MASTERARBEIT / MASTER'S THESIS

Titel der Masterarbeit / Title of the Master's Thesis

„Recommender Tool for Optimized Battery Charging Cycles for Energy Communities"

verfasst von / submitted by

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angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien, 2025 / Vienna, 2025

Studienkennzahl lt. Studienblatt / degree programme code as it appears on the student record sheet:	UA 066 926
Studienrichtung lt. Studienblatt / degree programme as it appears on the student record sheet:	Masterstudium Wirtschaftsinformatik UG2002
Betreut von / Supervisor:	ao. Univ.-Prof. Dipl.-Ing. Dr. Hermann Schichl

Acknowledgements

Our actions may be impeded, but there can be no impeding our intentions or dispositions. Because we can accommodate and adapt. The mind adapts and converts to its own purposes the obstacle to our acting.

The impediment to action advances actions. What stands in the way becomes the way.

- Marcus Aurelius

This thesis is dedicated to my supervising professor, Dr. Hermann Schichl, for his guidance, patience, faith, and support. Most importantly, I would like to express my gratitude for sparking my initial interest in the topic, continuously encouraging me throughout the process, and for the insightful conversations we shared along the way.

Thank you.

Abstract

For the past few decades, the energy sector has undergone a profound transformation, driven by the shortcomings of the conventional centralized power grid, the growing share of renewable energy sources in the mix of energy production, and the general advancement of information technology. One key aspect of the transformation process is the ongoing decentralization of energy generation and storage, which transfers more control to individual consumers, leading to the establishment of autonomous microgrids. The European Union has responded to these developments by passing respective legislation in the form of Renewable Energy Directive II, which was implemented by the Austrian government in 2021, allowing for the creation of so-called "energy communities": Associations of private and public individuals that act as unified market participants towards the main power grid by utilizing renewable energy sources to manage their own energy production, consumption, and storage within a certain geographical proximity. These developments have resulted in growing energy supply and demand fluctuations, which in turn require efficient energy storage systems on the one hand and powerful optimization and forecasting tools on the other.

This paper constitutes a comprehensive review of the power grid transformation process and the current state-of-the-art of energy storage systems. It includes a technical implementation of an exemplary master data management tool for Austrian energy communities ("Energy Community Management", ECM). This tool enables the creation of a simple digital twin of an energy community consisting of energy generation sources (solar panels), loads (households), and storage devices (lithium-ion batteries). The resulting model can be used for further optimization purposes; in scope of this paper, however, is the simulated optimization of the storage device - a mocked prediction of how the battery should be optimally charged/discharged based on certain characteristics (e.g., capacity, discharge rate) and internal/external information (e.g., load/generation profiles, prices). In summary, this paper represents an interdisciplinary approach of energy economics, mathematical optimization, and informatics, with the ultimate goal of creating a holistic picture of the current technological and societal decentralization trends of the Austrian energy sector.

Kurzfassung

In den letzten Jahrzehnten hat der Energiesektor einen tiefgreifenden Wandel durchlaufen, der durch die Schwächen des herkömmlichen zentralisierten Stromnetzes, den zunehmenden Anteil erneuerbarer Energiequellen in der Stromproduktion und den allgemeinen Fortschritt der Informationstechnologie vorangetrieben wurde. Ein zentraler Aspekt dieses Transformationsprozesses ist die voranschreitende Dezentralisierung der Energieerzeugung und -speicherung, die den einzelnen Verbrauchern mehr Kontrolle überträgt und zur Entstehung autonomer "Microgrids" führt. Die Europäische Union hat auf diese Entwicklungen mit der Verabschiedung entsprechender Gesetzgebung in Form der Erneuerbare-Energien-Richtlinie II reagiert, die 2021 von der österreichischen Regierung umgesetzt wurde und die Schaffung sogenannter „Energiegemeinschaften“ ermöglicht: Zusammenschlüsse von privaten und öffentlichen Haushalten, die als einheitliche Marktteilnehmer gegenüber dem öffentlichen Stromnetz agieren und erneuerbare Energiequellen einsetzen, um ihre Energieproduktion, -nutzung und -speicherung innerhalb einer bestimmten geografischen Nähe gemeinschaftlich zu verwalten. Diese Entwicklungen haben zu wachsenden Schwankungen von Stromangebot und -nachfrage geführt, was einerseits effiziente Energiespeichersysteme und andererseits leistungsstarke Optimierungs- und Prognosetools erforderlich macht.

Diese Arbeit bietet einen umfassenden Überblick über den Transformationsprozess des Stromnetzes und den aktuellen Stand der Technik von Energiespeichersystemen. Sie umfasst die technische Implementierung eines beispielhaften Stammdatenmanagement-Tools für österreichische Energiegemeinschaften („Energy Community Management“, ECM). Dieses Tool ermöglicht die Erstellung eines einfachen digitalen Zwillings einer Energiegemeinschaft, bestehend aus Energiequellen (Solarmodule), Verbrauchern (Haushalte) und Speichereinheiten (Lithium-Ionen-Batterien). Das resultierende Modell kann für weitere Optimierungszwecke verwendet werden; im Rahmen dieser Arbeit liegt der Schwerpunkt auf der Optimierung der Speichereinheit - eine simulierte Vorhersage, wie die Batterie basierend auf bestimmten Eigenschaften (wie z.B. Kapazität oder Entladerate) sowie internen und externen Informationen (wie z.B. Last- bzw. Erzeugungsprofile oder Strompreise) optimal geladen/entladen werden sollte. Zusammenfassend stellt diese Arbeit einen interdisziplinären Ansatz aus Energiewirtschaft, mathematischer Optimierung und Informatik dar, mit dem Ziel, ein ganzheitliches Bild der aktuellen technologischen und gesellschaftlichen Dezentralisierungstrends im österreichischen Energiesektor zu schaffen.

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1. The Energy Grid Transformation

This chapter deals with the transformation of the traditional power grid: the shift from centralized power production and distribution towards a more decentralized (yet highly interconnected) model. This transformation is largely driven by the shortcomings of the conventional power grid, the emergence of new technologies, and the increasing adoption of renewable energy sources, which are inherently more distributed, as well as evolving legal frameworks that empower private individuals and local communities with greater autonomy and self-sufficiency in energy production and consumption.

These changes not only redefine the roles of producers and consumers but also introduce innovative models and opportunities for participation, such as energy communities. The following sections will explore these emerging frameworks, the options they present, and the broader implications for the energy landscape.

1.1. From the Centralized Power Grid to Distributed Energy Resources

Throughout history, humans have utilized the resources available to them to generate, conserve, and distribute energy (mostly in its thermal form). With the advancement of civilization and the discovery of electricity, the methods and processes of energy creation, storage, and distribution have changed dramatically. This development can be roughly categorized into four "phases" or "eras":[Ert24]

- **Pre-Industrial Era (pre-1800)**: Energy is mostly produced by burning wood, charcoal, and animal waste, primarily to provide heat.
- **Industrial Era (1800-1950)**: The steam engine becomes the most dominant tool for energy generation, electricity its main method of distribution. The conventional, centralized power grid is established.
- **Fossil Fuel Era (1950-2000)**: Oil and natural gas become the main energy sources, nuclear energy is made available for civilian use. The demand for energy increases significantly.
- **Renewable Energy Era (post-2000)**: Renewable energy sources are added to the production mix, mostly solar and wind. The power grid starts to decentralize.

This section focuses on the development since the industrialization: The history of the conventional power grid and its ongoing transformation into a decentralized "grid of grids".

1.1.1. The Development of the Conventional Power Grid

What exactly is a power grid? A common definition explains power grids as the infrastructure (or network) that enables the delivery of electricity from the source of power generation to its consumers.[HZISC17, Ert24] Therefor, a power grid needs to complete three major tasks: Power generation, transmission, and distribution. See Figure 1.1 for a schematic overview.[HZISC17]

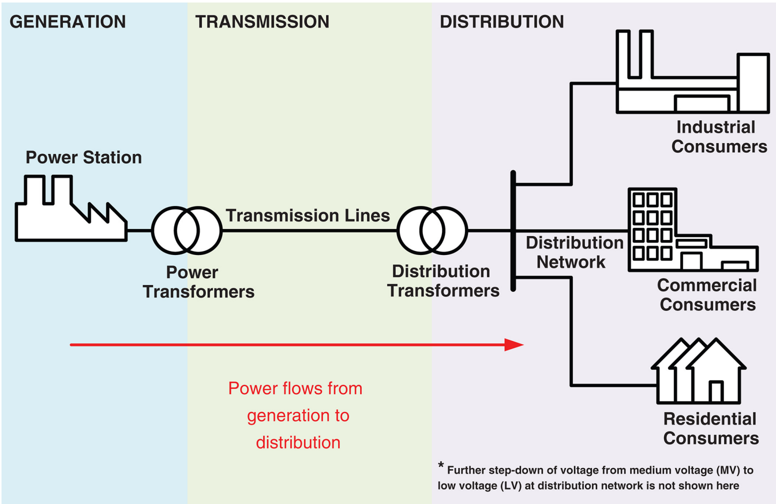


Figure 1.1.: The structure and tasks of power grids, according to [HZISC17]

The very first power grid was established by Thomas Edison in New York City in 1882, called the "Pearl Street Station".[TA16, Nob82] This grid supplied 85 customers with sufficient electricity to light about 400 lamps in the First District of Manhattan, generating energy by burning coal.[Nob82] Similar power stations serving their immediate neighborhoods were established throughout the world, growing bigger in size and capacity. Eventually, those isolated grids started to interlink with each other, forming integrated networks that became the conventional power grid that we know today (as an example, Figure 1.2 illustrates the development of the US power grid over the first half of the 20th century).[Coh19]

The traditional grid is therefore a network of electrical generators, power lines, transformers, switch gears, protection devices and other equipment that delivers electricity to its consumers.[Ert24] Typical characteristics of the conventional power grid are the "radial" topology (the power source being located at the center of the area it serves) and the unidirectional power flow - the energy only goes one way, from the generator to the consumer (as indicated in Figure 1.1).[HZISC17]

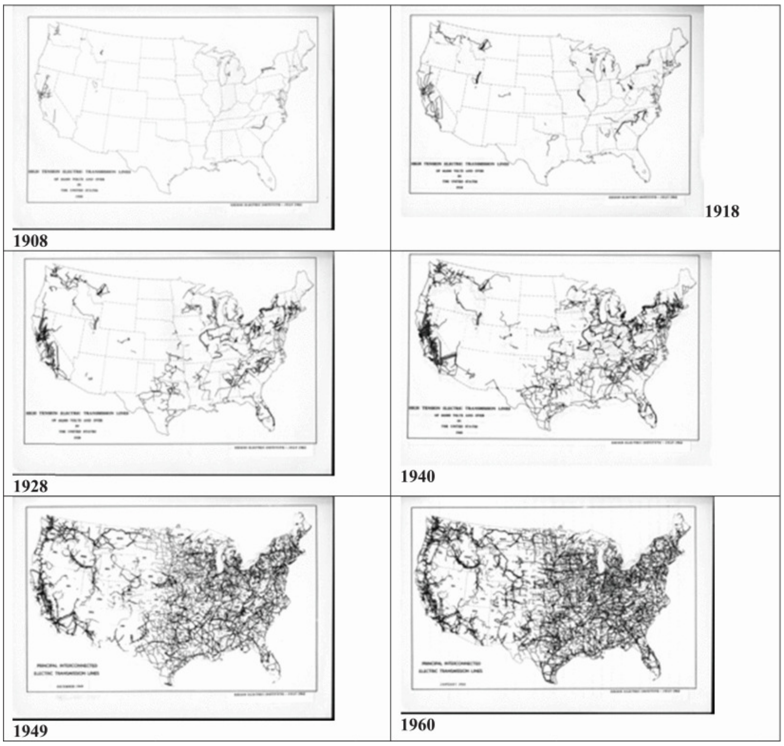


Figure 1.2.: The gradual fusing of the US power grid, according to [Coh19]

1.1.2. Current State and Challenges

The main objective of any power grid is the consistent and uninterrupted supply of energy to its customers while simultaneously managing costs and efficiency concerns.[Ert24] In free market economies, utility providers therefore need to balance the cost of a stable, safe, and reliable power infrastructure with market competition and profitability goals.[Fai04] In the current interdependent grid setup, this is not an easy task to perform; The main challenges of the traditional, centralized power grid can be summarized as follows:

- **Power Outages**: Power outages can happen due to broad variety of reasons: Generator breakdown, equipment malfunction, broken transmission lines, severe weather events, cyber attacks, etc.[SAJ+21] In a closed system, power outages are contained; However, in a centralized grid, failure of one system can have a cascading downstream effect on other parts of the grid. In the worst case, the whole grid (or large parts of it) could be affected by an outage, leading to a so-called "blackout".[SAJ+21] The larger and more interconnected a grid becomes, the harder it is to predict, prevent, and properly manage power outages.[Fai04]

- **Transmission Losses**: As indicated above, power transmission is one of the central tasks of a power grid. In the conventional grid, the produced electricity often needs to be transported over long distances to reach the distribution network; This is done by increasing the voltage to high levels at the energy source and decreasing it again to safer levels at the destination (see also Figure 1.1).[HZISC17] Nevertheless, transmission losses are inevitable. The longer the distances between producers and consumers and the larger the distribution network served by the producer, the more power is lost in the energy delivery process.[HZISC17]

- **Growing Energy Demand**: Demand in energy is constantly increasing, due to factors such as global population growth, technological and industrial advances in developing countries, and continuous broad implementation of EVs.[JTIA18] This adds additional pressure on the conventional grid; Construction of new power generators and the modernization of aging infrastructure increases the cost per kWh produced, which in turn makes the use of energy storage technologies on the consumer side more attractive: Energy saved is cheaper than energy produced.[JTIA18]
- **Supply & Demand Fluctuations**: Finally, the development and gradual addition of distributed energy resources (DERs, cf. 1.3.1) into the grid constitutes another challenge. A DER consists either of a low- or medium-voltage power generator or an energy storage component (cf. 2.3).[AHP10] The conventional grid, with its radial setup and unidirectional power flow (which determines instantaneous energy production/consumption),[Dil20] was initially not prepared to handle DERs and the demand/supply fluctuations they bring; However, they are increasingly recognized, integrated, and applied to enhance and support the power grid.[Ert24]

In short, the centralization of the grid has significantly increased its complexity, which is further exacerbated by the instability caused by increased energy demand and the supply fluctuations caused by DERs. Thereforee, new solutions have gradually started to emerge in order to deal with the challenges listed above, partly as a consequence of those challenges, partly as a by-product of the general progress of technology. In a way, the grid is returning to its origin: A decentralized grid of more independent (yet highly interconnected) junctions.

1.2. The Smart Grid

The following section describes a new way of thinking about the power grid, which is enhanced and transformed by modern technologies such as the internet of things, an abundance of sensors and communication devices, and processing of information in real-time: The smart grid.

1.2.1. Characteristics of the Smart Grid

At present, there is no unilateral or cohesive definition of what exactly a smart grid is; different parties and organizations have different understandings of what that term means in detail.[Dil20, TA16] However, a common approach to explain the smart grid is by visualizing how it differs from the conventional grid. Table 1.1 lists the most instructive distinctions.[TA16]

Conventional Grid	Smart Grid
Mechanization	Digitization
One-way delayed communication	Two-way real-time communication
Centralized energy generation	Distributed energy generation
Radial network	Dispersed network
Less data involved	Large volumes of data involved
Small number of sensors	Large number of sensors and monitors
High degree of manual control	High degree of automation
Small degree of security and privacy concerns	Prone to security and privacy breaches
Few user choices	Vast user choices
Simultaneous production and consumption of energy	Utilization of energy storage systems
Slow response to emergencies	Fast response to emergencies

Table 1.1.: The differences between the conventional and the smart grid, adapted from [TA16]

From this list it should become clear that the smart grid is characterized by its extensive usage of (and reliability on) modern technologies brought upon by the ongoing digitization, in addition to a high degree of automation, real-time monitoring (particularly smart metering), and decentralization. Remarkably, the smart grid breaks both with the unidirectional power (and information) flow and radial topology inherent in the conventional grid, transferring autonomy - and, thus, choice - to the consuming part of the grid (the distribution network).[TA16] This high level of interconnectedness of the various stakeholders is visualized by Figure 1.3.

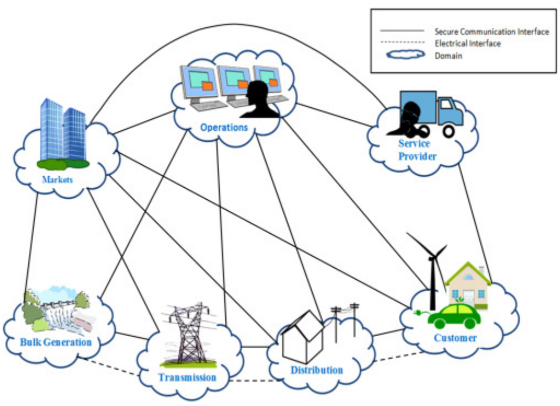


Figure 1.3.: A conceptual overview of the smart grid, according to [TA16]

Another way of defining the smart grid is to see it as an integrated "system of systems" (SoS), where each system is structured into different "layers".[KG17, URN+19, PDG+13] The details of these SoS-models differ from research group to research group; However, they usually have a "physical" layer at the bottom (portraying the real-world, physical grid infrastructure), followed by various "communication" and "information" layers before concluding with a "control" layer at the top. The "smart" part happens mostly on the intermediate layers - this is where most of the digital technology developments mentioned above are implemented and applied.[KG17, URN+19] See Figure 1.4 for an exemplary model.

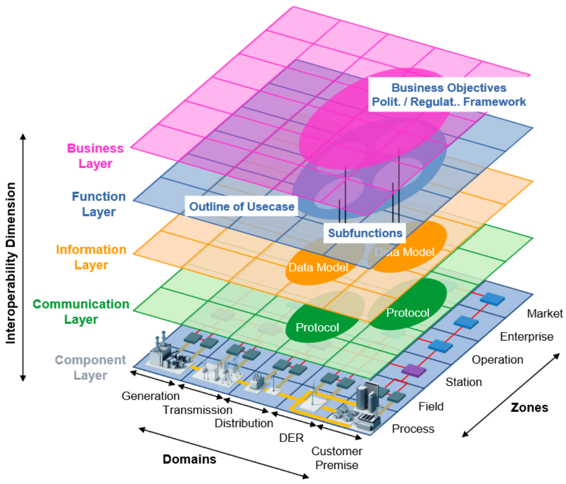


Figure 1.4.: An example of a layered smart grid architecture, according to [URN+19]

In conclusion, the smart grid is a means to deal with the increasing complexity of efficiently providing the right amount of energy at the right time to the right consumer. This is achieved by the decentralization of power generation and transmission while simultaneously strengthening the ties between the thereby newly created, more dispersed network participants through the application of modern digital technology.

1.2.2. Development and Challenges

There is no distinct "birthday" of the smart grid; Rather, it emerged organically with the advancement of technology, the rising visibility of the conventional grid's shortcomings, and, increasingly, the risks posed by climate change (and the subsequent rise of renewable energy sources).[TA16] However, it is generally agreed that the emergence of smart grids coincides with the first application of smart meters in the 1970s and 1980s - that is, technology that monitors energy consumption on the consumer side and delivers the information back to the utility.[TA16, Dil20, MBZMB21]

The first scientific papers about smart grids emerged in the late 1990s and early 2000s.[TA16] According to one author, the development of the smart grid approach can be grouped into various "generations": In the 1990s, a "smarter" grid meant the provision of more computational power and newer hardware to deal with the traditional grid's aging infrastructure.[Wer11] In the early 2000s, the second generation shifted the focus more towards real-time monitoring and control, making the grid faster in terms of adaptability and response to external events. This development was strongly driven by the deregulation of the energy sector, making new practices such as time-of-day-pricing (reflecting the actual energy production costs, which vary throughout the day, in the price) and load shifting (timed energy consumption in accordance with those more accurate market prices) possible.[Wer11]

The third generation of the smart grid concept focused on improving statistical models and corresponding software in order to optimize the balance between the grid's stability and market needs, while the fourth - and current - generation acknowledges the increasing role of renewable energy sources and strives for higher levels of automation.[Wer11] At present, the biggest challenges of the smart grid are the following:

- **Broad Application of EVs**: The growing share of electric vehicles (EVs) in the transportation sector and their direct effect on the grid (vehicle-to-grid, V2G) constitutes a major challenge: The more people plug in their EVs for charging at the same time, the more energy needs to be made available quickly.[YWQ+24] However, V2G has a reflexive relationship with the power grid: Just as EVs consume energy when being charged, they can also act as batteries that provide energy back to the grid, enabling "peak shaving" capabilities (short-term provision of energy when demand peaks).[YWQ+24]. So the emergence of EVs represents both a challenge and an opportunity that needs to be managed efficiently.

- **Privacy Concerns and Grid Protection**: Due to the intensive use of monitoring devices that collect vast amounts of data in addition to a high dependency on internet-based communication technology, the smart grid is particularly vulnerable to cyber attacks and data breaches.[TA16] Therefore, new standards and safeguards need to be developed and implemented to keep the individual's user data safe and the grid protected. One proposed way of achieving this is by adding a "security layer" to the smart grid architecture (cf. Figure 1.4).[TA16]

- **Data Management and Analytics**: Adding to the previous challenge, the vast amounts of data that are being generated also need to be analyzed and visualized accordingly: There is no point in collecting information if no insights can be derived from it. This necessitates both an infrastructure that can handle the enormous amounts of data as well as tools and algorithms that can process the information efficiently.[TA16]

- **Renewable Energy Sources**: Finally, the increasing share of renewable energy sources (particularly solar and wind) in the energy production mix puts additional pressure on the grid, mainly due to the supply fluctuations inherent in them. Put simply: If the sun does not shine or no wind is blowing, no energy can be produced, which makes accurate energy production planning impossible.[Wer11, FMXY12]

Summing up, the smart grid constitutes a different approach of structuring and designing the power grid, developed to adequately address and manage the challenges of the conventional grid. It does so by delegating more control to the participants at the edges of the grid by large-scale application of modern measuring and communication technologies, establishing a distributed network of highly interconnected units. It is important to note though that the smart grid will not "replace" the conventional grid; The existing infrastructure of bulk power generation as well as the transmission lines will remain and be further expanded to meet the increasing energy demand. Instead, smart grids should be viewed as the gradual "evolution" of the power grid with the ultimate goal to make it more resilient, efficient, and robust.

However, this development is met with its own challenges, most prominently the increasing complexity of managing this dispersed network and the supply instability of renewable energy sources. These challenges, in turn, ask for more sophisticated optimization and forecasting tools on the one hand and for advanced energy storage systems on the other, especially since more autonomy and control is being transferred to the consumers, who increasingly start operating their own little grids. The resulting solution approaches are presented in the upcoming sections and chapters.

1.3. Microgrids

As the name implies, a microgrid constitutes a small power grid, meaning it incorporates an energy source and an energy consumer.[KG17] Microgrids can be described as "intentional islands" that are either operated by utilities or by commercial/industrial institutions (see Figure 1.5). In its most basic form, a microgrid consists of at least one distributed energy resource (DER, see below) and a corresponding load.[KBD08] In many cases, the energy producer and consumer within a microgrid are one and the same entity, which led to the creation of the term "Prosumer".[KG17]

Depending on the concrete use case and application architecture, microgrids can be further sliced into smaller "sub-grids", dubbed nano- or picogrids.[CVR+22] Figure 1.6 illustrates such an example. Furthermore, microgrids can be distinguished by their mode of operation: stand-alone or grid-connected.[KG17] The former version, stand-alone, is usually applied in remote locations, where connection to the main power grid is neither possible nor practical (e.g, offshore drilling platforms). The latter mode of operation (grid-connected) is more common. Here, the microgrid can provide superfluous energy to the main grid or request additional energy in case of power scarcity.[KG17]

The concept of microgrids is not exactly new - in a way, the Pearl Street Station mentioned in 1.1.1 constituted the very first microgrid: One coal-powered energy source providing

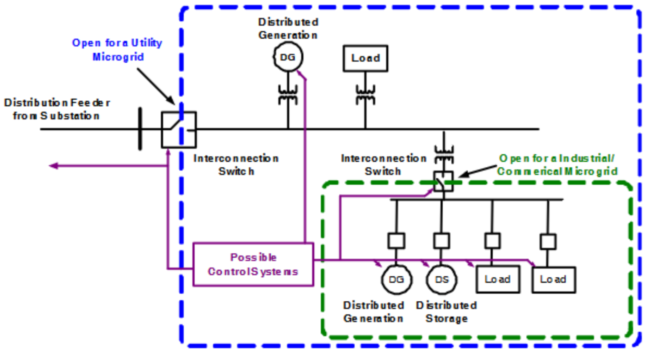


Figure 1.5.: An example of microgrid application, according to [KBD08]

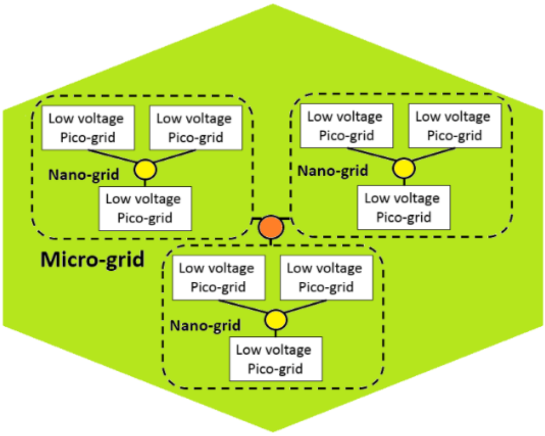


Figure 1.6.: A schematic overview of a microgrid that consists of individual nanogrids, according to [CVR+22]

power for 85 loads.[TA16] Also, emergency power back-up systems (e.g., in hospitals) can be viewed as microgrids. For the use case in scope of this paper however, the focus is put on a rather recent development: The establishment of microgrids in the form of local, residential energy communities.

1.3.1. Distributed Energy Resources

Before delving deeper into the details of those communities, this section describes distributed energy resources (DERs) in more detail. A DER is either a distributed (medium or low voltage) energy generation device or a distributed energy storage unit;[AHP10] Figure 1.7 presents a corresponding classification. As mentioned in previous sections, microgrids consist of at least one DER, which pose a challenge to the conventional grid, as DERs "disturb" the unidirectional power flow described in 1.1.1. This, in turn, leads to the aforementioned fluctuations in supply and demand.

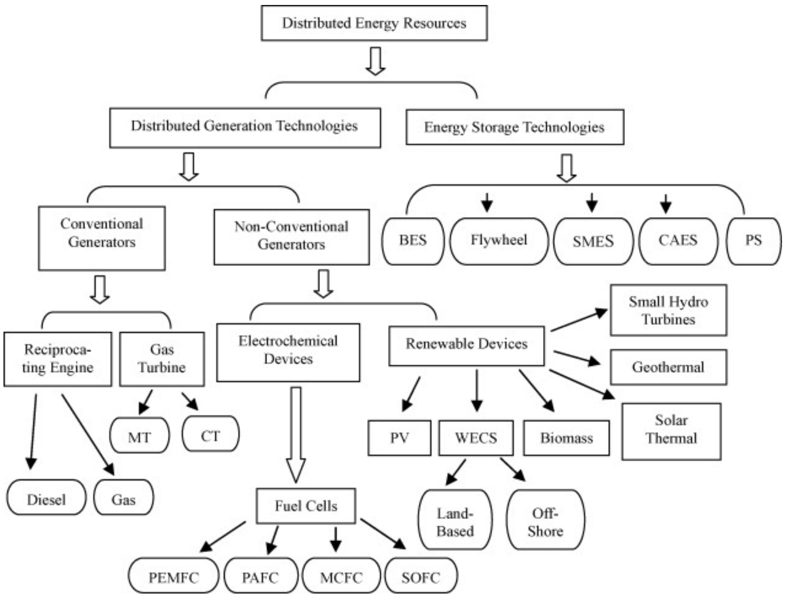


Figure 1.7.: A classification of DERs, according to [AHP10]

Microgrids typically employ both resources - generation and storage.[KBD08, KG17] With regard to the use case of this paper, for the energy production resource, I will focus on the non-conventional generators, specifically the renewable devices (see next section). Conversely, an extensive comparative review and analysis of energy storage systems is available in Chapter 2.

1.3.2. Energy Communities

There is no official definition of what exactly an energy community is;[BSD+22] as with the term "smart grid", the definition depends on who is asked. However, it is generally agreed that the term denotes an association of both private and (semi-)public entities with the common goal to manage energy production, storage, and consumption, typically generated by renewable sources, all of which depend on a certain geographical proximity[BSD+22] - or, in short, small towns and immediate neighborhoods. Moving forward, I will apply the definition of the Austrian government (see below).

Energy Communities in Scope

Since 2017, under Austrian law, individuals sharing space within the same building can share a common energy production source (e.g., a solar panel on the roof of an apartment building or a shopping mall). Since 2021, this can also be achieved across property lines, forming spread-out energy communities. The following activities are covered by this approach:[Ös23c]

- Joint energy production
- Joint energy consumption
- Joint energy storage
- Joint energy sale

This can be achieved by forming one of the following three entities:[Ös23c]

- **Shared Generator ("Gemeinschaftliche Erzeugungsanlage", GEA)**: This entity type includes the aforementioned exemplary solar panel on the apartment building, constituting the forerunner of the actual energy community. This kind of construct is the most basic version, requiring no legal form besides a contract between the participating parties. The main benefit is the liberation from external network charges (energy produced/consumed internally is virtually free); However, in this construct, only electricity is recognized as energy and the community is limited to its property line (Austrian grid network level 7).[Ös24]
- **Renewable Energy Community ("Erneuerbare-Energie-Gemeinschaft", EEG)**: This entity type describes a community that can produce, consume, store, and sell energy in the form of electricity, heat, and gas, provided that the energy comes from renewable sources (see Figure 1.9 for reference). The EEG can operate across property lines but is geographically limited to network levels 4-7. The external network charges are reduced and the establishment of the community requires a legal form.[Ös23b]
- **Citizen Energy Community ("Bürgerenergiegemeinschaft", BEG)**: This third community type can be operated across the whole federal territory of Austria (network levels 1-7), requires a legal form, and is not limited by renewable energy sources; However, only electricity is recognized as energy and there is no liberation from - or reduction of - external network charges.[Ös23a]

Figure 1.8 illustrates those three energy community forms and their territorial "reach". As can be derived from the descriptions above, the main benefit of forming an energy community lies in the opportunity to act as a unified market participant towards the public grid while exchanging energy internally at a self-set rate.

Legal Foundations and Operational Prerequisites

The legal foundation of the energy community construct was created in 2021, when the Austrian legislative authority implemented EU-directive 2018/2001 into national law.[Par19] This directive, also known as the Renewable Energy Directive II (RED II), establishes a framework for promoting renewable energy in the European Union. It originally set a binding target for the EU to achieve at least 32% of its total energy consumption from renewable sources by 2030, which was revised to 42.5% in November 2023.[Eurg] The directive encourages member states to adopt measures supporting renewable electricity,

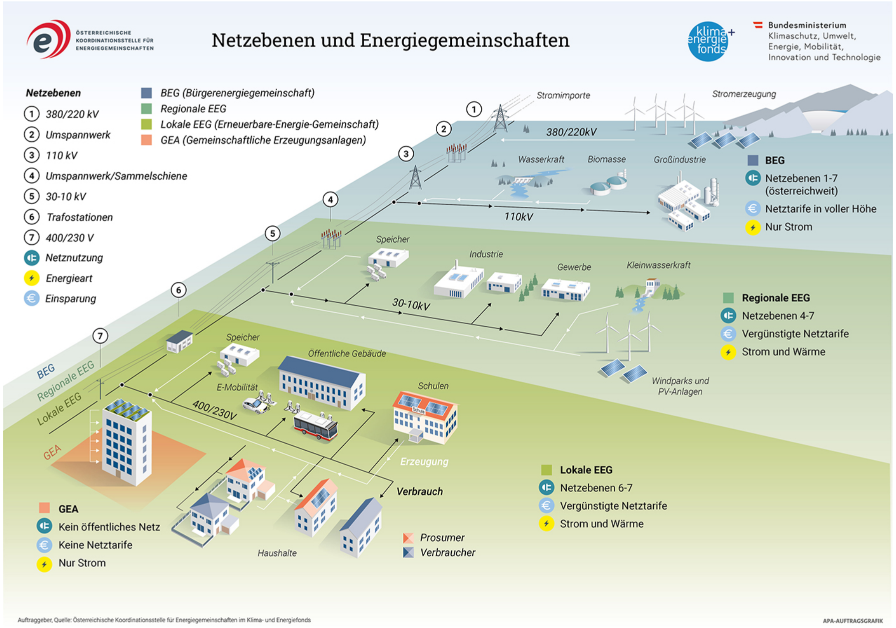


Figure 1.8.: The three energy community types available in Austria and their territorial reach, according to [Ös23b]

heating, cooling, and transport sectors; Among other aspects, it promotes decentralized renewable energy production, such as self-consumption and renewable energy communities, and enhances cross-border cooperation to integrate renewables into the EU's internal energy market.[Eurb, EUR18]

To establish an energy community under Austrian national law, a legal entity must be formed by at least two parties. The legal form of the entity does not matter, the community can take any form from charitable associations to limited liability corporations as long as the bylaws of the entity clearly state that it is non-profit.[Ös23b] The only other prerequisite to form (or join) an energy community is the implementation and use of a smart meter to accurately track energy production/consumption and enable internal settlement.[Ös23c]

Renewable Energy Sources

RED II clearly defines which energy sources are considered renewable under EU law:

- **Solar Power**: Technologies in the field of solar power convert sunlight into energy, either as electricity (photovoltaics) or heat (solar thermal energy). Photovoltaics operate through solar cells, which are assembled into solar panels and typically installed on freestanding surfaces or rooftops. Photovoltaics is a rapidly growing technology, accounting for 5,5% of total European electricity production in 2021.

Figure 1.9.: A model of a renewable energy community, according to [Ös23c]

Solar thermal energy, on the other hand, focuses on generating heat from sunlight, particularly for water heating using solar collectors.[Eurh]

- **Hydropower**: Hydropower currently represents one of the largest shares of renewable energy in the EU, accounting for 30% of renewable energy and 12% of total electricity production in 2022.[Eure] Hydropower typically includes domestic power plants such as run-of-river, reservoir, and pumped-storage plants, where flowing water drives a turbine that, in turn, converts this kinetic energy into electricity via a generator.[Bü11]

- **Wind Power**: Similar to hydropower, wind is harnessed in this case to generate electricity through the rotation of rotor blades. In 2022, wind energy accounted for roughly 38% of renewable energy in the EU, produced by both offshore and onshore wind parks.[Eurc]

- **Geothermal Power**: This form of renewable energy utilizes ambient heat; In the case of geothermal energy, this refers to heat stored beneath the Earth's surface, which is typically accessed using heat pumps. Both electricity and heat can be generated from geothermal energy, though the current focus is more on water heating than electricity production.[Eurd]

- **Bio Energy**: Bioenergy, as defined by the EU, encompasses various renewable energy sources, including biomass, bio fuels, and bio gases.[Eura] Biomass plays a significant role in electricity production, where organic materials of animal and plant origin are typically burned in biomass power plants and subsequently converted into electricity and heat.[Bü11]

- **Ocean Energy**: For the sake of completeness, energy generation from marine sources should also be mentioned, which harnesses ocean currents and tidal effects.[Eurf] However, this has no practical relevance for energy communities in Austria.

Among the renewable energy sources mentioned above, all - except for marine energy - are theoretically suitable as potential energy sources for renewable energy communities in Austria.

1.3.3. Conclusion

Summing up, energy communities constitute a rather recent application of the microgrid concept. Nevertheless, they already enjoy broad acceptance and popularity: As of December 2024, more than 6,000 energy communities have been created across Austria[EDA24], up from 1,300 in April 2023[Kö23]. This trend is a clear sign that the decentralization of the conventional grid is steadily progressing, which is in line with the power grid developments discussed in this chapter.

Throughout the remaining paper, I will apply the terms "microgrid" and "energy community" to refer to a group of individuals that collaboratively generates, consumes, stores, and sells electricity produced from solar power.

2. Energy Storage Systems

As highlighted in the previous chapter, the need for storing energy has gained increased interest over the past few decades, a development that can be attributed to two major factors:

- A move from conventional, centralized power generation (and distribution) to a more decentralized approach.
- A rising focus on (and subsequent addition of) renewable energy sources to the energy production mix, which requires effective solutions for dealing with the supply fluctuations inherent to renewable energy sources.

In this chapter, I will briefly outline the key definitions of energy and power, providing a foundational understanding of these concepts. I will then present the typical performance characteristics of energy storage systems (ESS), examining parameters such as efficiency, capacity, density, and cycle life, which are critical for evaluating their suitability and performance. Following this, I will discuss the various types of ESS technologies available today, highlighting their unique features, benefits, and limitations. Special emphasis will be given to those technologies that are most relevant for microgrids, considering factors such as scalability, cost-effectiveness, and integration capabilities. By exploring these aspects, this chapter aims to provide a comprehensive overview of the role and potential of energy storage in modern energy systems.

2.1. Definitions: Energy, Power, and Storage

Energy exists in various forms, such as mechanical, thermal, chemical, potential, kinetic, or nuclear (among others). The respective definition of energy therefore depends on the physical properties of the underlying system. However, on a general level, energy (measured in Joules) can be expressed as the integral of power (measured in Watt) with respect to time:[Ruf17]

$$E = \int_{t1}^{t2} P(t) \cdot dt \tag{2.1}$$

Power, on the other hand, is expressed as the exchanged energy over a given time frame divided by that particular time frame:[Ruf17]

$$P(t) = \frac{dE}{dt} \tag{2.2}$$

Typically, an ESS integrates an "electric vector", as electricity is a convenient way to control, transport, and convert the energy stored in a given system. While the energy as such is stored in its "base form" (e.g., mechanical), an electronic converter usually serves as the interface between the stored energy and the access point,[Ruf17] as outlined in Figure 2.1. This is an important aspect to keep in mind, as all following analysis of ESS in this paper will focus on how well a given system can store/provide energy in its electric form.

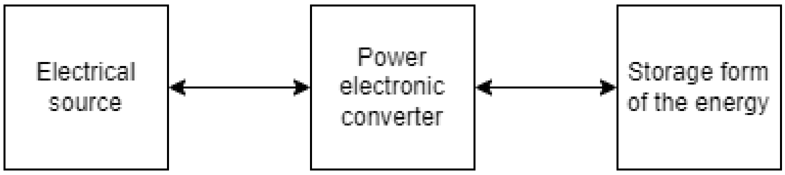


Figure 2.1.: A simplified view of the relation between an electrical source and an ESS, adapted from [Ruf17]

2.2. Characteristics of Energy Storage Systems

Various types of ESS technologies exist, in different states of maturity and leveraging different physical concepts. Depending on the particular use case, some ESS are more suitable than others (or may be entirely unsuitable). E.g., pumped hydro storage is unlikely to fit into an individual's backyard; Simultaneously, if (electric) energy needs to be made available quickly, electrochemical batteries are a better choice than thermal storage systems.

Typical characteristics to be considered in the decision for or against an ESS are thereforee aspects such as portability, storage duration and capacity, discharge time, cost, durability (cycling capacity), or efficiency.[IIP08] I will outline some of the most important characteristics relevant for comparison below.

2.2.1. Capacity

The capacity describes the nominal quantity of energy (measured in Ampere-hours, Ah) that is stored in an ESS after charging and is mathematically expressed as the integral of the current:[Ruf17]

$$C = \int_0^t i(t) \cdot dt \tag{2.3}$$

It is important to note that the actually retrievable amount of energy can differ significantly from the nominal capacity, as discharge is usually incomplete. Factors that contribute to the mismatch of nominal and actual capacity are, for instance, self-discharge over long periods of time, the surrounding temperature, internal resistance, or the "age" of the ESS (expressed as the number of charging cycles, see below).[IIP08]

2.2.2. Depth of Discharge and Discharge Time

Depth of Discharge (DoD) describes the already extracted quantity of electricity of an ESS in relation to its capacity:[Ruf17]

$$DoD = \frac{\int_0^t i_{dis}(t) \cdot dt}{Capacity} \tag{2.4}$$

Consequently, the discharge time describes the duration it takes to fully discharge an ESS at maximum power. This constitutes an important indicator of adequacy when deciding for an ESS for a given use case.[IIP08]

2.2.3. State of Energy and State of Charge

The State of Energy (SoE) is the ratio of the residual amount of energy available (E) and the total energy stored (E_{sto}) (or, in other words: how much energy is still left in the storage device in scope):[Ruf17]

$$SoE = \frac{E}{E_{sto}} \tag{2.5}$$

The residual energy available depends on the specific operating conditions (e.g., the temperature) mentioned above.[MHC21] It is a rather general concept that can be applied broadly across all ESS technologies.[Ruf17] However, as I will subsequently focus on the electrochemical storage technologies (batteries) and in reference to the "electric vector" mentioned earlier, State of Charge (SoC) is a more precise indicator. It describes the ratio of the remaining quantity of electricity available in a storage unit (the DoD) and the maximal available capacity:[Ruf17]

$$SoC = \frac{Capacity - \int_0^t i_{dis}(t) \cdot dt}{Capacity} \tag{2.6}$$

SoC and DoD are thus related as follows:

$$SoC = 1 - DoD \text{ or } DoD = 1 - SoC \tag{2.7}$$

2.2.4. Efficiency

Another crucial characteristic of an ESS technology is its efficiency (also called "round-trip efficiency"), meaning the ratio of how much of the stored energy can be effectively reclaimed from the storage device after charging it. I will start with an equation to demonstrate the the relation between the supply profile $SU(t)$, the production profile $PR(t)$ and the storage power $ST(t)$ of an ESS:[RJ12]

$$ST(t) + PR(t) = SU(t) \tag{2.8}$$

All three parts of the equation are functions of time. $ST(t)$ represents the storage power that an ESS can contribute to the grid (positive when delivering energy and negative when "consuming" energy, e.g., by being charged). $PR(t)$ denotes the production profile of the power production source, either delivering it to the grid or to the ESS. Finally, the supply profile $SU(t)$ is the time-structure of the power that the producer delivers to the grid.[RJ12]

However, in order to better model the actual behavior of power production and storage, an additional aspect needs to be added to the equation: The dissipative loss of an ESS, represented as scalar a:

$$ST(t) + PR(t) = a \cdot SU(t) \tag{2.9}$$

This is the power that is lost during energy storage (self-discharge) or during the process of making energy available (e.g., friction losses), and differs for each ESS technology; So the sum of energy produced and energy stored is what can be delivered to the consumer, reduced by a loss rate ($P_{loss}(t)$) that depends on the ESS technology used. It can be expressed as the difference of the integrals of produced and supplied energy:[RJ12]

$$P_{loss} = \int_{t1}^{t2} PR\,(t)\,dt - a \int_{t1}^{t2} SU\,(t)\,dt \tag{2.10}$$

Again, P_{loss} is different for each ESS. If this rate is known and assuming that it only depends on $ST(t)$, Equations 2.9 and 2.10 can be numerically solved for a and $ST(t)$. The result allows insights into the overall efficiency of an ESS technology, which can be expressed as follows:[RJ12]

$$\eta_{ESS}^{total} = \frac{a \int_{t1}^{t2} SU\,(t)\,dt}{\int_{t1}^{t2} PR\,(t)\,dt} \tag{2.11}$$

The efficiency of an ESS technology is a major factor in deciding which storage system to implement for a given use case.

2.2.5. Cycling Capacity

Also dubbed "durability", this indicator allows insight into the decline of the performance of an ESS over a longer period of time, typically measured in cycles (one cycle being a full charge and discharge of the device in scope). The decline in performance (usually measured in the reduction of capacity over a number of cycles) can be attributed to the fatigue of materials that come with wear of usage; Once again, this fatigue varies significantly from technology to technology.[IIP08]

2.2.6. Energy Density

Energy density (also called "specific energy") describes the relation between the amount of energy stored in a device and the device's size. A high energy density means that a large quantity of energy can be stored in a comparatively small or light storage device, whereas a low density describes the opposite.[WHM+20] Furthermore, energy density can be distinguished into "gravimetric" and "volumetric":[WHM+20]

- Gravimetric energy density describes how much energy a storage system contains relative to its mass and is measured in watt-hours per kilogram.
- Volumetric energy density describes how much energy a storage system contains relative to its volume and is measured in watt-hours per liter.

2.3. Types of Energy Storage Systems

Having discussed some basic definitions and characteristics related to energy storage systems, I will now briefly outline the most prominent types of technologies before focusing on those technologies in scope for energy communities. There are different ways of grouping and comparing ESS; a common approach is a grouping based on the physical storage concept of the system in scope.

2.3.1. Mechanical Energy Storage

Mechanical energy storage systems store the potential or kinetic energy of a given source by applying force to an appropriate medium to deliver acceleration, compression or displacement. Mechanical ESS constitute a very mature technology and are typically divided into pumped hydro storage (PHS), flywheel energy storage (FES), and compressed air energy storage (CAES).[MRO+20, NHT+19]

Pumped Hydro Storage (PHS)

Pumped hydro storage constitutes the largest energy storage system in the world, with a total storage capacity of up to 90% of the global energy production.[HTF+22] It is a mature and cost-effective technology that has been around for most of the last century. A typical PHS system consists of two reservoirs located on different altitudes (see Figure 2.2). During times of low energy demand, the water is pumped from the lower to the upper reservoir (the storage aspect of the ESS). Conversely, if the energy demand increases, the water is subsequently released from the upper reservoir, generating electric energy by driving a turbine on the way down.[IIP08]

The benefits of a PHS system include a high round-trip efficiency (between 65-85%, depending on characteristics[NHT+19, IIP08]), stability of energy production and storage, virtually unlimited cycling times, long durability and discharge time, low cost per kilowatt hour produced, and a general eco-friendliness. The downsides are mainly related to the size of a PHS installation: Pumped hydro storage occupies large areas of land and is limited to certain geographical prerequisites (rivers, slopes). PHS construction projects require large capital investment and take long to be completed. In addition, energy density is low and the reaction time (the duration between the request for energy and its delivery) is usually between 10-15 minutes.[NHT+19, MRO+20]

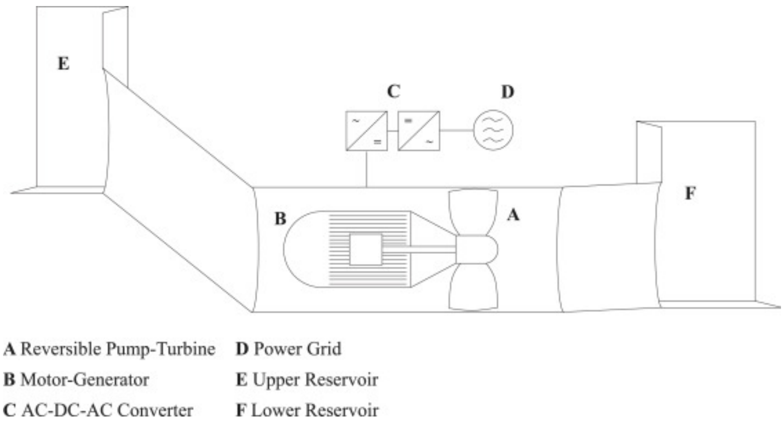


Figure 2.2.: A schematic view of a PHS system, according to [HTF+22]

Flywheel Energy Storage (FES)

Flywheel energy storage systems utilize rotating mass to store energy for the short term in the form of kinetic energy.[MRO+20] In its basic variant, a FES system consists of a rotating mass (e.g., a disc or ring), a set of bearings (usually magnetic), an electrical motor and generator, and a frequency inverter (see Figure 2.3). The flywheel system is typically installed in a containment system to provide a friction-less vacuum-based environment.[MRO+20]

Two main FES systems exist: low-speed and high-speed.[NHT+19] Low-speed systems operate at around 10,000 rotations per minute, while high-speed systems can reach up to 100,000, increasing the energy density from about 5 watt-hours/kg (low-speed) up to 200.[NHT+19]. However, the high cost of composite materials needed for a high-speed system leaves little economic benefit and limits the application to a few specific use cases in aerospace and traction applications.[NHT+19]

In general, FES systems have a high cycling capacity and are well suited for applications where energy needs to be stored and released quickly and repetitively. On the downside, FES systems suffer from high self-discharge losses due to friction and idling (efficiency can decrease by about 50% within a day)[IIP08] and are exceptionally prone to outside disturbances, rendering them inappropriate for long-term storage.[NHT+19]

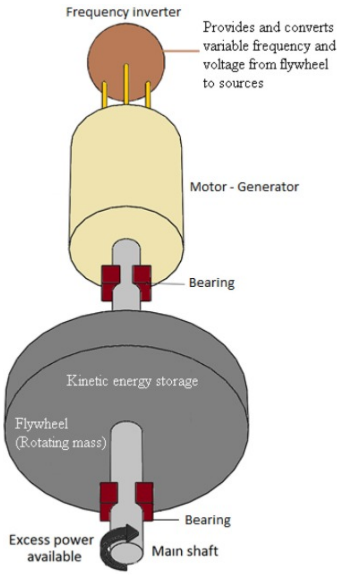


Figure 2.3.: The main components of a FES system, according to [HTF+22]

Compressed Air Energy Storage (CAES)

In its basic form, a compressed air energy storage system stores elastic potential energy by compressing air and subsequently releasing it to drive a turbine which in turn produces electricity.[Mol17] Two main concepts exist: Diabatic CAES systems, which decouple the energy storage and production process into separate phases, and adiabatic systems, which aim to establish a simultaneous process by incorporating a thermal application into the cycle.[Mol17]

Historically, only diabatic CAES systems have been successfully implemented commercially, while adiabatic systems are still in development.[BP21] Figure 2.4 outlines a typical (diabatic) system: The air is compressed into a storage unit (usually underground, using geographical properties such as abandoned mines) and subsequently released, heated, and combusted in order to drive high-power and low-power gas turbines, which in turn power a generator. The disadvantage of such a system is the requirement of fossil fuels (and resulting CO2 emissions) needed to heat up and combust the compressed air.[Mol17]

To solve this issue, adiabatic systems try to capture the heat created by compressing the air, storing it in a thermal storage unit (see section below), and reusing it for heating the air during the energy production phase.[Mol17]. According to some estimations, this

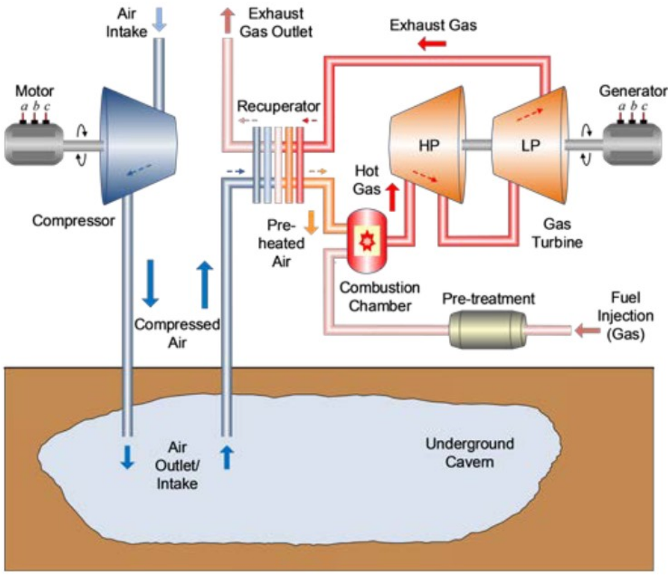


Figure 2.4.: A schematic view of a (diabatic) CAES system, according to [Mol17]

measure would increase efficiency to 70% (as opposed to the currently achievable 45-55% of traditional diabatic CAES systems), but so far, no large-scale commercial project has been realized.[BP21]

Nevertheless, compressed air energy storage systems remain an interesting option for the future of energy storage and are often compared to PHS systems: Both have a high energy and cycling capacity, low unit cost, and low cost per kilowatt hour produced. However, in addition to the typical downsides of a PHS system (such as dependency on specific geographical prerequisites or slow reaction time), the efficiency of current diabatic CAES systems is low and the need for fossil fuels makes it less attractive compared to more eco-friendly solutions.[Mol17]

Conclusion

In summary, mechanical energy storage systems are a mature and mostly eco-friendly way to store energy, usually encompassing high round-trip efficiencies in addition to their long service lifespans. However, due to the enormous capital investment requirements and size-related issues of PHS and CAES systems or the high self-discharge losses of FES systems, mechanical ESS remain unsuitable for the use case in scope of this paper.

2.3.2. Thermal Energy Storage

Thermal energy storage (TES) systems utilize the kinetic energy associated with the particles of a specific substance (or material) by means of changing its temperature.

Within TES systems, two major concepts can be distinguished: Sensible heat TES, where energy is stored/extracted through a change of temperature in the underlying material, and latent heat TES, where energy is swapped during a phase change of the material.[NHT+19, IIP08]

Sensible Heat TES

Sensible heat storage (SHS) is based on the concept of storing thermal energy by heating or cooling solid or liquid materials, such as, for example, water, stones, molten salts or sand.[SS18] In reality, water is the most popular choice due to its inexpensiveness and high specific heat (an indicator of how much heat a given material can store and release). The most common TES application is thereforee a simple water tank (see Figure 2.5). This device stores energy in the form of heat, usually by heating water with the power of solar energy or other generation methods (e.g., a fuel-based boiler).[SS18]

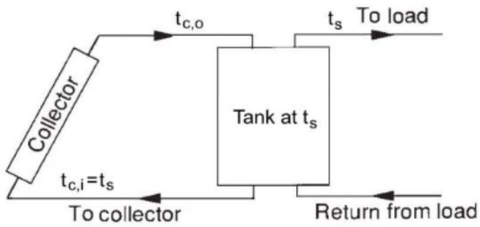


Figure 2.5.: A simple water tank application, according to [SS18]

Other SHS systems include underground storage (usually in the form of pits or caves), which makes use of the ground (e.g., soil, sand, clay) to store heat, or packed-bed storage, where a fluid - typically air - is circulated through a bed of loosely packed materials - typically pebbles - to add or extract energy. Applications range from small domestic solutions to large-scale industrial installations.[SS18]

Latent Heat TES

Conversely, latent heat storage (LHS) makes use of so-called phase change materials (PCMs) due to their property of absorbing or releasing energy with a change of physical state.[SS18] The advantage of LHS over SHS lies in the PCM's capacity of storing energy at a constant temperature level: While the stored heat of an SHS system increases and decreases with the temperature applied, the LHS system can absorb and release heat at a constant temperature level, since the storage process is tied to the phase change of the underlying material (e.g., going from solid to liquid).[SS18] Figure 2.6 illustrates this process.

LHS systems can be further distinguished into their phase change characteristics, namely

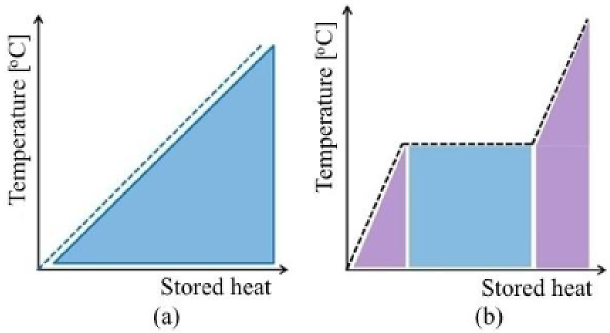


Figure 2.6.: Energy storage property of SHS (a) as compared to LHS (b), according to [SS18]

solid-solid, liquid-gas, and solid-liquid.[SS18] In reality, solid-liquid PCMs constitute the most commonly used materials, as they have a limited volume variation during their phase change and a high melting latent heat. Energy density is typically four times as high as with SHS options (up to 100 kWh/m^3 with LHS vs. typical 25 kWh/m^3 with SHS). Paraffin compounds, hydrated salts and fatty acids are the most widespread PCMs used, and typical applications include the heating/cooling of buildings and the maintenance of cool chains and refrigeration processes.[SS18]

Conclusion

Summing up, thermal energy storage systems represent a mature and eco-friendly technology, requiring comparatively low capital investment and excelling at low self-discharge rates (often less than 1% in a day).[NHT$^+$19] Latent heat storage solutions typically encompass higher energy densities and require less space than their sensible heat storage counterparts, whereas the latter system can be applied to a broader range of use cases, both domestic and industrial. As mentioned above (and as the name implies), TES systems are an ideal solution for situations where temperatures need to be controlled.[SS18]

However, this also constitutes the major disadvantage of TES: In addition to its rather low roundtrip efficiency (typically between 30-50%)[NHT$^+$19], the stored energy cannot be quickly released or easily converted into other forms of energy, such as electricity. The materials used in TES solutions need time to absorb and release its stored energy, rendering them rather unsuitable for the specific use case of this paper.

2.3.3. Chemical Energy Storage

Chemical energy storage (CES) systems store energy in the chemical bonds between the atoms and molecules of a material. This energy is subsequently released during chemical reactions, changing the original composition of the material by forming new chemical bonds.[MDM22] These materials (or fuels) can be all kinds of natural or synthetic substances (e.g., gasoline, natural gas, ethanol, etc.), but in reality, hydrogen, synthetic natural gas and solar fuels are the most commonly used materials.[MDM22]

Hydrogen Fuel Cells

Hydrogen is considered an ideal energy carrier due to its clean, carbon-free nature, making it a zero-emission option. It can be produced from water either by electrolysis or through photocatalytic water splitting using sunlight. A hydrogen energy system typically includes three main components: a hydrogen generation unit (such as an electrolyzer), a hydrogen storage system, and an energy conversion unit - the fuel cell (FC). In this system, hydrogen is produced and stored during periods of excess power and then converted back into electricity during peak demand using fuel cells. The electrolysis process splits water into hydrogen and oxygen, releasing oxygen into the atmosphere and storing hydrogen for future use.[MDM22] See Figure 2.7 for a schematic overview.

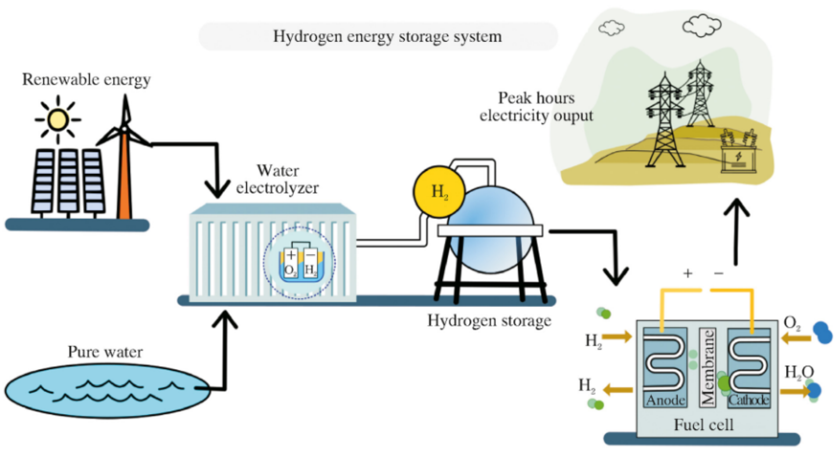


Figure 2.7.: A schematic overview of a CES system on the basis of hydrogen, according to [MDM22]

FCs in turn consist of four essential parts: an anode, cathode, electrolyte, and external circuit. It operates by oxidizing hydrogen at the anode to produce protons and electrons. Protons pass through the electrolyte, while electrons travel through an external circuit, creating an electric current. At the cathode, these protons and electrons combine with oxygen to produce water and heat, completing the process and generating electricity.[MDM22]

Recent research has explored advancements in hydrogen storage and its applications in various fields. Studies have reviewed developments in materials for hydrogen storage, focusing on methods for securely storing hydrogen over extended periods. Other investigations have looked into underground hydrogen storage. As of today, hydrogen-based CES systems are mostly applied to large-scale power utility storage, transportation, and aerospace/military use cases.[MDM22]

Synthetic Natural Gas

Natural gas is the most widely used fossil fuel and is considered the cleanest among them, making it a central energy source in today's supply. The conversion of coal to synthetic natural gas (SNG) offers a proven alternative energy production method, and biomass-based SNG production presents a carbon-neutral option. Historically, the methanation process was used for SNG production from coal, with recent advancements focusing on thermal gasification processes that can convert both coal and dry biomass (like wood and straw) into SNG through steps like drying, gasification, cleaning, methanation, and upgrading. SNG can be stored in pressurized tanks, underground caverns, or fed directly into the gas grid.[MDM22]

Solar Fuels

Solar energy storage aims to capture the sun's abundant energy, convert it into usable forms, store it in chemical bonds, and make it available on demand. Solar fuels are chemical compounds that hold energy harvested from sunlight. There are three main approaches to producing solar fuels: natural photosynthesis, artificial photosynthesis, and thermochemical production. In natural photosynthesis, plants, algae, and bacteria use solar energy to convert water and carbon dioxide into carbohydrates, which serve as fuel for the organisms' growth and maintenance. This natural process has inspired scientists to develop methods for replicating solar energy storage in other materials.[MDM22]

Artificial photosynthesis, then, is designed to mimic the natural process. In this method, sunlight is captured and used to convert water and carbon dioxide into chemical fuels. Another approach, the thermochemical method, uses sunlight to heat materials to extremely high temperatures, causing them to react with steam or carbon dioxide and produce hydrogen or carbon monoxide. These processes represent significant advances toward efficient solar fuel production, enabling storage of solar energy in a stable, chemical form for later use. However, this approach constitutes a rather recent development and no commercial real-world applications have been developed yet.[MDM22, NHT+19]

Conclusion

In conclusion, CES systems constitute an eco-friendly way for long-term energy storage solutions. The benefits include a high energy density, excellent convertibility into electricity, a long service lifespan and a corresponding high cycling capacity.[MDM22] On the other hand, the technology is rather new - Hydrogen-based ESS applications have started to catch on only at the beginning of the century. There is little infrastructure available yet for the secure storage of hydrogen (or other fuels suitable for the purpose), leading to high up-front costs. In addition, efficiency is rather low too: Hydrogen-based solutions range between only 20-55%.[MDM22, NHT+19]

2.3.4. Electrochemical Energy Storage

Electrochemical energy storage (EcES) solutions constitute the most common and widespread way of storing energy. The reasons are manifold: high energy density, eco-friendliness, ease of maintenance, versatility across various use cases, and availability in diverse shapes and sizes.[NHT+19] The major difference between electrochemical and chemical ESS lies in the nature (and potential reversibility) of the storage/extraction process: While chemical energy is stored in the bond between molecules (which is irreversibly altered by the release process), electrochemical energy relies on the redox reactions within a closed system, which, depending on the materials used, can be reversed and thus repeated multiple times.[WM22] Most electrochemical storage devices in use today serve as accumulators (also referred to as "secondary batteries"), meaning that the storage/extraction process is reversible.[LR19] Typically, EcES systems are divided into battery energy storage (BES) and flow battery energy storage (FBES).

Battery Energy Storage (BES)

Batteries are electrochemical devices that consist of three components: A negatively charged anode, a positively charged cathode, and an electrolyte that serves as the electric conductor between the two (anode and cathode are also referred to as electrodes or "active material"). As indicated above, batteries can be further distinguished into primary (single-use) and secondary (rechargeable) batteries;[MDM22] Moving forward, I will focus on the latter group, briefly outlining the most common types.

Lead-Acid Batteries The lead-acid battery type constitutes the oldest electrochemical storage device in the world and is still the most widespread battery option today, utilizing a sulfuric acid electrolyte and lead for the electrodes (see Figure 2.8). The ongoing popularity of this rather old battery type stems from its inexpensive production and maintenance costs in relation to its reliable performance and life characteristics. Applications vary from power tools over transportation and consumer goods to standby emergency power solutions; The most common use case, however, remains the classic car battery for starting, lighting and ignition.[LR19]

The advantages of lead-acid batteries are their high roundtrip efficiency (around 85%), a high cell voltage, good performance reliability in low or high temperatures, a broad variety of designs and sizes, availability in high quantities, and low manufacturing cost. The downsides, however, are their limited energy density (only 30-40 Wh/kg), a moderate durability (usually 300-1,500 cycles), risk of sulfation (corrosion of electrodes over extensive periods in a discharged state), and difficulty of producing them in very small sizes. Also, the potential leakage of the acidic electrolyte constitutes an environmental hazard.[LR19]

Nickel-Cadmium Batteries Nickel-cadmium batteries belong to the group of batteries that utilize nickel as a cathode material. The anode, in turn, typically consists of metallic cadmium and the electrolyte is potassium hydroxide (see Figure 2.9). Nickel-based storage

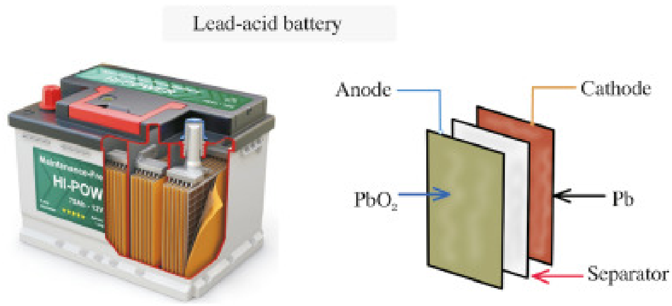


Figure 2.8.: An example of a typical car battery, using metallic lead for the anode and lead dioxide for the cathode, according to [MDM22]

devices constitute another very mature technology that has been been around since the beginning of the 20th century, owing their success to the low cost, abundant availability, and stability of the nickel compounds.[LR19] This battery type is primarily applied to industrial, aerospace, and electrical power use cases.[MDM22]

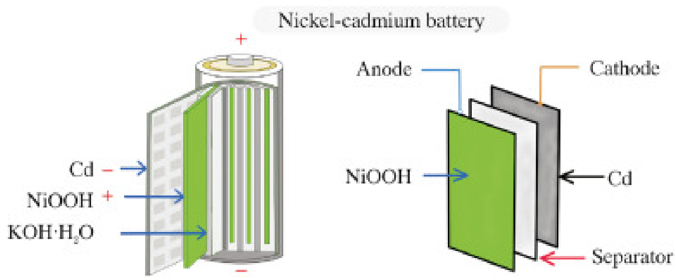


Figure 2.9.: Overview of a nickel-cadmium battery, according to [MDM22]

Nickel-cadmium batteries enjoy continuous popularity due to their long shelf life in a discharged state, good performance in low temperatures, high efficiency (70-90%), and a moderate self-discharge rate of around 10% per month. The disadvantages on the other hand include the "memory effect" (permanently reduced capacity due to incomplete discharge cycles) and the hazardous effect of cadmium on the environment, rendering them impossible to be disposed of in landfills and difficult to recycle.[NHT+19]

Lithium-Ion Batteries The first secondary lithium-based batteries were developed in the 1970s and their respective market has since expanded from a few niche applications to the most dominant battery energy storage technology of the 21st century.[LR19]. This battery type uses lithium storage compounds for both electrodes and an electrolyte that typically consists of a solution of lithium salts in an organic solvent; Lithium is thereforee present in all three phases of the battery. During cycles of charge and discharge, lithium ions wander back and forth between anode and cathode, as Figure 2.10 indicates. The predominant use cases for Li-ion batteries are portable electronics (cell phones, tablets, computers) and, increasingly, electric vehicles (EVs).[LR19]

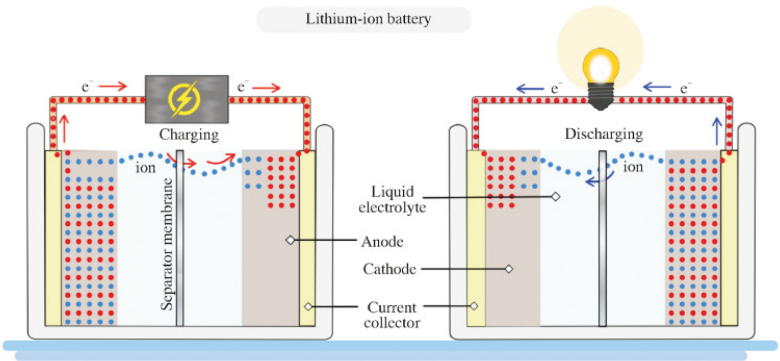


Figure 2.10.: The process of charging/discharging a lithium-ion battery, according to [MDM22]

The benefits of this battery type are its high energy density (275 Wh/kg), a low self-discharge rate (1-5% per month, depending on the state of charge and the surrounding environment), a long cycle life (up to 10,000 cycles), virtually no maintenance, design flexibility, and rapid charge capability. Conversely, Li-ion batteries need additional protective circuitry to manage over(dis)charge due to the lack of a chemical protection mechanism, they easily degrade in high-temperature environments, and the initial costs are quite high (as compared to lead-acid batteries, for example). Overcharging bears the risk of "thermal runaway", that is, the self-amplifying process of a rise in temperature until the device is destroyed.[LR19]

Metal-Air Batteries Metal-air batteries represent a "special" type of battery within BES devices. Unlike conventional batteries, metal-air batteries consist of one metallic anode while atmospheric oxygen - the air - serves as the cathode that is brought into the battery case from the outside.[MDM22] They can be recharged both mechanically (by replacing the "used-up" metallic anode) or electrically (by introducing an electrode that sustains oxygen evolution during charge). Depending on the metal used for the anode (e.g., zinc, aluminum, lithium), different types of electrolytes apply, both aqueous (alkaline or neutral) and non-aqueous (metallic salts).[LR19] See Figure 2.11 for a schematic overview.

Metal-air batteries have very high theoretical energy densities, long shelf life, and pose no ecological issues. However, due to limitations such as challenges with recharging, low power output, and susceptibility to external factors beyond air causing internal degradation, the use of this battery type has been limited to niche applications, such as medical devices or unmanned aerial vehicles.[LR19]

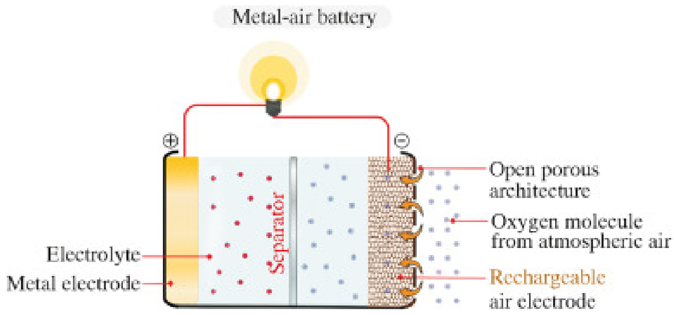


Figure 2.11.: Overview of a metal-air battery, according to [MDM22]

Flow Battery Energy Storage (FBES)

Flow batteries operate similarly to conventional batteries, but with the key difference that their active materials are aqueous electrolytes stored in separate tanks. A pump transfers the two liquids into a reactor (a stack of battery cells), where the actual energy transfer happens (see Figure 2.12).[MDM22] This reactor is comparable to the fuel cell as discussed above, with the difference that the whole process is reversible.[LR19] FBES devices are typically divided into redox and hybrid flow batteries.

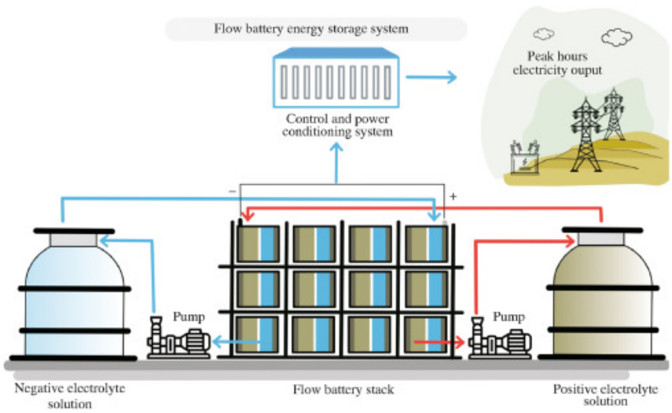


Figure 2.12.: A schematic overview of a flow battery, according to [MDM22]

Redox Flow Batteries Various redox flow battery technologies exist, with vanadium-based systems being the most common (VRB). This kind of battery stores energy through electron transfer between vanadium ions of different oxidation states, separated by a proton exchange membrane (differently charged vanadium ions serving as negative/positive electrolytes). Invented in 1986, VRBs have proven ideal for large-scale energy storage, offering capacities ranging from 1 MW to 100 MW. Their ability to store energy for long durations makes them suitable for applications like load leveling, peak shaving, frequency regulation, and uninterruptible power supply (UPS).[MDM22]

Despite their potential, VRBs face challenges such as high capital costs, limiting their widespread adoption. Research has focused on improving performance through advances in electrode architecture, flow field designs, and membrane technologies, such as hybrid polymer composites and nanocomposite membranes that enhance proton conductivity and reduce vanadium ion permeability. Field trials and installations in countries like Thailand and Japan have validated their performance, and VRBs remain the most developed type of flow battery. However, further advancements are necessary to overcome cost barriers and unlock broader commercial potential.[MDM22]

Hybrid Flow Batteries Hybrid flow batteries (HFBs) combine features of secondary batteries and flow batteries, with one active material stored inside the electrochemical cell and the other as a liquid electrolyte in an external reservoir. Their capacity depends on the size of the electrochemical cell, and at least one redox couple involves the deposition of solid or gaseous species during charging or discharging. Zinc bromine flow batteries (ZBBs) are a well-known example, offering high energy density (35–75 Wh/L), long life (10–20 years), and large discharge durations (8–10 hours). However, ZBBs face challenges such as zinc corrosion, toxic bromine, dendrite formation, hydrogen gas evolution, and lower round-trip efficiency (65–75%), which have limited their development.[NHT+19]

To address these issues, polysulfide bromine flow batteries have been developed, offering cost-effective solutions with highly soluble aqueous electrolytes. More recently, lithium flow batteries have emerged with impressive specifications, including a 3.8 V discharge voltage, energy density of 397 Wh/m^3, and high roundtrip efficiency. These systems promise up to 10 times the energy density of vanadium redox flow batteries, making them attractive for electric vehicle applications; However, at this point, HFBs constitute an immature technology and remain in a developmental stage.[NHT+19]

Conclusion

Electrochemical energy storage technologies are the most widespread, common, and well-known energy storage systems in the world. They excel at high energy densities, good roundtrip efficiency, compact size, and reliability; In addition, the majority of electrochemical technologies and and systems discussed here constitute safe and mature applications that have (mostly) been around for various decades. Out of all ESS systems discussed so far, EcES systems appear to be the optimal solution for the use case of this paper (energy storage for individual households and small communities).

Lithium-ion batteries in particular represent an interesting approach, as they have become the dominant technology for applications like portable electronics and electric vehicles. Their long lifespan, low self-discharge rate, and flexibility in design make them an excellent choice for decentralized energy solutions. While they require protective circuitry to prevent overcharging and are sensitive to high temperatures, their minimal maintenance needs and rapid charge/discharge capability make them ideal for residential and community-scale energy storage. Their potential as well as their limitations will be discussed in more detail below.

2.3.5. Other Energy Storage Systems

The ESS technologies discussed so far are not yet the end of the story - various further technologies and approaches exist, with varying degrees of maturity, safety, and actual practicality. Two more storage systems with the potential to become more important in the future shall be briefly presented here, electric and hybrid energy storage.

Electric Energy Storage

Electric energy storage (EES) systems store the energy directly in an electric field, without converting the electric energy into another form. EES systems are typically divided into electrostatic and magnetic storage devices.[MDM22]

Electrostatic Energy Storage Supercapacitors, also known as electric double-layer capacitors or ultracapacitors, consist of two conductive electrodes, an electrolyte, and a separator. They store energy as an electrostatic field created by a continuous DC voltage applied between the electrodes, which are made of activated carbon to provide a large surface area and higher energy density. A porous separator allows ions to move freely while preventing direct contact between the electrodes. When charged, ions accumulate at the electrode-electrolyte interface, forming charged double layers with polarity opposite to the electrode. Structurally, supercapacitors bridge the gap between batteries and traditional capacitors, combining features of both.[MDM22]

Key advantages of supercapacitor-based energy storage systems include robustness, reliability, adaptability to various environments, maintenance-free operation, immunity to depth-of-discharge effects, and an exceptionally long lifespan of nearly 10,000 charge-discharge cycles with about 95% round-trip efficiency. However, these systems also face challenges such as high self-discharge rates (10–40% per day), low energy density (only 5 Wh/kg), and substantial capital costs, limiting their widespread adoption.[NHT+19]

Magnetic Energy Storage Superconducting magnetic energy storage (SMES) systems store energy in the magnetic field generated by a direct current flowing through a superconducting coil. These systems consist of three main components: a superconducting coil, a power conditioning and control system, and a cryogenically cooled refrigeration unit. The superconducting coil is maintained at extremely low temperatures to retain its superconducting state. During operation, the coil's current increases during charging and decreases during discharging, with the control system regulating the energy flow and managing AC/DC conversion as required.[MDM22]

SMES systems excel in applications requiring rapid response times, high power output (in the multi-megawatt range), and exceptional efficiency. They were initially designed for large-scale load leveling, but have evolved to accommodate smaller-scale applications thanks to technological advancements. Their primary uses include supporting electric power grids and energy systems with fast, reliable power delivery. However, despite these strengths, the adoption of SMES remains limited due to its high upfront costs compared to other well-established energy storage technologies and the complex and fragile cooling mechanism of the coil.[MDM22, NHT+19]

Hybrid Energy Storage

Last but not least, hybrid energy storage (HES) systems typically represent mixtures of the various ESS systems discussed above. As the previous paragraphs have shown, no single technology satisfies every need - there are always upsides and downsides inherent in each approach. The ambition of HES systems is thereforee the combination of two (or more) existing ESS technologies in order to achieve a "super-ESS" system - e.g., the combination of a fast-response system (like supercapacitors) with a high-density system (like hydrogen fuel cells).[NHT+19] The few real-world applications that have been developed yet are mainly to be found in the power, transportation, and renewable energy sectors, and are usually large-scale industrial solutions.[MDM22]

Conclusion

Emerging energy storage systems, such as supercapacitors, superconducting magnetic energy storage (SMES), and hybrid energy storage (HES) systems, present innovative solutions with unique advantages. Supercapacitors excel in durability, maintenance-free operation, high efficiency, and rapid cycling. However, their low energy density, high self-discharge rates, and high costs limit their current applications. SMES systems, which store energy in magnetic fields using superconducting coils, offer rapid response times, high power outputs, and exceptional efficiency, but are still limited by their high initial costs and complex cooling mechanisms.

Hybrid energy storage systems in turn aim to combine the strengths of different technologies. While still in early development, HES systems have shown promise in power, transportation, and renewable energy applications. As these technologies advance, they could address the specific needs of microgrids, offering tailored solutions that balance fast response, high energy density, and cost-efficiency, making them increasingly attractive for decentralized energy systems.

2.4. Energy Storage Systems in Scope

As highlighted in the previous sections, a wide array of energy storage technologies is available; however, the most viable solution at present that is in scope of this paper is electrochemical storage, particularly lithium-ion batteries. The final section of this chapter delves deeper into the attributes and characteristics of this battery type, explaining why it is especially well-suited for use in energy communities. Additionally, the emerging technology of sodium-ion batteries, which shares similarities with lithium-ion batteries, will be explored as a promising option for future energy storage applications.

2.4.1. Lithium-Ion Batteries

A high-level, general introduction to lithium-ion batteries (LIBs) has been provided under Section 2.3.4. This part, in turn, aims to explore the physical composition of LIBs (including future trends), their potential in terms of stationary battery storage for microgrids, and their limitations in more detail.

Composition

Following the typical structure of an electrochemical battery, a LIB consists of an anode, a cathode, and an electrolyte, with lithium being present in all three phases.[LR19] Historically, lithium metal was used for the anode active material; However, the real breakthrough of LIBs was triggered by the introduction of carbonaceous compounds, which led to graphite becoming the dominating anode material today.[AAB+20] This shift was owed to the fact that lithionised graphite has a much higher melting point (180° Celsius) than the previous materials used, increasing the overall stability and performance of the battery.[ACDT17]

Despite the current success and overall reliability of graphite as anode material, it also has its shortcomings, the most critical being the process of "lithium plating". This effect describes the deposition of metallic lithium on the surface of the anode instead of it being intercalated into the anode material as lithium ions. This phenomenon typically occurs during "extreme charging" conditions (low temperatures, high charging current, overcharging), and the results of this process are decreased capacity and efficiency as well as safety hazards. In order to mitigate these risks, research has been directed towards the use of titanium and silicon oxides as anode materials, but as of today, these approaches are still in a development stage, occupying only niche applications.[AAB+20]

Conversely, lithium-metal oxides constitute the current state of the art when it comes to cathode materials. One of the most popular variants is a lithium iron phosphate active material, usually carbon-coated to increase electronic conductivity, which is commonly applied to electric vehicle (EV) and stationary energy storage use cases.[AAB+20] Other common cathode variants include cobalt and nickel oxides (preferred option when applied to consumer goods and portable electronics), with the downsides of higher production costs (due to cobalt) and environmental concerns (due to nickel). In order to eliminate these constraints, current research focuses on high-voltage spinal oxides and Li-rich layered transition metal oxides that both utilize manganese as main component, but no stable or safe commercial applications have been developed yet.[AAB+20]

The third part of the battery is the electrolyte, the "lubricant" between the electrodes, which allows the ions - and thus the electric current - to flow. Present LIBs typically employ a liquid organic solution as electrolyte, which in turn constitutes a mix of a conducting lithium salt, a linear or cyclic solvent, and a carbonate as an additive.[AAB+20] The drawbacks of this electrolyte mix are its susceptibility to thermal decomposition at comparatively low temperatures (around 105° Celsius) and high flammability of the solvent part, which becomes particularly dangerous in case of "thermal runaway" (see below). Therefore, current research is mostly focused on experimenting with different salts, chemicals, and materials (and different balances of these components) to make the electrolyte safer, more durable, and more effective.[AAB+20]

In conclusion, throughout the rest of this paper, the term "energy storage" will refer to a lithium-ion battery featuring a graphite anode, a lithium iron phosphate cathode, and a liquid organic electrolyte based on lithium salts.

Potential

Coming back to the beginning of the chapter, the advancing development and increasing share of renewable energy sources to the energy production mix introduce various challenges for the conventional power grid, mainly in terms of stability and planning capability. Therefore, ESS systems play a crucial role in balancing those supply fluctuations, saving energy during off-peak hours and providing it during peak times.[FHK+18] LIBs are particularly suitable for the application in microgrids, especially in the case of grid-connected microgrids (cf. Section 1.3).[MLRJ23]

The main reasons lie in the LIB's high energy density, long cycle life, high roundtrip efficiency, and fast response times. As explained in Section 2.2.6, high energy density means that significant amounts of energy can be stored in a relatively small device; Lithium-ion batteries achieve a gravimetric density of up to 275 Wh/kg,[LR19] allowing compact designs ideal for space-constrained microgrids in urban or residential areas. The comparatively high initial costs can be offset with a cycle life of up to 10,000 charge-discharge cycles in addition to virtually no operational costs, so the higher up-front investment amortizes across the overall lifespan of the battery.[FHK+18] In addition, round-trip efficiencies of 90–95%[LR19] imply that almost all the stored energy can also be released again, further improving the LIB's cost-benefit calculation.

In relation to grid-connected microgrid applications, another key advantage of LIBs is their ability to provide grid stability and resilience through their rapid response times, as this allows them to smooth out power fluctuations, maintain frequency stability, and act as an uninterruptible power supply during outages.[MLRJ23] The battery's characteristic of maintaining its capacity even during phases of fast (dis)charge under high-current conditions further strengthens the case in favor of LIBs.[MLRJ23] In conclusion, all these attributes, combined with scalability and adaptability, make lithium-ion batteries an essential component of modern grid-connected microgrids, enabling a cleaner, more efficient, and resilient energy ecosystem.

Limitations

Throughout this chapter, various downsides of LIBs have been addressed, mostly related to high initial costs and risks concerning thermic instability and missing internal protection from over(dis)charge (see Section 2.3.4). This section in turn aims to explore the consequences of these challenges for microgrid applications as well as further limitations.

The most pressing issue is thermal runaway (TR), the self-amplifying process of heat building up until the battery is destroyed. In extreme cases, the device might even catch fire, release toxic gases and explode, which constitutes a major health hazard.[CL20] TR can be caused by various external abuse conditions that trigger events inside the battery which in turn lead to the disastrous results described above; Figure 2.13 gives an overview of these abuses and their respective consequences.[CL20]

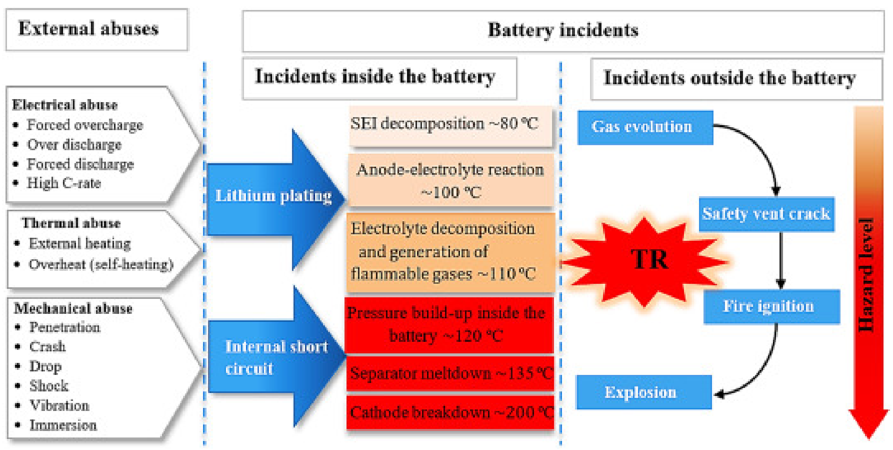


Figure 2.13.: A visualization of thermal runaway (TR) and its causes, according to [CL20]

Various strategies have been developed and proposed in order to mitigate this risk. They typically involve the introduction of a battery management system (BMS) that acts an "external" protective component, monitoring and controlling temperature, over(dis)charge, voltage, etc.[CL20] An alternative solution is to protect the battery "internally": This approach revolves around the development of safer electrodes and electrolytes (e.g., flame retardant solvents or overcharge protection additives).[CL20] As research and development activities in the latter area continue, the best solution for stationary LIB applications is, at present, the supplementation of the battery with a thermal BMS.

The issue of high initial costs of LIBs has been qualified by their rather long durability (up to 10 years);[FPS+18] However, other often overlooked limitations of lithium-ion batteries are the scarcity of the resources used for their production and the environmental concerns related to the respective mining processes. More than 50% of the global lithium supply comes from Chile, Argentina, and Bolivia (the so-called "lithium triangle"); Other major contributors are China, Australia, and the United States.[Kau20] The areas surrounding major lithium mining operations report sinking groundwater levels (due to the water-intensity of the extraction process) in addition to contamination of air, soil and other water supplies (due to the toxic chemicals used for lithium processing).[Kau20]

Considering the continuously increasing demand for battery-dependent energy storage, this last limitation seems to offer few alternatives besides an eventual turning away from lithium in favor of a different base component; The following emerging technology presents a promising solution.

2.4.2. Sodium-Ion Batteries

In relation to their ability to store energy, sodium-ion batteries (SIBs) share similar characteristics with LIBs as described in the previous section, with the advantage of the resource sodium being 1,000 times more abundant in the earth's crust than lithium. That is why in recent years, research and development of SIBs has gained increased interest both by the scientific community as well as the business world, driving the commercialization efforts of SIBs.[CJM+22, CMDN22]

SIBs were originally discovered around the same time as LIBs but were not further developed due to the inability of sodium intercalation in graphite anodes. However, interest in SIBs flared up again after hard carbon (HC) was introduced as anode material in the early 2000s. Since then, the development of sodium-ion batteries as a "beyond lithium"-alternative has accelerated significantly.[CJM+22] At present, one promising SIB composition consists of a HC anode, a sodium vanadium phosphate fluoride (NVPF) cathode, and a sodium salt-based electrolyte. The SIB's structure and way of operation roughly follows that of a LIB, with "wandering" sodium ions generating the electric current.[CJM+22, KFSG20] See Figure 2.14 for a schematic overview.

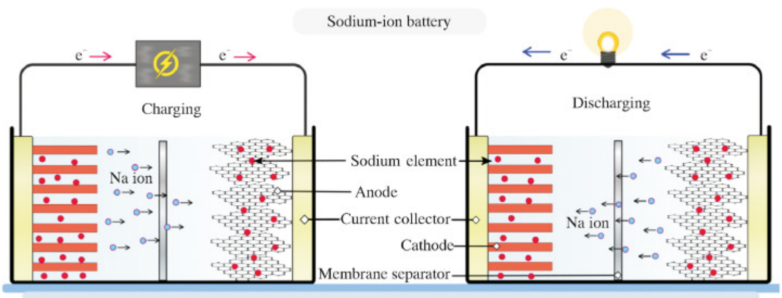


Figure 2.14.: A schematic overview of a sodium-ion battery, according to [MDM22]

At present, even though sodium shows similar characteristics as lithium, SIBs trail behind LIBs when it comes to energy density, meaning that a sodium-based battery needs to be larger in size in order to store the same amount of energy as a lithium-based storage device.[KFSG20]. However, this disadvantage is offset by the fact that sodium (and other earthly materials currently used in SIBs) are much more abundant in nature, significantly lowering the production costs and putting less burden on the environment. Therefore, while LIBs will likely continue to dominate the market of EVs and portable electronics (where size constitutes a crucial factor), SIBs may become the leading battery technology for less space-constrained stationary energy storage applications - as is the case with microgrids.[CMDN22]

In conclusion, while SIBs promise a cheaper and more eco-friendly alternative to lithium-ion batteries, the latter still remain the preferred option for now, mainly due to their higher degree of maturity.

3. Energy Community Management

This chapter finally delves deeper into the specifics of digital twins and linear optimization, concluding in an overview of the technical implementation of this thesis, the Energy Community Management (ECM) tool. The goal is to bring together all the aspects discussed throughout the paper: The microgrid/DER concept (expressed as a renewable energy community construct under Austrian law) and how to realize it in the digital realm, including the optimization of (dis-)charging cycles of lithium-ion batteries.

3.1. Digital Twins

In order to better understand the ECM application, this section provides a brief introduction of an emerging technological development in the IT sector: Digital twins.

3.1.1. Definition and Purpose

The concept of digital twins was established by the University of Michigan in the early 2000s and has gained massive interest and focus since.[WYC+20] In short, a digital twin can be defined as "a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems".[VM21] In other words, a digital twin is the "virtual image" of a real-world object or system, equipped with a corresponding interface between the two worlds (see Figure 3.1 for a high-level overview). Digital twins can be used to simulate, predict, monitor, analyze, and control the underlying physical entity in the digital realm.[WYC+20]

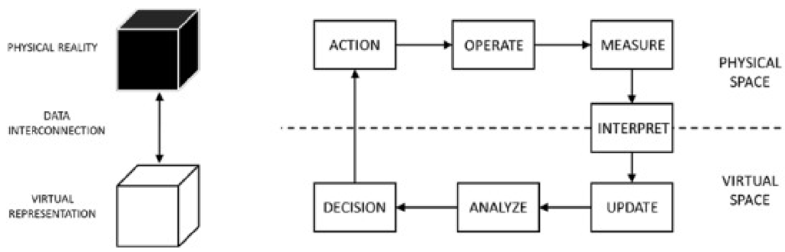


Figure 3.1.: An overview of the digital twin concept, according to [VM21]

According to Gartner, a digital twin requires four elements in order to provide its service: A digital model, linked data, identification, and real-time monitoring capabilities.[WYC+20]

Furthermore, digital twins can grouped into different categories; For example, the Institute of Business Engineering FHNW distinguishes three different types of digital twins:[KBF21]

- **Digital Product Twins**: The digital representation of a product, typically applied in the design stage of product development for the simulation of its features before being approved for mass production
- **Digital Production Twins**: The digital copy of a production process, used for simulation, control, and monitoring purposes
- **Digital Performance Twins**: This version is applied to gather more insights from a process by measuring performance characteristics (e.g., throughput times or quality features) with the ultimate goal to improve those characteristics

Depending on the specific use case, digital twins can also constitute a mix of those three types.

3.1.2. Application and Use Cases

The high interest in digital twins can be explained by the broader IT transformation that is currently taking place, especially - though not exclusively - in the manufacturing sector: Full automation of production processes by vast implementation of interconnected sensors and measuring devices, typically summarized and described by the term "Industry 4.0". This development is characterized by the extensive use of cyber-physical systems (CPS), internet of things (IoT), and, increasingly, artificial intelligence (AI).[PCB+19]

As indicated above, automation is largely driven by - and implemented in - the manufacturing sector. However, it is also increasingly applied to other sectors, most notably in the areas of smart cities, healthcare, transportation, and retail. As more data is being collected in those sectors, more powerful tools are required in order to adequately deal with this vast amount of information. Digital twins are a suitable option to face this challenge; By modeling a given process virtually, a digital twin can offer valuable insights and support decision makers with their respective tasks.[PCB+19]

With regard to the use case in scope of this paper, the modeling of energy communities, digital twins are an interesting option to consider. As outlined in Section 1.2, the smart grid essentially represents the "Industry 4.0" expression of the energy sector: An area that is being profoundly transformed by digital technology, which includes the vast application of measuring devices - most notably, the smart meter. This device constitutes the corresponding "link" between the physical and virtual space as indicated in Figure 3.1, providing real-time information about energy consumption and production on the consumer level. As demonstrated in Section 1.3.2, smart meters are also a formal (and, at present, the only) requirement for forming (or joining) an energy community; The ECM tool therefor constitutes the attempt to model an energy community as a digital twin.

3.2. Linear Optimization

Linear optimization (also known as linear programming, LP) is a branch of mathematical optimization that is characterized by the linearity of both the objective function and its corresponding constraints.[UD10] In other words: LP describes the search for the optimal (minimal or maximal) result of the question in scope, whereas the factors contributing to that result are linear. This section provides a basic overview of the concept and suggests how it can be applied to optimize charging cycles of batteries.

3.2.1. Foundations of LP

Linear programming has its roots in economics, more specifically in the areas of production planning and transportation. The Soviet mathematician L.V. Kantorovich proposed the method of LP in his paper *Mathematical Method of Production Planning and Organization* in 1939, presenting a mathematical solution approach for typical organizational resource allocation problems.[Ame80] A few years later, G.B. Dantzig showed that many logistic and economic optimization problems can be described as a linear system of equations and introduced the Simplex method to solve them (see below). With the ongoing advancement of computational power, LP has become a substantial field of research and development, playing a critical role in solving complex real-world problems across diverse domains such as logistics, finance, energy, manufacturing, and artificial intelligence.[UD10]

Mathematically, a linear program is expressed as:[Fre05]

$$\min_{\mathbf{x} \in P \subseteq \mathbb{R}^n} \mathbf{c}'\mathbf{x} = c_1 x_1 + \cdots + c_n x_n \tag{3.1}$$

$P \subseteq \mathbb{R}^n$ describes the feasible region, expressed as:

$$\begin{array}{ccccc} a_{11}x_1 & + \cdots + & a_{1n}x_n & \geq & b_1, \\ a_{21}x_1 & + \cdots + & a_{2n}x_n & \geq & b_2, \\ \vdots & \ddots & \vdots & & \vdots \\ a_{m_1 1}x_1 & + \cdots + & a_{m_1 n}x_n & \geq & b_{m_1}, \\ a_{m_1+1,1}x_1 & + \cdots + & a_{m_1+1,n}x_n & = & b_{m_1+1}, \\ \vdots & \ddots & \vdots & & \vdots \\ a_{m1}x_1 & + \cdots + & a_{mn}x_n & = & b_m \end{array} \tag{3.2}$$

The set of linear constraints (inequalities and equations) presented in Array 3.2 describes a convex set, meaning that for any two points x, y in the set, every point in the line segment between them also lies in that set. This is a prerequisite for applying linear optimization.[Fre05] In its most basic form, an LP thus requires an objective function ($c'x$), a feasible area (P) describing the constraints, and decision variables (x). Put simply, linear optimization algorithms strive to find the optimal variable value x^* that leads to the minimal (maximal) result of the the objective function, taking into consideration the given constraints.[UD10]

Under the condition that the constraints are presented in equation form and all variables are non-negative, an LP can be expressed in standard form:[Fre05]

$$\begin{aligned} \min \quad & c'x \\ \text{subject to} \quad & Ax = b, \\ & x \geq 0 \end{aligned} \tag{3.3}$$

LPs in standard form are easier to solve and most solver technologies require an LP to be entered this way. Ultimately, any LP can be transferred to a standard form by introducing slack variables to eliminate the inequality constraints and enforcing non-negativity of the decision variables.[Fre05] A maximization problem can be just as easily transformed into a minimization problem by being multiplied with -1, the relationship being

$$\max_{\mathbf{x} \in P} \mathbf{c}'\mathbf{x} = -\min_{\mathbf{x} \in P} (-\mathbf{c}')\mathbf{x} \tag{3.4}$$

This reflexive relationship is important in the context of duality: In many cases, it can be interesting to view the given minimization problem 3.3 from another perspective to provide more insight into the initial problem and call it the primal problem (PP).[UD10] The dual problem (DP)

$$\begin{aligned} \max \quad & b'y \\ \text{subject to} \quad & A^t y \leq c, \end{aligned} \tag{3.5}$$

can either provide upper/lower bounds to the PP's objective function (weak duality) or, if an optimal solution exists, constitute its exact opposite (strong duality), where the optimal solution of the PP also equals the optimal solution of the DP.[Fre05, UD10]

A practical example is manufacturing optimization, where a company maximizes profit by deciding how many units of a given good to produce under resource constraints. The dual problem interprets these constraints as shadow prices, indicating the marginal value of increasing resource availability. If a resource constraint is binding, its shadow price shows how much additional profit could be gained by relaxing that constraint. Strong duality allows businesses to optimize decision-making from either perspective: they can either solve the PP to determine production levels or the DP to assess resource valuation, leading to an efficient and balanced allocation of resources.[RM16]

3.2.2. Solvability of LPs and Solution Approaches

The solvability of linear programs is a fundamental topic in optimization, closely tied to the existence of feasible and optimal solutions within a given set of constraints. As we have seen in the previous section, a linear program is defined by a set of linear equations and inequalities that restrict a decision variable vector. The fundamental conditions for solvability involve feasibility - whether there exists at least one point satisfying all constraints - and boundedness, ensuring that the objective function does not tend toward infinity within the feasible region.[Fre05, UD10]

A central concept in the solvability of linear programs is the existence of extreme points, which play a crucial role in solution methods such as the Simplex algorithm (see below). If a feasible solution set forms a bounded polyhedron (the geometric shape defined by P in Array 3.2), there always exists an optimal solution at one of the extreme points. However, if the feasible region is unbounded and the objective function is not properly constrained, the problem may lack a finite optimal solution, leading to an unbounded optimization scenario.[Fre05]

Another critical aspect of solvability is the relationship between primal and dual formulations of a linear program (see above). Duality theory states that if a linear program has an optimal solution, then its corresponding dual program also has an optimal solution, and their objective values are equal. Conversely, if either the primal or dual problem is infeasible, the other must be either infeasible or unbounded, which is a key insight for understanding problem solvability.[Fre05] So in conclusion, the solvability of linear programs hinges on the interplay of feasibility, boundedness, and duality conditions.

In terms of solution approaches, two fundamental methods can be distinguished: The Simplex method and the Interior-Point method. Dantzig's Simplex method operates by traversing the edges of the feasible region (the convex polyhedron), moving from one vertex (extreme point) to a neighboring one while improving the objective function at each step. Although it performs well in practice, its worst-case complexity is exponential in the number of variables. However, due to its structured pivoting rules and efficient implementations, the Simplex method remains widely used in real-world applications.[UD10]

In contrast, Interior-Point methods, such as, for example, Karmarkar's algorithm[ARVK89], approach the optimal solution from within the feasible region rather than along its boundary. These methods rely on iterative steps that follow a central trajectory, gradually converging to the optimal point. Unlike Simplex, which may take exponential time in the worst case, Interior-Point methods operate in polynomial time, making them more suitable for large-scale optimization problems. However, they often require more complex computations per iteration, including matrix factorizations, which can be computationally expensive. In practice, the choice between Simplex and Interior-Point methods depends on problem size, structure, and computational constraints, with Simplex favored for small to medium problems and Interior-Point methods preferred for large-scale applications.[UD10]

The development of polynomial-time algorithms, such as Karmarkar's Interior-Point method, has enhanced the understanding of solvability. This method provided the first formal proof that linear programming can be solved in polynomial time, overcoming limitations of the Simplex method, which, in some cases, can require exponential iterations.[UD10] However, moving forward with this thesis, I will focus the latter method, as it is more intuitive, easier to illustrate, and ultimately sufficient for the use case in scope.

3.2.3. The Simplex Method

Simplex operates on the assumption that if there is a feasible solution for the problem in scope (meaning an x that satisfies the constraints posited in Equation 3.3), any local optimum found in the set also constitutes the global optimum - the optimal solution. The algorithm "starts" on any point on the edge of the polyhedron created by P (cf. 3.2) and "wanders" along the the edges of the shape in iterative steps until the local (and thus the global) optimum is found.[Fre05] I will illustrate the step-by-step process of the Simplex method with the help of a concrete example (adapted from an example provided by LibreTexts[Lib25]).

Let us assume a company owns two machines that can produce the same product. Machine 1 can produce 40 units per hour, machine 2 can produce 30. Due to a scarcity of electricity, the machines can only be operated for 12 hours per week, and only one at a time. Machine 1 requires 2 hours of preparation for each hour of operation, machine 2 requires 1 hour. Due to a shortage of staff, only 16 hours of preparation can be assigned per week. How should production be optimally allocated between the two machines to generate the highest output?

Applying Simplex, the optimal result can be calculated as follows:[Lib20]

1. **Definition of the problem**: Formulation of the objective function and the inequality constraints.

   Let x_1 be the hours of operation of machine 1, x_2 those of machine 2, and Z the optimum to be found. The objective function and its inequality constraints can then be defined as follows:

$$\begin{aligned} \max \quad & Z = 40x_1 + 30x_2 \\ \text{subject to} \quad & x_1 + x_2 \leq 12, \\ & 2x_1 + x_2 \leq 16, \\ & x_1 \geq 0; x_2 \geq 0 \end{aligned} \tag{3.6}$$

2. **Conversion of the inequalities into equations**: Introduction of a slack variable for each inequality.

The resulting LP is then in standard form (cf. 3.3):

$$\begin{aligned} \max \quad & -40x_1 - 30x_2 + Z = 0 \\ \text{subject to} \quad & x_1 + x_2 + y_1 = 12, \\ & 2x_1 + x_2 + y_2 = 16, \\ & x_1 \geq 0; x_2 \geq 0 \end{aligned} \tag{3.7}$$

3. **Construction of the initial Simplex tableau**: Formulation of the LP in tableau form. Column C describes the respective constraints.

	x_1	x_2	y_1	y_2	Z	C
1	1	1	1	0	0	12
2	2	1	0	1	0	16
	−40	−30	0	0	1	0

(3.8)

4. **Identification of the pivot element**: In order to start the algorithm, a pivot element needs to be selected. This is achieved by identifying the the pivot column first, which is defined by the most negative entry in the bottom row of the tableau. The far right column of the tableau is then divided by the values of the pivot column; The smallest quotient calculated this way identifies the pivot row. Ultimately, the pivot element is to be found at the intersection of pivot column and pivot row.

   In our example, the pivot column is x_1. We therefore divide the values in column C by 1, 2, and −40, respectively, resulting in the following tableau:

	x_1	x_2	y_1	y_2	Z	C
1	1	1	1	0	0	12
2	2	1	0	1	0	8
	−40	−30	0	0	1	0

(3.9)

   The pivot row is thus row 2, and the pivot element equals 2.

5. **Pivoting**: Obtain a 1 in the location of the pivot element and make all other entries in that column 0. The process is repeated from step 4 until no negative values remain in the bottom row of the tableau.

   To obtain a 1 for the pivot element, we divide row 2 by 2. To make the element above the pivot element 0, we multiply row 2 by −1 and add it to row 1. In order to achieve the same result for the last row, we multiply row 2 with 40 and subsequently add it to row 3, resulting in:

	x_1	x_2	y_1	y_2	Z	C
1	0	1/2	1	−1/2	0	4
2	1	1/2	0	1/2	0	8
	0	−10	0	20	1	320

(3.10)

Since we still have a negative value in the bottom row, the process is repeated from step 4.

6. **Finish**: The final result is to be found in the far right bottom corner of the tableau. In our case:

	x_1	x_2	y_1	y_2	Z	C
1	0	1	2	−1	0	8
2	1	0	−1	1	0	4
	0	0	20	10	1	400

(3.11)

The bottom row now corresponds to the following equation:

$$0x_1 + 0x_2 + 20y_1 + 10y_2 + Z = 400 \quad \text{or} \quad Z = 400 - 20y_1 - 10y_2 \tag{3.12}$$

The highest value that can be achieved is 400, which happens if y_1 and y_2 are 0. By only considering columns that have a 1 and all other entries 0 and arbitrarily setting y_1 and y_2 to 0, we receive the final tableau:

	x_1	x_2	Z	C
1	0	1	0	8
2	1	0	0	4
	0	0	1	400

(3.13)

Read: By operating machine 1 for 4 hours and machine 2 for 8, the company can produce the maximum amount 400 units per week. Since the slack variables equal 0, all the preparation hours available have also been used up.

3.2.4. LP in the Context of Informatics

As a matter of fact, the development and application of LP solver technologies also started with Simplex. In the 1950s, the algorithm was successfully implemented in IBM's 701, the company's first "scientific computer", which could solve LPs with up to 101 constraints.[Bix12] With the advancement of information technology, more powerful variants of simplex were developed, being able to process an ever-growing amount of constraints and decision variables. Today, a broad range of solver technologies is available, both commercial and open-source, with CPLEX and Gurobi constituting some of the most popular and wide-spread applications.[Bix12]

IBM's CPLEX is a powerful mathematical optimization software used for solving LP, mixed-integer programming (MIP), and quadratic programming (QP) problems across various industries. It features high-performance solvers, leveraging Simplex, Interior-Point, and other methods for efficient problem-solving. CPLEX supports modeling through the Optimization Programming Language (OPL) and offers APIs for Python, Java, C++, and C, enabling seamless integration into applications. Designed for large-scale problems, it utilizes parallel computing, heuristics, and cloud integration to find optimal or near-optimal solutions. Widely used in supply chain optimization, financial portfolio management, production scheduling, and resource allocation, CPLEX automates solver selection, making it faster and more efficient than manually implementing traditional methods like the Simplex algorithm.[IBM24]

Gurobi offers similar capabilities as CPLEX; However, they still differ in certain key aspects. Gurobi is often praised for its faster performance on MIP problems and better multi-threading efficiency, while CPLEX is known for its strong LP solvers and seamless integration with IBM technologies. Gurobi's licensing model tends to be more academic-friendly, offering free licenses for researchers, whereas CPLEX is widely used in enterprise applications due to its deep integration with IBM Watson and enterprise optimization tools. Ultimately, the choice between them depends on the specific problem structure, industry requirements, and integration needs.[Gur25, Jab15]

With regard to the use case of this paper, the optimization of charging/discharging cycles of batteries, LP represents a suitable solution approach. An exemplary objective function could be the minimization of costs that result from the purchase of energy from utility providers by making optimal use of the energy storage unit(s) available within a given energy community. In a very simple model, the battery's capacity (cf. 2.2.1) constitutes a constraint, while the state of charge (SoC, cf. 2.2.3) represents the decision variable - the battery's optimal charge level. Predicted for a longer time period (e.g., one day), the difference in the SoC for each point in time provides a "schedule" for optimal control of the storage device, ensuring minimal costs from "unnecessary" external energy purchases by charging the battery when internal energy production exceeds consumption and discharging it in case of the opposite scenario.

3.3. Technical Implementation

Finally, this last section provides a detailed description of the technical implementation, the web-app Energy Community Management (ECM). In the following sections, I will clarify the general motivation and scope of the tool, describe its technical architecture and service structure, discuss the results and limitations and provide an overview of the decisions made (and their consequences) in a corresponding log.

3.3.1. Use Case

The main idea behind ECM is to provide the administrators and participants of an energy community with a suitable tool to model, manage, and control their entity in the virtual space. It shall provide the means to support with planning and reconciliation activities, as those tasks get increasingly complex as the community grows in size and capabilities. Furthermore, the tool should be able to integrate and process external data sources (e.g., energy prices, weather forecast data, etc.) and provide an interface to third-party applications (e.g., solver technologies, smart meters, etc.) for meaningful simulations and predictions. Figure 3.2 provides a corresponding graphical overview.

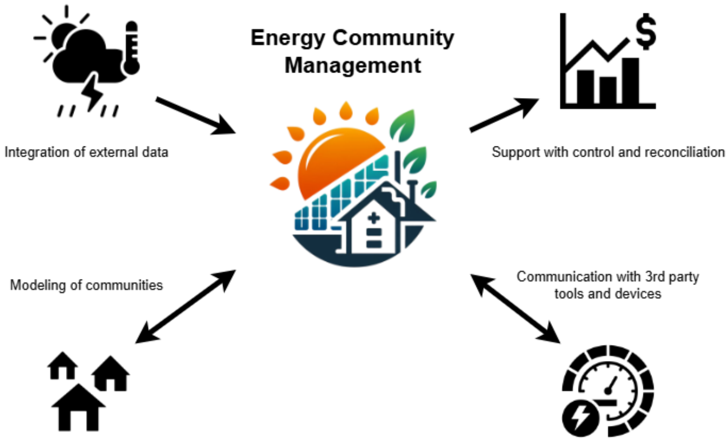


Figure 3.2.: The tasks of the ECM application

Eventually, the tool shall provide (and automatically implement) optimal control parameters for the DERs available in the community, based on the load profiles generated by the metering devices and the information delivered by the external data sources. It also predicts the individual contributions and consumptions of the participants, expressed both in monetary and actual quantities (e.g., EUR per kWh) and consolidates them on the community level. These predictions can later be offset with the actual results, once the "true" values and prices are available.

3.3.2. Scope

As indicated above, the tool's aim is to create a model (a digital twin) of an energy community. This model can then be further processed by a suitable solver, applying linear optimization to predict ideal 24-hour charge/discharge cycles of the energy storage devices (lithium-ion batteries) maintained in the model. Figure 3.3 provides a high-level overview of the tool's scope.

ECM can thus also be described as a master data management tool: The user creates/maintains information about the community for subsequent processing and result generation (see following section for detailed descriptions of the individual master data items). Scope-wise, it is important to note that only the model creation aspect is covered in this paper; the results generated and discussed here are only simulated. ECM therefore constitutes a proof of concept, hinting at the potential inherent in the implementation.

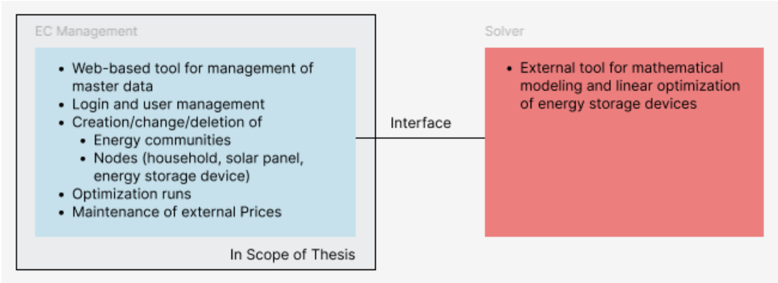


Figure 3.3.: The high-level structure and scope of ECM

3.3.3. System Architecture and Services

On a high level, ECM consists of three components: A frontend, a backend, and a database, all of which are deployed as docker containers. See Figure 3.4 for an architectural overview.

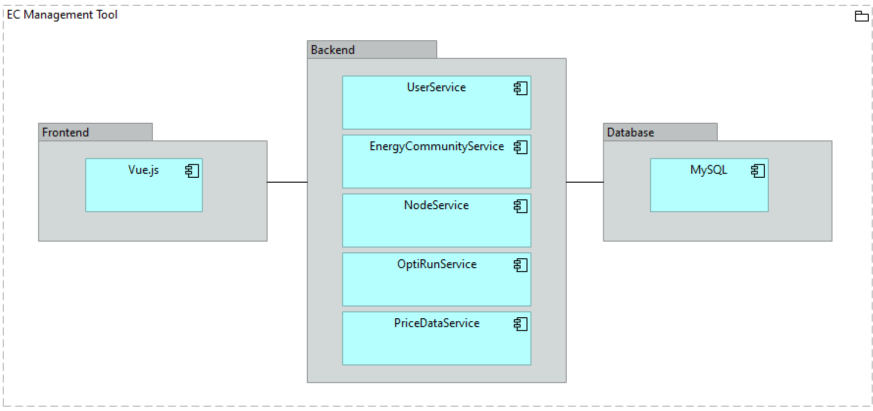


Figure 3.4.: An architectural overview of ECM's component and service structure

The ECM backend is built as a "modular monolith", combining the benefits of a simple monolithic structure with the flexibility, resilience, and adaptability of the modular microservice concept.[TNMA23] This approach establishes clear boundaries between the individual "contexts" (or modules) of the application, ensuring compliance with the software development design patterns of loose coupling between those modules and high cohesion within them.[TNMA23] Furthermore, the code structure follows the model-view-controller (MVC) pattern: The decoupling of business logic and user interface, allowing for more independence and adaptability between those two aspects.[LR01]

Tech Stack

Tables 3.1 and 3.2 provide an overview of the technologies, frameworks, and libraries used for development of ECM.

Development Stack		
Application Area	Technology	Version
IDE	IntelliJ	2021.3.3
Build Tool	Apache Maven	4.0.0
Version Control System	GIT	2.35.1.windows.2
Code Repository	GitLab	16.11.10
Modeling	Figma	124.4.7
Modeling	BeeUp	1.7
Modeling	ArchiMate	5.2.0
Modeling	Draw.io	25.0.2
API Testing	Postman	11.22

Table 3.1.: An overview of the development stack applied

Application Tech Stack		
Application Area	Technology	Version
Frontend meta framework	Nuxt.js	3.11.1
Frontend framework	Vue.js	3.4.21
Backend framework	Java Spring Boot	3.2.3
Backend SDK	Java DK	17
Database	MySQL	8.4.1
Deployment	Docker	26.1.1

Table 3.2.: An overview of the tech stack applied

The whole code of the application is available on the GitLab instance of the University of Vienna.[Kö24]

Service Description

This section provides a detailed overview over the services implemented.

- **User Service**: This service handles both the creation of new users in the system and a log-in functionality for existing ones. During user creation, the roles "User" or "Admin" can be assigned (admins can update external energy prices in the system, see service below).
- **Community Service**: This part of the implementation handles the creation, update, and deletion of energy communities, the umbrella structure for nodes (see below). The internal settlement prices for energy produced, consumed, and stored are also set on this level.
- **Node Service**: This service enables the user to create, update, and delete nodes within a community. Nodes represent the individual participants and components of a community (or, in other words, the DERs and corresponding loads of the microgrid).

A node can take one of three types: Household, Energy Source, and Storage Unit; depending on the respective type, different data needs to be maintained. E.g., a household requires a load profile to be added, while an energy source requires a corresponding generation profile (more on that below). Furthermore, nodes can be grouped together into so-called "settlement groups": In real life, a participant of an energy community is likely to be a "prosumer" (cf. 1.3), meaning that a household employs a DER (e.g., a solar panel and/or a storage device). Settlement groups are used to map the relationship between a household and its DERs, which also facilitates community-internal billing and reconciliation.

- **Optimization Run Service**: This service makes an energy community model (the community and all its nodes) available for optimization and stores the results as logs in a table. In the current setup, this optimization is simulated, meaning that this service triggers a mock-API via a POST-method that returns a randomly generated time series for each storage device maintained in the model.
- **Price Data Service**: This service manages the external energy prices (megawatt in EUR per quarter hour) maintained in the tool, collected from the Austrian Energy Exchange.[EXA24] As mentioned above, regular users can only display the prices, while admins can also upload a spreadsheet to update those prices.

Graphic Representation

To better illustrate the operating principles of the ECM application, Figure 3.5 provides a graphical overview of the service structure.

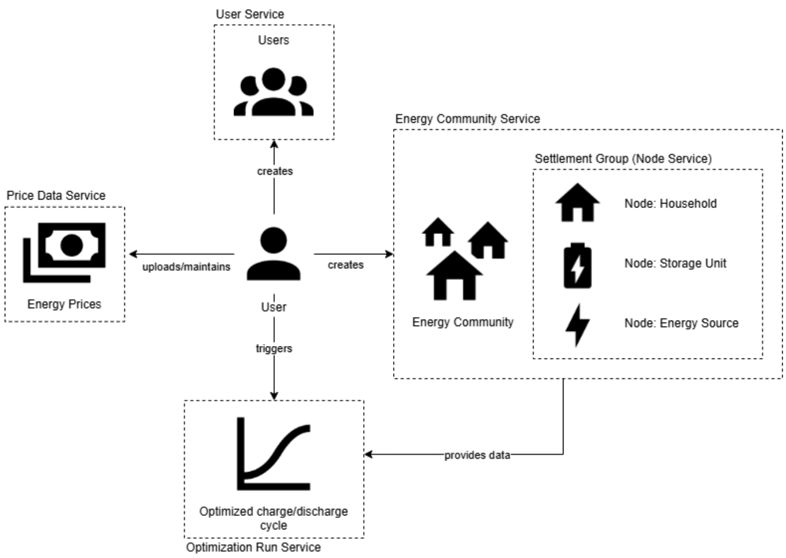


Figure 3.5.: A visualization of ECM's services

3.3.4. Data Model

Figure 3.6 provides an overview of ECM's data model.

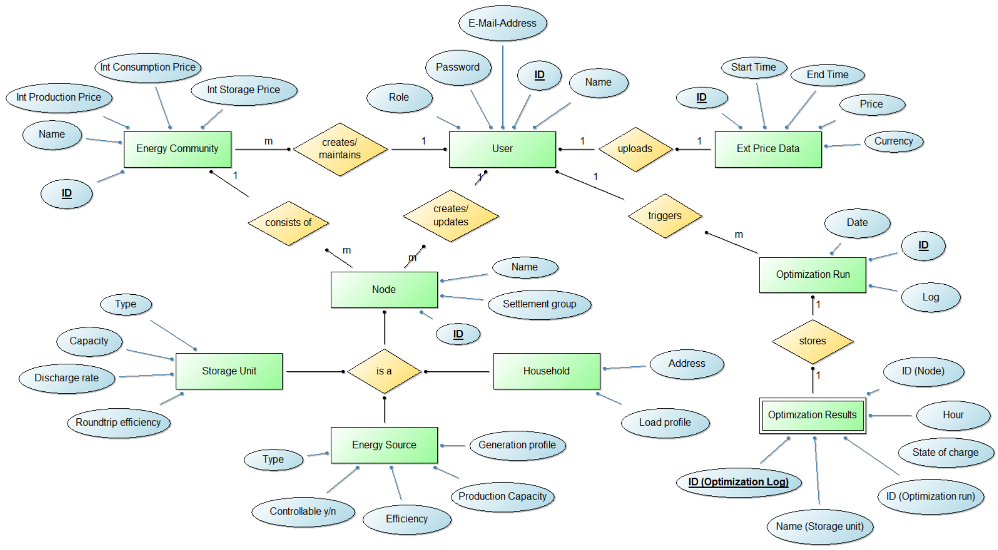


Figure 3.6.: The Entity-Relationship (ER) diagram of the ECM application

A detailed list of the attributes and their corresponding data types can be found in A.1.

Input Data

The (admin) user can upload three external data sources to the tool: A spreadsheet with energy prices extracted from the Austrian Energy Exchange, a load profile representing a household's energy consumption in watt-hours per quarter-hour, and a generation profile representing an energy source's power generation capabilities, also in watt-hours per quarter-hour. As for the profiles, I created five different versions for both loads and generation, respectively, which represent different household and solar panel sizes (and thus different consumption/generation values). The structure is loosely based on Germany's standard load profile[BDE24], which constitutes an aggregated average of many individual households. These profiles are maintained in the corresponding nodes (Household and Energy Source) and contain the consumption/generation values of three consecutive days, sliced into quarter hour segments and thus resulting in 288 data points per profile.

As for the Storage Unit node (the battery), the user needs to specify certain information, such as the unit's capacity (cf. 2.2.1), efficiency (cf. 2.2.4), or discharge rate (how much energy is lost due to self-discharge in percent over a given time frame). See Appendix A for a resulting JSON-model of a fully specified exemplary energy community.

3.3.5. Results

This section provides screenshots from the ECM application to visualize the implementation of the tool's features/services discussed above. Figure 3.7 shows the corresponding login site.

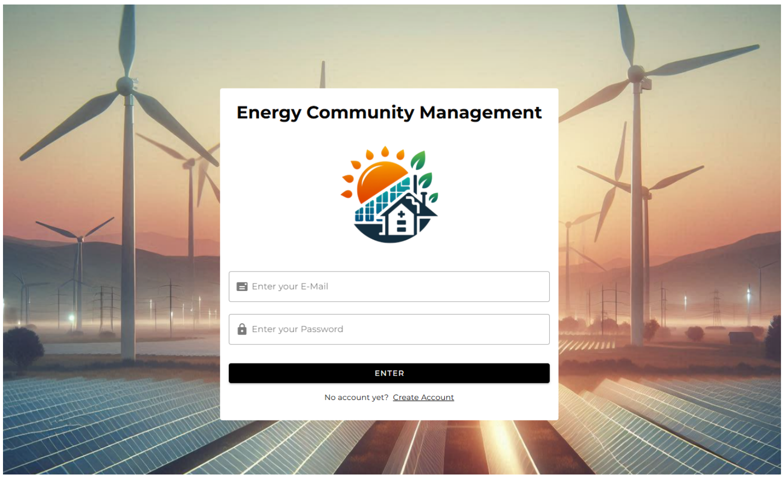


Figure 3.7.: ECM's login site. New users can be created following the "Create Account" link

Figure 3.8 demonstrates how the model (the digital twin) is created: The left side shows the communities, while the right side lists the nodes of a selected community.

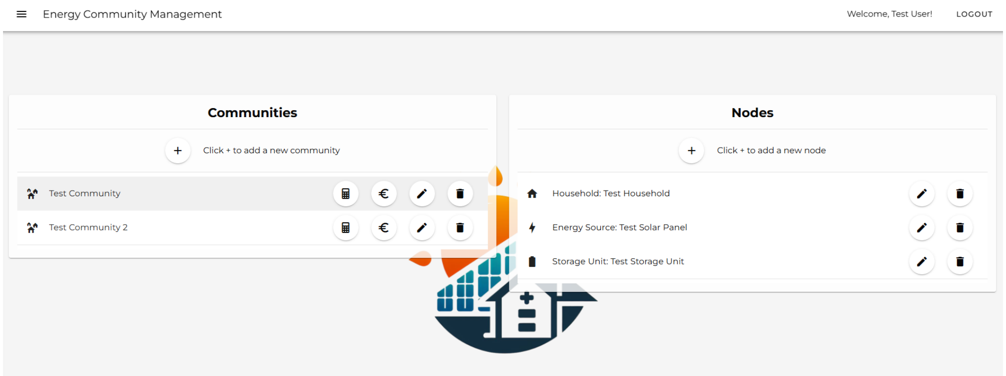
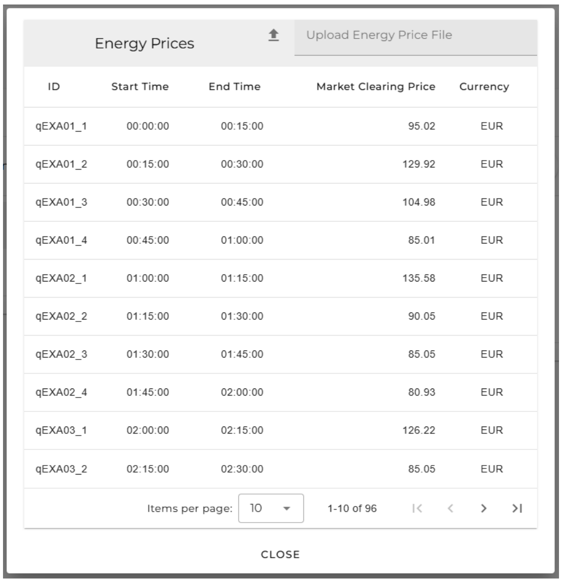


Figure 3.8.: The communities and their nodes. The community "Test Community" consists of three nodes: A Household, an Energy Source, and a Storage Unit

A view of EXA's energy prices is illustrated by Figure 3.9.

Optimization runs are stored in a log, as can be seen in Figure 3.10.



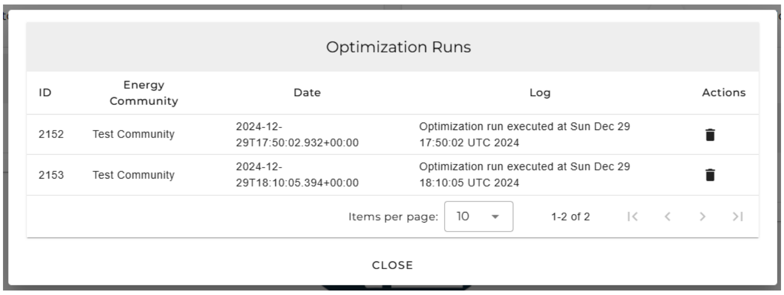
Energy Prices | Upload Energy Price File

ID	Start Time	End Time	Market Clearing Price	Currency
qEXA01_1	00:00:00	00:15:00	95.02	EUR
qEXA01_2	00:15:00	00:30:00	129.92	EUR
qEXA01_3	00:30:00	00:45:00	104.98	EUR
qEXA01_4	00:45:00	01:00:00	85.01	EUR
qEXA02_1	01:00:00	01:15:00	135.58	EUR
qEXA02_2	01:15:00	01:30:00	90.05	EUR
qEXA02_3	01:30:00	01:45:00	85.05	EUR
qEXA02_4	01:45:00	02:00:00	80.93	EUR
qEXA03_1	02:00:00	02:15:00	126.22	EUR
qEXA03_2	02:15:00	02:30:00	85.05	EUR

Items per page: 10 1-10 of 96

CLOSE

Figure 3.9.: The list of energy prices per quarter-hour in EUR/mWh



Optimization Runs

ID	Energy Community	Date	Log	Actions
2152	Test Community	2024-12-29T17:50:02.932+00:00	Optimization run executed at Sun Dec 29 17:50:02 UTC 2024	
2153	Test Community	2024-12-29T18:10:05.394+00:00	Optimization run executed at Sun Dec 29 18:10:05 UTC 2024	

Items per page: 10 1-2 of 2

CLOSE

Figure 3.10.: The list of optimization run logs

The result of an optimization run of a given energy community is a 24-hour time series, providing (simulated) optimal SoC-values for the energy community's storage unit(s), displayed as a line graph (time on the x-axis, SoC on the y-axis). Figure 3.11 provides a corresponding screenshot from the tool. I chose to set the lower bound of the battery's capacity to 20%, as over-discharge damages the battery.[OCL+18]

3.3.6. Limitations

This section aims to provide a structured overview of ECM's main limitations, some of which have already been addressed throughout the chapter. The decision log in the following section justifies some of those limitations (see below). At this point, I want to

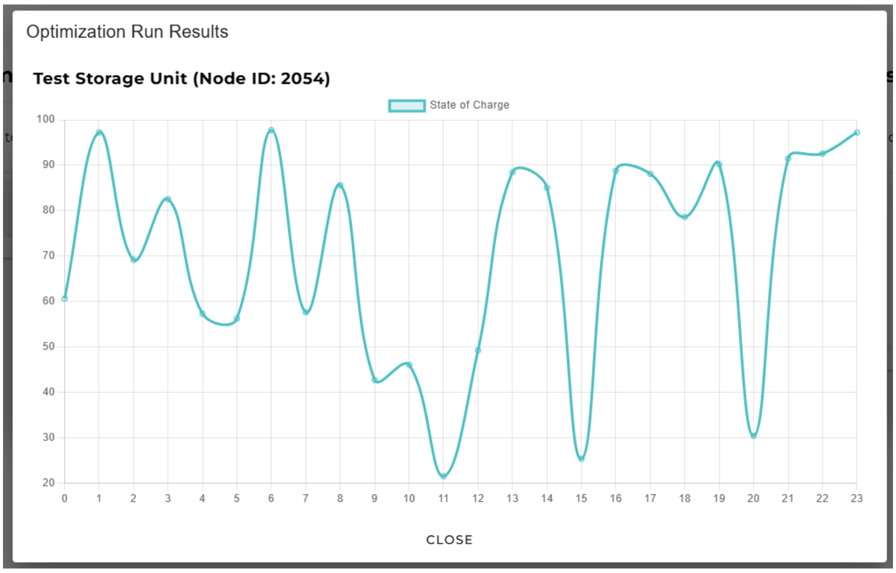


Figure 3.11.: A storage unit's optimal SoC (in percent) for the next 24 hours

emphasize again that ECM constitutes a proof of concept: If it were to be realized for real-world use, this paper indicates how it can be achieved.

- **Mocked optimization results**: The time series returned by the optimization run is randomly generated, there is no connection to an actual optimization solver technology. However, the JSON-model in the payload of the corresponding POST-request could be adapted to accommodate a potential solver's API.

- **Missing interface for external devices**: ECM does not include an interface for third-party tools or applications (e.g., a smart meter). In real life, metering devices would provide both historic and real-time information on energy production/consumption, rendering the load/generation profiles obsolete.

- **Missing parsing/storage of load and generation profiles**: Unlike the energy price data, the values from the load/generation profiles are not stored in the database. Instead, only the metadata of the uploaded files are stored (file name, type, and size). As indicated in the previous points, if this application were to be connected to actual metering devices, there would be no need for manual upload of those profiles anyway.

- **Missing financial consolidation**: No actual financial consolidation on community level is performed in this version of the tool.

- **Missing inclusion of further external data**: Besides the maintenance of external energy prices provided by EXA (see Figure 3.9), no additional external data sources are integrated into ECM.

- **Simplified model**: The current version of ECM operates with limited input data. In the real world, a more complete modeling of nodes (e.g., ambient temperature, age of the storage unit, maximal rate of charge/discharge, etc.) might lead to more accurate prediction results. Also, only lithium-ion batteries (as storage devices) and solar panels (as energy sources) are considered.

- **Missing graphical visualization**: At present, there is no graphical representation of the model (e.g., a network graph illustrating the connections between a household and its DERs), limiting the user experience (UX).

3.3.7. Decision Log

Finally, this last section shall provide on overview of the decisions made during the development of ECM, outlining the motivations, considerations, and consequences of those decisions.

Frontend and backend tech stack

Decision The frontend and backend technologies were chosen due to my familiarity with them in previous projects.

Consequences For the given application, a different tech stack may have been more suitable, but no other alternatives were seriously considered.

Database technology

Decision I decided to go for MySQL for the given application, as the data that is being created/edited/stored is structured and can therefore be easily handled by a relational database management system.

Consequences MongoDB was considered due to my familiarity with it in previous projects, but since I did not intend to work with unstructured or semi-structured data, I decided against it.

Node creation/maintenance and user ownership

Decision I decided to let a user create multiple energy communities, which in turn can have multiple nodes associated. However, it is not possible for different users to work on the same community (and subsequent nodes). In addition, a node can only belong to one community. So the user-community-node relationship follows a 1-n-n cardinality. This decision was made to make the creation/maintenance of communities and nodes as simple and straight-forward as possible.

Consequences In the real world, it would make sense to have multiple users edit/-maintain a community. The original design draft of the implementation also included a comprehensive user authorization service (a differentiation between "regular" users and more powerful admins) that was later dropped to focus more on the core functionalities (except for the upload of external price data - this can only be done by admins).

Proxy and Authentication Service

Decision The original design draft included NginX for reverse proxying/load balancing and an authentication service for user authentication. With regard to the rather "small" size of the implementation, the limited expected traffic, and the non-existent value of those services in relation to the purpose of the application in scope of this paper, I deemed these functionalities "too much", adding more complexity than usefulness, and therefore dropped them.

Consequences Real-world applications obviously need proxies and authentication services, and from a programming point of view it makes sense to implement them - and be it simply to demonstrate that it can be done. However, as with the user authorization service, it was decided to keep things simple and reduce potential error sources that do not add value to the actual scope of the application.

Simulation of optimized charge/discharge cycles

Decision The application was partly developed in cooperation with DAGOPT Optimization Technologies GmbH, a software development company specialized in mathematical modeling of complex systems.[DAG24] The company employs various solver technologies to optimize production processes. An API was developed to transfer the energy community JSON model to DAGOPT for "real" optimization of the charging cycle, but it was decided to exclude it from this thesis due to technology and trade secret concerns.

Consequences In its current form, the application constitutes a proof of concept, demonstrating the potential applicability and hinting at further development.

Billing Table

Decision Initially, the idea was to upload and parse values from the load/generation profiles into a respective "billing table" in order to enable community-internal clearing (based on the prices maintained in the community model). These calculations would have predicted a financial result to better illustrate which participant receives/owes which amount of money after the optimization. With ongoing development of the application, I deemed this feature "nice to have" and dropped it in order to focus more on the actual target of the implementation: The optimized charge/discharge cycle of the storage unit.

Consequences Without doubt, an accompanying billing table to illustrate the optimization also from a financial point of view would have made the tool more "complete", but as stated before, I decided to stick with the core aim of the implementation.

Load/Generation Profile Upload

Decision I decided to only store the metadata of the load/generation profiles of the respective households/energy sources in the Node model; Since the optimization only returns a simulated time series of randomly generated data points, I did not see the need to implement a parser.

Consequences As with the billing table, actually parsed, stored, and posted profile values would have resulted in a more "complete" application. However, on the other hand, the model remains leaner without it, as less information needs to be stored in the database.

4. Conclusion and Further Research

At present, there is no indication that the transformation process of the energy sector will be completed anytime soon. In fact, it appears that major changes have only just begun: Advancements and innovation of electromagnetic and hybrid energy storage technologies, rapidly increasing challenges posed by climate change, ever-growing demand for electricity and power, broad application of EVs, new developments in information technology, and, finally, the shift of control from centralized utilities to individuals and communities at the edge of the grid. All these developments will continue to fuel the transformation towards a more decentralized yet highly interconnected power grid that has to efficiently deal with all the challenges described above.

This paper's aim was to provide an overview of this transformation process, focusing on the current state of the art of energy storage systems and examining the Austrian model of how the grid's decentralization trends offer new opportunities for individuals. In summary, the paper established a clearer picture of the following key areas (and their connectedness):

- A historic account of the traditional power grid, its challenges and ongoing transformation activities
- The development of the smart grid and microgrids as well as their momentary states
- A brief introduction to the the European and Austrian legal frameworks that enable and regulate the grid's transformation process
- A presentation of the Austrian energy community concept
- An overview of the state of the art of energy storage systems (including comparison parameters) with a focus on electrochemical storage technologies
- A proof of concept for the modeling of energy communities, using the digital twin concept and the application of linear programming for optimal battery charging cycles
- A technical implementation of this proof of concept (the Energy Community Management tool)

As outlined in 3.3.6, the ECM tool comes with certain limitations, leaving room for further research and development areas. These areas in turn can be summarized as follows:

- The connection of ECM with an actual solver solution

- Implementation of a "financial layer", illustrating energy production, consumption, and sale in monetary terms
- Integration of external data sources, such as weather forecasts, current energy prices, or real-time energy production/consumption values
- Integration of additional model parameters, such as different energy generation and storage technologies/devices, power inverters, etc.
- Fine-tuning of model accuracy by adding more data inputs (e.g., orientation of solar panels, battery age, maximum charge/discharge speed, etc.)

In conclusion, I believe that the decentralization of the power grid and the resulting challenges also constitute an opportunity for a broad variety of innovative new solution approaches - one of which, ECM, has been presented in this paper. I also believe that those solution approaches cannot be developed within one singular realm (e.g., informatics), but require extensive knowledge and experience from different - yet relevant - areas. This is also why I chose to follow an interdisciplinary approach, combining mathematical and IT-related concepts with actual needs of both an economic sector (energy) and individuals (the new prosumers), trying to illustrate how these different interest groups can support and complement each other with their respective expertise.

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A. Appendix

A.1. Input Data Types

Attribute	Data Type
userId (Key)	Integer
userName	String
email	String
password	String
role	String

Table A.1.: Model: User

Attribute	Data Type
ecId (Key)	Integer
ecName	String
ecPriceProduction	BigDecimal
ecPriceConsumption	BigDecimal
ecPriceStorage	BigDecimal
userId	Integer
nodes	List<Node>

Table A.2.: Model: EnergyCommunity

Attribute	Data Type
nodeId (Key)	Integer
nodeType	String
hhName	String
hhAddress	String
hhLoadProfileName	String
hhLoadProfileType	String
hhLoadProfileSize	Long
esName	String
esType	String
esEfficiency	Float
esCapacity	Float

Attribute	Data Type
esControllable	boolean
esGenerationProfileName	String
esGenerationProfileType	String
esGenerationProfileSize	Long
suName	String
suType	String
suCapacity	Float
suEfficiency	Float
suRateOfDischarge	Float

Table A.3.: Model: Node

Attribute	Data Type
priceId (Key)	Integer
start	LocalTime
end	LocalTime
price	BigDecimal
currency	String

Table A.4.: Model: PriceData

Attribute	Data Type
optiRunId (Key)	Integer
date	Date
log	String
ecId	Integer
ecName	String
userId	Integer
results	List<OptiResult>

Table A.5.: Model: OptiRun

Attribute	Data Type
resultId (Key)	Integer
hour	Integer
stateOfCharge	BigDecimal
optiRun	OptiRun
nodeId	Integer
suName	String

Table A.6.: Model: OptiResult

A.2. JSON Model of an Energy Community


```
{
    "ecId": 1602,
    "ecName": "test",
    "ecPriceProduction": 0.4,
    "ecPriceConsumption": 0.4,
    "ecPriceStorage": 0.4,
    "userId": 952,
    "nodes":
    [
        {
            "nodeId": 905,
            "nodeType": "Household",
            "settlementGroup": 1,
            "hhName": "Test Household",
            "hhAddress": "Test Street",
            "hhLoadProfileName": "energy-prices.csv",
            "hhLoadProfileType": "text/csv",
            "hhLoadProfileSize": 3170,
            "esName": null,
            "esType": null,
            "esEfficiency": null,
            "esCapacity": null,
            "esControllable": false,
            "esGenerationProfileName": null,
            "esGenerationProfileType": null,
            "esGenerationProfileSize": null,
            "suName": null,
            "suType": null,
            "suCapacity": null,
            "suEfficiency": null,
            "suRateOfDischarge": null
        },
        {
            "nodeId": 906,
            "nodeType": "Energy Source",
            "settlementGroup": 1,
            "hhName": null,
            "hhAddress": null,
            "hhLoadProfileName": null,
            "hhLoadProfileType": null,
            "hhLoadProfileSize": null,
            "esName": "Test Energy Source",
            "esType": "Solar Panel",
            "esEfficiency": 55,
            "esCapacity": 44,
            "esControllable": true,
            "esGenerationProfileName": "preisdaten.xlsx",
            "esGenerationProfileType": "application/vnd.openxmlformats-officedocument.spreadsheetml.sheet",
            "esGenerationProfileSize": 16449,
            "suName": null,
```

```
            "suType": null,
            "suCapacity": null,
            "suEfficiency": null,
            "suRateOfDischarge": null
        },
        {
            "nodeId": 907,
            "nodeType": "Storage Unit",
            "settlementGroup": 1,
            "hhName": null,
            "hhAddress": null,
            "hhLoadProfileName": null,
            "hhLoadProfileType": null,
            "hhLoadProfileSize": null,
            "esName": null,
            "esType": null,
            "esEfficiency": null,
            "esCapacity": null,
            "esControllable": false,
            "esGenerationProfileName": null,
            "esGenerationProfileType": null,
            "esGenerationProfileSize": null,
            "suName": "Test Storage Unit",
            "suType": "Battery",
            "suCapacity": 44,
            "suEfficiency": 44,
            "suRateOfDischarge": 22
        }
    ]
}
```