Optimization of self-sufficient energy hubs

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Abstract

This master's thesis analyzes renewable energy hubs in the residential sector. Three fictitious multi-apartment buildings are modeled with different components for energy production and storage. The primary focus of the analysis lies in the electrical domain, optimizing the energy flows in the hub. In the first scenario the photovoltaic (PV) system is optimally sized in a design optimization, in the second scenario a battery storage system (BSS) is added and in the third scenario, the energy hub is extended with a hydrogen storage system (HSS). The study assesses the impact of these configurations on critical performance metrics, such as total annualized costs and self-sufficiency ratio (SSR) with the two objectives being minimized annualized costs and maximized SSR, respectively.

In Scenario 1, the integration of additional PV capacity led to a substantial reduction in annualized costs and an increase in SSR, underscoring the economic feasibility of optimized renewable energy production. Scenario 2 introduced a BSS, resulting in further cost reductions and increased SSR values, highlighting the advantages of storage systems. It was shown, that theoretically full autarky could be reached with the storage, but not in an economically viable way. In Scenario 3, the HSS extension proved to be uneconomical due to the high cost of the electrolyzer and fuel cell stack as well as the lower roundtrip efficiency compared to the BSS.

Expanding the scope to larger communities, including municipal buildings and companies, as well as other energy sources like heat, could yield insights into collective energy management and sector coupling potential. This research contributes to advancing optimization strategies for renewable energy hubs and provides valuable insights into the corresponding operation and composition.

Kurzfassung

In dieser Masterarbeit werden erneuerbare Energiequartiere im Wohnbereich analysiert. Drei fiktive Mehrfamilienhäuser werden mit verschiedenen Komponenten zur Energieumwandlung und -speicherung modelliert. Der Hauptfokus liegt auf der Optimierung der elektrischen Energieflüsse im Energiequrtier. Im ersten Szenario wird eine Photovoltaikanlage in einer Designoptimierung optimal dimensioniert, im zweiten Szenario wird ein Batteriespeichersystem hinzugefügt und im dritten Szenario wird das Energiesystem um ein Wasserstoffspeichersystem erweitert. Die Analyse untersucht die Auswirkungen der unterschiedlichen Konfigurationen auf zentrale Kennzahlen wie jährliche Gesamtkosten und den Autarkiegrad, wobei die beiden Zielfunktionen des Optimierungsproblems minimierte jährliche Kosten bzw. maximierter Autarkiegrad sind.

In Szenario 1 führt die Integration zusätzlicher PV-Kapazität zu einer erheblichen Verringerung der jährlichen Kosten und zu einer Erhöhung des Autarkiegrades, was die Vorteile einer Optimierung der Erzeugungskapazitäten unter Berücksichtigung des Lastprofils unterstreicht. In Szenario 2 wird das Energiequartier um ein Batteriespeichersystem erweitert, was wiederum zu Kostensenkungen und höheren Autarkiewerten führt und die positiven Effekte von Energiespeichersystemen hervorhebt. Es wurde gezeigt, dass mit dem Speichersystem theoretisch ein Autarkiegrad von 100 % erreicht werden kann, jedoch nicht auf wirtschaftlich sinnvolle Weise. In Szenario 3 erweist sich die Erweiterung um ein Wasserstoffspeichersystem aufgrund der hohen Kosten des Elektrolyseurs und der Brennstoffzellen sowie des geringeren Gesamtwirkungsgrads im Vergleich zur Batterie als unwirtschaftlich.

Die Ausweitung auf größere Gemeinschaften mit kommunalen Gebäuden und Unternehmen, sowie anderer Energiesektoren, wie Wärme oder Mobilität, kann weitere Einblicke in das Sektorkopplungspotenzial und Möglichkeiten des Energiemanagements aufzeigen. Daraus können sich wertvolle Erkenntnisse über den optimalen Betrieb und die Zusammensetzung von verschiedenen Energiequartieren ergeben.

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List of Abbreviations

ACO	Ant colony optimization
AF	Annuity factor
BSS	Battery storage system
EXAA	Energy Exchange Austria
EC	Energy community
EMS	Energy management system
FIT	Feed-in tariff
GA	Genetic algorithm
HOMER	Hybrid Optimization of Multiple Energy Resources
HSS	Hydrogen storage system
IPCC	Intergovernmental Panel on Climate Change
IPM	Interior-point method
KPI	Key performance indicator
kWh	Kilowatt hours
kWp	Kilowatt peak
LCOE	Levelized cost of energy
LP	Linear programming
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
MIQCP	Mixed integer quadratic constrained programming
MWh	Megawatt hours
NPV	Net present value
OeMAG	Austrian settlement agency for green energy
PEM	Proton exchange membrane
PMS	Power management system
PSO	Particle swarm optimization
PV	Photovoltaic
RED I	Renewable energy directive I
RED II	Renewable energy directive II
RES	Renewable energy sources
SOC	State of charge
SSR	Self-sufficiency ratio

1 Introduction

1.1 Motivation

Currently the need for green, renewable energy as well as affordable energy is larger than ever. The climate crisis is nothing new but the current rise in energy prices is unprecedented. Not only companies that heavily rely on fossil fuels as energy sources but also households and municipalities struggle with rising energy bills. They need alternatives that will be reliable in the long run. Alternatives like this exist, they are not always cheap, but with the rise in energy prices and increasing carbon taxes, they get more and more affordable. One example would be the foundation of so-called Energy Communities (EC) where private households, municipalities, or small and medium companies can share their collectively produced energy within the community. This can range from simple neighborhood communities with only a couple of PV panels to whole towns running their collective storage systems and getting fully independent from external energy suppliers. In most cases, total energy independence, also called self-sufficiency can only be reached at a very high cost [1]. To build systems like this, energy production capacities are necessary. They can include PV panels, wind turbines, small hydropower plants, heat pumps, geothermal plants, and many more components. Additionally, to overcome the variability of renewable energy sources (RES) and to shave the peaks in energy production, storage solutions are needed. In order to reach full self-sufficiency these production and storage capacities need to be very large which goes hand in hand with large overproduction that often stays unused. This fact is another opportunity for ECs because there the surplus energy can be shared and consumed within the community. Depending on the storage system, it enables the user to store the produced energy during the daytime for the nighttime or to shift the energy from summer to winter. In general, energy production that is not directly needed at the same time can be shifted to times when it is needed. Two potential storage solutions are batteries and hydrogen storage with electrolyzers and fuel cells. The daily and seasonal patterns of intermittent renewables are known, but they need to be fed into intelligent algorithms to be able to store the yearly energy production in a way that the yearly energy demand can be fulfilled at the time it arises. This can be done with the help of energy management systems (EMS) that know about the characteristics of yearly energy production and household energy consumption. With this data, the storage systems can be filled and drained in an optimal way.

Exactly that is the goal of this thesis: To find out, what the optimal sizes of different components in the energy system are, to fulfill a given energy demand in a cost-minimal scenario and an SSR-maximal scenario.

1.2 Problem statement

The problem that arises when building up renewable capacities in the residential sector is that the individual consumption and production profiles are not known beforehand and that all the houses or buildings are only designing projects that fit their own need. Everyone decides on their own and the outcome for the community as a whole is not optimal, only for each individual. This often results in total higher costs and lower self-sufficiency than in the other case, where more people or buildings get together and design a holistic energy system that fits their collective needs.

Most of the time the needed data to simulate such holistic systems is missing and the knowledge of individuals about potential solutions is limited.

1.3 Approach

To solve this problem and to analyze the dynamics of larger scopes than individual households, assumed load profiles for three multi-apartment buildings that each have their own PV panel were set up and analyzed. The PV system produces collective energy for all the parties living or working in the houses instead of only belonging to one party to fulfill their demand.

In order to optimally fulfill the demand of the energy hub, different scenarios are set up. There are always two objectives for each scenario, namely minimal annualized costs and maximum reachable self-sufficiency. The Baseline scenario describes the existing energy hub with the PV production as it is and models the total costs and self-sufficiency to set a baseline and show the status quo. Scenario 1 utilizes a design-optimization approach to optimally size the PV system for the houses of the energy hub. Scenario 2 adds a BSS to see how the costs and the SSR change. Scenario 3 adds an HSS to see if it is an economically viable option for energy hubs.

In Chapter 2, a comprehensive literature review is conducted and the most relevant sources in the field of optimization and design of energy hubs are documented and compared. The necessary background information about energy hubs and production and storage components is provided.

In Chapter 3 the goal and scope of the study are expressed and the research questions are defined. The composition of the energy hub is documented and the optimization approach is explained. The objective functions, constraints, variables, and parameters for all the scenarios are mentioned.

After the description of the optimization model, the results are reported in Chapter 4. The outcomes of all the scenarios and for both objectives are documented and then compared in the discussion, together with a graphical illustration of the energy flows in the hub in an exemplary week of the year.

To summarize the results a conclusion is drawn in Chapter 5. Limitations of this study are pointed out and potential objectives for future research are mentioned. The scope of this study can be extended in many different directions by adding to the optimization model to gather new insights into different types of energy hubs.

2 Theoretical Background

To understand the concepts and methods used in this thesis, some background knowledge concerning definitions and frameworks is necessary:

- What are energy hubs or energy communities in general?
- Why do they need energy management or an optimization of the energy flows?
- What optimization frameworks do exist and what are the differences?
- Which frameworks are used in the scientific literature for what purpose?

This chapter provides basic knowledge, an overview, and answers to the questions at hand.

2.1 Energy communities and energy hubs

In 2018 the European Union (EU) revised the Renewable Energy Directive I (RED I) from 2009 and created the Renewable Energy Directive II (RED II) within the Clean Energy for all Europeans package. This legislation had to be integrated into national laws within two years and has been legally binding since June 2021. Apart from the goal to ramp up renewable production and increase sector coupling between the mobility, heating, and electricity sectors in the EU it also includes principles on how to produce, consume, and share renewable energy within ECs [2]. This concept is already fully integrated into Austrian law and made the foundation of ECs possible at the end of 2021 [3]. ECs are energy hubs that consist of at least two members with at least one renewable production plant. These members are allowed to collectively produce, share, store, and consume their own energy together, either within the same property, for example in a multi-apartment building as shown in Figure 1 or by using the public electricity grid. This is incentivized by implementing a lower grid fee for electricity that is shared within a local EC.

Additionally, the members of an EC decide on the energy price for their electricity on their own. This means that producers can potentially get a higher remuneration than from

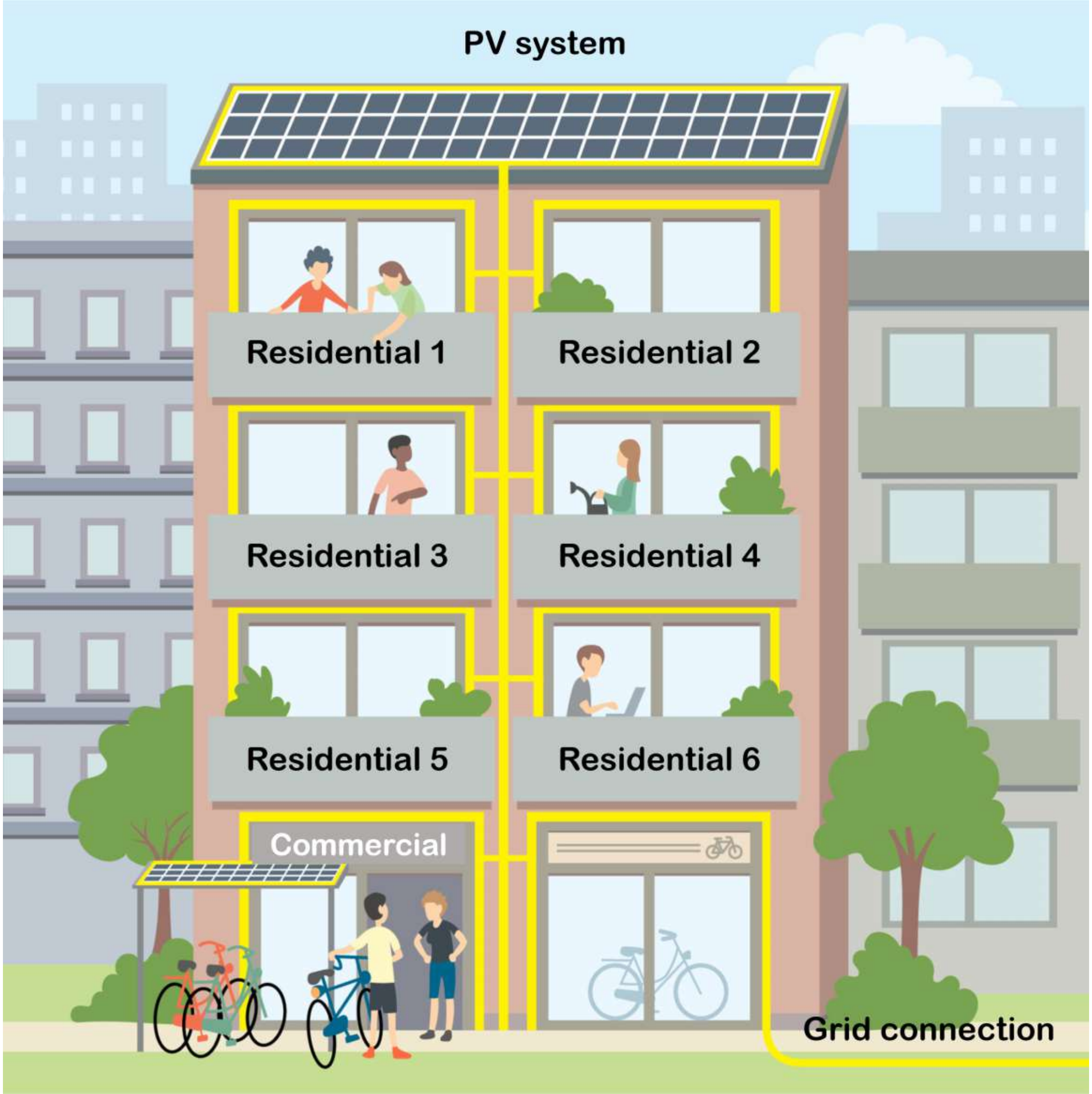

Figure 1: *Framework of the concept of a community generation plant in Austria [4]. Both residential and commercial consumers collectively use energy from the same PV system. Additionally, a means of storage could be implemented into this existing energy hub.*

a feed-in tariff for their energy and consumers are able to buy cheaper energy than they would get from their energy provider. This concept of ECs aims to increase renewable energy production as well as local consumption and therefore self-sufficiency. Moreover, it gives individuals, households, municipalities, real estate owners, small and medium-sized enterprises, or larger organizations the ability to become more independent from their energy providers by supplying themselves partly or fully with their own collective energy and only need the public grid as a backup energy source [5]. What remains is the problem of the intermittency of renewable energy sources. Neither the sun nor the wind can produce energy around the clock. That is why sector coupling between the sectors of electricity, heat, and mobility can provide potential solutions. In times when there is an excess of renewable electricity production, this electricity can be used to prepare and store heat for times when it is needed, or it can be used to charge electric vehicles or batteries that serve as energy storage in general. This also has a positive side effect on the public grid and the loads that it needs to handle. ECs, or in general renewable energy hubs can be easily implemented, but in order to make a real difference a lot of effort in the proper planning and building of the energy systems is needed. Additionally, through optimization methods energy flows between the production, storage, and consumption components can be optimally allocated to reach maximum efficiency and self-sufficiency. Depending on the goal, the energy system can be optimized for different objectives, like minimizing costs or reaching a certain level of self-sufficiency for the lowest cost. To reach this and to set up proper optimization models, different frameworks and algorithms exist. These are described in the next section.

2.2 Energy management and optimization

The concept of energy management considers existing consumption and production capacities and physically manages the energy flows between them in an optimal way, or at least in a previously decided manner to reach certain goals. To be able to implement energy management in buildings or larger energy hubs, hardware components are necessary. Before this can actually happen it can be useful to set up a digital model of the energy system to simulate the energy flows between the components in an optimization model. This model includes all the component parameters and necessary pre-calculations and defines variables and constraints that describe the functioning and the interaction of the corresponding components. Depending on the given information, the existing components, and the optimization goals, different frameworks or algorithms can be used. It is possible to differentiate by the type of optimization, or by the employed optimization algorithm, depending on the nature of the variables and constraints. Two important optimization types are design and operation optimization. In a design optimization problem, the solution is the optimal sizing and design of the components in the energy system that are not previously known. Depending on the requirements, constraints, and objectives the optimal design of the energy system in the energy hub is the outcome. Compared to this an operation optimization approach aims to find the optimal operation strategy of a given set of components and their interaction to reach a certain objective. In the energy context, this is often called a unit commitment problem that takes different production and consumption units into account and matches their load profiles, complying with the constraint that the demand needs to be fulfilled and the component and operation-related constraints. The outcome is an operation schedule of the components over a certain time horizon to fulfill the demand and minimize or maximize a certain objective. To solve problems like these, different algorithms can be employed. [6] There are deterministic algorithms like linear programming (LP), mixed integer linear programming (MILP), or mixed integer non-linear programming (MINLP) and there are stochastic algorithms, like genetic algorithm (GA), particle swarm optimization (PSO), or ant colony optimization (ACO), sometimes also called meta-heuristic algorithms. [7]

Deterministic optimization algorithms have the advantage of reaching an optimal solution in case one exists or at least finding a solution in close proximity to the optimum. If the optimization problem is not explained precisely enough so that there is no optimum because of missing constraints it is called unbounded. On the other hand, if there are contradicting constraints that do not have a matching solution space there is no possible solution and the problem is called infeasible. One problem with using these algorithms can be the computing time. It increases exponentially with the size of the problem. Nowadays there are already very efficient solvers that are still able to find optimal results. [8] For some very large or complicated problems there is the possibility, that no optimal solution can be found. Either because no individualized solution algorithm exists or because the computing time increases exponentially with the input parameters. This brings up the need for reaching good enough solutions in a justifiable timeframe. Exactly this is the advantage of statistical algorithms, also called heuristics. They do not necessarily find the global optimum but they can lead to good enough solutions and local optima. [9]

The explained algorithms are mentioned in the following Sections 2.2.2 - 2.2.7 and give an overview of other used methods in the area of optimization mentioned in the literature from Table 1.

2.2.1 Linear programming (LP)

LP, also called linear optimization can be used for solving a wide variety of optimization problems. They are also applied in other optimization frameworks to solve initial smaller problems. Two well-known ways to solve such problems are the Simplex-algorithm and the interior-point method (IPM). [8] For the Simplex-algorithm the starting point is the finding of an initial starting point that fulfills the constraints and is a feasible but not optimal solution itself. The feasible solution space can be thought of as a Polyeder, where the Simplex-algorithm jumps from edge to edge on the surface of this polyeder to find out if the next possible solution is better than the previous one. Opposed to that, the IPM algorithm does not operate at the surface but inside the polyeder to find new possible solutions and compare them to the previously best solution. Finally, the optimal solution is always found on the surface of the solution space, both for the Simplex-algorithm and the IPM. These techniques are often used for solving subproblems of other problems, like nonlinear optimization problems, MILP and also MINLP. To guarantee an efficient way of solving, especially for problems with a large number of inputs it is useful to define clear objective functions, non-redundant constraints and an orderly built up equation matrix for solving. [8]

2.2.2 Mixed integer linear programming (MILP)

In linear programming all the constraints and the objective function are linear and the variables are continuous and constrained. This often does not represent reality, because in real-life problems many variables are not continuous but discrete. This stays true for binary decisions where the value of the variable can be either zero or one, like on/off states, decisions between two options, or open/close decisions. [7] This also counts for other values, like product entities and sizes or number of employees, that can only be given in discrete integer numbers. The complexity of such problems increases exponentially with the number of binary or integer variables. Luckily, there are very efficient solving algorithms like branch-and-bound or branch-and-cut. [10]

2.2.3 Mixed integer non-linear programming (MINLP)

In comparison to MILP problems with linear constraints and objectives, more general MINLP problems additionally have non-linear constraints or even a non-linear objective function [9]. These are generally complex to solve. That is why MINLP problems, or at least parts of them can be linearized or reformulated. This leads to relaxations of the given constraints or objectives and therefore a deviation from the truly optimal solution.

The advantage on the other hand is, that it is easier to solve the problems or it takes less computing time, and therefore an acceptable solution can be found faster. Relaxations of the non-linearities often result in problems that can be characterized as mixed integer quadratic programming or MILP problems and can be solved more easily. [7]

2.2.4 Particle swarm optimization (PSO)

PSO takes into account the whole solution space and starts with a certain swarm size of particles that are randomly positioned within the system boundaries in the whole space. Each of these particles represents a vector containing the current position, the velocity and direction of movement, and the solution at the current position. In an iterative process, the velocity and the direction of movement are updated continuously depending on the best solution and position of the particles in the close surroundings and on the best historical solution and position that has been found in all the previous iterations. Iteration by iteration, that particles will move across the solution space and find different local or global optimums within the boundaries. The final solution strongly depends on parameters like the initial swarm size and the number of iterations. [11] Starting from a random solution in the space the PSO often quickly converges towards the optimum. That is, why energy system modeling often employs this type of algorithm because it can be fast and results in reliable solutions. [6]

2.2.5 Ant colony optimization (ACO)

Similar to the PSO algorithm, ACO is also an evolutionary algorithm inspired by nature. ACO algorithms mimic the food search of an ant colony. Similar to the ants in real life, agents search for optimal solutions in the solution space. Once food is found they secrete pheromones for other ants to find the correct path, thus optimizing the way to the food source. The same applies to the mathematical algorithm. Different nodes in the solution space are randomly found by the ants. Depending on how good the solution is, more or less pheromones are secreted. Through this in a second iteration, some nodes have a higher probability of being found than others. It is still possible, that the ants find even better solutions randomly or in proximity to the previous best solution, therefore optimizing the objective from iteration to iteration. The food search continues until all the ants follow the same path to an optimal solution or until some threshold value is reached. [12]

2.2.6 Genetic algorithm (GA)

GA is a so-called (meta)heuristic algorithm. Due to its iterative process, it is also an evolutionary algorithm, similar to PSO and ACO. Other solution techniques for optimization problems are able to find an exact solution for the problem at hand. Sometimes this is not possible due to the nature of the problem, because it cannot be formulated in enough detail, or because the computing time increases exponentially. In that case, it is necessary to find heuristics that are able to compute an acceptable solution for the optimization problem, without being able to define the proximity to the truly optimal solution. Like many other heuristics, GA is inspired by processes that actually occur in nature. In this case by the theory of evolution. The idea is that there is not one single solution but a whole generation or population of admissible solutions. Starting from an initial population, pairs of solutions can create new solutions. The so-called parents create the children's generation. This can be purely random or following some structure, depending on the problem. Additionally, mutations in the children's generation are possible through random changes. The new population is then integrated into the old one by replacing all or some members by analyzing their solutions. The best solutions stay and the worst are kicked out until a certain threshold is reached. This threshold defines when the optimization and the generation of new populations is terminated because a good enough value is reached. [9]

2.2.7 Other software tools for optimization

There are other software tools in existence that provide energy system modeling, optimization, and sensitivity analyses. One example is the HOMER software [13], which stands for Hybrid Optimization of Multiple Energy Resources. In general, it is used to model all forms of energy systems. They can model everything from small energy systems like small villages and off-grid island systems to large energy systems like whole cities or other grid-connected energy hubs. By defining the input parameters and setting up the used or potentially used components it models the operation over a period of up to one year in individualized timesteps. In the next step, this can be used for the optimal design of the system if there are different possible compositions and sizes of each of the components as well as the optimal operation for different objectives, depending on production, storage, and consumption patterns. [13]

2.3 Literature Review

The mentioned algorithms in Section 2.2 are employed and described in many scientific articles, representing the research base of smart energy systems, self-sufficient energy hubs, microgrids, or in general energy system modeling and optimization. Depending on the scope of the technology at hand different types are used or a comparison between different algorithms is concluded. Out of nearly 50 papers in the literature research, the following nine turned out to be the most relevant for the optimization approach and comparison between different types of energy hubs, due to their explanations of the used methodology, paired with the detailed mathematical descriptions of the employed constraints and objectives. They are listed in Table 1. The modeling of the PV system, the BSS, and the HSS provided guidance for the modeling of the present energy hub. The rest of the literature was either on a different topic in the area or not connected with an optimization approach. The specifics and the findings of the individual articles are described in the next paragraphs.

Abo-Elyousr et al. (2021) analyzed a hybrid microgrid with renewable production from wind and solar PV and a diesel generator as backup. As a means of energy storage, they modeled a hydrogen system and proposed two hybridized PSO and ACO algorithms with the objective of minimizing the Levelized cost of energy (LCOE). They tested their algorithm with data from three different geographic locations around the world, namely Egypt, Mozambique, and Denmark. [12]

Chen et al. (2022) propose an optimal capacity planning strategy for microgrid configurations with PV and wind as intermittent renewable sources. A battery storage serves for load shifting, and a diesel generator and the grid as backup energy sources for times where no renewable production is available. Their objectives are maximum renewable energy utilization, minimal costs, and minimal carbon emissions. A multi-objective PSO algorithm is used for optimization. [14]

De Oliveira e Silva and Hendrick (2017) analyzed households in Belgium and their capability of reaching self-sufficiency in two different scenarios, namely PV only and with added battery storage. They found out that up to 30% of self-sufficiency can be reached with solar energy alone. With a battery storage system, rates higher than 40% are feasible, resulting in substantially higher LCOE due to larger PV installations and an increase in battery capacity. This increase in cost was not cost-competitive to grid prices back in 2017. [15]

Ibáñez-Rioja et al. (2022) analyzed an off-grid hydrogen production system with solar PV and battery integration to minimize the cost of green hydrogen. They used a PSO algorithm for simultaneous control and component sizing optimization. They found out that the main purpose of the battery is to prevent the electrolyzer from frequent startup and shutdown and stabilize hydrogen production during the day. Additionally, they argue that the proton exchange membrane (PEM) electrolysis has the largest impact on hydrogen cost. For future research, they suggest including capacity-dependent component prices and degradation factors as well as additional renewable production capacities such as wind or small-hydro. [11]

K/bidi et al. (2022) optimized the components in the analyzed microgrid with a coupled power management system (PMS) and an EMS. While the EMS looks at the energy production and demand profiles and schedules the components like battery, electrolyzer, and fuel cell, the PMS is for instantaneous management. The authors take the specific operating behaviors of the different components into account and therefore try to limit degradation through unsuitable operating behavior, like for example many on/off cycles for electrolyzers and fuel cells. This is reached through special constraints that are implemented to simulate the operation. Additionally, the optimization is performed every 30 minutes scheduling a commitment plan for the next six hours, in case some weather parameters change. [16]

Monforti Ferrario et al. (2021) looked at a stand-alone microgrid and the optimal sizing of a corresponding hybrid energy storage system, consisting of a battery and hydrogen storage system (HSS). They analyzed four different scenarios, namely battery-only, hydrogen-only, hybrid battery priority, and hybrid hydrogen priority. What they found out is, that the hybridized models perform better than the single models in terms of energy security and efficiency while resulting in increased total costs because of the high prices of the HSS. [1]

Murray et al. (2018) compared the potential for hydrogen storage systems to that of battery and thermal storage for several years between 2015 and 2050. In three scenarios, that are defined according to a report from the Intergovernmental Panel on Climate Change (IPCC) they analyze long- and short-term storage options and use a multi-objective optimization approach that considers both cost and emission minimization. A whole range of components is considered, including PV, small-hydro and wind power, heat pumps, gas turbines and boilers, electrolyzers, fuel cells, a battery, and thermal and hydrogen storage systems. In the first step, the energy demand is modeled before the RES is included. After that, the multi-objective optimization is conducted. The results show, that neighborhoods with a large amount of surplus energy are more suited to use hydrogen storage systems, especially from 2035 to 2050 and those with less surplus energy should consider the short-term option with battery and thermal storage systems. [17]

Pang et al. (2022) looked at the possibility of power-to-heat and hydrogen to supply both the hydrogen demand and produce enough electricity, heating, and cooling power to supply the integrated buildings. They looked at an off-grid system consisting of PV panels, wind turbines, batteries, electrolyzers, heat storage, hydrogen tanks, and absorption chillers and minimized the total life cycle costs while ensuring optimal sizing and scheduling of the components. They achieved an optimal outcome with a mixed integer quadratic constrained programming (MIQCP) methodology and fulfilled both the hydrogen demand and the building energy demand for heating, cooling, and electricity. [18]

Zhang et al. (2017) studied the differences between battery and hydrogen storage in grid-connected systems with PV as a means of electricity production. They looked at two operation strategies and a combination of these two as a third one. They found out that hydrogen storage performs better when grid power fluctuations are considered, resulting in a better value for net present value (NPV) and SSR. They also mention that batteries are normally considered over hydrogen because they are cheaper, have better efficiency, and are considered to be the more mature technology although hydrogen has a higher energy density, no self-discharge rate, and is suited for long-term storage, unlike batteries. [19]

This literature review was used to find out about existing strategies and use cases and to compare the outcomes between them. Two main differences to the present thesis are the geographical location of Austria and the scope of the energy system. The reviewed systems are based all around the globe in locations like Egypt, Mozambique, Denmark, China, Northern, Central and Southern Europe. Many studies include more than one energy source, for example renewables like PV, wind turbines, small hydropower or also diesel generators. Some even connect different sectors like electricity and heat. This is reasonable because they also analyze larger scopes, like whole cities or off-grid communities. Especially in the off-grid scenarios hydrogen utilization is present, while in the grid-connected cases, it is often only feasible at higher costs. This is mostly due to the need of longer-term storage of excess energy. There is no other source than the renewables that are supposed to replace fossil sources like the diesel generator and therefore enough storage capacity in the form of batteries, hydrogen or heat storage are needed.

While for larger scopes, like in the mentioned literature in Table 1, more advanced methods and algorithms like PSO, ACO or GA are implemented, we decided to use a MILP approach. This approach was chosen due to its ability to produce optimal results instead of sometimes finding only regional optimums and the fact that optimization problems can be implemented easily. The other mentioned algorithms are more complex and need a lot more computing power to find reasonable solutions. Compared to whole off-grid communities that rely on total self-sufficiency in this thesis three multi-apartment buildings with access to the public electricity grid are implemented. The results are compared to results from this literature research in Section 5.1 where all the research questions are answered.

Reference	**Year**	**Location**	**Components**	**Data**	**Grid/ Stand-alone**	**Main objective**	**Method**	**Software**
Abo-Elyousr et al. [12]	2021	Egypt, Mozambique, Denmark	PV, wind, diesel engine, hydrogen storage	Copernicus Atmosphere Monitoring Service (CAMS)	Off-grid, Stand-alone	LCOE, component sizing	PSO, ACO	MATLAB
Chen et al. [14]	2022	Northern China	PV, wind, battery, diesel generator, power grid	Historical data profile generation through GAN	Grid	RES utilization, Cost, Carbon emissions	Multi-objective PSO	Python
de Oliveira e Silva and Hendrick [15]	2017	Belgium	PV, battery	Household load profiles, Belgian Royal Meteorological Institute	Grid	SSR, LCOE	-	-
Ibáñez-Rioja et al. [11]	2022	Southeastern Finland	PV, PEM electrolyzer, battery storage	PV data from a semi-detached house in southeastern Finland (10 kWp, 26° tilt)	Off-grid	Minimal cost of green hydrogen production	PSO, GA	MATLAB
K/bidi et al. [16]	2022	French island close to Madagascar (University of La Réunion)	PV, electrolyzer, fuel cell, battery	Solar irradiance, ambient temperature and load data from University of La Réunion	Off-grid	Consists of three parts: Minimize each elements power, minimize number of start/stop of FC and EL, minimize difference between BESS SOC and its reference	MIQP (Mixed Integer Quadratic Programming)	MATLAB
Monforti Ferrario et al. [1]	2021	Huelva, Spain	PV, wind, battery, hydrogen	Meteorological data, demand data	Off-grid, island-mode	Loss of load, overproduction, roundtrip storage efficiency η_{ESS}, total storage cost C_{tot}	PSO & multi-dimensional parametric analysis	MATLAB
Murray et al. [17]	2018	Switzerland (cities of Zernet and Altstetten)	PV, wind, small hydro, heat pump, electrolyzer, fuel cell, gas turbine, gas boilers, battery-, thermal-, hydrogen storage	Weather data, building geographic and statistical data for demand and renewables supply calculations	Grid (gas, heating, electricity)	Cost and emission minimization	multi-objective optimization using the epsilon-constraint method	Python with CPLEX solver
Pang et al. [18]	2022	Zhangbei City, China	PV, wind, batteries, electrolyzers, heat storage tanks, hydrogen tanks, absorption chillers	Meteorological data, economic data	Off-grid	Minimal total lifecycle costs	MIQCP (Mixed Integer Quadratic Constrained Programming)	Python
Zhang et al. [19]	2017	Gothenburg, Sweden	PV, electrolyzer, fuel cell, battery, hydrogen storage	Consumption data, local weather data	Grid	NPV, SSR	GA	MATLAB

Table 1: *Result of the literature research. The papers are compared according to different categorizations.*

3 Optimization

In this chapter the general goal and scope of the optimization approach are explained with the system boundaries for the different scenarios. The energy hub, consisting of all the conversion and storage components in the energy system is introduced. The production and consumption behaviour and the methodology of the optimal sizing is explained with all the parameters, variables, constraints, and objective functions that are used for the optimization.

3.1 Goal and scope

The goal of this thesis is to optimize the energy flows in the given energy hub under different scenarios that are explained in detail in Sec. 3.2. The narrow scope is continuously extended from scenario to scenario by adding components like PV panels, battery storage, and hydrogen storage. Initially, only the basic energy hub with a given electricity demand and a grid connection is examined, serving as a benchmark to compare with the results of the other scenarios. Each of the scenarios is optimized for two different objectives. The first one minimizes the annual costs of the whole energy hub and the second objective maximizes the SSR of the energy hub. For the second objective, the costs of the energy system are not constrained. The goal is to see how the annualized costs and the maximum reachable SSR value change from scenario to scenario. It is expected, that the total annualized costs decrease by adding storage capacities to the energy hub, due to the fact, that more self-produced energy can replace energy from the public energy grid. Additionally, the SSR should increase by adding storage to the system, simply by providing a means of shifting peak production to times of no self-production. The given energy hub consists of three fictitious multi-apartment buildings, located in Austria. The composition of the apartments is very diverse, including single-person households, couples, families, and both working and retired people. There is also data on the energy consumption of two commercially used areas in the building. Each building also measured the common electricity consumption for the general area and lighting and the PV production on each of the houses. The respective compositions are shown in the

Tables 2, 3 and 4.

The performance of the different scenarios is measured by two objectives, namely costs and SSR. The costs represent the economic factor and the SSR represents the efficiency of the system by showing how much grid electricity can be replaced by renewables and storage capacities and which level of energetic autarky can be reached. Both of these are important metrics for decision-makers, to evaluate the economic and energy efficiency as well as the ideal size of the system.

Figure 2 shows the interaction between input parameters, system modeling, and the optimization framework, which is a design optimization approach that optimizes the component sizes and the corresponding energy flows between them over the period of a whole year of operation. The final outcomes are the two objectives, minimized costs and maximized SSR, as well as the component sizes and other key results as the energy flows between the components.

3.1.1 Research questions

Inspired by the literature research and practical interest in the given energy hub to find out how efficient different constellations of production and storage capacities work together, the following research questions were formulated and are evaluated in this thesis:

- What amount of theoretical and real self-sufficiency is reachable for the given energy hub in the different scenarios?
- Can this amount be increased by increasing PV capacity or adding storage potential, or is it already optimally sized?
- What is the economically optimal size of the components (PV, battery storage, hydrogen storage) for the given demand, and which level of self-sufficiency can be reached at this point?
- What is the maximum level of self-sufficiency that can be reached, neglecting costs, and which sizes do the components have?
- Is it possible to reach full electric autarky with the resources available in the given area?
- What is the difference between the scenarios concerning costs and SSR?

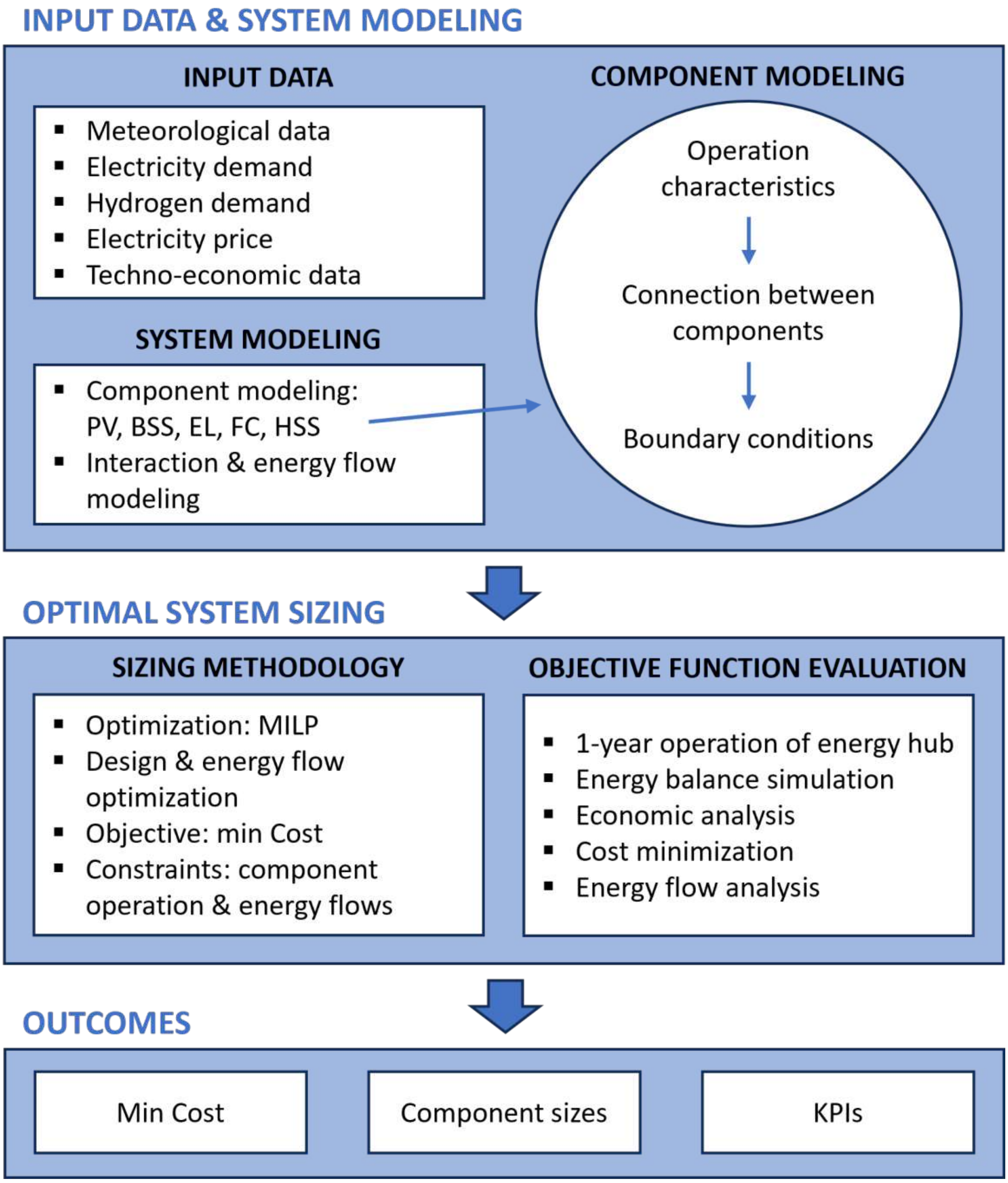

Figure 2: *Optimization framework for the optimal sizing of the energy system. Graphic inspired by Marocco et al. [20]*

3.1.2 Energy hub

As mentioned, the energy hub consists of three fictitious multi-apartment buildings. Each of the buildings has a PV system mounted on its roof. The PV production as well as the household consumption data is given in hourly intervals. The sum of the electricity consumption of each household, as well as the total annual production of the PV panels is given in the Tables 2, 3 and 4. Therefore, the total annual electricity production and demand can be derived for each of the three houses.

Table 2: *Composition of the energy hub and the corresponding electricity consumption/production from house 1 in* kWh*.*

House 1	Apartment type	Electricity consumption in kWh
1	Residential	4.350
2	Residential	3.335
3	Residential	12.552
4	Residential	4.067
5	Residential	3.274
6	Residential	2.162
7	Residential	6.193
8	Residential	3.474
9	Residential	3.000
-	Commercial	2.953
-	Common consumption	833
-	PV production	15.793
-	Total consumption	46.193

The starting point is the Baseline scenario where grid electricity from the Austrian power grid is consumed in addition to the electricity produced by the existing PV panels. With these annual consumption and production patterns the values for the different energy and cost flows, like the total electricity demand, the total PV production, the feed-in from the PV to the grid, the remuneration for feed-in, the consumption of grid electricity, and the costs for that electricity can be calculated. Additionally, with the given parameters for the PV sizes, specific costs for the PV panels, an interest rate, and the lifetime of the panels, an annuity factor can be calculated. Together with the other

Table 3: *Composition of the energy hub and the corresponding electricity consumption/production from house 2 in* kWh.

House 2	Apartment type	Electricity consumption in kWh
1	Residential	2.137
2	Residential	2.442
3	Residential	2.729
4	Residential	1.721
5	Residential	3.111
6	Residential	4.305
7	Residential	3.324
8	Residential	2.688
9	Residential	3.007
10	Residential	2.850
11	Residential	7.901
12	Residential	4.548
13	Residential	2.739
14	Residential	1.909
-	Common consumption	2.005
-	PV production	14.465
-	Total consumption	47.516

Table 4: *Composition of the energy hub and the corresponding electricity consumption/production from house 3 in* kWh.

House 3	Apartment type	Electricity consumption in kWh
1	Residential	3.581
2	Residential	4.770
3	Residential	3.055
4	Residential	2.732
5	Residential	2.543
6	Residential	2.799
7	Residential	2.910
8	Residential	3.124
9	Residential	3.150
-	Commercial	33.277
-	Common consumption	1.254
-	PV production	15.965
-	Total consumption	63.195

expenses the total annualized costs can be calculated. All of these values can be derived for the energy hub as a whole, as well as for each house individually. The results of these calculations are documented in Section 4.1.

The present problem analyzes the three fictitious multi-apartment buildings with 9, 14, and 9 households, respectively. Each of them is equipped with a PV system. The demand data of the individual households as well as the PV production data are known in an hourly resolution. In addition, the common electricity consumption of each house is measured. The total electricity demand of the energy hub over the whole year is nearly 157 MWh while the production of the PV panels adds up to about 46 MWh. This means that theoretically, the maximum reachable SSR value is 30%, if all the produced electricity from the PV panels is directly consumed. In reality, this is not the case because the demand and supply of electricity are not always coherent in time. The real SSR was calculated to be 27%. To increase this value, two measures need to be taken. The first one is to increase the PV system size so that more energy can be produced, which will in some cases help to supply more energy during the daytime but will mostly lead to higher

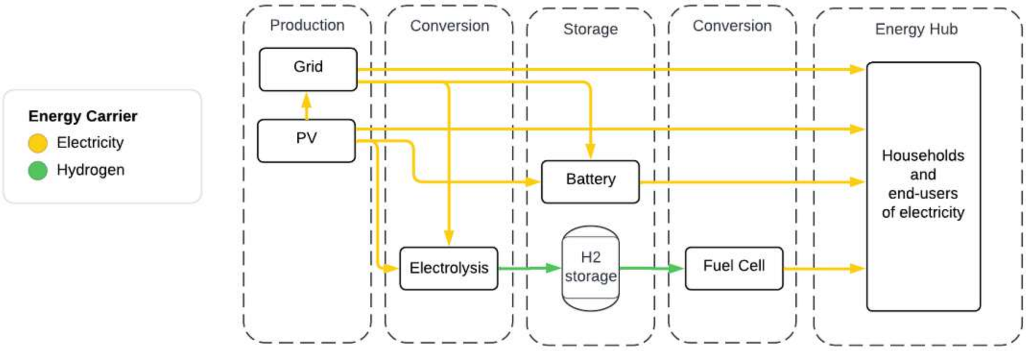

Figure 3: *Flowchart of the energy flows between the different components of the energy hub and the households and end-users. Depending on the scenario different components are active.*

overproduction that is going to be fed back into the grid. The second measure is to add storage solutions to shift the excess available overproduction to times of excess demand, for example from daytime to nighttime. For these short-term energy shifts, batteries are a viable option. For long-term energy shifting from summer to winter a hydrogen storage system could be a feasible solution. The energy hub with the components and the energy flows is pictured in Figure 3. In the case of storage integration, the size of the PV system needs to be increased as well in order to be able to reach higher SSR values than the current rate of theoretically 30%. Therefore, without higher production, even storage solutions won't lead to higher SSR values, due to the total electricity demand being currently much larger than the supply in the Baseline scenario. The goal is to find out which SSR values are reachable in a cost-minimal scenario and in an SSR-maximized scenario.

In the following scenarios, the size of the components is modeled through a design optimization approach. This approach optimizes the size of the components as well as the hourly energy flows between the components and the consumers in the energy hub over the period of one year. Here the only parameters that are given are the annual electricity demand of the energy hub in an hourly resolution and the hourly production of a 1 kWp PV panel in the geographical location of Austria from the PVGIS-SARAH2 database [21].

In Scenario 1, the PV panels are design-optimized to see what the size would be for a cost-optimal outcome on the one hand and for maximized self-sufficiency on the other hand. The electricity production from the PV panels will partly replace the grid electricity, but most of the solar production will be fed into the grid. This excess renewable energy could be used to fulfill the demand during times when the sun does not shine, therefore reaching both lower costs and higher self-sufficiency. To be able to do this, storage solutions are necessary.

Storage is added in the next scenario. In Scenario 2, the scope is extended with a BSS to store excess solar electricity or cheap electricity from the grid for times when there is no PV production or only expensive energy from the grid available. Again, a design optimization for the optimal sizing of the PV and BSS is performed, modeling the energy flows between the optimally sized components over the period of one year. The energy hub is optimized for minimal costs and maximal self-sufficiency.

In the final scenario, Scenario 3, an additional means of storage is added. The HSS with an electrolyzer, a storage tank, and a fuel cell for the storage of excess energy is modeled to see if it is a viable solution for residential energy storage, complementing the already existing PV and battery system from the previous scenario.

3.2 Methodology and optimization model

In order to simulate the existing energy hub with an optimal PV, BSS and HSS size, a MILP methodology was applied to the optimization problem. The MILP framework was implemented in MATLAB using the intlinprog solver [22]. This framework was chosen because of its efficiency in dealing with non-continuous but discrete variables and constraints and for its reliability in finding a truly optimal solution in the whole solution space. If there is no optimal solution, the problem is either unbounded because constraints are missing or it is infeasible because two or more constraints violate each other and do not find a compatible solution. For this purpose, the following components were implemented with fixed parameters, variables, constraints, and objective functions: PV panels, BSS, HSS. The respective components were added to the optimization in the different scenarios, whereas in the Baseline Scenario, no optimization took place. Only the actual state of the given energy hub was analyzed as is. The parameters in Table 5 were the same in every scenario. The feed-in tariff of $0,14$ €/kWh is the tariff from the OeMAG, the Austrian settlement agency for green energy, for the third quarter of 2023 [23].

The formula for the calculation of the annuity factor AF_i for the different components is shown in Equation 1. The annuity factor is a weighting factor that takes the assumed lifetime T_i of the components and a given interest rate r_i into account. Multiplied with the total investment cost it results in an interst-adjusted annualized investment cost over the whole lifetime of the component that considers the upfront payment.

Table 5: *General parameters for all the scenarios.*

Parameter	Description	Unit	Value
n	Number of hours	-	8.760
n_{houses}	Number of houses	-	3
dt	stepsize	h	1
FIT	Feed-in tariff	€/kWh	$0,14$ [23]

$$AF_i = \frac{r_i}{1-(1+r_i^{-T_i})} \qquad \forall i \in \{PV, BSS, HSS\} \tag{1}$$

There are three indexed arrays with an entry for each hour of the year as parameters. First, the electricity demand D, that has been measured for each house. Second, the PV profile PV_{prod} for a 1 kWp PV panel at the given location [21]. And third, a variable electricity price profile el_{price} from the Energy Exchange Austria (EXAA) [24]. This is shown in Table 6.

Table 6: *Parameters for measured electricity demand, PV production, and electricity price in hourly intervals.*

Parameter	Description	Unit	Dimension
D	Demand profile of the three houses	kWh	nxn_{houses}
PV_{prod}	PV profile for a 1 kWp PV panel	kWh	nx1
el_{price}	Variable electricity price	€/kWh	nx1

3.2.1 PV panels

The PV panels were modeled by the following parameters and variables in the respective Tables 7 and 8. The size of the PV system n_{PV} is going to be optimized, so it can become any size from $0-150$ kWp for the cost-optimized scenario with an increment of 1 kWp. For the SSR maximization, it can be even larger. The specific price c_{PV} ranges from $1.250-2.600$ €/kWp for PV systems ≥ 10 kWp, according to the Austrian Ministry for Climate action [25] and has therefore been set to 2.000 €/kWp for the simulation.

For the PV system, there are non-negativity constraints and sizing constraints that need to be fulfilled for every hour of the year. They are shown in the Equations 2-4. They are the same in all the scenarios. The non-negativity makes sure, that no negative PV

Table 7: *Parameters for the PV panel.*

Parameter	Description	Unit	Value
P_{PV}	Potential PV sizes	kWp	$0 - 150$
c_{PV}	Specific PV cost	€/kWp	2.000 [25]
T_{PV}	Assumed lifetime of a PV panel	years	25 [17]
r_{PV}	Assumed interest rate for annuity factor	%	5
AF_{PV}	PV annuity factor	-	$0,071$

Table 8: *Variables for the PV panel.*

Variable	Description	Unit	Dimension
n_{PV}	Optimal size of PV	kWp	$1\text{x}n_{houses}$
b_{PV}	Boolean array for the chosen PV size	bool	$101\text{x}n_{houses}$

sizes can be chosen in the optimization. The sizing constraints find out the economically optimal size for the PV panels through the boolean variable b_{PV}. This variable has an entry for every possible size from $0 - 150$ kWp and is constrained in a way, that only one of these entries can have the value 1 for the chosen size, all the others are 0. This is declared in Equation 4. The boolean vector b_{PV} is then multiplied with the vector P_{PV} that includes all the potential PV sizes. By multiplying these two in a scalar multiplication only one value remains, exactly where b_{PV} had the entry 1.

$$n_{PV} \geq 0; \;\; b_{PV} \geq 0 \tag{2}$$

$$n_{PV} = P_{PV} \cdot b_{PV} \tag{3}$$

$$\sum b_{PV} = 1 \tag{4}$$

The PV distribution constraints differ between the scenarios and are shown in the Equations 5- 7. The mentioned energy flows from the PV to the house $pvToHouse$, from the PV to the grid $pvToGrid$, from the PV to the house and BSS $pvToHnB$, and from the PV to the house, BSS, and HSS $pvToHnBnH2$ are explained in Table 13. The constraints in the Equations 5-7 state that the produced energy, given by the multiplication of the chosen PV size n_{PV} with the production profile PV_{prod} must equal the sum of the energy flows from the PV to the different components and to the grid.

$$n_{PV} \cdot PV_{prod}(i) \geq pvToHouse(i) + pvToGrid(i) \qquad : \forall i \in n \tag{5}$$

$$n_{PV} \cdot PV_{prod}(i) \geq pvToHnB(i) + pvToGrid(i) \qquad : \forall i \in n \tag{6}$$

$$n_{PV} \cdot PV_{prod}(i) \geq pvToHnBnH2(i) + pvToGrid(i) \qquad : \forall i \in n \tag{7}$$

3.2.2 Battery storage system

The BSS was modeled by the following parameters and variables in the respective Tables 9 and 10. The size of the BSS n_B is going to be optimized, so it can become any size P_B from $0-100$ kWh with an increment of 1 kWh. For the SSR maximization larger values are possible.

Table 9: *Parameters for the BSS.*

Parameter	Description	Unit	Value
P_B	Potential BSS sizes	kWh	$0-100$
c_B	Specific BSS cost	€/kWh	550 [20]
T_B	Lifetime of the BSS	years	15 [26]
r_B	Assumed interest rate for annuity factor	%	5
AF_B	BSS annuity factor	-	$0,0963$
η_B	BSS charging/discharging efficiency	%	95 [20]
R_B	Assumed max charge/discharge rate	kWh/h	15

Table 10: *Variables for the BSS.*

Variable	Description	Unit	Dimension
n_B	Optimal size of BSS	kWh	1xn_{houses}
b_B	Boolean array for the chosen BSS size	bool	101xn_{houses}
SOC_B	SOC of the BSS	kWh	nxn_{houses}
F_B	In- & outflow of the BSS	kWh/h	nxn_{houses}

For the BSS, there are again non-negativity constraints and sizing constraints. They are shown in the Equations 8-10 and work exactly as explained for the PV sizing. The one entry of b_B that is equal to 1 determines the optimally chosen size of the BSS.

$$n_B \geq 0;\ b_B \geq 0;\ SOC_B(i) \geq 0 \qquad : \forall i \in n \tag{8}$$

$$n_B = P_B \cdot b_B \tag{9}$$

$$\sum b_B = 1 \tag{10}$$

The battery balance, state of charge (SOC) and battery flow constraints need to be valid for the whole year and are shown in the Equations 11-15. Equation 11 defines the boundary conditions of the battery SOC at the beginning and at the end of the year. The SOC cannot be negative as determined in the non-negitivity constraint and it can only be equal or smaller than the chosen battery size n_B, specified in Equation 12.

$$SOC_B(1) = SOC_B(n) = 0 \tag{11}$$

$$SOC_B(i) \leq n_B \qquad : \forall i \in n \tag{12}$$

Apart from the first and last hour of the year, the battery SOC is determined as shown in Equation 13. The SOC at the next timestep $SOC_B(i+1)$ is always the sum of the SOC at the current timestep $SOC_B(i)$ and the battery flow F_B multiplied with the efficiency η_B. The initial battery flow is constrained to be 0 in Equation 14 while it can be anything between the negative and positive charge/discharge rate R_B for the rest of the year, defined in Equation 15.

$$SOC_B(i+1) = SOC_B(i) + F_B(i) \cdot \eta_B \cdot dt \qquad : \forall i \in n \tag{13}$$

$$F_B(1) = 0 \tag{14}$$

$$-R_B \leq F_B(i) \leq R_B \qquad : \forall i \in n \tag{15}$$

3.2.3 Hydrogen storage system

The HSS was modeled by the following parameters and variables in the respective Tables 11 and 12. The size of the HSS n_{H2} is going to be optimized, so it can become any size from $0-1000$ kWh with an increment of 20 kWh. For the SSR maximization much larger values are possible.

For the HSS, there are again non-negativity constraints and sizing constraints. They are shown in the Equations 16-18 and work exactly the same as in the PV and battery sizing.

Table 11: *Parameters for the HSS.*

Parameter	Description	Unit	Value
P_{H2}	Potential HSS sizes	kWh	$0 - 1.000$
c_{H2}	Specific HSS cost	€/kW	8.547 [20]
T_{H2}	Lifetime of the HSS	years	15 [26]
r_{H2}	Assumed interest rate for annuity factor	%	5
AF_{H2}	HSS annuity factor	-	$0,0963$
η_{H2}	HSS charging/discharging efficiency	%	65 [20]
R_{H2}	Assumed max. HSS charge/discharge rate	kWh/h	30

Table 12: *Variables for the HSS.*

Variable	Description	Unit	Dimension
n_{H2}	Optimal size of HSS	kWh	$1\mathrm{x}n_{houses}$
b_{H2}	Boolean array for the chosen HSS size	bool	$101\mathrm{x}n_{houses}$
SOC_{H2}	SOC of the HSS	kWh	$n\mathrm{x}n_{houses}$
F_{H2}	In- & outflow of the HSS	kWh/h	$n\mathrm{x}n_{houses}$

$$n_{H2} \geq 0;\ b_{H2} \geq 0;\ SOC_{H2}(i) \geq 0 \qquad : \forall i \in n \tag{16}$$

$$n_{H2} = P_{H2} \cdot b_{H2} \tag{17}$$

$$\sum b_{H2} = 1 \tag{18}$$

The hydrogen balance, SOC and hydrogen flow constraints need to be valid for the whole year and are shown in the Equations 19-23. They also work similar to the corresponding battery constraints for the SOC and flow rate.

$$SOC_{H2}(1) = SOC_{H2}(n) = 0 \tag{19}$$

$$SOC_{H2}(i) \leq n_{H2} \qquad : \forall i \in n \tag{20}$$

$$SOC_{H2}(i+1) = SOC_{H2}(i) + F_{H2}(i) \cdot \eta_{H2} \cdot dt \qquad : \forall i \in n \tag{21}$$

$$F_{H2}(1) = 0 \tag{22}$$

$$-R_{H2} \leq F_{H2}(i) \leq R_{H2} \qquad : \forall i \in n \tag{23}$$

3.2.4 Energy flows

The energy flows between the different components are modeled through flow variables that are optimized. The energy flows are from the public grid to the house $gridToHouse$, to fulfill the excess energy demand, from the PV system to the house $pvToHouse$, and from the PV system to the grid $pvToGrid$ for feed-in of the overproduction. These energy flows are modeled for each of the three houses. In Scenario 2 the same energy flows are considered, with the only difference being that the battery is seen as part of the house in $gridToHnB$ and $pvToHnB$. The differentiation between the amount of electricity that actually goes towards the household demand and the amount that is stored in the BSS or HSS is reached in the energy balance constraints in the Equations 28 and 29, where the in- and outflow of energy to and from the battery is considered. The energy flows with their dimensions are shown in Table 13. The non-negativity constraints in Equations 24-26 constrain the variables to only become positives or zeros during the optimization over the period of the whole year for all the scenarios.

In the energy balance constraints for the three scenarios in the Equations 27-29, also called the fulfill demand rule, the different sources that fulfill the demand are connected.

Table 13: *Variables for the energy flows between the components for Scenarios 1-3.*

Variable	Description	Unit	Dimension
$gridToHouse$, $gridToHnB$, $gridToHnBnH2$	Hourly energy flow from the grid to the house, BSS and HSS	kWh	$n\text{x}n_{houses}$
$pvToHouse$, $pvToHnB$, $pvToHnBnH2$	Hourly energy flow from the PV to the house, BSS and HSS	kWh	$n\text{x}n_{houses}$
$pvToGrid$	Hourly energy flow from the PV to the grid	kWh	$n\text{x}n_{houses}$

$$gridToHouse(i) \geq 0;\ pvToHouse(i) \geq 0;\ pvToGrid(i) \geq 0 \qquad : \forall i \in n \tag{24}$$

$$gridToHnB(i) \geq 0;\ pvToHnB(i) \geq 0 \qquad : \forall i \in n \tag{25}$$

$$gridToHnBnH2(i) \geq 0;\ pvToHnBnH2(i) \geq 0 \qquad : \forall i \in n \tag{26}$$

In the energy balance constraints in the Equations 27-29 the household demand D has to be fulfilled at every timestep and is constrained to be exactly equal to the amount of energy that comes from the grid, the PV system and the storage, depending on the scenario.

$$D(i) = gridToHouse(i) + pvToHouse(i) \qquad : \forall i \in n \tag{27}$$

$$D(i) = gridToHnB(i) + pvToHnB(i) - F_B(i) \qquad : \forall i \in n \tag{28}$$

$$D(i) = gridToHnBnH2(i) + pvToHnBnH2(i) - F_B(i) - F_{H2}(i) : \forall i \in n \tag{29}$$

3.2.5 Objective function

For each of the scenarios two main objectives were analyzed. To find out what the cost-optimal size of the components was, a cost-minimization objective was introduced that minimizes the total costs C, while an SSR-maximization objective was used to find the largest potential SSR values. For Scenario 1 these are the Equations 30 and 31, for Scenario 2 the Equations 32 and 33 and for Scenario 3 the Equations 34 and 35. In each of these minimize costs equations, the costs are the sum of the annualized component costs $n_i \cdot AF_i \cdot c_i$ with $i \in \{PV,\ BSS,\ HSS\}$, the costs for electricity from the grid with the el_{price} multiplied with the energy flow from the grid, and the remuneration for fed-in electricity to the grid $FIT \cdot pvToGrid$. In the maximize SSR objectives the SSR is equal to the sum of PV electricity provided to the house and storage systems divided by the total demand over the whole year.

$$\begin{aligned} min\ C = {} & n_{PV} \cdot AF_{PV} \cdot c_{PV} \\ & + \sum_{i=1}^{n} (el_{price}(i) \cdot gridToHouse(i) - FIT \cdot pvToGrid(i)) \end{aligned} \tag{30}$$

$$max\ SSR = -\frac{\sum_{i=1}^{n} pvToHouse(i)}{\sum_{i=1}^{n} D(i)} \tag{31}$$

$$\begin{aligned} min\ C = {} & n_{PV} \cdot AF_{PV} \cdot c_{PV} + n_B \cdot AF_B \cdot c_B \\ & + \sum_{i=1}^{n} (el_{price}(i) \cdot gridToHnB(i) - FIT \cdot pvToGrid(i)) \end{aligned} \tag{32}$$

$$max\ SSR = -\frac{\sum_{i=1}^{n} pvToHnB(i)}{\sum_{i=1}^{n} D(i)} \tag{33}$$

$$\begin{aligned} min\ C = {} & n_{PV} \cdot AF_{PV} \cdot c_{PV} + n_B \cdot AF_B \cdot c_B + n_{H2} \cdot AF_{H2} \cdot c_{H2} \\ & + \sum_{i=1}^{n} (el_{price}(i) \cdot gridToHnBnH2(i) - FIT \cdot pvToGrid(i)) \end{aligned} \tag{34}$$

$$max\ SSR = -\frac{\sum_{i=1}^{n} pvToHnBnH2(i)}{\sum_{i=1}^{n} D(i)} \tag{35}$$

Additionally, in Scenarios 1-3 the minimal costs for different SSR values were evaluated as shown in the Tables 30-32 in Section 4.1. Here the minimal cost objective was active while the additional constraints for Scenario 1-3 in the Equations 36-38 were inserted, iteratively constraining the SSR values between $50 - 99\%$.

$$\begin{aligned} & \frac{\sum_{i=1}^{n} pvToHouse(i)}{\sum_{i=1}^{n} D(i)} = \\ & [0,50;\ 0,55;\ 0,60;\ 0,65;\ 0,70;\ 0,75;\ 0,80;\ 0,85;\ 0,90;\ 0,95;\ 0,99] \end{aligned} \tag{36}$$

$$\begin{aligned} & \frac{\sum_{i=1}^{n} pvToHnB(i)}{\sum_{i=1}^{n} D(i)} = \\ & [0,50;\ 0,55;\ 0,60;\ 0,65;\ 0,70;\ 0,75;\ 0,80;\ 0,85;\ 0,90;\ 0,95;\ 0,99] \end{aligned} \tag{37}$$

$$\frac{\sum_{i=1}^{n} pvToHnBnH2(i)}{\sum_{i=1}^{n} D(i)} = [0,50;\ 0,55;\ 0,60;\ 0,65;\ 0,70;\ 0,75;\ 0,80;\ 0,85;\ 0,90;\ 0,95;\ 0,99] \tag{38}$$

4 Results and Discussion

In this chapter, the optimization results are documented and analyzed in the discussion. The outcome is underlined with graphical representations of an exemplary week of the year for each of the scenarios and for all of the relevant energy flows to and from the employed components.

4.1 Scenario results

In this section the results for the different scenarios are mentioned. The optimal values for the component sizes, the energy flows, the cost components in the objective, and the SSR values are collected.

4.1.1 Baseline scenario

The Baseline scenario is the existing energy hub as it is. Only the houses with their electricity demand, the existing PV panels, and the public grid from Figure 3 are viewed here. It consists of three multi-apartment buildings in Austria. Each of them has a certain electricity demand and PV production. The sum over the whole year was calculated as well as the corresponding self-consumption, the amount of fed-in electricity, and the amount of electricity consumed from the grid. The existing PV systems, mounted on the respective rooftops of the houses are shown in Table 14 and the measured energy flows between PV, house, and grid are documented in Table 15.

Table 14: *PV system sizes for the Baseline scenario in* kWp.

House number	PV system size
1	15
2	14
3	15
Total	44

Table 15: *Annual electricity consumption and production data in* kWh *for the Baseline scenario.*

House number	Electricity demand	PV production	PV to grid	Grid to house
1	46.193	15.793	1.682	32.081
2	47.516	14.465	1.998	35.050
3	63.195	15.965	988	48.218
Total	156.904	46.223	4.668	115.349

The measured demand and production profiles and the resulting energy flows that were calculated lead to real and theoretically possible SSR values for each house and the energy hub as a whole in Table 16.

Table 16: *Real and theoretically possible SSR values for the Baseline scenario.*

House number	SSR theoretical	SSR real
1	34,2%	30,5%
2	30,4%	26,2%
3	25,3%	23,7%
Total	29,5%	26,5%

The corresponding total costs were calculated with the variable electricity price el_{price}, mentioned in Table 6, with the annuity of the PV system AF_{PV} and with the feed-in tariff FIT from Table 5 and were compared to the electricity costs that would arise if there was no PV installation at all. These numbers are shown in Table 17.

Table 17: *Annual electricity cost in € for the Baseline scenario.*

House number	Total cost without PV	Total cost with PV	Electricity cost	PV annuity cost	PV feed-in remuneration
1	14.190	11.970	10.077	2.129	235
2	14.414	12.448	10.741	1.987	280
3	18.615	16.238	14.247	2.129	138
Total	47.219	40.656	35.065	6.245	654

4.1.2 Scenario 1: PV only

In this scenario the same energy hub is analyzed. The same demand profile D and electricity price profile el_{price} as in the Baseline scenario are given. The difference to the Baseline scenario is, that the PV production profile PV_{prod} is given for a 1 kWp PV panel from the PVGIS database for the location of Austria [21]. The optimal size of the PV system n_{PV} for each house is evaluated for a cost-minimized scenario and for an SSR-maximized scenario with a design optimization approach. The possible energy flows are from the PV to the houses and to the grid and from the grid to the houses and are visualized in Figure 4.

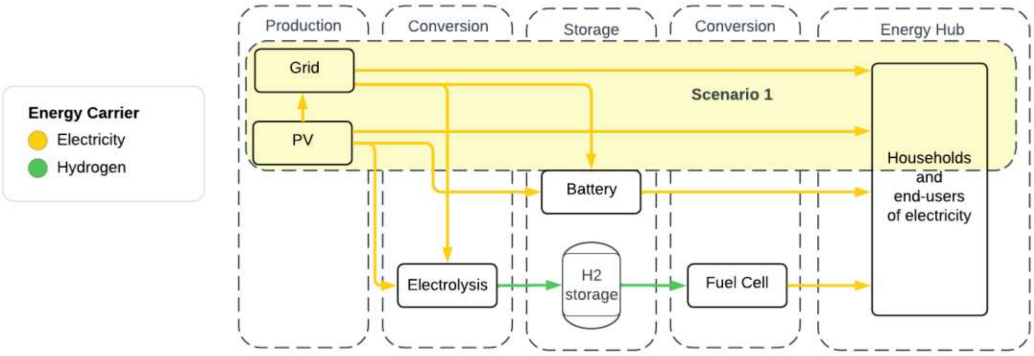

Figure 4: *Flowchart of the energy flows between the different components of the energy hub and the households and end-users. In this scenario only the yellow-colored area is active.*

Minimized cost

The results for the optimal sizing of the PV systems are shown in Table 18, while the consumption and the energy flows to the house are shown in Table 19, and the PV production and the energy flows from the PV are shown in Table 20.

This results in real and theoretically possible SSR values for each house and the energy hub as a whole, shown in Table 21.

The theoretically possible SSR values show, that the PV system is over-dimensioned and that it could either provide electricity for more consumers or that this overproduction could be stored for the times when there is no production from the PV panels. The second possibility is modeled with a BSS and a HSS as a means of energy storage in the next scenarios. The corresponding total costs are calculated with the variable electricity

Table 18: *Design optimized PV system sizes for the cost-minimal Scenario 1 in* kWp.

House number	PV system size
1	124
2	115
3	136
Total	375

Table 19: *Annual electricity consumption and energy flows to the house in* kWh *for Scenario 1.*

House number	Electricity demand	Grid to house	PV to house
1	46.193	24.221	21.972
2	47.516	27.826	19.690
3	63.195	36.061	27.134
Total	156.904	88.108	68.796

price mentioned in Table 6, with the annuity of the PV system and with the feed-in tariff from Table 5 and were compared to the electricity costs that would arise if there was no PV installation at all. These numbers are shown in Table 22.

Maximized SSR

In this scenario the objective is changed from minimized costs in Equation 30 to maximized SSR in Equation 31. After finding the maximum SSR values in percent, a minimized

Table 20: *Annual electricity production and energy flows from the PV in* kWh *for Scenario 1.*

House number	PV production	PV to house	PV to grid
1	121.870	21.972	99.900
2	113.020	19.690	93.330
3	133.660	22.134	106.530
Total	368.550	68.796	299.760

Table 21: *Real and theoretically possible SSR values for Scenario 1.*

House number	SSR theoretical	SSR real
1	264%	48%
2	238%	41%
3	212%	43%
Total	235%	44%

Table 22: *Annual electricity costs in € for Scenario 1.*

House number	Total cost without PV	Total cost with PV	Electricity cost	PV annuity cost	PV feed-in remuneration
1	14.190	10.965	7.354	17.596	13.985
2	14.414	11.511	8.258	16.319	13.066
3	18.615	14.742	10.357	19.299	14.914
Total	47.219	37.218	25.969	53.214	41.965

costs approach is used again to find the minimal size of the PV system for these maximum SSR values. The goal is to see what the maximum SSR value would be if the PV was not constrained by size or cost. This results in larger values for the PV size and larger costs, but only a mediocre SSR value, as shown in Table 23.

Table 23: *Size of the PV panels and corresponding annualized costs for maximized SSR values in Scenario 1.*

House number	Size in kWp	Costs in €	SSR real
1	1.220	15.272	57%
2	2.900	23.081	50%
3	2.400	23.892	53%
Total	6.520	62.245	53%

4.1.3 Scenario 2: PV + battery

The difference between this scenario and Scenario 1 is the additional BSS, which can be seen in Figure 3. This means that here both the PV system and the BSS are optimally sized in a design optimization for each of the three houses. The battery will help to utilize more of the self-produced energy. The two objectives are cost minimization in Equation 32 and SSR maximization in Equation 33. The hourly demand profile, PV profile, and electricity price profile over the whole year are still the same. The additional constraints for the battery modeling from Section 3.2.2 are added. The active components and the energy flows are visualized in Figure 5.

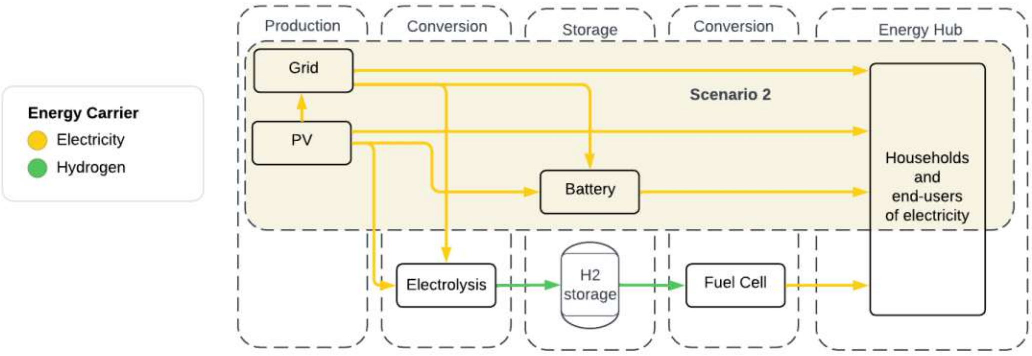

Figure 5: *Flowchart of the energy flows between the different components of the energy hub and the households and end-users. In this scenario only the yellow-coloured area is active.*

Minimized cost

The solution for the optimal sizing of the PV and BSS is shown in Table 24, the electricity consumption and the energy flows from the grid, PV and BSS to the house are shown in Table 25 together with the energy from the grid to the battery. Additionally, the PV production as well as the energy flows from the PV to the house, to the BSS, and to the grid are shown in Table 26.

Table 24: *Design optimized PV system sizes in* kWp *and BSS sizes in* kWh *for the cost-minimal Scenario 2.*

House number	PV system size	BSS size
1	116	32
2	108	35
3	141	42
Total	365	109

Table 25: *Annual electricity consumption and energy flows to the house and from the grid to the battery in* kWh *for Scenario 2.*

House number	Electricity demand	Grid to house	PV to house	Battery to house	Grid to battery
1	46.193	8.537	17.871	19.785	6.280
2	47.516	10.205	18.730	18.582	7.331
3	63.195	14.124	26.246	22.826	9.052
Total	156.904	32.866	62.847	61.192	22.663

Table 26: *Annual electricity production and energy flows from the PV in* kWh *for Scenario 2.*

House number	PV production	PV to house	PV to battery	PV to grid
1	114.010	17.871	13.506	82.629
2	106.140	18.730	11.251	76.162
3	138.580	26.246	13.774	98.556
Total	358.730	62.847	38.531	257.357

This results in real and theoretically possible SSR values for each house and the energy hub as a whole, shown in Table 27.

Table 27: *Real and theoretically possible SSR values for Scenario 2.*

House number	SSR theoretical	SSR real
1	247%	68%
2	223%	63%
3	219%	63%
Total	229%	65%

The corresponding total costs were calculated with the variable electricity price mentioned in Table 6, with the annuity of the PV system and the BSS, and with the feed-in tariff from Table 5, and were compared to the electricity costs that would arise if there was no PV and BSS installation at all. These numbers are shown in Table 28.

Table 28: *Annual electricity cost in € for Scenario 2.*

House number	Total cost without PV	Total cost with PV and BSS	Electricity cost	PV annuity cost	BSS annuity cost	PV feed-in remuneration
1	14.190	9.746	3.158	16.461	1.692	11.568
2	14.414	10.213	3.695	15.326	1.851	10.663
3	18.615	13.154	4.718	20.009	2.223	13.789
Total	47.219	33.113	11.571	51.796	5.766	36.020

Maximized SSR

In this scenario the objective is changed from minimized costs to maximized SSR values using Equation 33. The goal is to see what the maximum SSR value would be if the PV and BSS were not constrained by size and costs. The largest reachable value was found to be close to 100%. For finding out the minimal costs for the components, the threshold for maximum SSR was set to 99%. Due to the modeling approach, reaching 100% was not possible because the BSS is set as empty at the beginning of the year in the boundary constraints. Therefore, the first hours of demand in the year can't be satisfied by anything else than the electricity from the grid. The costs and sizes for the PV system and BSS in the maximum SSR case are shown in Table 29.

Table 29: *Size of the PV panels, the BSS, and corresponding costs for maximized SSR values (99% SSR) in Scenario 2.*

House number	SSR	PV size in kWp	BSS size in kWh	Costs in €
1	99%	460	80	12.729
2	99%	560	95	14.114
3	99%	3.100	275	36.780
Total	99%	4.120	450	63.673

Additionally, the minimal sizes for PV and BSS have been calculated for different SSR values to show how much more investment is necessary to reach another 5%, 10%, or 20% of self-sufficiency for each of the houses. The additional constraints active here are mentioned in the Equations 36 - 38. The numbers for the three houses are shown in Tables 30-32.

Table 30: *SSR values from* 50 – 99% *for house 1 with the corresponding component sizes and costs for Scenario 2.*

SSR	PV size in kWp	BSS size in kWh	Costs in €
50%	82	25	10.033
55%	91	27	9.900
60%	101	28	9.805
65%	111	31	9.756
70%	119	33	9.750
75%	131	37	9.796
80%	145	41	9.916
85%	162	46	10.138
90%	182	52	10.474
95%	260	64	11.205
99%	460	80	12.729

Table 31: *SSR values from* 50 – 99% *for house 2 with the corresponding component sizes and costs for Scenario 2.*

SSR	PV size in kWp	BSS size in kWh	Costs in €
50%	84	28	10.362
55%	93	30	10.267
60%	103	33	10.220
65%	112	36	10.217
70%	127	39	10.267
75%	146	44	10.392
80%	161	49	10.620
85%	177	56	10.946
90%	216	67	11.476
95%	326	79	12.395
99%	560	95	14.114

Table 32: *SSR values from* $50 - 99\%$ *for house 3 with the corresponding component sizes and costs for Scenario 2.*

SSR	PV size in kWp	BSS size in kWh	Costs in €
50%	111	32	13.377
55%	124	36	13.242
60%	134	40	13.170
65%	146	43	13.158
70%	157	49	13.215
75%	179	55	13.356
80%	195	60	13.602
85%	227	66	13.979
90%	304	77	14.642
95%	516	94	16.237
99%	3.100	275	36.780

4.1.4 Scenario 3: PV + battery + hydrogen

In this scenario a HSS was modeled in addition to the PV system and the BSS. The extension with the corresponding energy flows is pictured in Figure 6. The approach was the same as in the previous scenarios, namely a design optimization approach, modeling the energy flows between the components over a whole year of operation. Due to the higher price of the HSS and the substantially lower roundtrip efficiency, the HSS is not economically viable in this scenario. The low efficiency is the result of first producing hydrogen through electrolysis with the produced electricity at an efficiency of around 65% and then electrifying this hydrogen in a fuel cell with the same efficiency again. Therefore, the outcome of this scenario is the same as in Scenario 2 where only the BSS is chosen as a means of storage over the HSS. Although hydrogen is more likely to act as a long-term storage solution it is too expensive for the residential use case here. This could also be due to the availability of the grid connection, where comparatively cheap electricity is available at any time. For off-grid cases, mentioned in the analyzed literature from Table 1 hydrogen can be of use, although it is still only viable with increased costs.

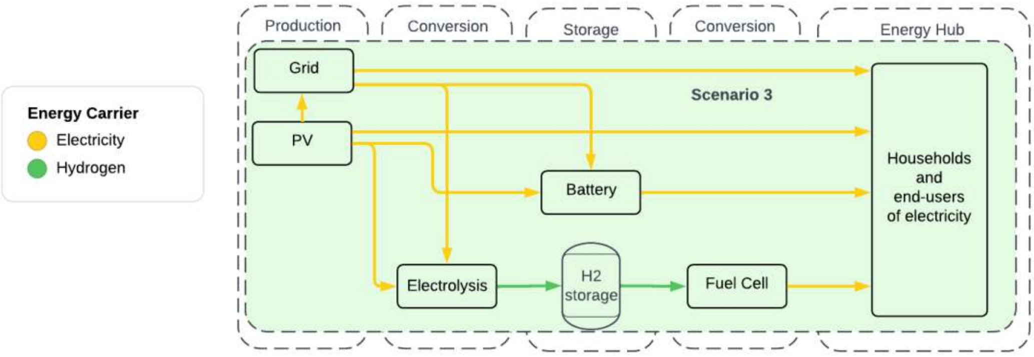

Figure 6: *Flowchart of the energy flows between the different components of the energy hub and the households and end-users. In this scenario only the green-colored area is active.*

4.2 Discussion

In this section the research questions are discussed and the different scenarios are compared by their results from Section 4.1.

Both the PV design optimization in Scenario 1 and the PV and BSS design optimization in Scenario 2 reach significant improvements in both the annualized costs and the SSR values. The HSS from Scenario 3 is not economical and therefore not considered in the optimization model. Hydrogen production with electrolyzers and re-electrification in fuel cells is still an expensive and inefficient task. Although it is not yet economical it might still bring benefits in certain circumstances. Depending on the use-case it could be used as a long-term storage to shift renewable energy resources from summer to winter or it can be used somewhere, where hydrogen gas is directly needed instead of re-electrifying it and losing energy due to the fuel cell efficiency. Hydrogen could be utilized in the industrial sector where direct hydrogen is needed or larger amounts of renewable energy would need to be shifted. This is not the case in the residential sector. Nevertheless, storage potential is necessary to reach high levels of self-sufficiency and to be able to shave the peaks of PV production during the daytime. Which storage type is used, strongly depends on the price, which is also proved by the outcome of this study.

4.2.1 Cost minimization

The approach was to minimize the annualized total costs for the given energy systems in the different scenarios. All the cost components were taken into account, from the electricity consumption from the public grid, the positive feed-in remuneration for overproduction, to the annualized investment costs of the technical components. The results compared between the different scenarios for the cost minimal objective are documented in Table 33. With every scenario or component extension, a drop in total annualized costs can be seen. The most expensive case is the one without PV and storage systems. It lies 16% above the baseline. The Baseline Scenario, which analyzes the fictitious energy hub with its PV, acts as the benchmark with 100%. Scenario 1, with a design-optimized PV system, achieves a cost reduction of 8% while Scenario 2 with a design-optimized PV system and BSS achieves a cost reduction of 19% compared to the Baseline. In Scenario 3 the HSS system is not economical, therefore the result is the same as in Scenario 2. One reason for these cost reductions is the significantly higher SSR in these cases. Scenario 1 reaches a real SSR value that is increased by 17% compared to Baseline, while Scenario 2 and 3 can increase the real SSR by 38%. Theoretically, the maximum reachable SSR values in the Scenarios 1, 2, and 3 could be even higher, as stated in Table 33. The values for the scenarios are 235%, 229%, and 229% respectively. These are only theoretical values that imply that the annual electricity demand could be fulfilled more than once. This shows, that an SSR increase could be reached by increasing the PV system size and by adding storage solutions, in this case, a BSS. The economically optimal size for each scenario is shown in Table 33.

Table 33: *Comparison of component sizes, total annualized costs, real SSR, and theoretical SSR between the scenarios for the minimal cost objectives.*

Scenario	PV size in kWp	BSS size in kWh	HSS size in kWh	Costs in €	SSR real	SSR theoretical
No PV	-	-	-	47.219	-	-
Baseline	44	-	-	40.656	27%	30%
1	375	-	-	37.218	44%	235%
2	365	109	-	33.113	65%	229%
3	365	109	-	33.113	65%	229%

The Figures 7-9 show the energy flows from the different sources to the house, from the PV to the house and grid, and the total demand and PV profile for an exemplary week of the year, respectively. Figure 7 stacks the energy flows that fulfill the demand, grid to house in blue color and PV to house in orange color, on top of each other and additionally shows the feed-in from the PV to the grid in yellow. It is visible, that the variable electricity price, shown in Figures 8 and 11 for all the scenarios, has an influence

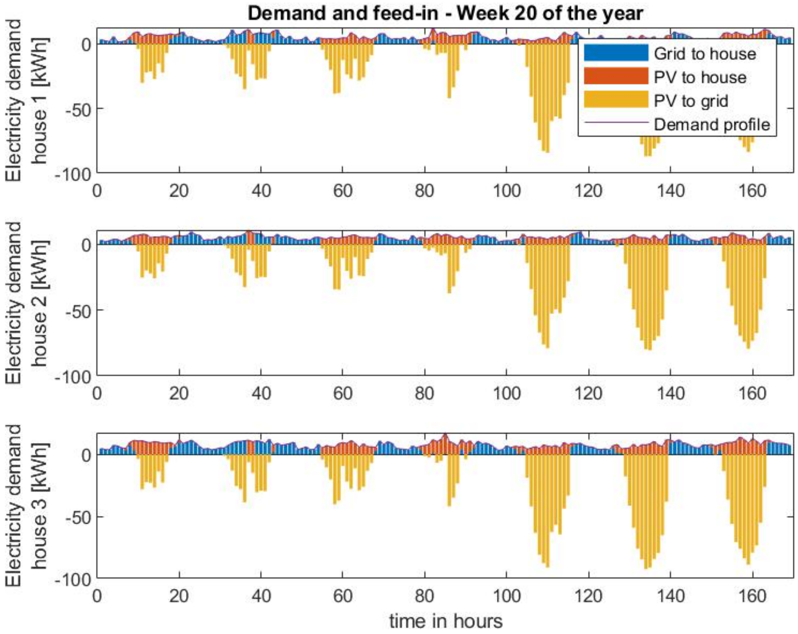

Figure 7: *Energy flows to and from each house in an exemplary week of the year in Scenario 1.*

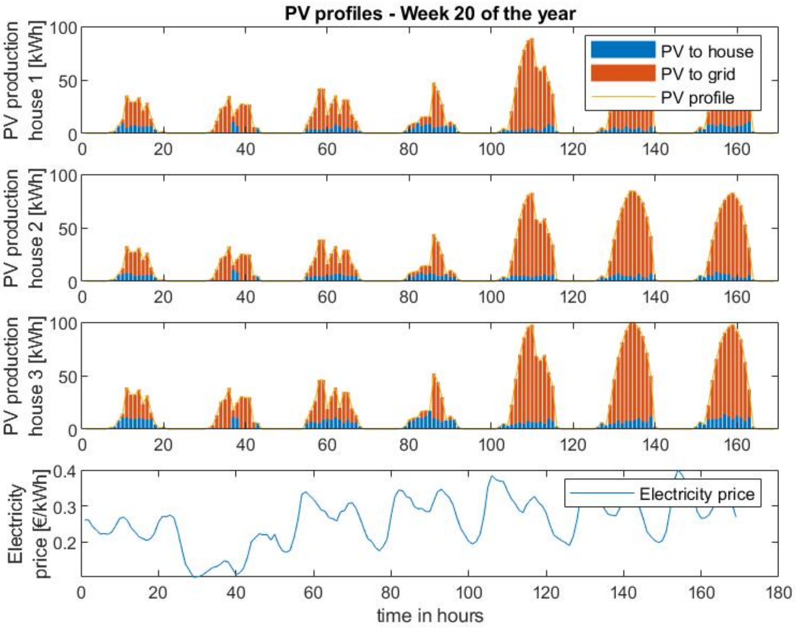

Figure 8: *PV production of each house and variable electricity price development in an exemplary week of the year in Scenario 1.*

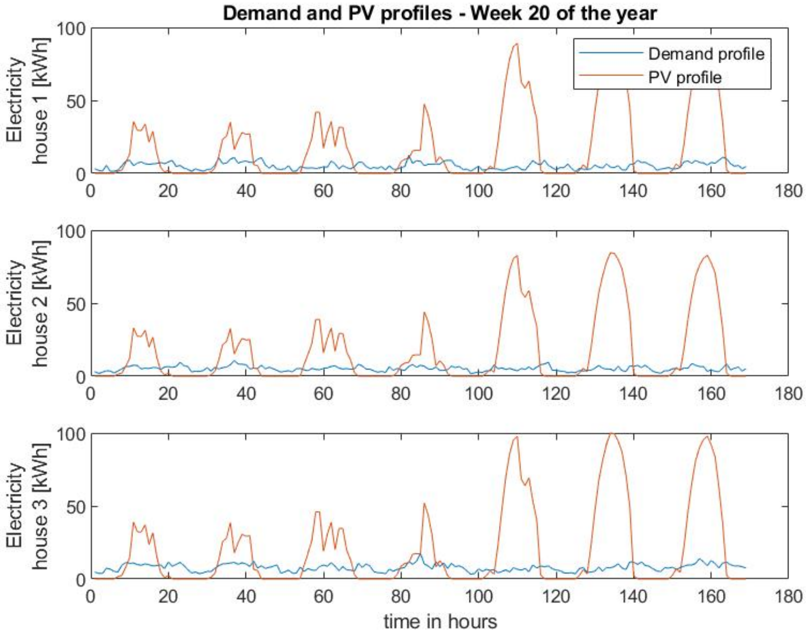

Figure 9: *Comparison of demand and PV production profile of each house in an exemplary week of the year in Scenario 1.*

on the choice of the electricity source of the house. In Figure 7 and 10 around the hour 40 the house uses grid electricity, pictured in blue color, although the PV system produces loads of energy. This is the case because the energy price from the grid is low during that time. Due to the higher feed-in remuneration the producer gets, all the production is fed to the grid while the consumption is simultaneously satisfied from the grid.

Figure 8 shows the production profile of each house and the variable electricity price profile. The energy that goes to the house is colored blue, while the energy that goes to the grid is shown in orange color.

The last figure from Scenario 1, Figure 9, shows a comparison between the production and demand profiles of each house. The production clearly exceeds the demand due to the large PV system size that was found to be optimal in the design optimization, which indicates the need for storage or more consumption during those times.

In Scenario 2 the stored energy in the battery can be saved for times when the electricity price is higher again and no self-production is available. This is sometimes the case during nighttime as can be seen in Figure 10. This figure shows the components that fulfill the energy demand of the three houses. There are three sources of energy that the house can draw from, namely the electricity grid in blue color, the PV system in orange

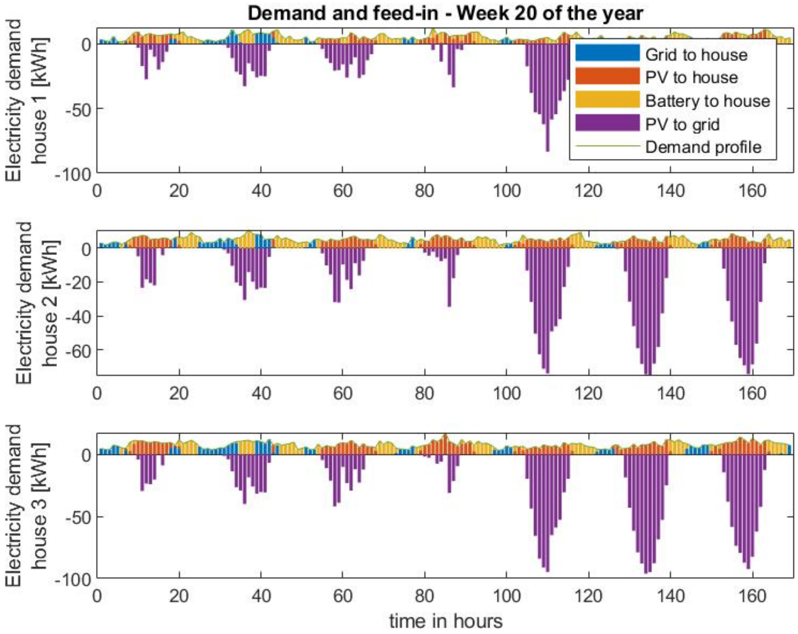

Figure 10: *Energy flows to and from each house in an exemplary week of the year in Scenario 2.*

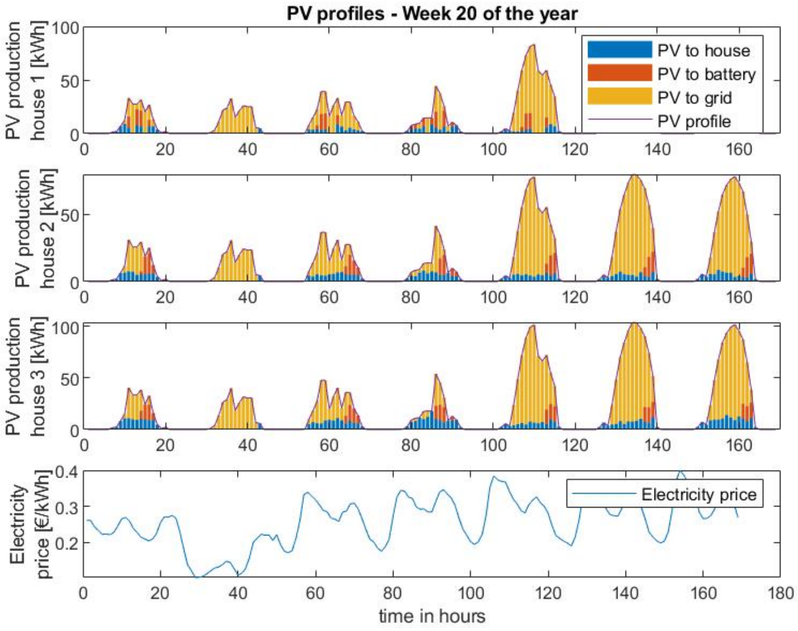

Figure 11: *PV production of each house and variable electricity price development in an exemplary week of the year in Scenario 2.*

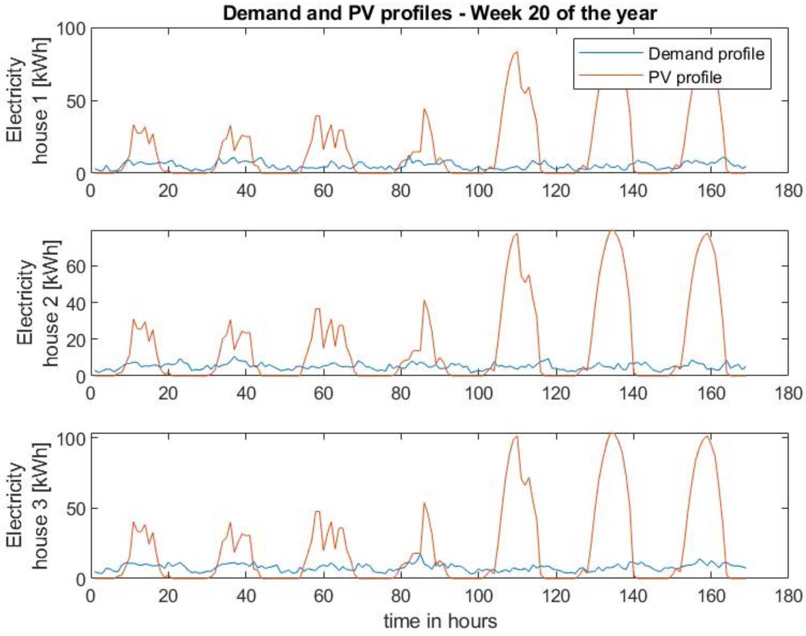

Figure 12: *Comparison of demand and PV production profile of each house in an exemplary week of the year in Scenario 2.*

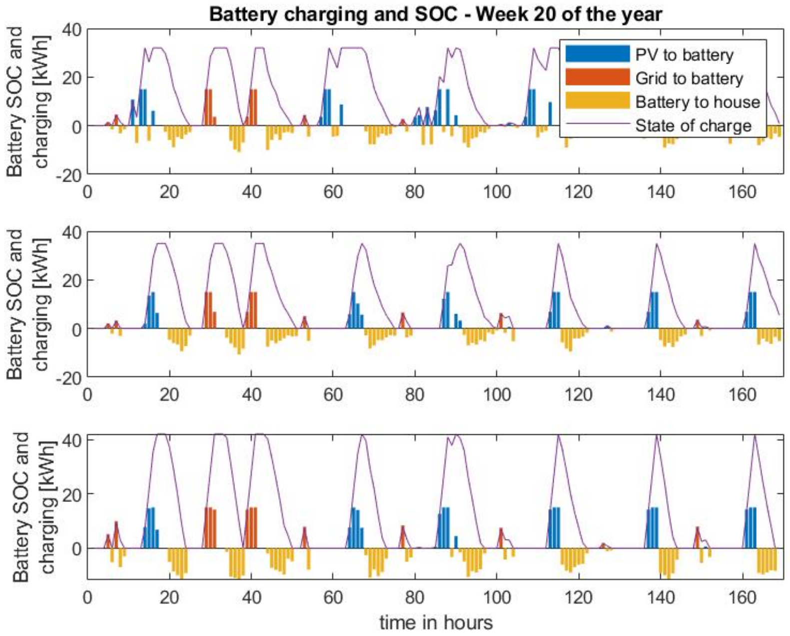

Figure 13: *SOC and battery in- and outflows for each house in an exemplary week of the year in Scenario 2.*

color, and the battery in yellow color. Additionally, the feed-in from the PV to the grid is pictured in purple color.

In Figure 11 the PV production is pictured and split up in the energy flows to the different consumers. The energy flow from the PV to the house is shown in blue color, from the PV to the battery in orange color, and from the PV to the grid in yellow color. The last plot in this figure shows again the electricity price profile.

Figure 12 again compares the demand and production profile of the optimally sized PV systems in Scenario 2, showing that production exceeds the demand.

The last figure of Scenario 2 for the minimized cost objective is Figure 13. It shows the BSS SOC for all three houses and the operation of the battery. Battery charging from the PV system is shown in blue, charging from the grid is orange, and discharging to the house is pictured in yellow. The purple line indicates the total SOC of the battery over time. It is also interesting to mention, that during times of low energy prices, the battery is sometimes charged with electricity from the grid, although excess PV electricity would also be available. This is the effect of cost minimization because if the battery operates in a way, where it stores cheap grid electricity, it is able to discharge and provide energy to the house when no other source except the expensive grid is available.

4.2.2 SSR maximization

The maximum levels of self-sufficiency for Scenario 1 and 2 are documented in Tables 23 and 29, respectively. In Scenario 1 moderate SSR levels can be reached, but full autarky is not possible with PV only, due to the fact, that the PV system only produces electricity during the day. Thus, the nighttime demand cannot be fulfilled and the grid needs to be taken as a source. This shows the need for additional storage capacity to shift the produced energy to times when no production takes place. In comparison to this, in Scenario 2 full autarky is reachable with values of 99% SSR. 100% is not possible because, in the initial hours of the year, the demand cannot be fulfilled by the PV or BSS due to the starting constraints. The BSS was modeled empty in the beginning. This could have been avoided, if the initial SOC of the BSS was not zero. The goal behind this was to find out if electric self-sufficiency was theoretically possible in the given area of Austria in Central Europe. Theoretically, it would be possible but economically and also concerning the area for a large PV system and BSS this would not be viable. The Figures 14 - 16 show the sizes of the components for different SSR values. In these diagrams, it can be seen, that the last 5 - 10% require comparatively more additional production and storage capacity. This is due to the fact, that the remaining electricity that is supplied by the grid is the most difficult to replace because the demand occurs in the middle of the night and the storage needs to uphold some production from the daytime. Or because there are a couple of days with very little sun in a row. In that case, this small time of the year defines the size of the components because due to the constraints, the whole demand has to be fulfilled by PV production or stored electricity. Figure 17 visualizes the annualized costs for the energy system needed to reach exactly these SSR values. It shows how much annualized investment is needed to reach another 5%, 10%, or 20% of self-sufficiency and goes hand in hand with the previously stated facts. The last percentage points are the most expensive ones because they require a disproportionately large increase in the component capacities.

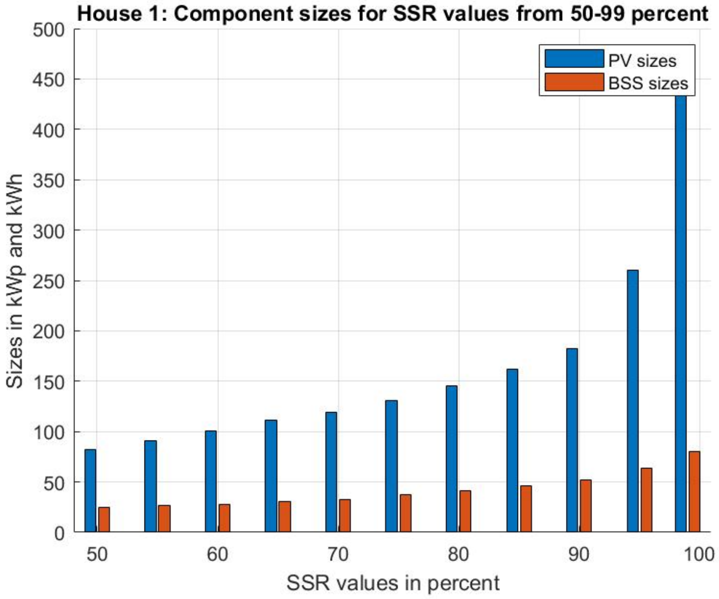

Figure 14: *Component sizes of house 1 for different SSR values in Scenario 2. PV size is given in kWp and BSS size in kWh.*

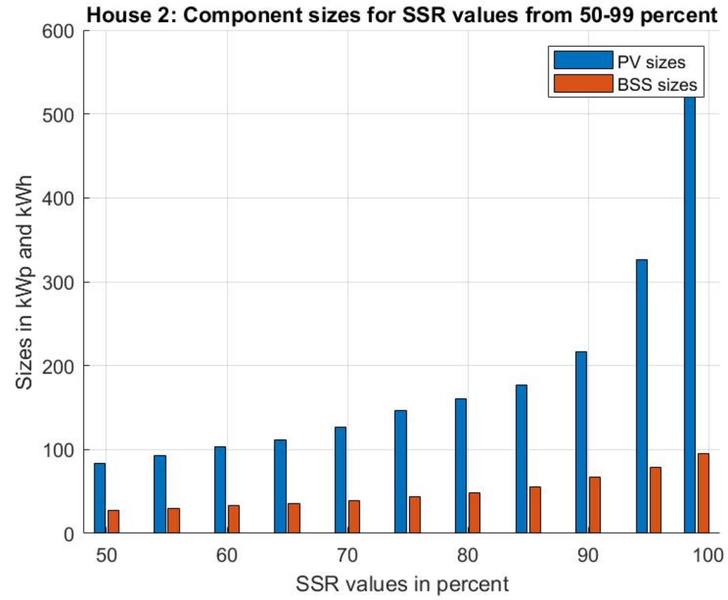

Figure 15: *Component sizes of house 2 for different SSR values in Scenario 2. PV size is given in kWp and BSS size in kWh.*

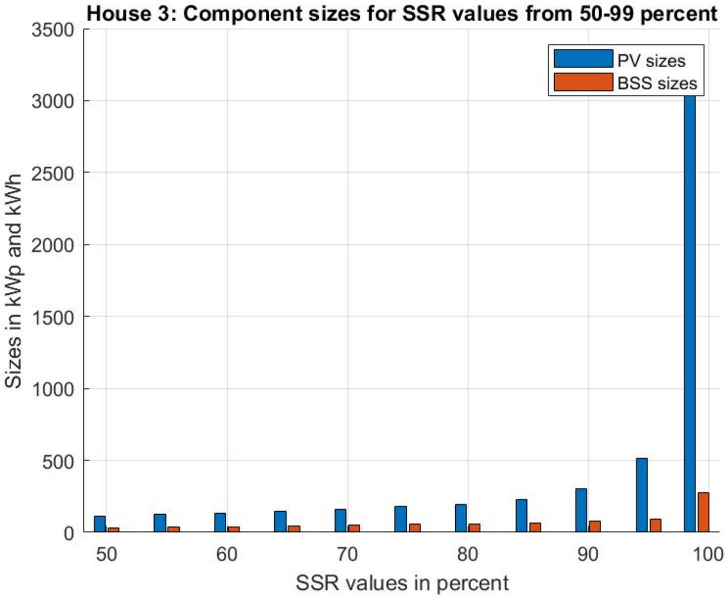

Figure 16: *Component sizes of house 3 for different SSR values in Scenario 2. PV size is given in kWp and BSS size in kWh.*

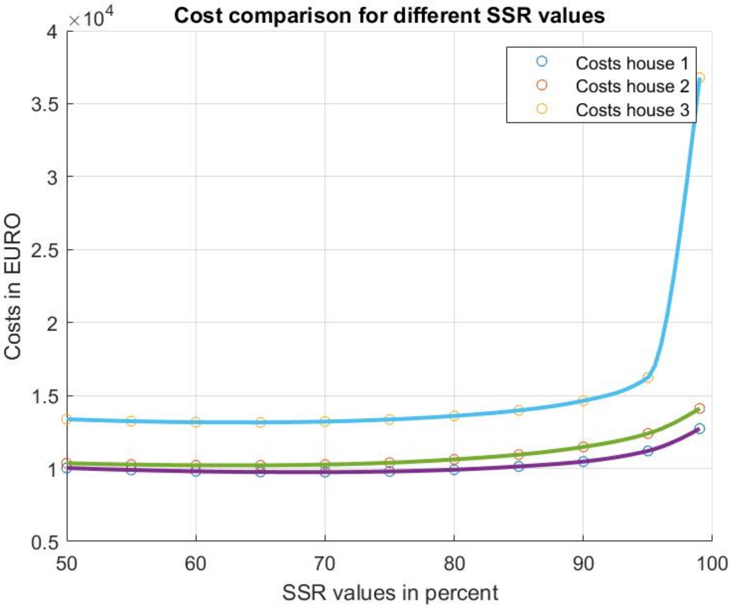

Figure 17: *Annualized cost comparison of the three houses for different SSR values in Scenario 2.*

5 Conclusion and Outlook

In this chapter a summary and conclusion are drawn. The scope of the thesis is revisited and the limitations of the given energy hub with its boundaries are pointed out. From these limitations, an outlook on potential extensions and future research opportunities are listed that could be implemented with the optimization model with minor changes.

5.1 Summary

To summarize, the analysis of the given energy hub showed an improvement in both total annualized costs and SSR with every system extension that was made in the different scenarios.

At first, the existing energy hub with its demand and PV production was analyzed and set as a benchmark. The following design optimization was conducted under two objectives, namely minimizing annualized costs and maximizing the self-sufficiency of the energy hub. In Scenario 1 the PV system was optimally sized, taking into account the meteorological data at the location of the energy hub and calculating both total annualized costs and SSR. In Scenario 2 both the PV system and a BSS were optimally sized for the two objectives. The results from the first two scenarios are similar to those found in the literature and can be compared to the results from De Oliveira e Silva and Hendrick (2017) [15]. They analyzed similar scenarios in different geographic locations. In Scenario 3 an additional HSS was modeled as an alternative means of storage. It could be demonstrated that the annualized costs decrease significantly when adding additional PV capacity in Scenario 1 and when adding a BSS in Scenario 2. In Scenario 3 the HSS was too expensive and the efficiency was too low, compared to the BSS. Therefore, the HSS was never chosen as an active component in the simulation. Ibáñez-Rioja et al. (2022) draw a similar conclusion, although a hydrogen system is integrated with their model because they looked at off-grid energy hubs [11]. Monforti Ferrario et al. (2021) conclude, that in the hybridized storage scenario with a BSS and HSS higher energy security can be reached, although facing a disproportional increase in cost [1]. In addition to the cost decrease, the SSR values mentioned in Table 33 increased from scenario to scenario, showing that it is not only economically attractive to optimize the component sizes for a given demand, but even more from an energy independence point of view. Due to additional PV and storage capacities, the energy hub increased its autarky and became more independent of energy providers. It could also be shown, that theoretically full autarky could be reached in Scenario 2 with the PV and BSS combination. Full autarky would also be possible with an HSS, but the economical aspect is not even given for the maximized SSR case in Scenario 2 with PV and BSS. And it would be even less true for an HSS that is dimensioned in a way to reach full autarky. The only cases where full self-sufficiency would be necessary are off-grid scenarios that fully rely on their own self-production and storage of excess capacities. In this case, the literature finds hybridized production and storage combinations as the most efficient forms [1]. Although hydrogen is still not cost-competitive it is more environmentally friendly than other possibilities like diesel generators [11]. The hydrogen system would be included if a fixed rate of hydrogen would be directly needed instead of re-electrifying it in the fuel cell because then the hydrogen demand needs to be fulfilled at any time and the costs play only a secondary role. Heat coupling, fuel cell electric vehicles, or direct utilization in the industry would be possibilities.

In short: An optimized sizing of the components for renewable energy production and storage leads to educated decisions on whether to build or not to build it. The optimal size leads to significant cost reductions, higher SSR values, and energetic independence. It definitely pays off to invest in renewable energy systems to fulfill the own energy demand.

The research questions could all be answered. The theoretical and real SSR values were calculated for all the different scenarios and it was shown that it increases with additional PV and storage capacity. The optimal size for minimized annual costs was found and the corresponding SSR values were calculated, as well as the maximum SSR values without the cost-minimizing objective. Full autarky could theoretically be reached in Scenario 2.

5.2 Scope and limitations

The scope of this study includes three residential buildings with individual households, general consumption, two commercial units, and a PV panel on each of the houses. The analysis examines the electrical side of the energy system and only considers the electricity demand and production of the included entities. The energy hub is located in Austria representing the mountainous area of Central Europe.

With this said, this approach does not include any other energy sources or sectors, such as heating or mobility. The implementation of sector coupling and different energy carriers can have a large impact on the outcome. If the heating in the house were provided by heat pumps the annual electricity demand would triple or even quadruple. The same applies to E-mobility. If the households would all charge their electric vehicles with electricity from their PV panels, the whole balance would look different and the components would probably be sized very differently. If hydrogen could be used for both electricity and heat production the value would increase, due to the replacement of other heat sources and due to increased efficiency because not all the hydrogen would be re-electrified in a fuel cell, only the amount that is needed to fulfill electricity demand. In the scope of this thesis, these possibilities are not included.

5.3 Future research

In future research the shortcomings or limitations mentioned in Section 5.2 need to be considered. As this study purely looked at the electrical side of residential multi-apartment buildings, it would be interesting to see how sector coupling, like the integration of heat production and consumption or mobility, in whatever form would influence the outcome. This would also paint a broader picture of residential energy systems as a whole. It also implies that detailed data about the heat demand of the households needs to be known, which is currently largely unavailable. The granularity would need to be similar to that of electricity demand data. Mobility could be another system extension, to find out how electric vehicles could be utilized in the energy system as intermediate storage options or to replace combustion engine vehicles and therefore save carbon emissions. Emissions savings could be another weighting objective to extend the evaluation criteria beyond just economic aspects. These possibilities can be easily integrated into the existing model as system extensions with minor changes to the energy balance constraints and with an additional description of the added components. This immediately paints a more holistic picture of the energy demand and the needed production capacities in a residential energy hub.

Another scope extension could be the expansion of the geographical boundaries from the three buildings to whole towns or cities. Here, the interaction between individual production and consumption behaviors of a larger number of components could be researched. This could even include other consumers than just households, like for example industry locations, small or medium companies, or municipal buildings. In that case, the synergy potential could potentially be larger due to the increased number of different load and energy profiles.

If both of these approaches are combined, larger communities could be analyzed including all the necessary energy sectors, electricity, heat, and mobility. This leads further in the direction of energy communities and collective energy production and consumption. With larger scopes, the results from this thesis become less theoretical and could really be implemented. Larger areas for production would exist and maybe even hydrogen could be of use in some of these cases, especially to decarbonize hard-to-abate industry sectors where hydrogen could be produced from excess renewable energy and used directly to replace fossil fuels instead of re-electrifying it. Hydrogen could be used in both the electricity sector and even more effectively in the heat sector. It could also serve as long-term energy storage to cut production peaks and fulfill the demand in times of little renewable production.

All of this can be added to the existing framework with more or less sophisticated adaptations, depending on the given use case and the boundaries. The more holistic the model should be, the more important it is to have access to resilient data sources for the modeling of all the components as well as for detailed production and consumption data of electricity, heat, and potentially hydrogen or other energy carriers. The availability of this data is key to finding proper solutions for the systems under assessment.

After seeing the results of this thesis and the possible cost savings on the electrical side alone, there might be even larger potential on the heat and mobility side.

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