWh
Amount of energy charged into the battery annually (day)	$E_{Charged,a,day}$	kWh
Amount of energy charged into the battery annually (night)	$E_{Charged,a,night}$	kWh
Maximum power supply from grid	$P_{Grid+, max}$	kW
Maximum power delivery into the grid	$P_{Grid-, max}$	kW
Total number of dis-/charge cycles per year	C	-
Number of hours with residual load >0 annually	R^{+}	-
Number of hours with residual load <0 annually	R^{-}	-

Amongst others, the most conclusive field of determination within this thesis are flexibility needs on different time horizons across a year computed in a regional model. With the hourly residual load values and the calculation method given by the EUROPEAN COMMISSION, DIRECTORATE-GENERAL FOR ENERGY (2019), that was already holistically explained in Chapter 2.3.1, the flexibility needs are computed while sticking to the computation methods. Exemplary, Equation 17 gives the positive daily flexibility need for one specific time step t and the annual sum of positive daily flexibility need FN_{D+} , what is being stated in MWh per year. Following this method, the flexibility needs on daily, weekly, monthly, and yearly basis are calculated and summed up. Those needs and their behavior according to RES-e penetration levels and storage penetration levels will be discussed in Chapter 5.

Equation 17: Calculation method for flexibility need

$$\Delta FN_{D+,t} = L_{Residual} - \frac{1}{n}\sum_{i-1}^{n} L_{Residual,i} \quad ; \forall i \qquad ,n = 24$$

$$FN_{D+,t} = \Delta FN_{D+,t} \quad ,if\ \Delta FN_{D+,t} > 0$$

$$FN_{D+} = \sum_{t} FN_{D+,t} \quad ; \forall t$$

Economic evaluation methods and key-figures

An economic evaluation of the results can be carried out when prices, both electricity prices in the form of tariffs or investment costs for storage technologies are taken into account. The variable revenue and cost streams that appear to be available through the electricity flow analysis are stated in the following:

1. **Energy supply costs**: Despite RES-e generation within the modelled regional system, it may happen, that electricity must be supplied from the grid, both during daytime and in night hours, when there is no RES-e generation, and the storage capacity is already exploited. The costs occurring through electricity supply per year are calculated as shown in Equation 18.

Equation 18: Grid supply costs

$$Cost_{Grid,Day} = E_{Grid,Day} * \frac{1}{10^3} * P_{el,Day}$$

$$Cost_{Grid,Night} = E_{Grid,Night} * \frac{1}{10^3} * P_{el,Night}$$

2. **Feed-In Revenue**: In hours of the year, when RES-e generation exceeds both the demand and the maximum storage capacity, there are two options for the generated electricity: feeding into the grid or curtailment. In this thesis, curtailment is not considered an option as it aims to assess whether grid connection is unconditionally needed for a region and to what extent. The feed-in tariff is taken to calculate the possible revenue from the grid. This is computed alike Equation 19.

Equation 19: Revenue through feed-in tariff

$$Rev_{feed-in} = E_{feed-in} * \frac{1}{10^3} * P_{feed-in}$$

3. **Storage economics**: The economic performance of the Li-Ion battery storage systems is measured by the avoided costs per kWh discharged from the battery at the time of demand, when residential electricity prices (day, night) would have had caused costs. Even though it is not accelerated in this model, to maximize profits through feed-in tariffs, the opportunity costs generated by charging the battery while feeding in would provide instant revenue, must be taken into account. The storage economics are therefore calculated as it is shown in Equation 20. E_{Batt} already considers the depth of discharge (DoD), that reduces the nominal capacity to a lower useable capacity of the battery, thus there is no additional efficiency reduction factor in the calculation. The net profits of every

kilowatt hour stored in the battery must be calculated by the difference in the opportunity costs (non-leveraged feed-in tariff) and the residential electricity price effective in a specific hour, which would have had to be paid instead.

Equation 20: Storage revenue (avoided costs)

$$AvCost_{Batt} = \left(E_{Discharged,day,a} * \frac{1}{10^3} * P_{el,Day}\right) + \left(E_{Discharged,night,a} * \frac{1}{10^3} * P_{el,Night}\right)$$

To go more into detail with the economic evaluation of those investments in flexible assets, two key-figures are chosen to determine the value of the investments:

- Net present value (NPV)
- Modified profitability index (MPI)

The net present value is a commonly used metric to decide whether an investment will be profitable or not. It is being used, both in decision making for public funding into specific projects or subsidies and also for companies' investments, because it states the current value of an investment via discounted cash flows into the present. As the NPV is measured in an absolute number in terms of money, it is harder to be understood and compared with other investments because it is lacking a relative measure to compare. This limitation is tackled by using the modified profitability index of the investment, comparing present investments with the discounted future net revenues. The formulas for both, the net present value and the modified profitability index applied to the case of regional flexibility evaluation are stated in Equation 21 and Equation 22.[89;90]

Equation 21: Net present value of a storage investment[91]

$$NPV = \sum_{t=1}^{n} \frac{AvCostAvCost_{Batt,t}}{(1+r)^t} - Cost_{inv,Batt}$$

Equation 22: Modified profitability index a storage investment[92]

$$MPI = \frac{NPV}{Cost_{inv,Batt}}$$

---

[89] Cf. Range, A., Santos, J., et al. (2016), p.15 f.

[90] Cf. García-Gusano, D., Espegren, K., et al. (2016), p. 57 f.

[91] Cf. Range, A., Santos, J., et al. (2016), p. 15.

[92] Cf. Range, A., Santos, J., et al. (2016), p. 16.

5 Analysis of the modeling results

As was already highlighted in the introductory section to Chapter 4, this thesis discusses three scenarios. A sensitivity analysis will be carried out in each of the scenarios, both on the iRES-e penetration side and the storage penetration side.

5.1 Scenario 1 – Solar PV-dominated system

The characteristic of a solar PV-dominated system is clear: The sun is shining during the day, if no bad weather interferences happen, and thus it is generating electricity throughout the day. In the night, there is no option to generate electricity at all. Storage technologies could lead the way out of the darkness for such systems. The following findings, derived from the modeling, show the effects of Li-Ion BES systems on regional flexibility needs and the economic feasibility of the technological setup.

5.1.1 Regional flexibility need

Flexibility needs determined by computing the hourly residual load according to the framework defined in Chapter 3.2.1 are being pictured in Figure 26 on different time scales. Flexibility need is defined as the positive difference between the average residual load and the actual residual load in a time step. Computing this on a daily basis means to subtract the residual load in a certain hour of the day from the average residual load of the whole day (24 hours). According to the calculation method, the sum of all positive differences over the course of one year is considered the flexibility need on a daily level. The same goes for weekly, monthly, and yearly flexibility needs.

The curves in Figure 26 state five data-series, which have been acknowledged most relevant during the computational process. For the sake of comparability, those five sensitivities of iRES-e factors (in this case solar PV), in numbers multiplied by a factor of 0.5, 0.75, 1, 2 and 5, will be featured in all scenarios. In general, Figure 26 outlines how flexibility need changes with more storage being added to the system expressed as percentage change normed to the maximum flexibility need within each sensitivity. The light green shaded area indicates the span of battery penetration change that most influence the change in flexibility need.

It can be seen in Figure 26a, that the relative change in flexibility need on a daily basis comes down by constant rates for all curves. The rates are similar high for the 0.5x, 0.75x and 1x sensitivities, and tend to be less steep for higher penetrations of solar PV. Additionally, across all of the curves, except the 50% penetration curve, there is a bend, where the curves lose their rate of decrease at around 80% of storage penetration meaning, that looking at daily flexibility need, it is most effective to add battery storage at 80% of all households to decrease the need for flexibility. Taking a look at Figure 26b and Figure 26c, it can be realized that the effects on flexibility need for weekly and monthly timespans are zero for storage penetration levels below 70-80%. Bearing in mind that higher storage capacity can help meeting the demand over a longer time period, even if the maximum duration of discharge of the battery is below two hours. The effects on yearly flexibility needs are in very small percentage ranges and can be considered as non-relevant. What is applicable to daily, weekly, and monthly flexibility is the fact, that the 50% solar PV sensitivity as well as the very high penetrations of 200% and 500% are far less effected by added storage capacity than the one's with solar PV factors of 0.75 and 1.

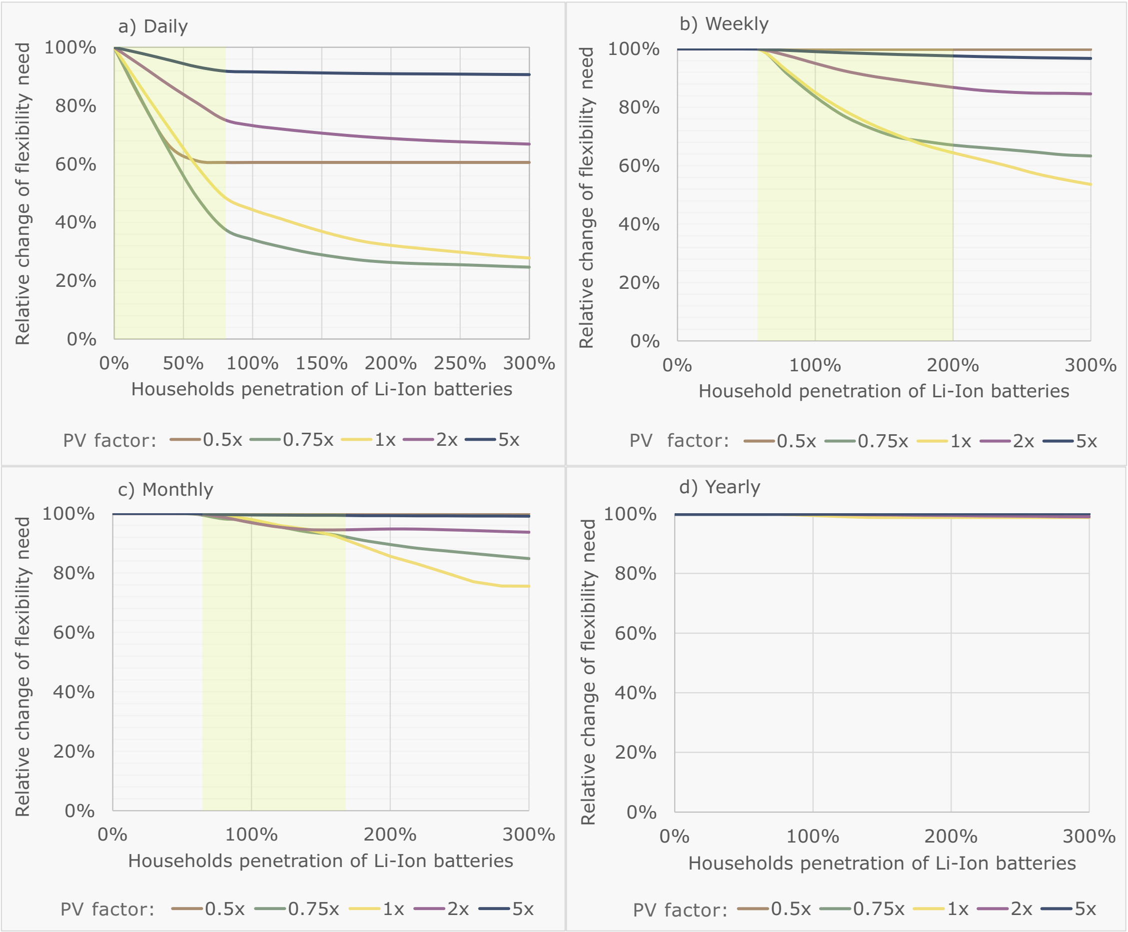


Figure 26: Relative change of flexibility needs[93]

The effects of different sensitivities of solar PV penetration and the variations of storage penetration are high for some specific cases (e.g., 0.75x) and diminish across wider time frames of consideration. As daily flexibility needs are highly affected by higher storage penetrations, it becomes less on a weekly and monthly basis and decreases to close to zero effects over the course of one year.

5.1.2 Economic key-figures

It is at the core of this thesis to assess whether investments in flexible assets make economically sense or not. As explained in previous chapters, the two key-figures to

---

[93] Source: Own illustration

evaluate those investments are the net present value and the modified profitability index. Both metrics have been computed for the sensitivities defined in the beginning.

The picture drawn by Figure 27 is quite clear: The results show no variant in sensitivities using initial investment sums that concludes with a positive net present value. A positive NPV would mean that over a 10-year lifetime of the installed battery storage systems, not a single scenario would end up creating additional value to the investors. The impact of the CAPEX invested in those calculations are enormous. The curves of various solar PV penetration curves are following a steep path downwards as storage penetration levels increase.

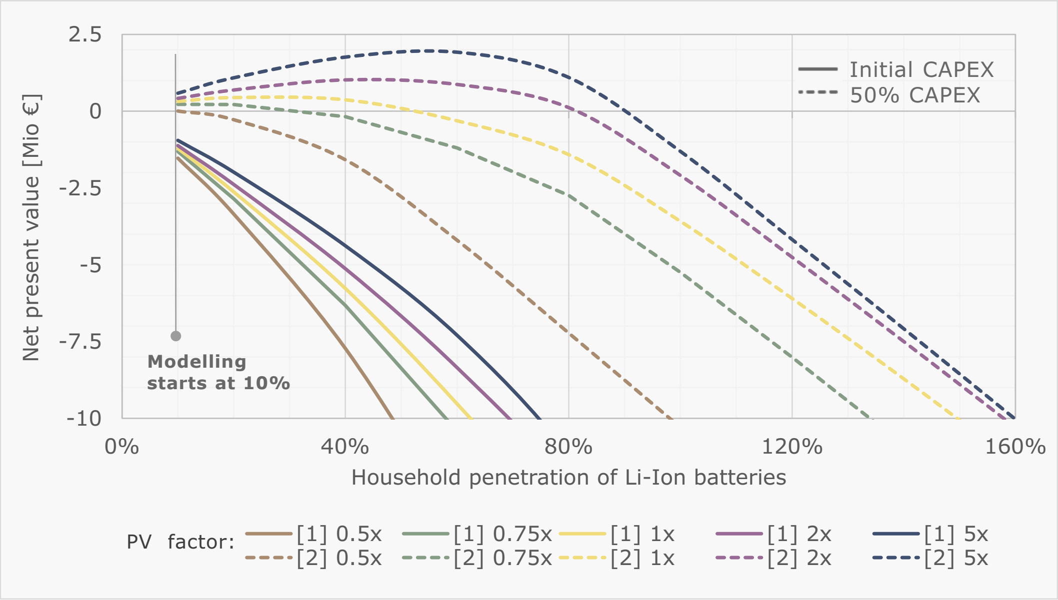


Figure 27: Net present values of total storage investments[94]

Taking the calculation into a possible future scenario where it is assumed to have less expensive storage technologies, the picture changes. As an assumption, CAPEX of Li-Ion battery storage systems were set to 50% of its initial value to model whether this affects the net present value as heavily as needed to gain profit. Taking a look at the different curves, it is interesting that even with the 50% reduction in capital expenditures, the 0.5x variant will not be profitable. All other curves, starting at 0.75x, are gaining profit in the course of a 10-year operating time. The monetary value of the investments increases to a certain tipping point of the curve with higher storage penetration before it falls down and intersect the zero axis. The higher the share of solar PV penetration in the system, the higher the economically feasible share of Li-Ion batteries, but even for the highest scenario of 500% solar PV installed in the region, it does not make economically sense to utilize more than roughly 100% of storage penetration.

Translating those absolute monetary numbers that the net present value provides into comparable relative values, Figure 28 provides the results from the model expressed in the modified profitability index of each variants investments. As this measure is highly corelated to the net present value, the trends that can be seen are similar. What is

---

[94] Source: Own illustration

interesting to compare in this case, is the relative values of profitability. Having extremely negative profitability on the variants using the initial costs, the profitability for the reduced CAPEX scenarios is creating immense value through high MPI rates. The general evidence that profitability can be created through a set of technological setups not exceeding 100% penetration of storage remains.

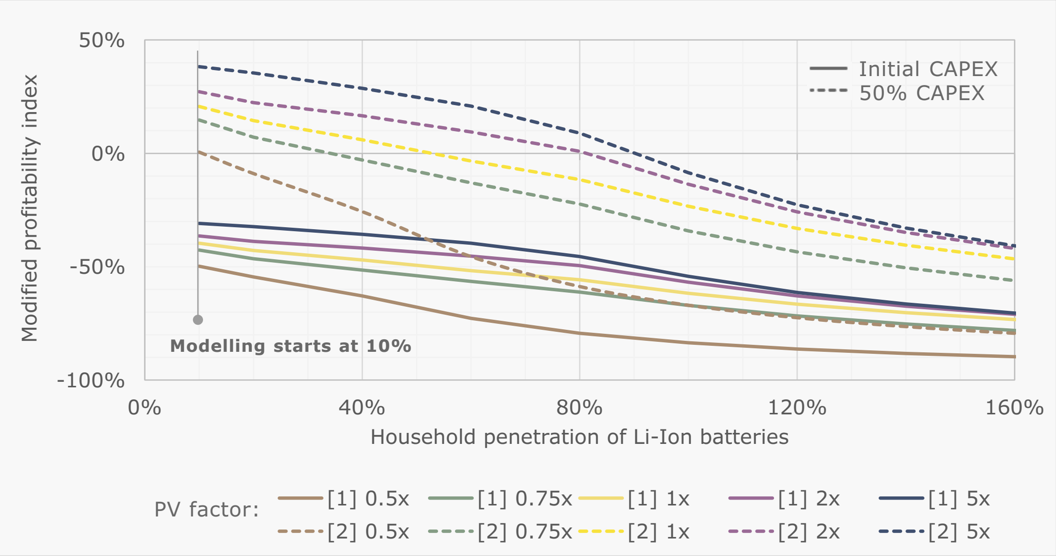


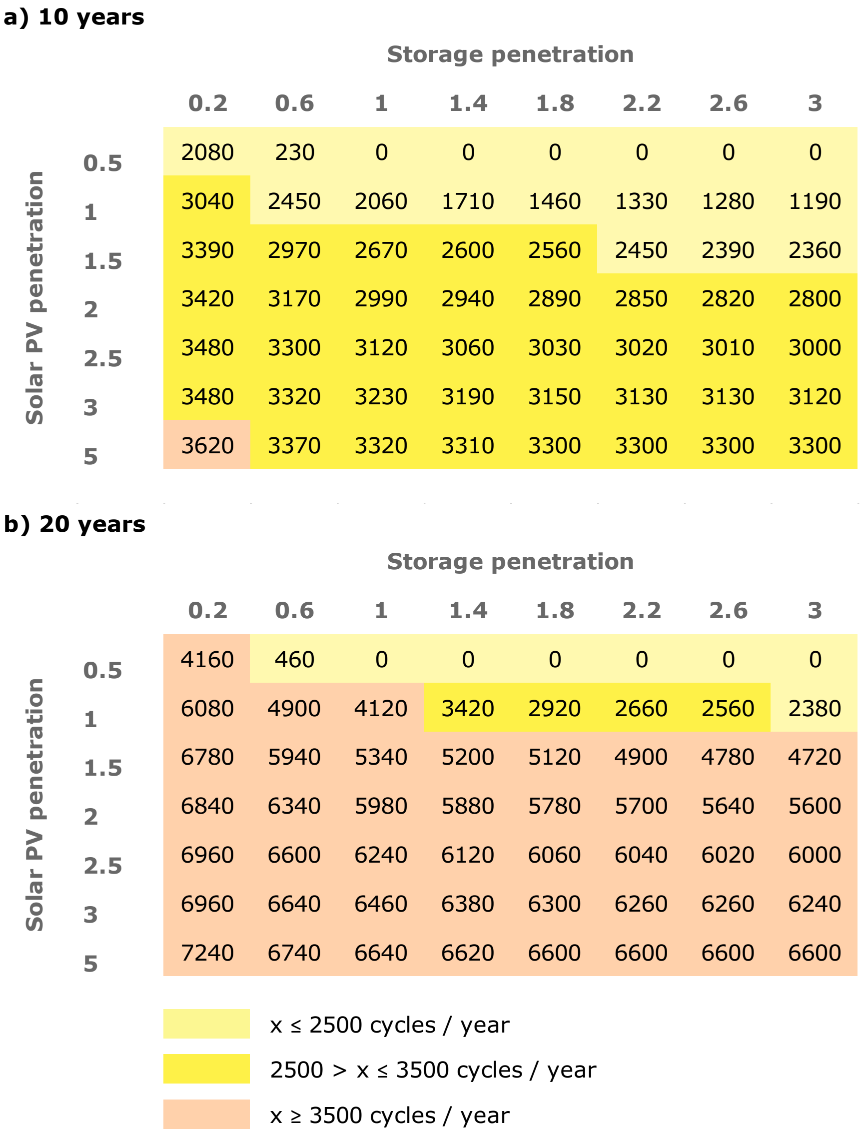
Figure 28: Modified profitability index of total storage investments[95]

As investments are commonly calculated over longer lifetimes than 10 years, the model computed the 20-year-scenario as well to compare whether it makes sense to extend the number of years. The results show that this would increase profitability by a small measure of impact but is technologically not feasible. Summing up the cycles of fully discharge Li-Ion batteries across the year, it must be concluded, that the BES systems would not endure such strains. According to the research carried out across various Li-Ion battery manufacturer producing similar sized batteries, developers propose a range between maximum 3000-3500 cycles on average for their BES systems.[96] Figure 29a shows that with a lifetime of 10 years, in fact all of the computed variants lie within this range. Figure 29b pictures the cycles demanded from the storage systems by the model when computing a lifetime of 20 years.

---

[95] Source: Own illustration

[96] Cf. ENERGIESPEICHER-ONLINE GMBH, https://www.energiespeicher-online.shop/, (Zugriff: 05.10.2022).



a) 10 years

	Storage penetration							
Solar PV penetration	**0.2**	**0.6**	**1**	**1.4**	**1.8**	**2.2**	**2.6**	**3**
0.5	2080	230	0	0	0	0	0	0
1	3040	2450	2060	1710	1460	1330	1280	1190
1.5	3390	2970	2670	2600	2560	2450	2390	2360
2	3420	3170	2990	2940	2890	2850	2820	2800
2.5	3480	3300	3120	3060	3030	3020	3010	3000
3	3480	3320	3230	3190	3150	3130	3130	3120
5	3620	3370	3320	3310	3300	3300	3300	3300

b) 20 years

	Storage penetration							
Solar PV penetration	**0.2**	**0.6**	**1**	**1.4**	**1.8**	**2.2**	**2.6**	**3**
0.5	4160	460	0	0	0	0	0	0
1	6080	4900	4120	3420	2920	2660	2560	2380
1.5	6780	5940	5340	5200	5120	4900	4780	4720
2	6840	6340	5980	5880	5780	5700	5640	5600
2.5	6960	6600	6240	6120	6060	6040	6020	6000
3	6960	6640	6460	6380	6300	6260	6260	6240
5	7240	6740	6640	6620	6600	6600	6600	6600

▫ x ≤ 2500 cycles / year

🟨 2500 > x ≤ 3500 cycles / year

🟧 x ≥ 3500 cycles / year

Figure 29: Utilized yearly battery cycles[97]

5.1.3 Grid necessity and utilization

A major inducement for regional communities, municipalities, and other regional entities to invest in flexible assets may be the reduction of grid supply costs. Power grid infrastructure creates an exorbitant amount of public spending to ensure grid stability and security of supply to all consumers. As this thesis investigates the effects of flexibility, it also looks into the interrelations of a regional, decentralized power system with the grid provided by state-owned distribution grid operators.

The model computes the post-storage residual loads in every hour of a year. If this residual load is negative, electricity is fed into the grid by the regional system. The other way around would mean that the system cannot cope with its demand and lacks iRES-e generation on the local level, thus electricity must be supplied via the public grid. Figure 30 shows the relative change of negative grid-use incidents (feed-in) within a modeled

---

[97] Source: Own Illustration

year, whereas Figure 31 depicts the opposite case of electricity being supplied from the grid. For both figures it is quite intuitive that low solar PV penetration rates lead to less feed-in and higher grid supply and the other way around. Nevertheless, there is a very interesting habit of the curves decreasing to a certain point and increasing again after reaching a tipping point. As the model scales-up storage capacity, the maximum dis-/charging power of the aggregated storage system is increased accordingly. That has major impact on the duration of the battery. In hours where there is very high availability of solar PV generation, the storage is charged faster having an increased maximum dis-/charging power available. The same accounts for hours with very low or zero iRES-e generation but high demand.

As a conclusion it can be said that the utilization of storage technologies within a solar PV-dominated system helps to decrease the use of grid infrastructure across all computed variants until storage levels at approximately 100% penetration rate are reached. After this point, the need for grid use both for feeding in and supply is increasing back again.

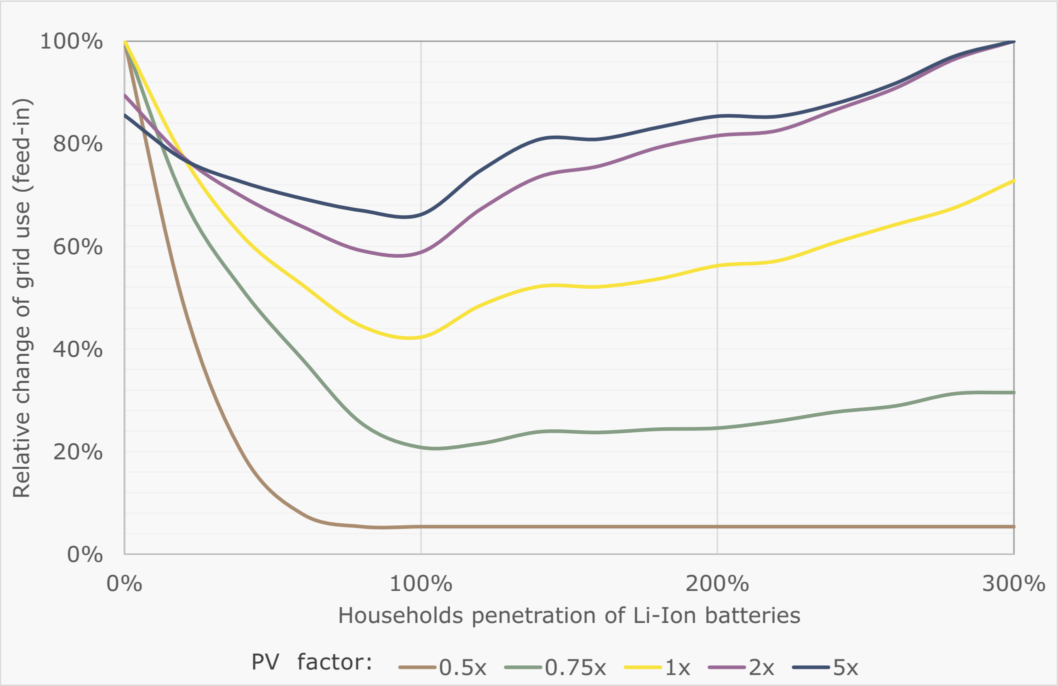


Figure 30: Grid utilization via feed-in[98]

---

[98] Source: Own illustration

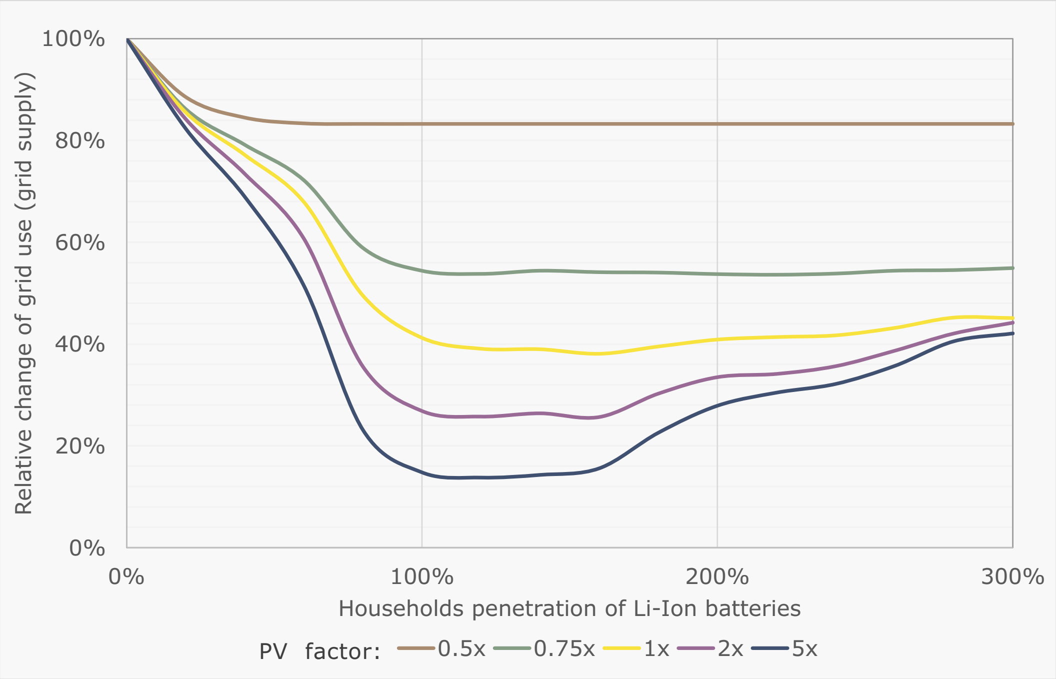


Figure 31: Grid utilization through supply[99]

5.2 Scenario 2 – Wind power-dominated system

The characteristic of a wind power-dominated system is more irregular as solar PV. Wind profiles depend heavily on the surface of the region. The load curve across one year is less fluctuates less than solar energy. The following findings, derived from the modeling, show the effects of Li-Ion BES systems on regional flexibility needs and the economic feasibility of the technological setup in a wind powered system.

5.2.1 Regional flexibility need

As it was already explained in Chapter 5.1, the determination of flexibility needs is computed according to the framework defined in Chapter 3.2.1. Figure 32 outlines how flexibility need changes with more storage being added to the system expressed as percentage change normed to the maximum flexibility need within each sensitivity for a wind-dominated system. The light green shaded area indicates the span of battery penetration change that most influence the change in flexibility need.

It can be seen in Figure 32a, that the relative change in flexibility need on a daily basis comes down by constant rates for all curves, but with way less dynamic than for solar PV-dominated systems. The decreasing effects on flexibility demand is less steep but does not stop decreasing at a certain point. The curves with wind power rates of 0.5x, 0.75x and 1x are affecting the decrease of flexibility demand way more than 200% and higher penetrations when storage capacity is added. The effect on flexibility needs on weekly and monthly level are way more visible than within the solar PV powered system.

---

[99] Source: Own illustration

It can be seen that the impact on the flexibility needs starts far earlier on weekly and monthly levels as this was given by the solar PV-dominated system. Yearly flexibility need is not significantly affected by wind storage penetration levels. In total, it can be said that the impact from higher storage penetration levels on flexibility need is less effective than for solar PV systems.

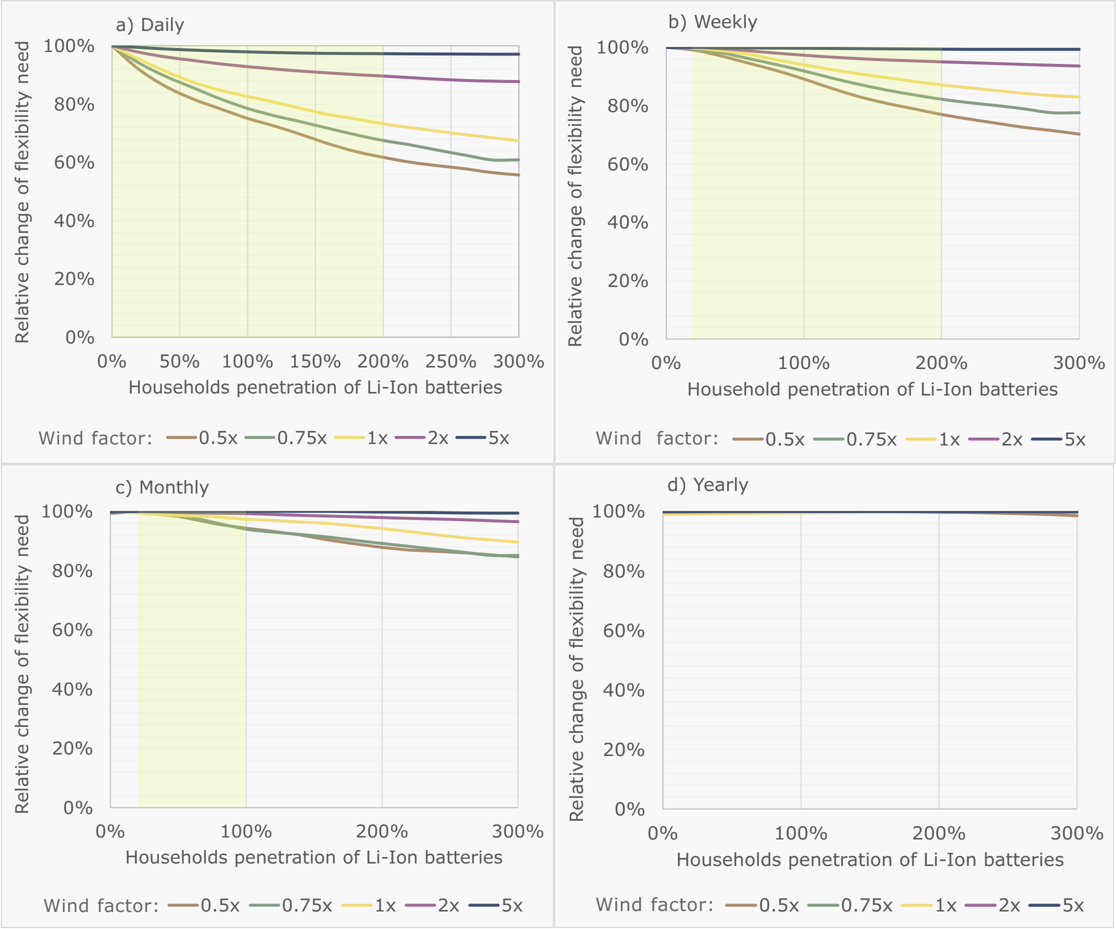


Figure 32: Relative change in flexibility needs[100]

5.2.2 Economic key-figures

Figure 33 pictures rather vividly, that the economic evaluation of storage investments in a wind power-dominated system with the set boundaries and the defined model will not be profitable. The net present values of the investments at initial cost levels are decreasing rapidly from their starting point at about -2.5 Million Euros at 10% storage penetration and following a steep downwards trend as storage penetration levels increase. This picture can be rolled over all sensitivities of wind power penetration as the scattering between them remains very low. Transforming the scene by reducing CAPEX of Li-Ion battery storage systems lead to an improvement of the net present values, but

---

[100] Source: Own illustration

still all of them remain below zero. This forces the evaluation to be acknowledged as non-profitable for wind-dominated systems.

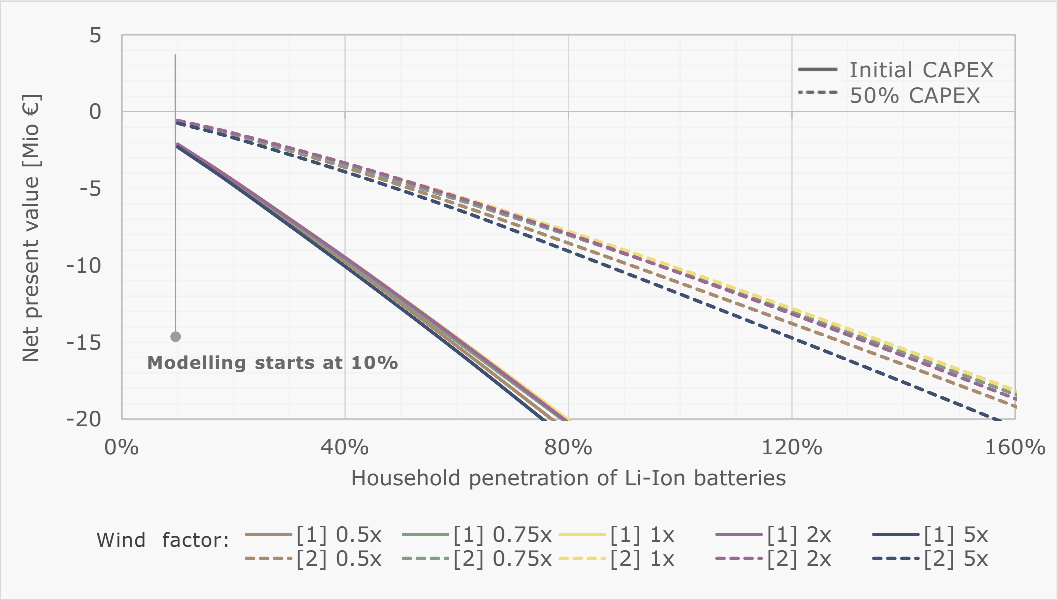


Figure 33: Net present values of total storage investments[101]

Taking the results for the modified profitability index into account, the picture does not essentially change as it can be seen in Figure 34. Even the best curves end up at around -40% MPI at the storage penetration level of 10%.

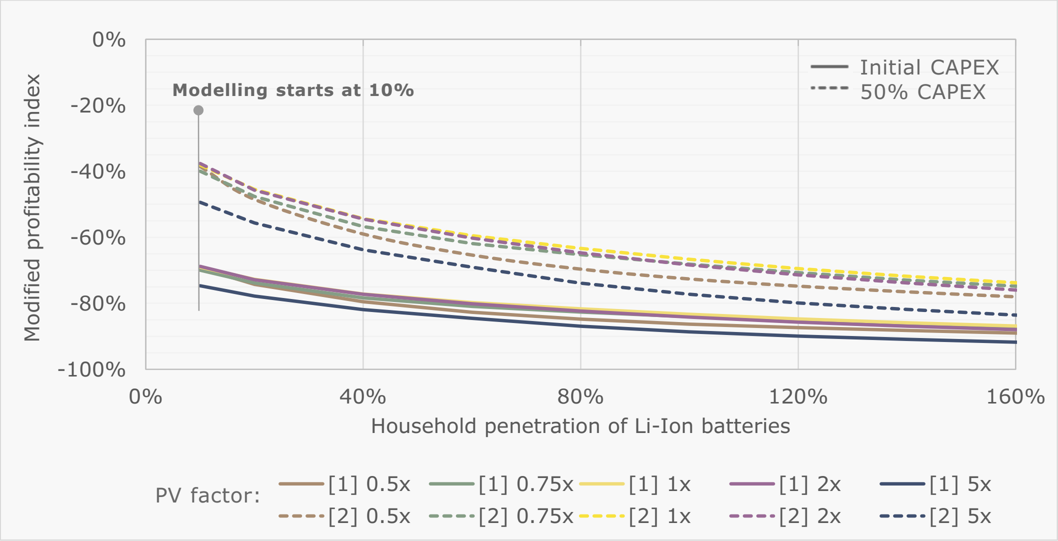


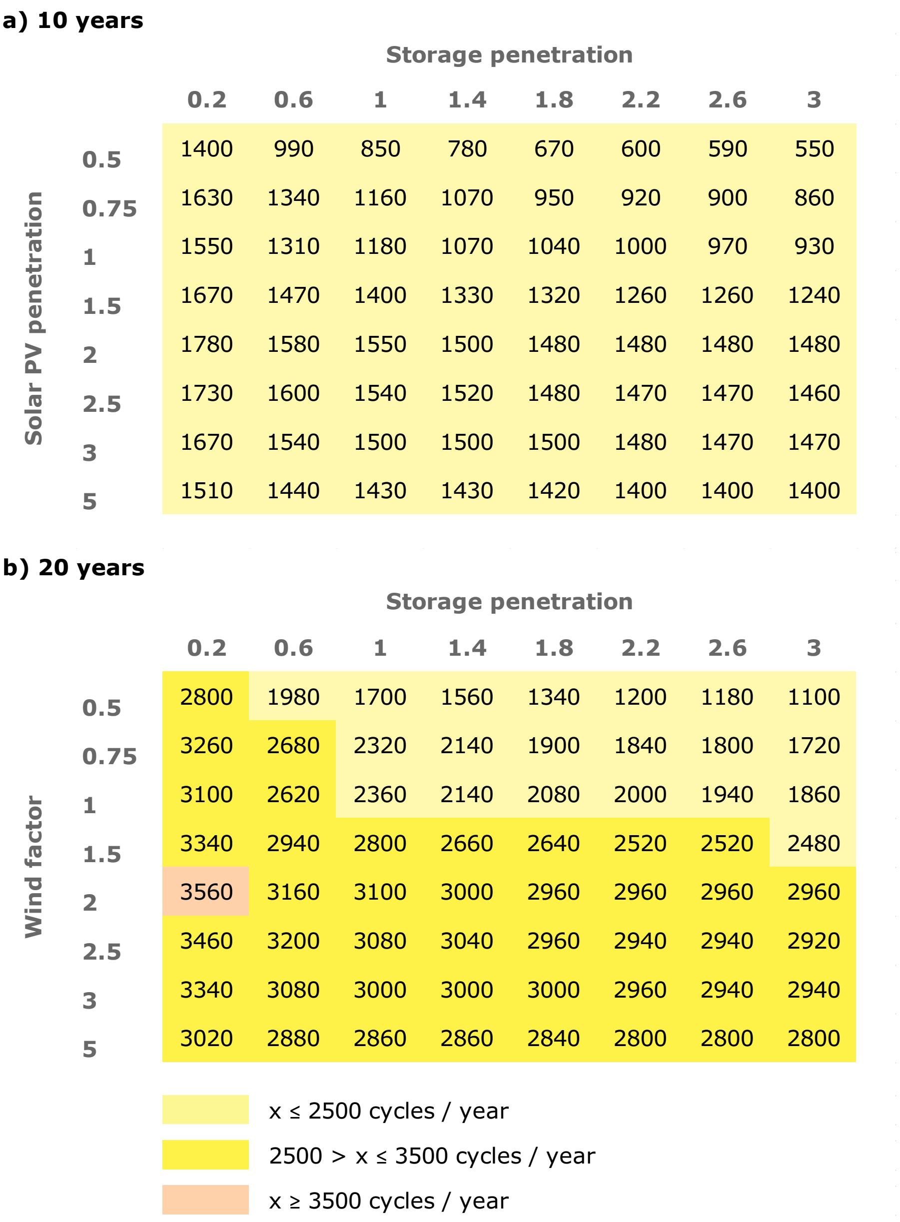
Figure 34: Modified profitability index of total storage investments[102]

---

[101] Source: Own illustration

[102] Source: Own illustration

Within solar PV-dominated systems, the storage technologies were utilized to capacity within 10 years of lifetime in most cases. This changes by looking at the results of the wind model stating the cycles per year in Figure 35. The cycles utilized in the wind model are around half of what the cycle numbers have been for the solar PV system. Even when looking at the 20-year lifetime matrix, close to all cases would be doable for the technologies. As it can be derived from the economic evaluation, more cycles per year lead to more revenue created by the battery. This explains partly the low profitability in a 10-year timespan.



a) 10 years

Storage penetration

Solar PV penetration	0.2	0.6	1	1.4	1.8	2.2	2.6	3
0.5	1400	990	850	780	670	600	590	550
0.75	1630	1340	1160	1070	950	920	900	860
1	1550	1310	1180	1070	1040	1000	970	930
1.5	1670	1470	1400	1330	1320	1260	1260	1240
2	1780	1580	1550	1500	1480	1480	1480	1480
2.5	1730	1600	1540	1520	1480	1470	1470	1460
3	1670	1540	1500	1500	1500	1480	1470	1470
5	1510	1440	1430	1430	1420	1400	1400	1400

b) 20 years

Storage penetration

Wind factor	0.2	0.6	1	1.4	1.8	2.2	2.6	3
0.5	2800	1980	1700	1560	1340	1200	1180	1100
0.75	3260	2680	2320	2140	1900	1840	1800	1720
1	3100	2620	2360	2140	2080	2000	1940	1860
1.5	3340	2940	2800	2660	2640	2520	2520	2480
2	3560	3160	3100	3000	2960	2960	2960	2960
2.5	3460	3200	3080	3040	2960	2940	2940	2920
3	3340	3080	3000	3000	3000	2960	2940	2940
5	3020	2880	2860	2860	2840	2800	2800	2800

x ≤ 2500 cycles / year

2500 > x ≤ 3500 cycles / year

x ≥ 3500 cycles / year

Figure 35: Utilized yearly battery cycles[103]

Cross-checking the assumption, that the profitability would increase strongly by adding 10 additional years of operation, these variants have been computed. The results of the

---

[103] Source: Own illustration

20-year variant are still disillusioning and can be seen in Figure 36. Even though a lifetime of 20 years and a reduction of today's investment cost levels for Li-Ion battery electric storage systems by 50% are not enough to create profit.

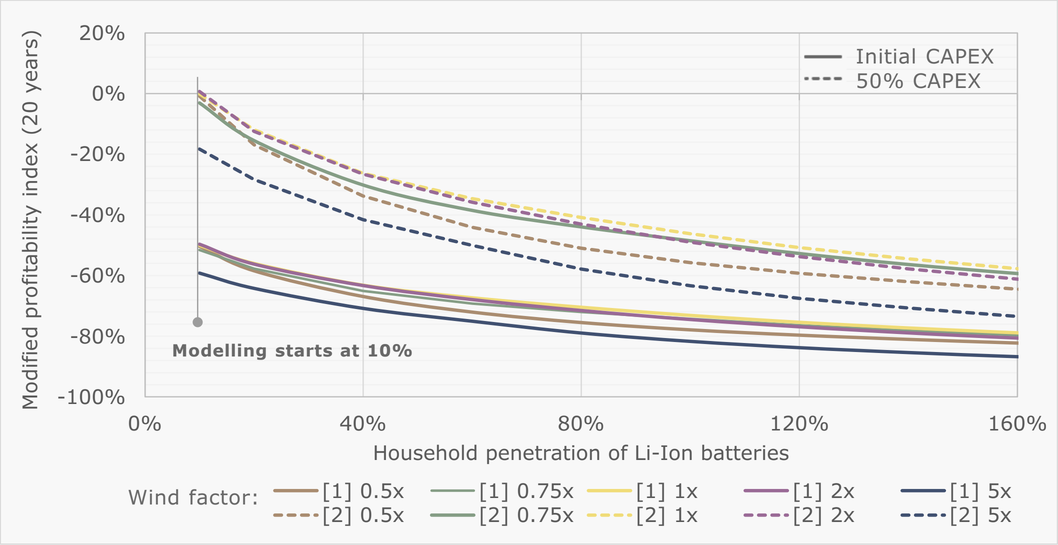


Figure 36: Modified profitability index - 20 years investment[104]

5.2.3 Grid necessity and utilization

Figure 37 shows the relative change of negative grid-use incidents (feed-in) within a modeled year, whereas Figure 38 depicts the opposite case of electricity being supplied from the grid. Focusing on the feed-in side first, it can be acknowledged that adding storage to the system leads to a reduction in grid utilization. As the penetration rate of batteries increase this effect is gone for extremely high penetration of wind power and lessen for the other variants. For the sensitivities 1x and below, the number of hours throughout the year where electricity is fed into the grid is reduced until reaching a storage penetration rate of approximately 100%. Beyond that point, the same effect as described in Chapter 5.1.3 unfolds. Consequently, the utilization rates for grid usage increases again, for all penetration rates of wind power.

As a conclusion it can be said that the utilization of storage technologies within a wind power-dominated system help decrease the use of grid infrastructure across all computed variants until storage levels are reached at approximately 100% penetration rate. After this point, the need for grid use both for feeding in and supply is increasing back again.

On the other hand, grid supply decreases by adding more and more storage to the system. Figure 38 pictures that the impact of adding storage until a level of 200% penetration rate is reached, hours of grid supply can be decreased significantly. The example of the 100% penetration of wind power states the benefits vividly. At a storage

---

[104] Source: Own illustration

penetration rate of 200%, the relative change in grid supply incidents is at 50% of the starting value for the sensitivity of 1x wind power.

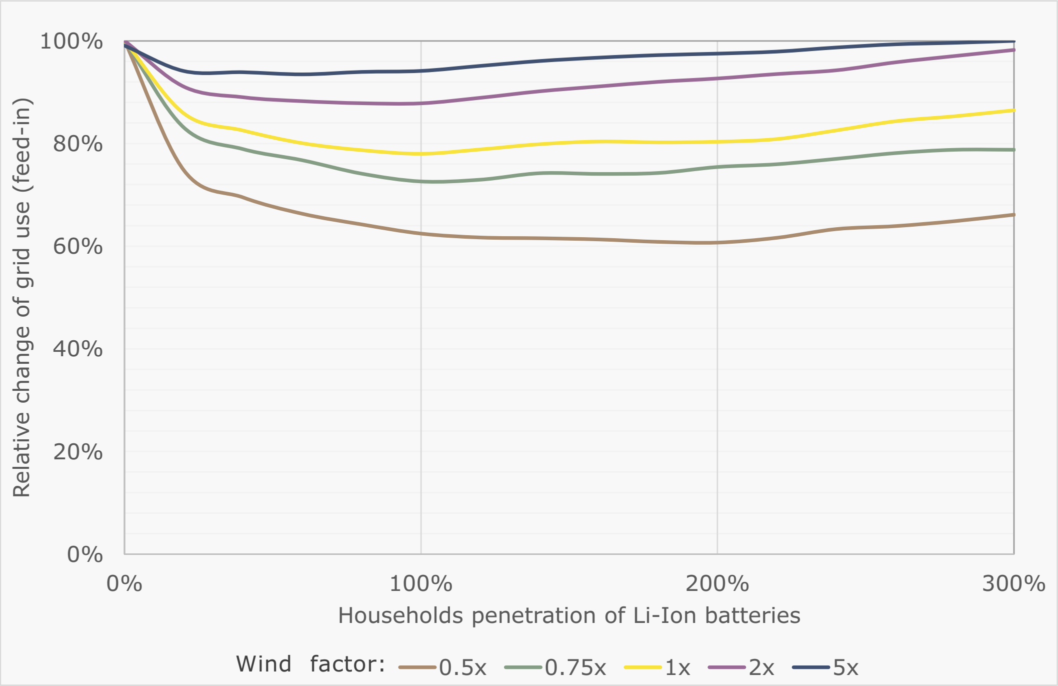


Figure 37: Grid utilization via feed-in[105]

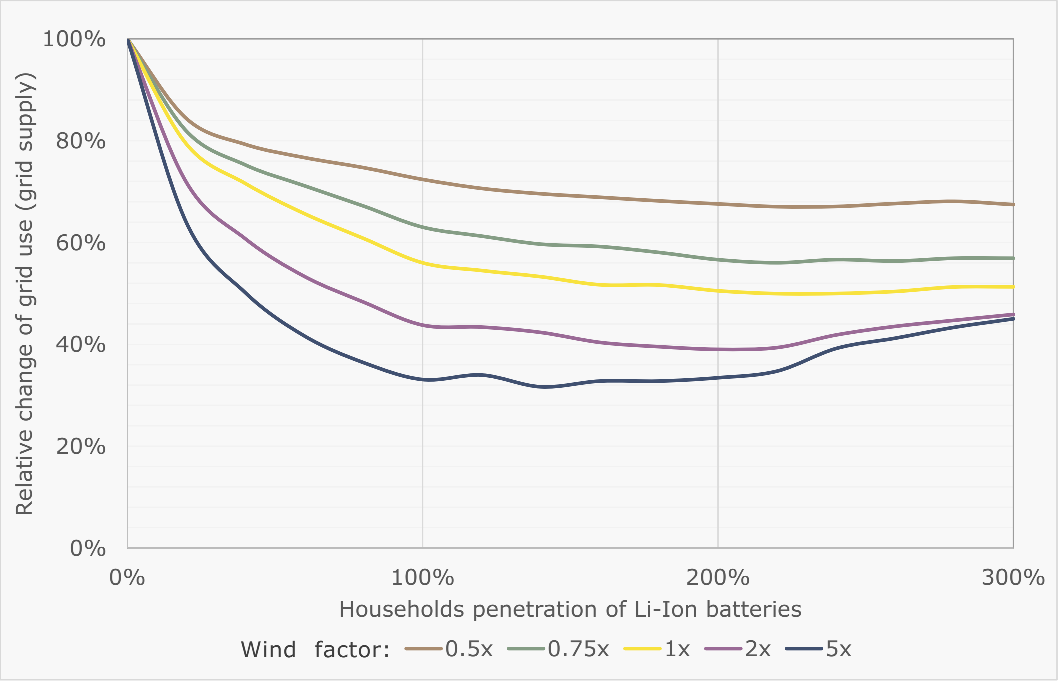


Figure 38: Grid utilization through supply[106]

---

[105] Source: Own illustration

[106] Source: Own illustration

5.3 Scenario 3 – Combined wind & solar PV powered system

The mix of solar PV and wind power in this system is defined as 50% split according to the maximum of the installed capacity per technology. The effects on the regional flexibility evaluation carried out in this thesis, will be shown in the next chapters.

5.3.1 Regional flexibility need

Figure 39 illustrates the flexibility needs on different time horizons. Firstly, the daily flexibility need is decreasing for three sensitivities of iRES-e (0.5x, 0.75x and 1x), while the two variants with 200% and 500% penetration of iRES-e are not influencing flexibility need reduction significantly. Given the different resolutions in time, the holistic impact on the flexibility need in each of them is indicated by the light green space in Figure 39a-d. The light green area is way broader than it was before for solar and wind solely – as flexibility need start to decrease from very low storage penetration levels onwards. Figure 39d shows an unpredicted flexibility decrease, thus on the yearly perspective. Even the reduction is below 10%, the relative impact compared to the solar and wind systems, is higher.

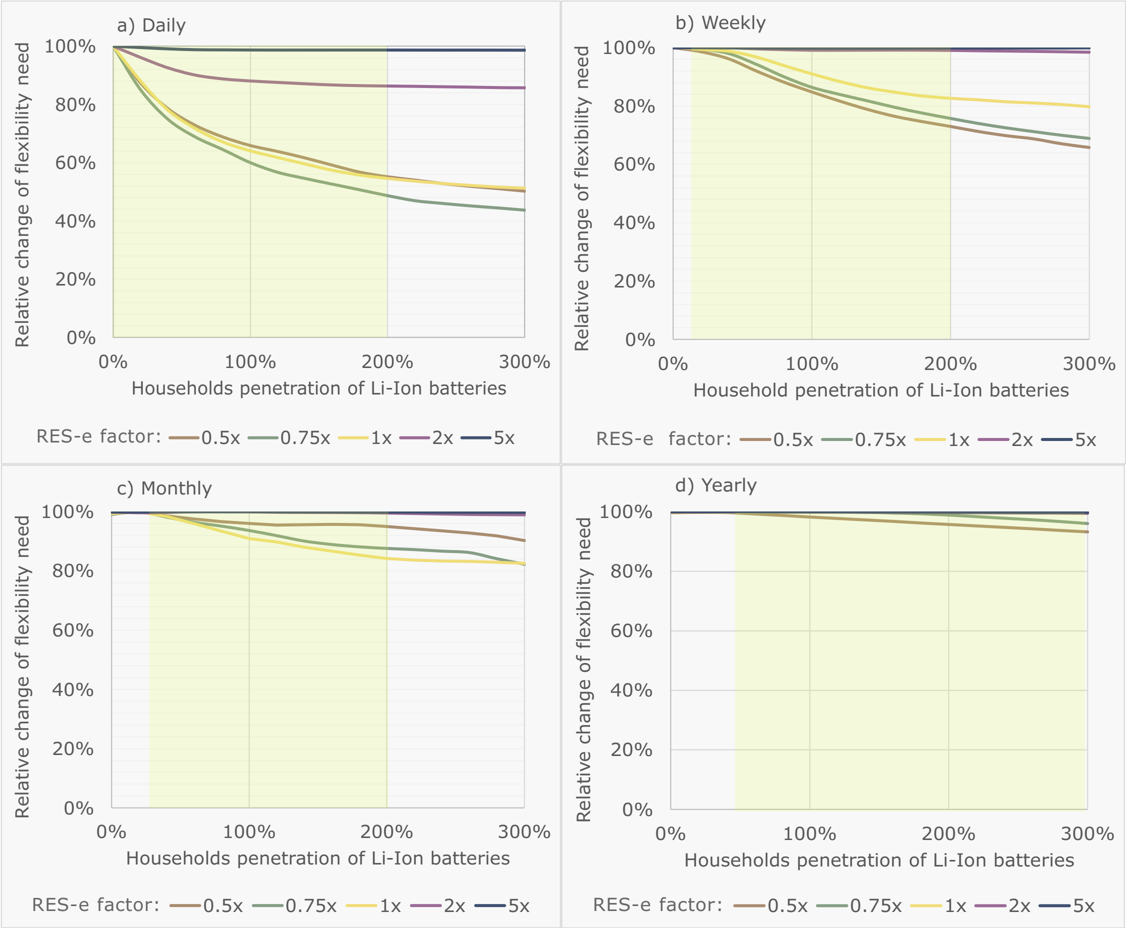


Figure 39: Relative change in flexibility needs[107]

---

[107] Source: Own illustration

5.3.2 Economic key-figures

Combining solar PV and wind helps to balance the excess electricity generated by iRES-e, but flexibility need is still to be covered. The economics of Li-Ion batteries in such regional electricity system according to the modeling are pictured in Figure 40 and Figure 41. The picture look very much familiar with the results given by the wind power-dominated system. Even with decreasing the CAPEX of storage investments there is no scenario to be economically profitable.

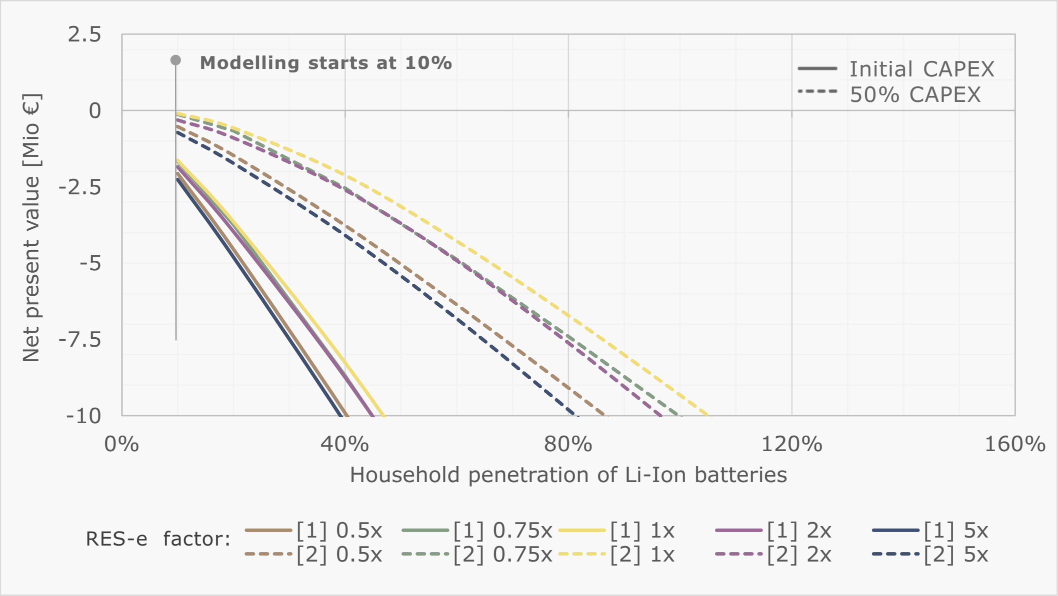


Figure 40: Net present values of total storage investments[108]

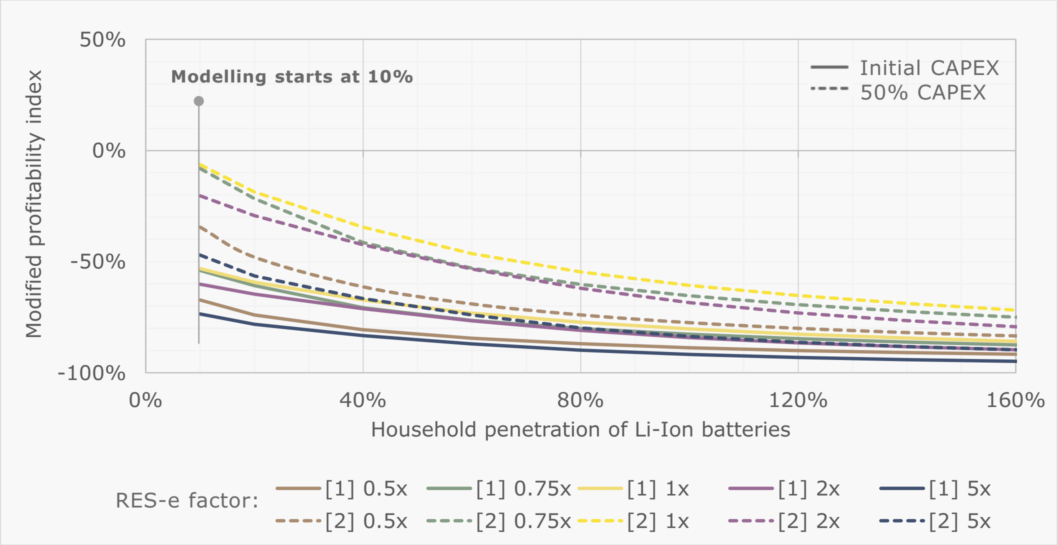


Figure 41: Modified profitability index of total storage investments[109]

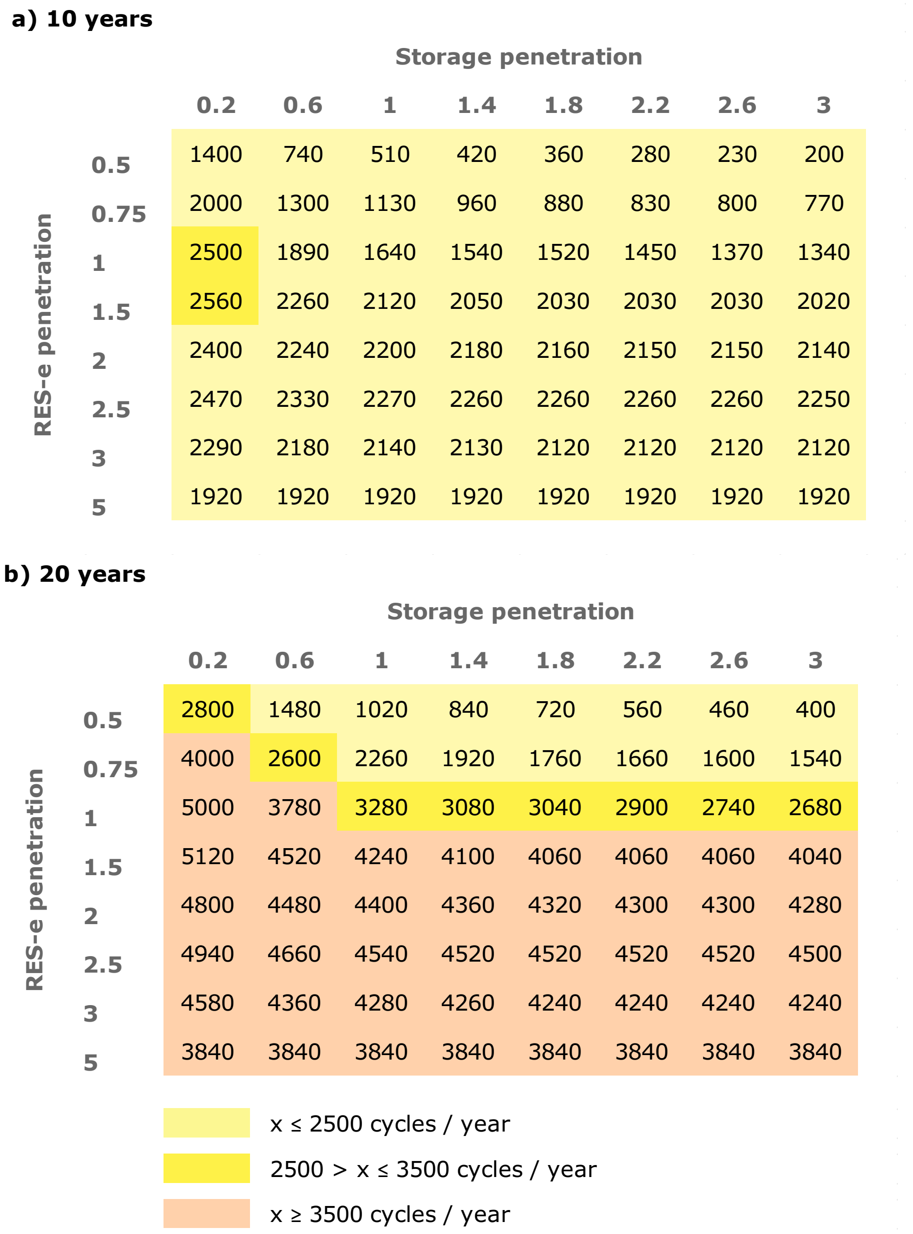
Taking a closer look at the fully charged and discharged cycles that the installed Li-Ion batteries were undergoing (see Figure 42), it clarifies the lack of revenue created by the

---

[108] Source: Own illustration

[109] Source: Own illustration

storage technologies. The system is running on rather low cycles. On the 20-year perspective, batteries could be computed additionally 10 years without degrading too fast for at least 0.5x, 0.75x and 1x penetration rates. The calculation for this addition are yet to be computed.



a) 10 years

Storage penetration

RES-e penetration	0.2	0.6	1	1.4	1.8	2.2	2.6	3
0.5	1400	740	510	420	360	280	230	200
0.75	2000	1300	1130	960	880	830	800	770
1	2500	1890	1640	1540	1520	1450	1370	1340
1.5	2560	2260	2120	2050	2030	2030	2030	2020
2	2400	2240	2200	2180	2160	2150	2150	2140
2.5	2470	2330	2270	2260	2260	2260	2260	2250
3	2290	2180	2140	2130	2120	2120	2120	2120
5	1920	1920	1920	1920	1920	1920	1920	1920

b) 20 years

Storage penetration

RES-e penetration	0.2	0.6	1	1.4	1.8	2.2	2.6	3
0.5	2800	1480	1020	840	720	560	460	400
0.75	4000	2600	2260	1920	1760	1660	1600	1540
1	5000	3780	3280	3080	3040	2900	2740	2680
1.5	5120	4520	4240	4100	4060	4060	4060	4040
2	4800	4480	4400	4360	4320	4300	4300	4280
2.5	4940	4660	4540	4520	4520	4520	4520	4500
3	4580	4360	4280	4260	4240	4240	4240	4240
5	3840	3840	3840	3840	3840	3840	3840	3840

🟨 x ≤ 2500 cycles / year
🟨 2500 > x ≤ 3500 cycles / year
🟧 x ≥ 3500 cycles / year

Figure 42: Utilized yearly battery cycles[110]

---

[110] Source: Own illustration

5.3.3 Grid necessity and utilization

In terms of grid usage, the mixed system improves compared with the wind-dominated system but lacks on performance compared to the solar PV-dominated system. Figure 43 shows the effects on the feed-in mechanism of the modeled energy system. The overall improvement can be acknowledged when looking at the decrease of the 0.75x and 1x penetration of wind power curves. After they reached 100% storage penetration levels, their rate of increasing the number of feed-in incidents is slower compared to a wind-dominated system.

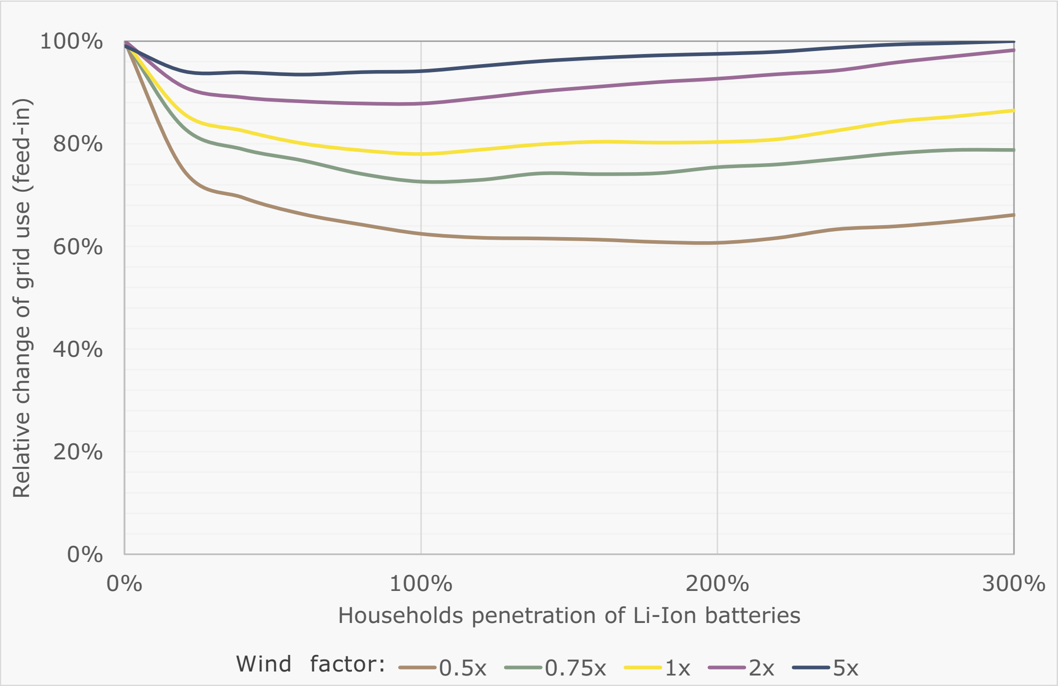


Figure 43: Grid utilization via feed-in[111]

A closer look at Figure 44 shows the improvements in using the grid to supply local demand. It is possible for the combined system to decrease the need for grid supply through all variants, the higher the iRES-e penetration the steeper the decrease when looking at the storage penetration levels. For 2x and 5x penetration rates of wind power, the trend increases again at ~90% and ~70% storage penetration rate respectively, while the yellow (1x) and the green (0.75x) curves remain low.

---

[111] Source: Own illustration

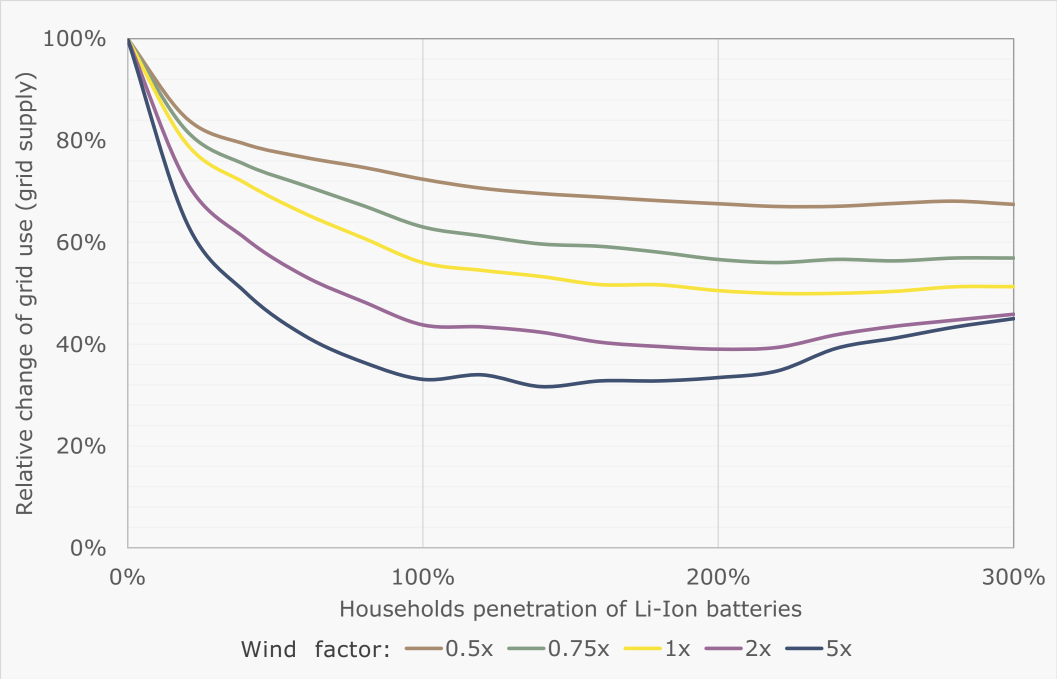


Figure 44: Grid utilization through supply[112]

5.4 Interpretation of socio-economic impact

As most of the results, basically across all three scenarios, showed a weak economic performance, some may think that storage technologies are not practicable for future, renewable energy systems. This thesis proofs that there is potential to harvest for technologies like Li-Ion battery storages but might not be economically feasible at current date and time. There are still some implications on the societal impact of flexible assets that have not yet been addressed by this thesis.

Today's energy system is stabilized by strong infrastructure, that is paid for by all citizens of a country or wider region. The infrastructure connects the demand with generation and every stakeholder in between. Simulating growing iRES-e capacity – like it was modeled in this thesis – lead to high volatility in the system independent of its size, without considering the effects of cross-national transmission capacities for balancing. These infrastructural assets bear the need for flexibility in various ways (e.g., redispatch) as it was explained in Chapter 2. The costs for this 'flexibility' are carried by the society through taxes and other duties. This thesis just shows very striking that flexibility has a price, and that price is paid by all consumers. Computing the negative NPV for different sensitivities does not mean that those investments are completely nonsense. They rather suggest increasing awareness of the price for flexibility or in other words: its value.

It is not the only value to provide the system with stability and secure electricity supply at any given time. Another dimension of societal value of flexible assets in decentralized power systems is the increased sustainability in the region. With reducing fossil-fueled energy generation, not just in the electricity sector, but also in heavy industry,

---

[112] Source: Own illustration

transportation and heating, a whole chain of positive effects will be kicked off. The evaluation of the modelled results show that adding flexible assets (e.g., Li-Ion batteries) to the system increases the economic feasibility of an increased capacity of iRES-e in a local energy system. This can be derived as a direct measure to increase the overall sustainability of the region.

Energy or electricity autonomy is at highest relevance not just between continents or countries. It also plays a major role on a regional level. The higher the degree of self-supply of electricity the higher the independence from outside the boundaries. Additionally, the higher the share of bilateral trade within the region, the lower the share of electricity needed to be supplied from the grid. This, if the relevant regulatory schemes will be set in place, could have a major impact on the economics of this regional energy system and create value to the consumers and households acting as stakeholders in this newly established system. As the results of the thesis also point out, the influence of BES systems on the necessary utilization of grid infrastructure is strong.

In the process of transitioning towards a future energy system, that is entirely powered by iRES-e, curtailment is the worst nightmare. Not just because of its opportunity costs, but more because this amount of energy could have been used if infrastructure were to be built. Flexible assets on a regional level can help buffering those amounts of energy both via demand-side management at the consumer side and small to large scale Li-Ion batteries as it was shown by the model in previous chapters.

6 Summary and Outlook

Historically, the development of electricity grids was driven by private companies promoting the benefits of electric power. In the beginning it was a luxury, but it eventually became a necessary part of everyday life. In much of the developed world, the ubiquitous availability of electric power is now considered an essential societal need, without which many of the goods and services society depends upon could not be produced or delivered. Along with this growing dependency on electricity, a different set of values has emerged. Electric vehicles, the ongoing changeover to electric devices, electric heating and cooling systems and the ability of every household to become a prosumer (being able to demand electricity from grid and supply electricity to the grid) made the power system of today more complex, but also provide the stakeholders with possibilities to leverage the effects of this complexity.

The research issue of this thesis was to investigate in flexibility needs and its accompanying potential and value to end-users. Additionally, the effects of different iRES-e penetrations were to be analyzed in a solar PV-dominated, a wind-dominated and a mixed iRES-e-dominated system with a regional model approach. Those issues were tackled via the establishment of a framework to determine the value of regional flexibility. The framework considered Li-Ion batteries as the available storage technology, constant residential electricity prices and a mathematical approach to compute flexibility needs on a regional level.

Taking the results from the modeling following the established evaluation framework, flexible assets are able to exploit excess iRES-e generated electricity by charging and discharging energy from storage, shifting energy into hours of demand. The thesis points out, how regional power systems are affected by the deployment of Li-Ion batteries through calculating various scenarios of iRES-e penetration rates. The impact of batteries on the utilization of grid infrastructure depends on the iRES-e scenario and its penetration rate. In a solar PV-dominated system the impact of BES systems are very big due to the fact that the sun is solely shining during the day, where the storage can be charged and discharged during night hours. This also reduces the usage of grid infrastructure, creating value to end-users and the public by spending less on additional infrastructure. The picture changes when looking at wind-dominated systems because wind generation is way less volatile over the course of a year. There are tipping points perceived by exceeding penetration rates of storage capacity of 100% (every household owns a battery – see Chapter 4.1 for details) and more where the effects on the utilization of the grid are reversed. This issue is explained by the simplicity of the model. An increased share of storage capacity linearly increases the total dis-/charging power of the aggregated battery leading to faster charging and discharging of the stored energy. This increases the number of hours where grid infrastructure is needed. It shows that increasing storage capacity and iRES-e capacity within a region makes sense as long as concomitant factors are taken into account for the various penetration rates. The results show that with current CAPEX levels of Li-Ion batteries the economic value of those flexible assets for end-users is not profitable under the modeled circumstances.

Cutting CAPEX in half will, for some cases in the solar-PV scenario, conclude to profitable use-cases of those BES systems.

The findings of this thesis incentivize to add more flexibility options like demand-response via electric vehicles in a vehicle-to-grid mode and other storage options utilizing heating and cooling devices in households to the model. Whereas this thesis kept residential power prices constant over the year, a future model could incorporate flexibility markets on a regional level to leverage the economics of storage technologies. The data granularity within this thesis was based on hourly time-steps. Current power markets undergo an extensive price shock and wholesale electricity trading is step-by-step developing towards a close-to-real-time market. To cope with this in the modeling of regional electricity systems, the framework needs to be adjusted to those developments by running the model on shorter time-steps (e.g., 15-minutes) instead. This offers the flexible assets the possibility to react faster and thus intercept incidents of extreme volatility as well as leveraging possible price spikes if real-time flexibility trading would be established.

More to encounter are future developments of residential electricity price levels and a possible refinement in the tariff model as this may arise from market developments on lower grid levels. Accordingly, investment costs for flexible assets, especially Li-Ion batteries, shall be monitored in years to come. To strengthen the evaluation of flexibility needs, the computation model could be revised through further research and the integration of differing approaches.

As it can be seen in the results of this thesis solely increasing the iRES-e capacity leads to an enormous volatile and instable system where the need for grid infrastructure skyrockets. As a consequence, further developments of the model need to take measures to cushion those effects taking into account all flexibility options that are available. In a system, where there are regulatory schemes that support investments in storage technologies and markets where the participation of those technologies is being implemented, an incentive is created to establish a system that is secured by storage and iRES-e replacing fossil-fueled, outdated power generation. This may lead to a stable and secure system that runs entirely on green energy.

7 Bibliography

Abrell, J., Rausch, S.; Streitberger, C. (2019): Buffering volatility: Storage investments and technology-specific renewable energy support. In: Energy Economics, Jg. 84, Nr. , S. 104463.

Abrell, J., Rausch, S.; Streitberger, C. (2021): The Economic and Climate Value of Flexibility in Green Energy Markets.

BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. (2017): Standardlastprofile Strom. URL: https://www.bdew.de/energie/standardlastprofile-strom/ (Zugriff: 05.10.2022).

Denholm, P., Mai, T., Kenyon, R., Kroposki, B.; O'Malley, M. (2020): Inertia and the Power Grid: A Guide Without the Spin.

DNV AS (2021): Energy Transition Outlook 2021 dataset. URL: eto.dnv.com/forecast-data (Zugriff: 05.10.2022).

Energie Steiermark AG (2022): Preisblatt Strom: SteirerStrom Sonne. URL: https://www.e-steiermark.com/fileadmin/user_upload/downloads/Kundeninformation_und_Preisblatt_SteirerStrom_Sonne.pdf (Zugriff: 05.10.2022).

ENERGIESPEICHER-ONLINE GMBH (2022): Energiespeicher. URL: https://www.energiespeicher-online.shop/ (Zugriff: 05.10.2022).

Esterl, T., Resch, G., Von Roon, S., et al. AIT Austrian Institute of Technology GmbH, Technische Universität Wien (TU Wien), Energy Economics Group, Forschungsstelle für Energiewirtschaft FfE (Hrsg.) (2022): FLEXIBILITÄTSANGEBOT UND -NACHFRAGE IM ELEKTRIZITÄTS-SYSTEM ÖSTERREICHS 2020/2030.

EU Science Hub (2022): PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM. URL: https://re.jrc.ec.europa.eu/pvg_tools/en/ (Zugriff: 05.10.2022).

European commission (2022): "Fit for 55": Council agrees on higher targets for renewables and energy efficiency. URL: https://www.consilium.europa.eu/en/press/press-releases/2022/06/27/fit-for-55-council-agrees-on-higher-targets-for-renewables-and-energy-efficiency/ (Zugriff: 24.09.2022).

European commission, Directorate-General for Energy (2019): Mainstreaming RES : Flexibility portfolios : Design of flexibility portfolios at Member State level to facilitate a cost-efficient integration of high shares of renewables, Publications Office.

Fünfgeld, C., Tiedemann, R. Brandenburgische Technische Universität Cottbus (Hrsg.) (2000): Anwendung der Repräsentativen VDEW-Lastprofile.

García-Gusano, D., Espegren, K., et al. (2016): The role of the discount rates in energy systems optimisation models. In: Renewable and Sustainable Energy Reviews, Jg. 59, Nr. 56–72.

Gonzalez Aparicio, I., Zucker A., et al. (2016): EMHIRES dataset. Part 1: Wind power generation European Meteorological derived high resolution RES generation time series for present and future scenarios.

Goutte, S., Vassilopoulos, P. (2018): The Value of Flexibility in Power Markets.

IG Windkraft (2018): Mehr als 20 Jahre rasante Entwicklung der Windkraft in Österreich. URL: https://www.igwindkraft.at/?xmlval_ID_KEY[0]=1045 (Zugriff: 04.10.2022).

IG Windkraft (2022): Windkraft in Österreich.

International Energy Agency (2021): World Energy Outlook 2021.

Jelti, F., Allouhi, A., Büker, M. S., Saadani, R.; Jamil, A. (2021): Renewable Power Generation: A Supply Chain Perspective. In: Sustainability, Jg. 13, Nr. 3, S. 1271.

Migliavacca, G., Rossi, M. et al. (2021): The Innovative FlexPlan Grid-Planning Methodology: How Storage and Flexible Resources Could Help in De-Bottlenecking the European System. In: Energies, Jg. 14, Nr. 4.

Monopolkommission (2021): Competition between electricity exchanges in Germany.

Mueller-Bloch, C.; Kranz, J. (2015): A Framework for Rigorously Identifying Research Gaps in Qualitative Literature Reviews.

Österreichs Energie (2020): Netzberechnungen Österreich - Einfluss der Entwicklungen von Elektromobilität und Photovoltaik auf das österreichische Stromnetz.

Range, A., Santos, J., et al. (2016): Modified Profitability Index and Internal Rate of Return. In: Journal of International Business and Economics, Jg. 4, Nr. 2.

Salihu, M., Delplanque, L. (2021): Energy service delivery will change in the next decade—and public-private cooperation will be key to the pivot. URL: https://blogs.worldbank.org/ppps/energy-service-delivery-will-change-next-decade-and-public-private-cooperation-will-be-key (Zugriff: 27.09.2022).

Selectra SAS (2022): Wie funktionieren die Nachtstromtarife in Österreich? URL: https://stromliste.at/strompreis/tarifarten/unterbrechbar/nachtstrom#:~:text=In%20%C3%96sterreich%20ist%20der%20Nachtstrom,Strombedarfs%20werden%20durch%20Wasserkraft%20generiert. (Zugriff: 05.10.2022).

STATISTIK AUSTRIA (2021): Energiestatistik: MZ Energieeinsatz der Haushalte 2019/2020.

Suna, D., Totschnig, G., et al. (2022): Assessment of flexibility needs and options for a 100% renewable electricity system by 2030 in Austria. In: Smart Energy, Jg. 6, Nr. 100077.

Westphal, K., Pastukhova, M.; Pepe, J. M. (2022): Geopolitics of electricity.

Williamson, S. (1999): Notes on Macroeconomic Theory.

Zerrahn, A., Schill, W., Kemfert, C. (2018): On the economics of electrical storage for variable renewable energy sources.

Appendix

Standard load profiles for households

These profiles are based on data provided by BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. which can be seen in Table 9:[113]

Table 9: Standard load profiles for households

[W]	Winter (1.11.-20.3.)			Summer (15.05.-14.9.)			Spring/Autumn (21.3.-14.5.;15.09.-31.10.)		
	Saturday	Sunday	Working	Saturday	Sunday	Working	Saturday	Sunday	Working
00:00	74.8	79.2	64.6	91.1	92.5	82.1	81.9	85.5	74.1
01:00	57.1	61.1	45.4	69.1	71.7	57.3	60.3	67.4	51.7
02:00	43.6	46.7	40.0	54.0	56.4	50.8	47.9	51.0	45.1
03:00	40.1	42.0	38.7	50.3	51.2	47.3	44.2	45.1	43.1
04:00	38.7	39.2	38.7	50.3	50.0	47.8	43.2	43.2	43.7
05:00	39.1	38.4	42.9	51.0	49.2	54.9	44.1	43.3	48.5
06:00	48.3	40.1	76.2	58.9	49.7	86.0	53.4	44.3	80.2
07:00	73.4	46.0	123.6	84.6	62.8	125.0	83.1	58.1	123.9
08:00	110.6	75.9	134.5	119.8	99.8	139.1	122.0	98.1	137.1
09:00	138.6	127.3	126.1	150.4	149.8	144.7	146.4	149.1	136.6
10:00	146.6	166.3	117.1	164.0	181.8	140.3	160.4	180.5	133.1
11:00	152.7	196.5	116.9	168.6	201.0	139.9	170.0	200.0	131.6
12:00	163.9	209.6	127.4	180.1	211.9	153.9	179.1	211.1	145.2
13:00	167.9	183.6	132.2	179.7	186.2	157.3	180.6	180.7	150.0
14:00	156.6	143.6	118.7	161.6	149.5	136.4	165.3	141.2	130.7
15:00	145.7	120.4	106.9	149.4	129.6	121.3	151.2	125.0	116.5
16:00	142.3	107.7	103.4	145.7	111.1	114.8	145.7	109.8	106.8
17:00	168.9	117.8	120.6	146.5	107.5	119.4	154.8	108.2	111.8
18:00	205.9	149.8	157.0	161.5	121.2	136.4	177.0	130.1	136.7
19:00	212.2	173.2	185.2	178.5	146.0	160.4	196.8	157.2	167.1
20:00	185.1	167.8	175.9	176.9	160.3	168.7	187.9	158.7	171.8
21:00	139.9	139.9	146.6	158.0	152.8	159.4	154.4	145.6	158.3
22:00	125.0	121.2	123.6	149.2	143.7	149.3	139.0	133.9	143.0
23:00	110.0	92.3	94.1	134.0	118.5	121.9	125.5	102.9	109.4

---

[113] Cf. BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., https://www.bdew.de/energie/standardlastprofile-strom/, (Zugriff: 05.10.2022).

Li-Ion batteries

The following list (see Table 10) includes all technologies considered for the creation of the averaged Li-Ion battery used for the modeling in Chapter 5. The information was extracted from the manufacturer's data sheets downloaded in the following stated source.[114]

Table 10: List of Li-Ion battery systems

Manufacturer	Name	Capacity	Dis-/Charge power	Discharge time	Costs
		kWh	kW	h	€/kWh
TESLA	Powerwall	13.50	4.60	2.93	834
Alpha ESS	SMILE-i3	5.5	3	1.83	1285
Alpha ESS	SMILE-Hi10	7.4	10	0.74	1608
BMZ	Hyperion 7.5	7.5	4.6	1.63	628
BYD	B-Box HVM	11.04	10.2	1.08	689
BYD	B-Box HVM	8.28	7.65	1.08	695
BYD	B-Box HVS	7.68	7.68	1.00	803
Fenecon	Home 8.8	8.8	4.48	1.96	1526
Heckert Solar	Symphon-E8.8	8.8	4.48	1.96	1707
HUAWEI	LUNA2000-10-S0	10	5	2.00	827
HUAWEI	LUNA2000-15-S0	15	5	3.00	740
LG Chem	RESU 10	8.8	5	1.76	755
LG Chem	RESU 12	11.7	5	2.34	641
RCT	Power Battery 9.6	8.64	9.6	0.90	976
RCT	Power Battery 7.6	6.91	7.6	0.91	1017
VARTA	Pulse 6 neo	6.5	3.2	2.03	1174

---

[114] Cf. ENERGIESPEICHER-ONLINE GMBH, https://www.energiespeicher-online.shop/, (Zugriff: 05.10.2022).