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Young Energy Professionals (YEP), 5. Zyklus

Final Report

Group: Energy Storage

Title: ***"A Comparison of Current Energy Storage Technologies: Batteries, Pumped Storage and Green Hydrogen. Potential, Challenges, and Prospects"***

ÜBER YOUNG ENERGY PROFESSIONALS

Die Young Energy Professionals (**YEP**) bilden das interdisziplinäre Netzwerk junger Berufstätiger im WEC Austria. Gegründet „von jungen Menschen für junge Menschen“ auf dem Weltenergiekongress 2007 in Rom, sind die Ziele der Young Energy Professionals:

- **faktenbasiert Wissen** zu energiewirtschaftlichen Themen zu vermitteln,
- ein fachlich übergreifendes **Netzwerk** aufzubauen,
- **junge Entscheidungsträger und Meinungsbildner** sowie den energiewirtschaftlichen Nachwuchs anzusprechen,
- **Erfahrungs- und Wissensaustausch** innerhalb des WEC-Netzwerks zu ermöglichen sowie
- die internationalen Aktivitäten der **Future Energy Leaders** Community von WEC zu unterstützen.

Der WEC Austria beschloss im Jahr **2015** eine **nationale YEP-Gruppe** zu etablieren. Zum einen werden auf nationaler Ebene Lösungsvorschläge zu verschiedenen energiewirtschaftlichen Fragestellungen erarbeitet. Hierbei deckt ein interdisziplinärer Pool an jungen Berufstätigen der Energiewirtschaft vielfältige Themenbereiche ab. Zum anderen unterstützen die YEP von WEC Austria die Arbeiten der internationalen Nachwuchsorganisation des World Energy Council. Ein Board aus Mentoren unterstützt und begleitet die YEP.

Der YEP-Zyklus dauerte in dieser Kohorte ein Jahr. Im Anschluss werden die YEP-Programmteilnehmer in die YEP-Alumni-Community aufgenommen.

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GROUP

Energy Storage

TITLE

A Comparison of Current Energy Storage Technologies: Batteries, Pumped Storage and Green Hydrogen. Potential, Challenges, and Prospects

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1. Introduction

Austria's transition to a climate-neutral energy system by 2040 demands a fundamental shift in how energy is generated, stored and distributed. As renewable energy sources like wind and solar power expand, the need for flexible, reliable and scalable energy storage solutions becomes critical. These technologies must balance supply and demand, ensure grid stability, and support the integration of intermittent renewables into the national energy mix.

This working paper explores the role of energy storage in Austria's energy transition, focusing on both established and emerging technologies. It reviews electrochemical batteries, mechanical storage systems, hydrogen solutions, pumped hydro, thermal storage, and innovative approaches such as organic redox flow batteries and virtual batteries. Each technology is assessed for its technical potential, economic feasibility, and environmental impact, with a particular emphasis on Austria's unique energy landscape and regulatory framework.

The analysis is structured around three core themes: a comprehensive technology review, an examination of future energy scenarios for 2030 and 2040, and a series of practical use cases demonstrating how storage solutions can address real-world challenges. The paper concludes with recommendations to guide policymakers, industry leaders, and researchers in accelerating Austria's path to a sustainable and resilient energy future.

2. Technology Review

This chapter reviews the main energy technologies and discusses their principles, applications, and performance.

2.1. Batteries

A battery is an electrochemical device that stores chemical energy and converts it into electrical energy through reactions between two electrodes, an anode and a cathode, separated by an electrolyte that enables ion transport while preventing direct contact. Primary (non-rechargeable) batteries, such as zinc–carbon, alkaline, and lithium primary cells, are designed for single use and are discarded after depletion. In contrast, secondary (rechargeable) batteries allow reversible reactions, enabling repeated charge-discharge cycles. Common rechargeable systems include lead-acid, nickel-cadmium, nickel-metal hydride, and, most prominently today, lithium-ion batteries, which dominate portable electronics, electric vehicles, and energy storage due to their high energy density and efficiency. Lithium-ion technology encompasses several chemistries-most notably nickel-manganese-cobalt (NMC), nickel-cobalt-aluminum (NCA), and lithium-iron-phosphate (LFP)-each balancing energy density, cost, safety, and lifespan differently.

Beyond conventional technologies, emerging battery systems aim to improve sustainability, safety, and performance. Solid-state batteries replace flammable liquid electrolytes with solid materials, offering the potential for significantly higher energy density and improved safety, though large-scale commercialization remains challenging. Sodium-ion batteries substitute lithium with abundant sodium, reducing cost and resource constraints at the expense of lower energy density, making them promising for stationary storage and cost-sensitive applications. Other innovations, such as flow batteries for grid storage, zinc–air concepts, and silicon-enhanced anodes, are under development to address specific limitations of current systems.

The following table presents some key characteristics and costs:

Battery Type	Key Technology Characteristics	Approx. Cost
Sodium-Ion (Na-ion)	Uses abundant sodium instead of lithium; lower energy density (100-160 Wh/kg)	$70-100/kWh (expected 20–40% cheaper than lithium-ion)
NMC (Nickel-Manganese-Cobalt)	Lithium-ion chemistry with balanced performance and high energy density up to ~250 Wh/kg; widely used in EV batteries.	$100-120/kWh (dependent on nickel and cobalt prices)
NCA (Nickel-Cobalt-Aluminum)	Nickel-rich cathode with very high energy density (250-300 Wh/kg) and long lifetime.	$110-130/kWh
LFP (Lithium Iron Phosphate)	Very stable and safe chemistry with long cycle life (>3000 cycles); lower energy density (~170-180 Wh/kg).	$80-100/kWh (one of the lowest-cost lithium-ion options)
Solid-State Batteries	Solid electrolyte replaces liquid electrolyte, improving safety and enabling very high energy density (>400 Wh/kg potential).	$200-500/kWh (early-stage production)

Battery technology development is closely linked to economic and environmental considerations. Material availability, manufacturing scalability, lifecycle performance, and recycling are increasingly important as global demand rises, particularly for electric mobility and renewable energy integration. Most of the batteries are imported from Asia, where many manufacturers produce and work on the development of future cell technology, the dependency of Europe is therefore high. Within the European Union, including Austria, battery deployment is governed by comprehensive regulations that set requirements for sustainability, recycled content, carbon footprint reporting, collection targets, and design for reuse and recycling. These policies support a circular economy approach and aim to reduce environmental impact while strengthening a domestic battery value chain. Consequently, modern battery research focuses not only on performance improvements but also on safety, cost reduction, and compliance with evolving regulatory frameworks, positioning advanced batteries as a key enabling technology for the energy transition.

2.2. Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) is a method of storing energy by compressing air in underground caverns or high-pressure tanks during periods of low electricity demand or surplus renewable generation. When energy is needed, the compressed air is released, heated (typically using natural gas or renewable heat), and expanded through a turbine to generate electricity. There are two main types of CAES systems: diabatic (heat is released during compression and reheated during expansion) and adiabatic (heat from compression is stored and reused during expansion, improving efficiency and reducing emissions). CAES is considered a long-duration energy storage solution, ideal for grid-scale applications. Due to the fact, that underground caverns are widely available, CAES is a promising future technology for long duration storage with a lot of ongoing research.

The cost of CAES systems varies widely depending on the system type, location, and scale. Traditional diabatic CAES plants have lower capital costs than battery storage but rely on natural gas, which affects operational costs and emissions. Adiabatic systems, while more environmentally friendly, are still in the demonstration phase and involve higher upfront investment due to thermal storage technology.

Globally, installed CAES capacity is limited, with less than 500 MW in operation, mainly in the U.S. and Germany. The most notable plants are the Huntorf (Germany) and McIntosh (USA) facilities, both operational since the late 20th century. The Huntorf plant has approximately 300 MW electric power and a storage capacity of around 2.100 MWh. However, interest is growing rapidly, driven by the need for long-duration storage. Forecasts suggest CAES capacity could reach 5–10 GW globally in the next decade, depending on regulatory support, technological progress, and integration with renewable energy deployment.

2.3. Flywheel energy storage

Flywheel energy storage (FES) is a mechanical energy storage technology that stores electricity in the form of kinetic energy by accelerating a rotating mass (rotor) to very high speeds. When energy is needed, rotational energy is converted back into electrical power.

Modern systems operate in vacuum enclosures and use magnetic bearings to minimize friction losses, enabling high efficiency and long service life. Key components include the rotor, bearings, vacuum housing, power electronics for grid interaction, and a control system that manages operation and safety. The stored energy depends on the rotor's mass distribution and rotational speed, with advanced carbon-fiber composites allowing speeds exceeding 20,000 rpm.

FES systems are characterized by extremely fast response times, capable of charging or discharging within milliseconds to seconds. This makes them particularly valuable for grid frequency regulation, power quality management, and buffering sudden demand peaks such as those created by electric vehicle fast-charging stations. Unlike electrochemical batteries, flywheels experience negligible degradation over time and can achieve hundreds of thousands to millions of cycles with minimal maintenance. They also offer environmental advantages because they use largely recyclable materials and contain no hazardous chemicals. However, their relatively low energy density compared to batteries limits their suitability for long-duration storage, positioning them instead as high-power, short-duration solutions.

Research and development in Europe, including Austria, focuses on improving rotor materials, bearing technologies, and system integration with renewable energy and smart grids. Projects have demonstrated the use of flywheels as local energy buffers for solar and wind power and as support for fast-charging infrastructure, where they can deliver high power without overloading the grid. Austria hosts several pilot initiatives led by academic and industry partnerships, highlighting the country's role as an emerging innovation hub, although commercial-scale deployment remains limited.

Economically, flywheel systems typically have higher upfront costs per unit of stored energy than lithium-ion batteries, but their long lifespan and low operating costs can result in competitive lifetime economics, particularly in applications requiring frequent cycling. Market growth in Europe is expected to be moderate but steady, driven by increasing renewable penetration and electrification of transport. Policy frameworks at the EU and national levels recognize energy storage as essential for grid stability and decarbonization, indirectly supporting FES deployment through funding programs and regulatory reforms.

Overall, flywheel energy storage represents a complementary technology within the broader energy storage landscape. While unsuitable for long-term or large-scale energy storage, it provides unique advantages in rapid response, durability, and sustainability. In Austria's energy transition, flywheels are likely to play a niche but important role in stabilizing decentralized renewable systems, supporting electric mobility infrastructure, and enhancing grid resilience alongside batteries, hydrogen, and pumped hydro storage.

2.4. Gravity Storage

The term gravity storage generally refers to energy storage systems that use solid materials such as rock or metal to store potential energy through vertical displacement (e.g., using elevators or funicular railways). In contrast, pumped storage power plants, which use liquid water as the storage medium, are not typically included in this category, even though they also store potential energy. Technically, any type of system that enables vertical movement, whether vertical or inclined, can be used, and various lifting mechanisms such as cables or levers may be employed.

One advantage over traditional pumped storage plants lies in the higher energy density of solid materials: they store significantly more energy per unit volume. The efficiency of such systems is comparable to that of pumped storage plants, ranging from approximately 70-85%. Another benefit is that the stored energy remains fully intact over time, the power output is independent of the fill level, and energy can be made available very quickly. The power output is independent of the fill level because each storage unit (e.g., a stone block) releases the same amount of energy over the same distance during discharge, regardless of how many other units are still stored.

There are already examples such as mountain railways or elevators that generate electricity when descending. These systems are also considered as gravity storage. One example is the newly constructed material cableway at the Bolgenach reservoir operated by illwerke vkw AG in Vorarlberg. The removal of sediment from the reservoir generates more electrical energy than the material ropeway consumes. Another approach is the Buoyant Energy concept. Here, a small reservoir floats within a larger one (e.g., a lake or the sea), and water is moved between the two reservoirs. When energy is supplied to the system via pumping, the entire structure is lifted. To recover energy, the storage system is lowered in a controlled manner, generating electricity via turbines. In 2023, Energy Vault built a gravity storage system in China with a capacity of 100 MWh, and the cost was 500 US dollars per kWh.

2.5. Hydrogen Storage

Hydrogen storage is becoming a key element in the transition to a low-carbon energy system, particularly as renewable energy generation increases and requires more flexibility. In Austria, hydrogen is expected to play a major role in achieving climate neutrality by 2040, both as an energy carrier and as a raw material for decarbonizing hard-to-electrify sectors such as steel, chemicals, and heavy transport. Storage is especially important for balancing seasonal fluctuations, allowing surplus renewable energy in summer to be stored and used during winter, while also improving security of supply and enabling higher utilization of electrolyzers.

In Austria, hydrogen storage is closely linked to existing natural gas infrastructure, particularly in depleted gas fields in Lower and Upper Austria, which could be repurposed for large-scale storage. Smaller-scale storage is already used in mobility and industry through physical methods such as compressed gas and, to a lesser extent, liquid hydrogen. Compressed hydrogen storage is the most mature technology and is widely used in refueling stations in cities like Vienna, Graz, and Linz, storing hydrogen at high pressures (350-700 bar). It is reliable and suitable for decentralized applications, although it has low volumetric energy density and requires significant energy for compression. Liquid hydrogen offers higher energy density by cooling hydrogen to around -253 °C, but it involves high energy losses and complex infrastructure, limiting its current use.

For large-scale and seasonal storage, geological solutions are considered the most promising. While salt caverns are widely used in other parts of Europe, Austria's limited geological suitability makes depleted natural gas fields the main option. These reservoirs offer very large storage capacities and are already integrated into the gas grid, although technical challenges such as hydrogen leakage, material compatibility, and microbial reactions must be addressed. Even partial conversion of existing storage capacity could cover a significant share of future hydrogen demand.

Hydrogen storage supports the energy system by providing long-duration and seasonal storage beyond batteries, enabling grid balancing and sector coupling.

It is particularly relevant for industrial applications, such as green steel production at Voestalpine in Linz, and for refining and synthetic fuels at OMV in Schwechat. It also supports hydrogen-based mobility and positions Austria as a potential hub within the future European hydrogen network.

The main challenges include high investment costs, efficiency losses across the hydrogen value chain, evolving regulatory frameworks, and the early-stage maturity of large-scale storage technologies. However, Austria's hydrogen strategy and European initiatives are expected to drive development, with increasing demand for storage driven by industry, mobility, and energy system integration. Demonstration projects such as Underground Sun Storage 2030 operated by the RAG Austria AG have already shown that underground hydrogen storage in porous reservoirs is technically feasible, highlighting strong potential for future large-scale deployment.

2.6. Pumped Storage Hydropower

A pumped storage hydropower plant (PSH) stores electrical energy as potential energy by pumping water to an upper reservoir during low-demand periods or high renewable generation and releasing it through turbines when electricity is needed. It is especially common in regions with significant elevation differences, such as the Alps, due to its high efficiency.

Open-loop systems use natural water sources, making them cheaper but more sensitive to fluctuations in water availability and environmental impacts. Closed-loop systems circulate water only between two artificial reservoirs, ensuring stable operation and lower ecological risks but requiring higher upfront investment. Because of their environmental advantages, closed-loop plants are increasingly preferred.

PSH plants provide flexible grid support, including balancing power and peak-demand supply. They are important tools for grid stability and often operate in turbine direction during high-demand periods. Investment costs are substantial. For example, Austria's Ebensee project (170 MW) costs around €450 million, while Lünerseewerk 2 with 1.1 GW and no additional reservoir is budgeted at €2.65 billion, reflecting the generally high capital intensity of PSH.

Current research focuses on optimized plant operation, digitalization, predictive maintenance, and ecological improvements to enhance public acceptance. Europe is a major hub for hydropower innovation.

Europe's technical hydropower potential is 1.121 TWh per year, with current production at 569 TWh per year and 258 GW of installed capacity. The global PSH market is growing, driven mainly by rapid growth in Asia-Pacific, led by China, Japan, and Australia, while mature European markets show limited expansion.

Despite high initial investment costs, PSH remains a key technology for energy storage and grid reliability, and its development is shaped by economic and environmental considerations.

2.7. Thermal Energy Storage

Thermal energy storage (TES) plays an important role in Austria's energy transition by allowing energy generation and consumption to be separated over time. This is particularly important for integrating renewable energy sources such as solar and wind power.

Storage solutions in Austria range from large seasonal heat storage systems for district heating networks to small daily storage units in residential buildings, covering temperature levels from low-temperature heating to high-temperature industrial processes.

Large-scale or seasonal storage systems store heat over weeks or months and are mainly used to store surplus solar energy or industrial waste heat from summer for use during winter. Typical technologies include pit thermal energy storage, borehole storage, large hot water tank storage, and aquifer storage. One example is the large heat storage facility in Vienna-Simmering Thermal Storage, which has a storage volume of around 50,000 m³ and a capacity of approximately 1.4 GWh of thermal energy. Medium-sized storage systems operate as buffers over hours to days and are used in district heating networks, large buildings, and industrial processes, typically consisting of hot water tanks or latent heat storage systems. Small decentralized storage systems are commonly used in households together with solar thermal systems or heat pumps to store heat for daily use.

Thermal storage systems can also be classified by temperature levels. Low-temperature storage below 50 °C is mainly used in low-temperature district heating and heat pump systems. Medium-temperature storage between 50 °C and 100 °C is standard for domestic hot water and conventional district heating systems. High-temperature storage above 100 °C is mainly used in industrial applications or for reconversion to electricity using technologies such as molten salt or thermal oil storage.

Thermal energy storage supports Austria's decarbonization strategy by improving the use of renewable electricity, integrating industrial waste heat, increasing the flexibility of district heating networks, and enabling sector coupling through Power-to-Heat systems. The main challenges are investment costs, space requirements for large storage systems, and regulatory barriers, but studies show that thermal storage could support around 25-30% of Austria's district heating supply by 2040.

3. Scenarios 2030 & 2040

This chapter briefly discusses and analyzes key Austrian energy planning studies and strategies, including the Austrian Integrated Network Infrastructure Plan (ÖNIP), the Electricity Strategy 2040, and the identified flexibility and storage requirements of the Austrian energy system.

3.1. The Austrian Integrated Network Infrastructure Plan (Integrierter österreichischer Netzinfrastrukturplan [„ÖNIP"])

The Austrian Integrated Network Infrastructure Plan (ÖNIP) is a strategic instrument of the Austrian Federal Government, developed on behalf of the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, which is now institutionally located within the Federal Ministry for Economic Affairs and Energy. Its purpose is to support the strategic planning and coordination of energy infrastructures in Austria, particularly electricity, gas and hydrogen, and to align these with the objective of achieving climate neutrality by 2040. The ÖNIP is prepared and updated at regular three-year intervals. This periodic revision is mandated by law in order to adapt planning to new energy policy objectives, technological developments, and current scenarios of energy demand and supply. The first edition was published in 2024, and the next update is scheduled for 2027.

The ÖNIP serves as an overarching framework for the network planning activities of individual companies and promotes sector coupling as well as the utilization of synergies between energy carriers and sectors. Based on an inventory of the existing energy infrastructure and a transition scenario developed by the Austrian Environment Agency (Umweltbundesamt), energy supply and demand are modelled for 2030 and 2040, the target year for climate neutrality. The ÖNIP analyses the potential for renewable energy expansion, national and European network planning initiatives (APG, AGGM, TYNDP), and derives corresponding transport and network requirements, as depicted in Figure 1. Its results are compared with existing studies and plans, and it also addresses technological developments such as the use of underground cables in the transmission grid and onshore wind energy expansion targets up to 2030.

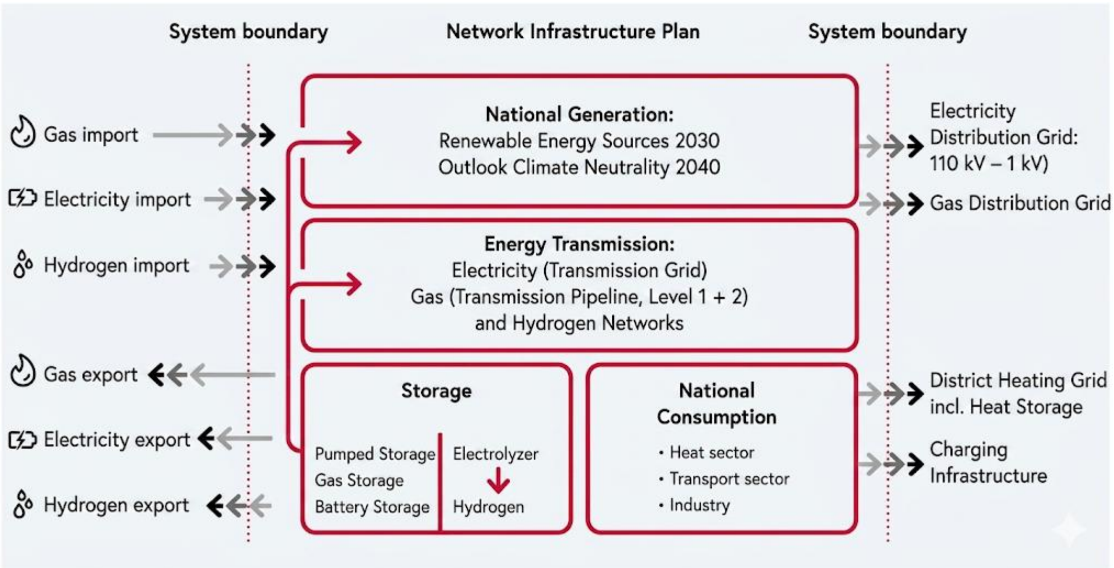

Figure 1: Overview Netzinfrastrukturplan (AI translation with the model Nano Banana 2 from Google Gemini from ÖNIP, page 9).

The starting point is an inventory of the existing energy infrastructure as well as the current supply and consumption of electricity and gas, which is presented in Chapter 2 of ÖNIP. Subsequently, Chapter 3 outlines the assumed future energy demand and supply for the years 2030 and 2040. This is based on the transition scenario developed by the Austrian Environment Agency (Umweltbundesamt) which defines the possible energy volume frameworks for 2030 and 2040. This scenario was selected for the NIP because energy infrastructure must be designed in the medium to long term to achieve climate neutrality, i.e. the complete replacement of fossil energy carriers.

On the generation side, renewable expansion potentials for electricity and biomethane are drawn from the study *"Scenarios for Realisable Renewable Electricity Generation in 2030 and 2040"* conducted by the Austrian Environment Agency. In addition, an overview of the currently applicable expansion targets and plans of the federal provinces is provided for the year 2030. Finally, current network infrastructure planning is reviewed at the European level through the Ten-Year Network Development Plans (TYNDP) and at the national level through the network development plans of Austrian Power Grid AG (APG) and Vorarlberger Übertragungsnetz GmbH (VÜN), as well as the Coordinated Network Development Plan and the long-term integrated planning of Austrian Gas Grid Management AG (AGGM).

Chapter 4 of ÖNIP describes the principles and economic benefits of future integrated planning of network infrastructure for electricity, gas and hydrogen. The core of this chapter is the derivation of transport requirements and network needs for the years 2030 and 2040, based on the adjusted energy volume frameworks described in Chapter 3 and the identified spatial potentials for renewable electricity and biomethane generation. This analysis is conducted using comprehensive, scientifically model-based methods developed within the framework of a research cooperation for the NIP. The planning documents of APG and AGGM (status as of September 2023) are incorporated into the network infrastructure presented in the NIP.

Chapter 5 presents and discusses the results. The findings and assumptions of the NIP are compared with the planning documents of APG and AGGM, as well as with the results of the studies *"The Role of Gas Infrastructure in a Climate-Neutral Austria 2040"* and *"Energy Infrastructure 2040 - Scenarios and Expansion Plans for a Sustainable Economic System in Austria"*. An excursus on the use of underground cables in the electricity transmission network as a possible technological option discusses technological developments and new insights relating to underground cabling at the transmission network level. A further excursus on wind power generation in 2030 disaggregates the targets of the Renewable Energy Expansion Act (EAG), or the targets referenced in Section 4a of the Environmental Impact Assessment Act (UVP-G) to the level of the individual federal provinces.

Austria's gross inland energy consumption remained largely stable between 2005 and 2021 despite population and economic growth, with declines following the financial crisis in 2009 and the COVID-19 pandemic in 2020. In 2021, consumption increased slightly due to economic recovery and colder weather conditions. Fossil energy carriers continue to dominate the energy mix; however, their share is steadily declining in favour of renewable energy sources, as is illustrated in Figure 2 below. In order to achieve the target of climate neutrality by 2040, a complete transition to renewable energy carriers is required. The Integrated Network Infrastructure Plan therefore focuses on grid-based energy carriers - electricity and gas - and their consumption, generation and transport structures.

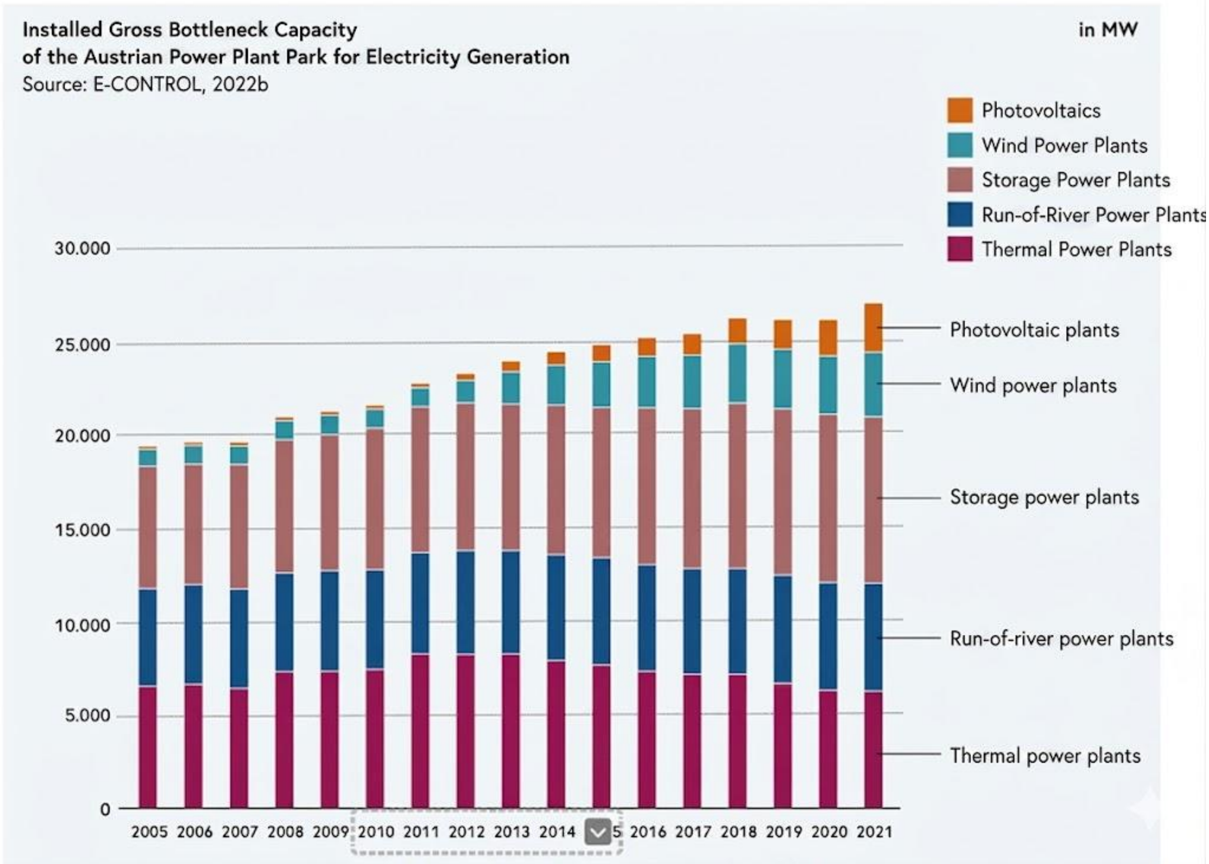

Figure 2: Installed gross capacity of Austria's power plant fleet for electricity generation. Source: E-Control, 2022b in MW (AI translation with the model Nano Banana 2 from Google Gemini from ÖNIP, page 19).

3.2. Austria's Electricity Strategy (Stromstrategie) 2040

As the representative body of the Austrian electricity industry, Oesterreichs Energie conducts its own simulations on behalf of its member companies in order to provide stakeholders with the most comprehensive information possible. The Electricity Strategy 2040 developed by Oesterreichs Energie and prepared by COMPASS LEXECON outlines a pathway for achieving climate neutrality in the Austrian electricity system by 2040. In this context, projected electricity demand is contrasted with potential electricity generation from weather-dependent renewable energy sources.

Given that security of supply is the highest priority for the member companies, the modelling places particular emphasis on assessing the level of flexibility required to ensure that electricity generation from renewable sources can be maintained during periods of low renewable output (so-called Dunkelflauten). Another important point is the seasonal shift from summer to winter, where renewable generation is lower and demand higher.

The projected generation capacities up to 2040 are illustrated in figure 3. In particular, renewable energy sources such as photovoltaic and wind power are expected to be expanded significantly. In parallel, battery storage capacities are also projected to increase substantially, from approximately 100 MW to more than 3.600 MW by 2040.

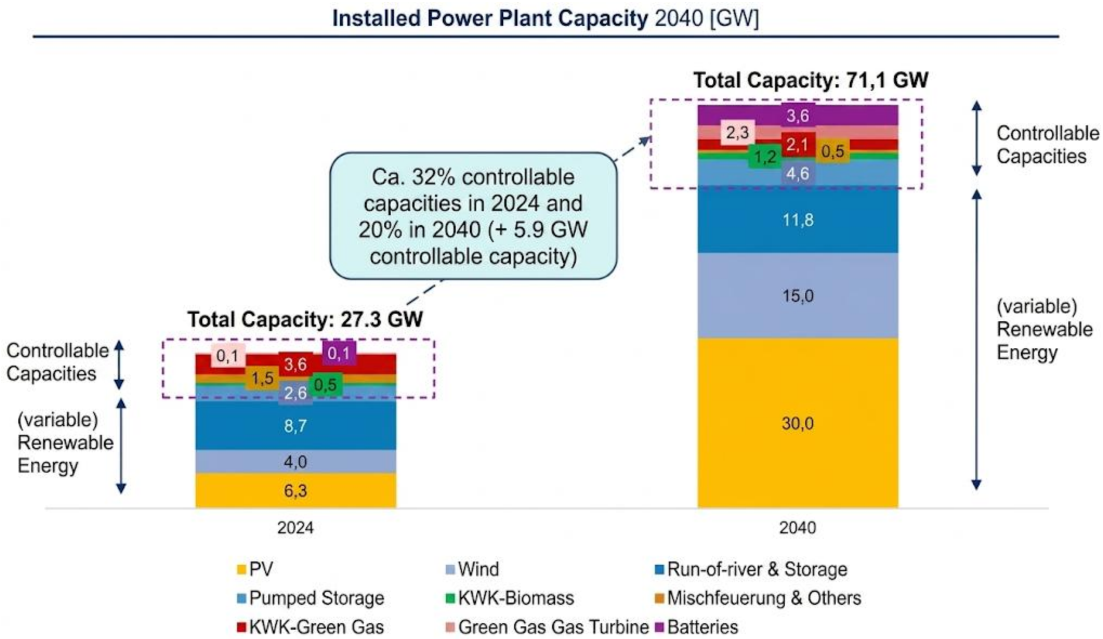

Figure 3: Installed Power Plant Capacity 2040 in GW (AI translation with the model Nano Banana 2 from Google Gemini from Stromstrategie 2040 by Oesterreichs Energie).

The generation portfolio shown in Figure 3 forms the basis for a decarbonised energy system. As generation volumes differ between technologies, not only the installed capacity but also the electricity generation per technology is of particular relevance. For example, photovoltaic installations in Austria generate approximately 1.000 kWh per kWp of installed capacity. By contrast, wind turbines achieve significantly higher full-load hours, which, depending on the location, can range between 2.000 and 3.000 full-load hours per year. Electricity generation by technology is illustrated in figure 4.

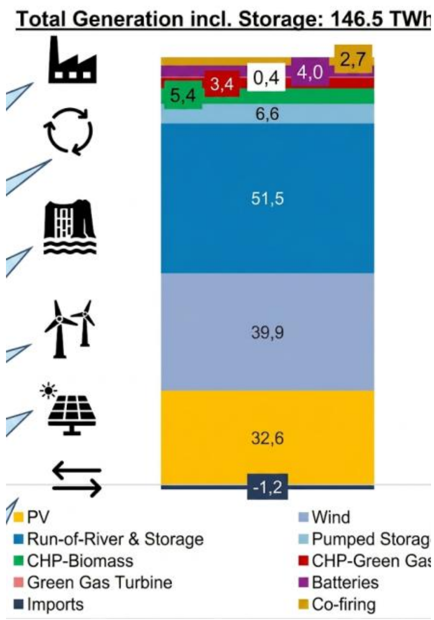

Figure 4: Total generation incl. storage (AI translation with the model Nano Banana 2 from Google Gemini from Stromstrategie 2040 by Oesterreichs Energie).

As a result of electrification in the sectors of space heating and mobility, electricity demand in a decarbonized energy system is expected to be approximately twice as high as in 2024. Owing to the substantial expansion of wind power and photovoltaic capacity, electricity generation from these technologies increases significantly. Notably, however, hydropower remains the single largest source of electricity generation by technology, producing 51.5 TWh, despite having a considerably lower installed capacity than photovoltaic and wind power, for example. This is attributable to the significantly higher full-load hours of hydropower plants compared with wind and photovoltaic installations.

The resulting flexibility requirements are illustrated in figure 5. On the x-axis, all hours of an entire year are represented. Each individual bar indicates the residual load occurring in the system, which must be balanced by energy storage through either electricity withdrawal from or injection into the system. During critical hours, the system experiences a shortfall of almost 25 GW or, conversely, a surplus of nearly 15 GW.

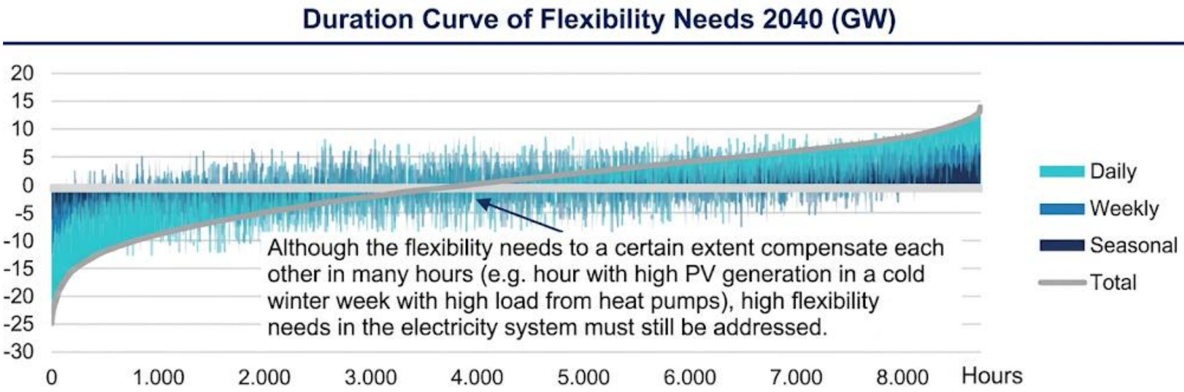

Figure 5: Duration curve of flexibility requirements 2040 in GW (AI translation with the model Nano Banana 2 from Google Gemini from Stromstrategie 2040 by APG).

To balance the residual loads shown in Figure 5, sufficient import and export capacities must be available in addition to the provision of the following flexibility options within the system. In particular, daily flexibility capacities need to be expanded substantially, increasing from approximately 5 GW to around 15 GW of installed capacity. This demand is driven primarily by the expansion of photovoltaic generation. However, weekly and seasonal flexibility options must also be significantly enhanced, as see in figure 6.

Figure 6: Annual Total Flexibility Requirements in TWh and Range of Flexibility Requirements in GW (AI translation with the model Nano Banana 2 from Google Gemini from Stromstrategie 2040 by Oesterreichs Energie).

These flexibility options can be categorized into seasonal, weekly and daily flexibility. Depending on the required storage duration, different technologies are deployed. Figure 7 illustrates the energy volumes that are stored on a seasonal, weekly and daily basis by the respective technologies.

Battery storage systems, for example, are well suited to providing daily flexibility due to their high storage efficiency, despite relatively high costs per unit of storage capacity. Hydrogen, by contrast, offers the advantage of low storage capacity costs, making it suitable for long-term energy storage. However, its use as a daily energy storage option would not be competitive, for instance, due to efficiency disadvantages compared with battery storage systems.

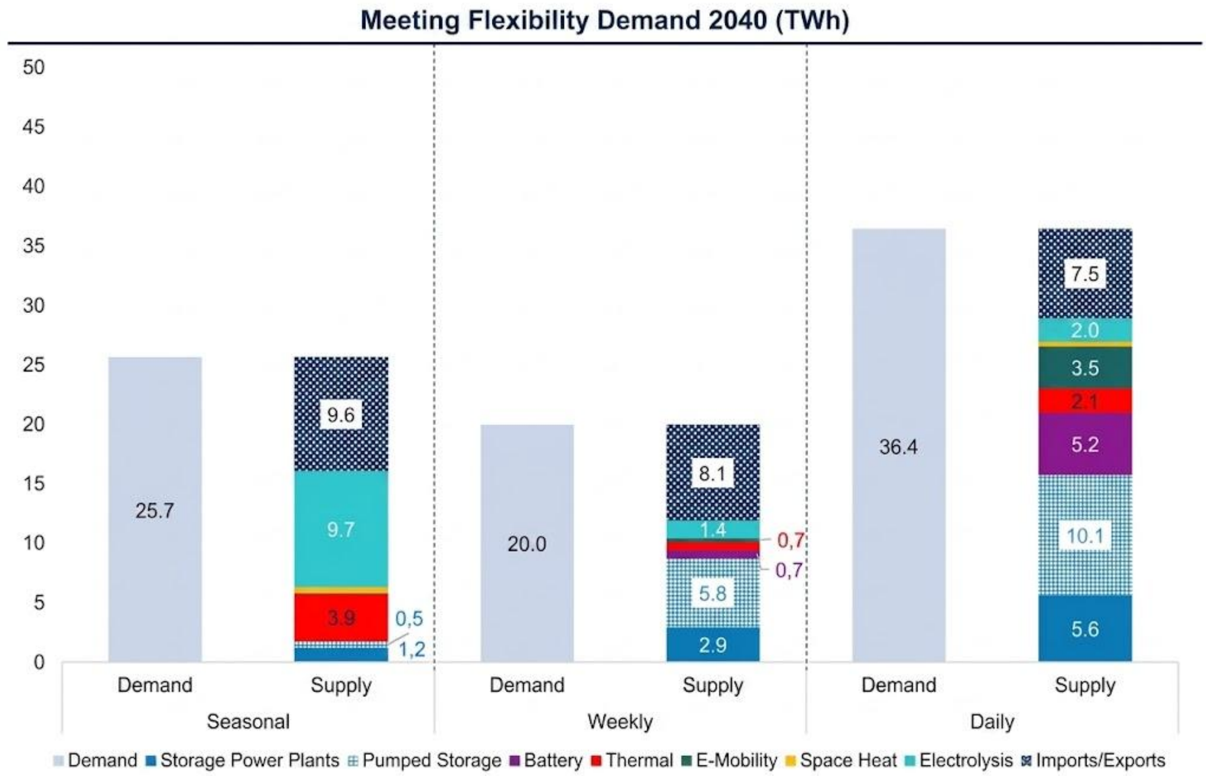

Figure 7: Coverage of Flexibility Needs 2040 in TWh (AI translation with the model Nano Banana 2 from Google Gemini from Stromstrategie 2040 by Oesterreichs Energie).

3.3. Flexibility and Storage Requirements in the Austrian Energy System

Austria's Electricity Strategy demonstrates that the sharply increasing intraday and seasonal shifting requirements in the Austrian electricity system up to 2040 can only be managed through an integrated combination of battery storage systems, pumped-storage hydropower, flexible power plants, grid expansion and sector coupling. Battery storage systems, with a total charging capacity of 8.7 GW, emerge as the central pillar of short-term flexibility, while the transmission grid and thermal green gas power plants play a crucial role in safeguarding security of supply, particularly under extreme scenarios.

A key concept in assessing flexibility needs is residual load, defined as total electricity demand minus generation from photovoltaic and wind sources. It serves as a quantitative indicator for determining flexibility and storage requirements.

Methodologically, the shifting demand is calculated as the sum of deviations of the hourly residual load from temporally aggregated mean values (daily, weekly and annual). This approach enables clear differentiation and quantification of intraday, weekly and seasonal flexibility requirements. Figure 8 illustrates the fundamental logic underlying the definition of residual load and shifting demand in a clear and accessible manner and is well suited for methodological contextualization.

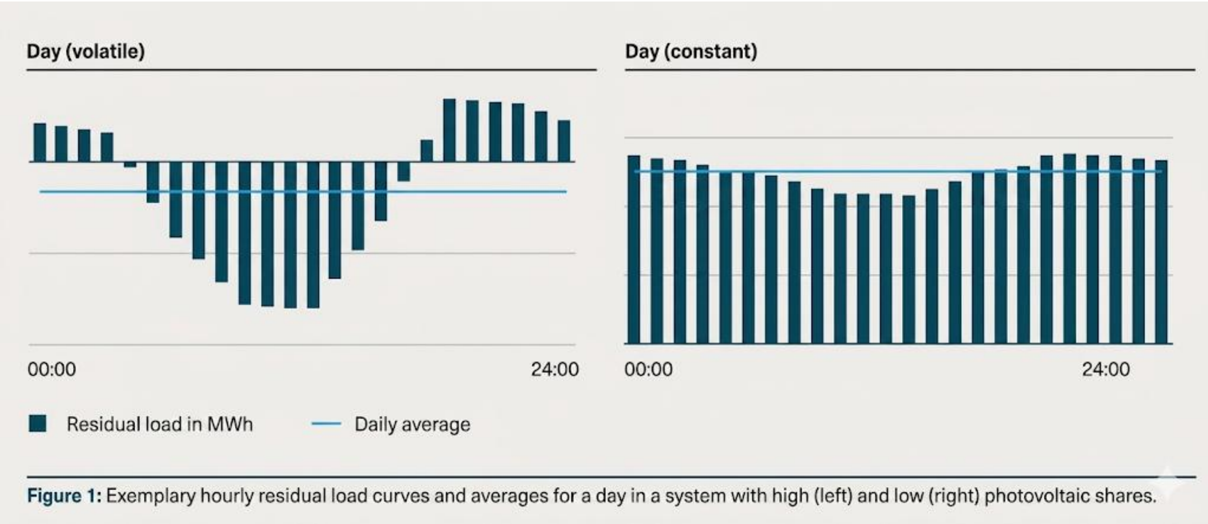

Figure 8: Example hourly residual load curves and averages for one day in a system with high (left) and low (right) photovoltaic share (AI translation with the model Nano Banana 2 from Google Gemini from zusammen2040 by APG).

The study identifies a pronounced increase in flexibility requirements in the future energy system. In particular, intraday shifting demand, i.e. the amount of energy that must be shifted within a single day, is projected to increase by approximately a factor of six by 2040, rising from 6.8 TWh in 2024 to around 41 TWh in 2040. Seasonal shifting demand also increases significantly, doubling over the period under consideration. This development highlights the growing importance of storage and flexibility options in a renewable energy system, with both intraday and seasonal flexibility becoming increasingly critical.

To address this issue, the study identifies several complementary flexibility options:

- Battery storage systems emerge as a key component for short-term and decentralized flexibility. By 2040, a total installed capacity of 8.7 GW is envisaged, comprising 2.7 GW of large-scale battery systems and approximately 6 GW of decentralized small-scale battery storage. The expansion of battery storage is strongly correlated with the rollout of photovoltaic capacity. With an average of around 300 charging cycles per year, these systems play a crucial role in daily load management.
- Pumped-storage hydropower plants gain increasing importance as a versatile flexibility option, particularly for medium-term and seasonal storage. Installed capacity for this technology is expected to increase by around 3.5 GW by 2040, making a substantial contribution to overall system stability.
- Thermal power plants remain relevant, especially for covering peak loads and ensuring security of supply. However, their role changes fundamentally: operation increasingly relies on climate-neutral energy carriers such as biogas, synthetic methane or hydrogen. Existing gas-fired power plants are gradually converted to hydrogen-ready ("H_2-ready") operation by 2040.

- Sector coupling, particularly through hydrogen electrolysis, enables flexible integration of the electricity and hydrogen systems. Electrolysis capacity is projected to increase to around 3.4 GW by 2040 and is primarily located in wind-rich regions in eastern Austria. This allows surplus renewable electricity to be utilized and stored efficiently.

In addition to the baseline scenario, the study analyses alternative framework conditions:

- In the extreme weather year scenario, prolonged periods of low renewable generation with high electricity demand (Dunkelflauten) and dry spells are simulated. Despite these more challenging conditions, security of supply is maintained through the interaction of storage systems, thermal power plants, imports and demand-side management measures.

- The "Reduced Electricity Transport" scenario assumes constrained grid expansion. This results in significantly higher electricity costs, averaging around 13 Euro/MWh, corresponding to annual additional costs of up to 1.6 billion euros. At the same time, regions are increasingly forced to rely on self-supply. Under these conditions, pumped-storage hydropower plants can be used less efficiently, while large-scale battery storage systems gain importance.

Focusing on regional allocation of battery storage, the study distinguishes between centralized large-scale battery storage and decentralized small-scale battery systems in households and the commercial sector. Regional analysis is conducted both at the level of the federal provinces and at district level (NUTS-3).

The deployment of decentralized, small-scale battery storage is progressing dynamically. Installed capacity increases from approximately 3.7 GW in 2030 to around 6 GW in 2040, representing a growth of 62%. A pronounced east–west gradient is evident, largely driven by the more rapid expansion of photovoltaic capacity in eastern Austria. Particularly strong growth in household battery storage is observed in northern Burgenland and the Vienna metropolitan area. Commercial battery storage, by contrast, is primarily concentrated in urban agglomerations such as Linz, Wels, Graz and Vienna.

Installed capacity of large-scale battery storage increases from 1.375 GW in 2030 to approximately 2.685 GW in 2040, nearly doubling over the period considered. Site selection is primarily determined by grid connection availability. Consequently, no further fine-grained spatial differentiation within the federal provinces is undertaken.

Beyond the specific expansion pathways, the study provides several fundamental system-level insights:

- System-wide price signals: Dynamic electricity pricing that adequately reflects spatial and temporal scarcity is considered a necessary precondition for prosumers, industry and flexible consumers (e.g. battery electric vehicles, power-to-heat, electrolysers) to adjust their operating behaviour to system needs and for the modelled flexibility potentials to be realised in practice.

- Smart charging of electric vehicles: Time-optimised charging or discharging can reduce demand peaks and provide additional flexibility to the electricity system.

- Residential battery storage: These systems not only optimise self-consumption but also reduce feed-in peaks and grid draw, thereby alleviating pressure on distribution networks.

- Grid expansion: Ambitious grid expansion is a key prerequisite for the successful integration of renewable energy sources and for limiting overall energy costs. Insufficient grid development, by contrast, leads to substantial additional costs and inefficient regional supply structures.

3.4. Analysis and Conclusion

⇒ Electricity demand in 2040: The *ÖNIP, Austria's Electricity Strategy and the Flexibility and Storage Requirements in the Austrian Energy System* assume a substantially increased electricity consumption compared with today. Both the *Electricity Strategy 2040* and the *Flexibility and Storage Requirements in the Austrian Energy System* study project a doubling of demand to approximately 120-125 TWh. The ÖNIP arrives at a qualitatively similar conclusion, justified by full decarbonization and electrification, but uses its own quantitative framework developed by the Austrian Environment Agency.

⇒ Generation capacities: The *Electricity Strategy 2040* assumes around 45 GW of combined wind and PV capacity, producing 72.5 TWh of electricity. In contrast, the explicit *ÖNIP* scenario assumes a system dominated more by PV, with approximately 41 GW of PV and 12 GW of wind capacity. The *Flexibility and Storage Requirements in the Austrian Energy System* study builds on this approach by providing a detailed quantification of the resulting flexibility and storage requirements.

⇒ Battery storage: The *Electricity Strategy 2040* envisages an expansion of battery storage to over 3.6 GW, whereas the *Flexibility and Storage Requirements in the Austrian Energy System* study models a total battery capacity of 8.7 GW in the baseline scenario, including decentralized storage. This makes the latter scenario significantly more ambitious, explicitly incorporating the small-scale storage level.

⇒ Flexibility requirements: All three studies identify flexibility as a central system parameter. The *Flexibility and Storage Requirements in the Austrian Energy System* study provides the most detailed quantitative estimate, with 41 TWh of intraday shifting demand projected for 2040. The *Electricity Strategy 2040* emphasizes residual load peaks of ±15-25 GW nowadays, while the *ÖNIP* primarily situates flexibility in connection with grid expansion and sector coupling.

4. Use Cases

Chapter 4 presents and discusses different use cases relevant to the studied energy technologies and system requirements.

4.1. Use Case: Battery Storage as a Solution for Grid Bottlenecks between Eastern and Western Austria

Austria's energy landscape is characterized by significant regional differences: While the south and east of the country have large capacities of wind and photovoltaic systems, the west side has high capacities of pumped hydro storages. However, this geographical distribution creates a structural challenge: transmission grids between east and west are limited. During periods of high wind, the generated energy cannot be fully transported to other regions. The result is curtailment of wind turbines, which not only leads to welfare losses but also hinders the integration of renewable energy.

Congestion management is essential to avoid grid system failure. In some locations this is not a problem today, but it will be in the future when more wind turbines are installed. Within the framework of "Modellierung der Stromstrategie 2040", an expansion of about 30 gigawatts of wind turbine capacity and roughly 15 gigawatts of photovoltaic capacity are projected. At the same time, grid operators face the regulatory task of ensuring supply security while promoting the expansion of renewable energy.

A promising strategy is investing in large-scale battery storage near wind farms or photovoltaic systems in the east or south. As described in Chapter 2, by 2040 there will be batteries with a total capacity of 3.6 gigawatts. These storage facilities could also be financed with capital from western Austria. The concept is simple: During grid bottlenecks, excess wind energy is stored and later fed into the grid once grid capacity becomes available. The same holds for excess energy from photovoltaic systems. Technically, this requires storage systems with high capacity in the GWh range and fast charging and discharging capabilities.

The use of battery storage reduces curtailments and increases the share of renewable energy in the grid. At the same time, it relieves transmission lines and contributes to grid stability. Economically, operators benefit from arbitrage effects: Electricity is stored when prices are low and sold later at higher prices. Additional revenues come from guarantees of origin. Ecologically, the solution reduces CO_2 emissions, as wind turbines and photovoltaic systems achieve more full-load hours.

Battery storage is key to the efficient use of renewable energy in Austria. It enables better integration of wind and photovoltaic power, enhances supply security, and creates economic and ecological benefits. Thus, it makes an important contribution to the energy transition and the stability of Austria's power grid.

4.2. Use Case: Long-Term Storage and Seasonal Balancing through H2

Within the ZusammEn2040 initiative, the Austrian Power Grid (APG) investigates how Austria can achieve a climate-neutral energy system by 2040. A central challenge is the seasonal storage of renewable electricity.

As wind and solar generation fluctuate heavily throughout the year, the system requires storage technologies capable of bridging weeks to months, a task conventional batteries or pumped storage can not solve alone.

Excess electricity from photovoltaic and wind plants is transformed into green hydrogen (H_2) via electrolysis. This hydrogen is stored in underground caverns or pressurized tanks and later converted back into electricity during periods of low renewable production, or used in other sectors such as industry, heating, or mobility. The result is a flexible, carbon-free system that can buffer seasonal gaps between summer surplus and winter scarcity.

According to the study Modellierung Stromstrategie 2040, the assumed electrolyser capacity is around 5.1 GW, with approximately 5 TWh of hydrogen reserved for security of supply (Oesterreichs Energie 2024). The study Perspektiven der Sektorkopplung reports similar values around 4 GW Power-to-Gas capacity and app. 1.9 TWh of annual hydrogen production. TU Graz estimates a round-trip efficiency of roughly 35% for the hydrogen chain (electrolysis, H2storage reonversion via fuel cell).

This equals roughly 1% (0.7 TWh) of Austria's yearly electricity consumption, enough to cover about 5% of winter demand during a typical low-generation month. Electrolysers would operate only a few hundred hours per year during renewable surplus periods.

There are plenty of benefits which can be named in this regard. First of all, hydrogen contributes to security of supply as it´s storage bridges winter "dark doldrums." Furthermore, it serves as grid relieving element, due to the fact that electrolysis absorbs surplus electricity and reduces curtailment. It can also play an important role when it comes to sector coupling, because it links electricity with heat, transport, and industry. Finally, as reducing energy independence becomes essential in modern times, it can also help to reduce dependence on fossil fuel imports.

Low utilization rates, high CAPEX requirements, and grid connection availability make electrolysers economically difficult to operate. Seasonal storage requires suitable geologic formations (e.g., RAG's USS 2030 project) that are still under development. With a round-trip efficiency of only approximately 35%, substantial energy is lost, making supportive policies and CO_2 pricing essential. Despite these barriers, hydrogen is considered indispensable for ensuring long-term security of supply in a fully renewable system.

4.3. Use Case: Second-life EV Batteries as BESS Deployment in Austria

The rapid uptake of electric vehicles across Europe, including Austria, is giving rise to a growing stock of used traction batteries that still retain significant technical value at the end of their automotive life. Typically, electric vehicle batteries preserve around 70-80% of their original capacity when retired from mobility applications, a level that is often insufficient for automotive performance requirements but remains well suited for stationary energy storage. In the context of Austria's energy transition and the objectives of the ZusammEn2040 strategy, which foresees a highly renewable, flexible, and resource-efficient energy system, the repurposing of these batteries into stationary battery energy storage systems represents a promising and complementary flexibility option.

Second-life battery energy storage systems offer the possibility of delivering storage capacity at substantially lower cost and with shorter deployment times compared to new batteries.

By reusing existing battery assets, such systems can be rapidly scaled to support the increasing flexibility needs driven by rising shares of variable renewable generation, electrification of end uses, and more dynamic electricity markets. At the same time, they align strongly with the circular economy principles embedded in European and Austrian climate and industrial policy, reducing material intensity and extending the useful life of critical raw materials.

In Austria, the technical and economic feasibility of this concept has been demonstrated through collaborative initiatives such as the “SecondLifeBatteries4Storage” project, involving a consortium of domestic industrial and technology partners. Within this framework, standardized and mobile procedures for assessing battery health have been developed, enabling rapid and manufacturer-independent evaluation of state of health, remaining capacity, and degradation characteristics. On this basis, tailored battery management systems are designed to optimally configure, monitor, and control heterogeneous battery modules. The resulting storage solutions are inherently modular and scalable, ranging from small installations of approximately 100 kWh to utility-scale systems on the order of 100 MWh, and can be deployed across a wide spectrum of applications.

The economic and environmental advantages of second-life battery systems are closely intertwined. Repurposed electric vehicle batteries typically exhibit upfront investment costs that are approximately 30-60% lower than those of new battery systems, significantly improving project economics for certain applications. At the same time, the approach extends the functional lifetime of each battery by an additional five to eight years, extracting further value from the original manufacturing investment. From an environmental standpoint, second-life use delays the recycling of valuable materials such as lithium, cobalt, and nickel, thereby improving resource efficiency and supporting circular material flow. Moreover, by avoiding or postponing the production of new batteries, associated greenhouse gas emissions from energy- and resource-intensive manufacturing processes are reduced, while the integration of renewable electricity is facilitated. The overall effect is a reduction in battery waste generation and a lower environmental footprint of the storage sector.

Apart from these benefits, several challenges must be addressed to enable large-scale deployment. One of the key technical issues lies in the heterogeneity of second-life batteries, which differ in chemistry, design, usage history, and degradation patterns, increasing the complexity of system integration and battery management. Safety considerations are also critical, as aged batteries may present elevated risks of thermal events, necessitating robust system design, monitoring, and compliance with stringent Austrian and European safety and grid connection standards. In addition, the economic viability of second-life storage remains sensitive to market conditions and regulatory frameworks, as revenue streams from ancillary services or arbitrage can fluctuate and may be affected by future changes in storage incentives or recycling obligations.

4.4. Use Case – V2G: Vehicle-to-Grid as a Distributed Flexibility Resource

In a renewable dominated energy system flexibility is critical for balancing fluctuating wind and solar generation. Beyond large-scale storage technologies, millions of electric vehicles (EVs) in Austria represent a large, decentralized energy reservoir that can provide short- and medium-term balancing services. V2G enables EV batteries to not only charge from the grid but also discharge electricity back into it when needed.

V2G relies on bidirectional charging infrastructure, allowing EVs to act as distributed energy storage units. When renewable production is high, vehicles charge. When demand peaks or the system is strained, aggregated EV fleets feed energy back into the grid. Smart charging algorithms ensure that vehicle owners' mobility needs are always prioritized. In the ZusammEn2040 context, V2G supports frequency regulation, congestion management, peak shaving, and improved integration of PV and wind power.

If Austria reaches around 2 million EVs by 2040, consistent with EU Fit-for-55 trajectories, the resulting flexibility potential could amount to several gigawatts through smart charging and other distributed flexibility services. European pilot projects have demonstrated high roundtrip efficiencies for battery-based flexibility solutions, generally outperforming hydrogen-based storage pathways. While ZusammenEn2040 does not define a fixed V2G target, APG highlights distributed flexibility — including EVs — as an important tool for reducing grid congestion and balancing the variability of renewable generation.

There are several benefits which can be listed when it comes to V2C. First, it stabilizes the grid and reduces the peak load. Secondly, it absorbs excess PV during the day and returns it at night, leading to higher renewable utilization overall. And finally, it possibly can lower system costs as it avoids investments in dedicated battery farms by using existing EV batteries.

On the other hand, bidirectional chargers must be widely available, and standards (ISO 15118-20) must be consistently adopted. Also, battery lifetime concerns require smart charging protocols that limit depth of discharge, especially in the early phases. Additionally, regulatory frameworks and market access for small flexibility providers still must evolve effectively to enable V2G participation.

4.5. Use Case: Gravity Storages – A Costly but Promising Solution to Reduce Global Resource Dependence

Solar and wind power only generate electricity when nature cooperates. To maintain grid stability, surplus energy must be stored. Lithium-ion batteries reach their limits here: They are resource-intensive, dependent on raw materials from other regions, and lose capacity over time. Gravity storage, on the other hand, relies on a mechanical principle that is durable and sustainable.

Austria has large pumped-storage capacities, but such plants are not feasible everywhere and face strict regulatory requirements when building it. Gravity storage could be a complementary solution because it is location-independent and ideal for flat regions such as the east and south of Austria. The blocks can be made from recycled materials, reducing the ecological footprint, and the efficiency exceeds 80 percent.

By 2040, Austria could rely on a hybrid storage system, with mechanical storage such as gravity systems playing a major role. Especially in combination with large scale PV installations and wind farms, they offer a way to avoid grid bottlenecks and shift energy over days or even seasons, like pumped hydro storage. Examples show how this technology is already being used worldwide: In Rudong, China, Energy Vault operates a gravity battery with a capacity of 25 megawatts and 100 megawatt-hours.

The technology is still very expensive as described previously and requires space and suitable locations.

Therefore, appropriate funding models are essential nowadays. Gravity storage is not a competitor but a complement to existing solutions. It could help reducing dependence on chemical batteries and thus decrease Austria's reliance on resources from abroad. Whether it becomes widespread depends on economic viability and political will, but its potential would be enormous.

4.6. Use Case: Pumped Storage with Focus on Daily and Seasonal Balance

Austria already occupies a pivotal position within the Alpine power system, effectively acting as a "green battery" for Central Europe. Pumped hydro storage constitutes the backbone of large-scale electricity storage in the country, with an installed capacity of approximately 8-9 GW and further expansion potential identified in national energy scenarios. In the context of the national energy strategy ZusammEn2040, which targets full decarbonization and a high penetration of variable renewable energy sources, primarily solar photovoltaics and wind, the availability of flexible, large-scale storage becomes a critical system requirement.

The increasing share of solar and wind generation introduces pronounced intraday, daily, and multi-day variability that cannot be adequately managed by short-duration battery systems alone. Pumped hydro storage offers a mature, efficient, and technologically proven solution capable of shifting large energy volumes over daily and weekly time horizons. By absorbing surplus renewable generation during periods of excess supply and releasing electricity during demand peaks or extended phases of low wind and solar output, pumped hydro storage contributes decisively to system stability, security of supply, and price convergence within the electricity market.

From a technical perspective, pumped storage operates as a closed-loop energy storage system based on two water reservoirs located at different elevations. During periods of low electricity prices, commonly around midday on sunny days or during windy night-time hours, electric pumps utilize surplus power to transfer water from the lower to the upper reservoir. When electricity demand increases or renewable output declines, the stored water is released through turbines to generate electricity. Modern pumped hydro plants exhibit high operational flexibility, including rapid ramping capabilities, partial-load operation and frequent cycling. Although daily cycling driven by intraday price differentials remains the predominant operational mode, sufficiently large reservoirs also enable weekly balancing or yearly, allowing energy to be stored over several days to bridge extended periods of low renewable generation.

The underlying business case typically assumes an Austrian pumped hydro facility with an installed power capacity in the range of 500 to 1.000 MW and an energy storage capacity between 6 and 30 GWh, depending on reservoir volume. A round-trip efficiency of approximately 70-85% is considered, accounting for both pumping and generation losses. Daily operation is primarily optimized through arbitrage in the day-ahead and intraday markets, with pumping during low-price periods, for instance below 40 €/MWh, and electricity generation during peak price windows, such as those exceeding 80 €/MWh. In addition, weekly balancing operation presumes sufficient reservoir capacity to store energy for three to seven days, enabling dispatch during prolonged renewable shortages or cold winter periods characterized by elevated demand. Participation in ancillary service markets, including frequency control and reserve provision, including FCR, aFRR and mFRR, constitutes an additional and relevant revenue stream for such assets.

From a system perspective, pumped hydro storage delivers multiple benefits. It enables effective grid balancing by smoothing short-term fluctuations in solar and wind generation while also providing the capability for weekly energy management. The combination of high installed power and rapid response supports grid stability, frequency control, and overall system adequacy. Economically, pumped storage facilitates price arbitrage between low- and high-price periods, thereby supporting the integration of volatile renewable generation and stabilizing revenues. At the system level, it contributes to reduced renewable curtailment and complements cross-border electricity trading within the interconnected European market. Furthermore, pumped hydro storage represents a long-term and sustainable infrastructure solution, with operational lifetimes exceeding 70 years and a comparatively low environmental footprint once constructed, making it a strategic asset in a fully decarbonized energy system.

Despite these advantages, several challenges constrain further deployment. New pumped storage projects are often associated with lengthy permitting procedures and complex environmental impact assessments, particularly in sensitive alpine regions. The technology is highly capital-intensive, with significant upfront investments required for civil engineering works and grid connections, necessitating stable long-term market signals or dedicated remuneration mechanisms to ensure bankability. Geographical limitations further restrict expansion, as suitable sites are predominantly located in mountainous areas where competing land and water uses may arise. In addition, interannual hydrological variability can affect reservoir availability and storage performance, introducing an element of uncertainty into long-term operational planning.

4.7. Use Case: Thermal Storage for Austria’s District Heating

Austria’s district heating sector supplies on the order of 20-30 TWh of thermal energy per year, corresponding to approximately 25-30% of the country’s total heat demand. Within the framework of the national energy strategy ZusammEn2040, which aims at full decarbonization and a strong expansion of renewable electricity generation, district heating systems are expected to play a central role. At the same time, they must evolve from relatively rigid supply systems into flexible assets capable of responding to the increasing variability of solar and wind power. In this context, thermal energy storage emerges as a key enabling technology, allowing renewable and low-cost electricity to be converted into heat and stored efficiently for later use.

Advanced thermal energy storage concepts, including molten salt thermal batteries as well as other high-temperature solutions such as phase-change materials and thermochemical storage, are gaining relevance as large-scale and long-duration storage options. When integrated into district heating networks, these technologies can substantially reduce the reliance on fossil-fired backup units, mitigate peak heat demand, and provide an additional degree of freedom for operators to optimize their interaction with electricity markets. Compared to electrochemical storage, thermal storage offers inherently lower costs per unit of stored energy and is particularly well suited for applications where heat, rather than electricity, is the final energy carrier.

From a functional perspective, the system combines power-to-heat technology with a central thermal storage unit. High-capacity electric boilers or large industrial heat pumps convert electricity into thermal energy during periods of low electricity prices, which typically coincide with high solar generation around midday or strong wind conditions.

The generated heat is then stored in a molten salt medium at temperatures typically ranging from 250 to 550°C, depending on the specific storage technology and design. When electricity prices increase again, for instance during morning and evening peak hours, the stored thermal energy is discharged through heat exchangers and supplied to the district heating network. In this configuration, the thermal storage unit acts as a buffer that decouples heat production from short-term electricity market fluctuations. Depending on its size and operational strategy, the system can be optimized for daily cycling or for covering multi-day variations in heat demand and renewable electricity availability.

The underlying techno-economic assessment assumes an Austrian-type district heating system with an annual heat demand in the range of 20-30 TWh and peak winter day requirements of approximately 80-100 GWh. Power2heat units are assumed to operate predominantly during hours at which electricity prices fall within the lower quartile of the day-ahead market. The charging efficiency of the molten salt storage is typically in the order of 90-95%, while thermal losses are assumed to amount to roughly 1-2% per day. Heat is discharged at temperature levels compatible with conventional district heating supply, usually between 80 and 120°C, via appropriate heat exchanger configurations. The storage capacity is dimensioned according to the targeted flexibility service, ranging from 6-12 hours for intraday optimization up to 24-48 hours or more for enhanced system flexibility.

The integration of molten salt and advanced thermal storage into district heating networks offers several system-level advantages. It enables a higher utilization of renewable electricity, reduces curtailment, and significantly lowers fossil fuel consumption during peak heat demand periods. By decoupling heat generation from instantaneous demand, thermal storage improves overall network flexibility and reduces the need for gas-fired peak load boilers. From an economic standpoint, the concept creates a robust arbitrage opportunity, allowing heat to be produced during periods of very low electricity prices and delivered when prices rise. In addition, thermal storage enhances system resilience by providing a buffer during grid constraints or temporary supply disruptions.

Despite its strong potential, the deployment of molten salt and advanced thermal storage systems is associated with several challenges. High-temperature operation requires specialized materials, components, and safety concepts, increasing engineering complexity. Although costs are declining, upfront investment remains substantial and may require dedicated support schemes or stable market incentives, particularly in early deployment phases. Furthermore, the economic performance of such systems is closely linked to electricity price volatility; prolonged periods of low-price spreads can weaken the business case. Finally, operational experience with long-duration thermal energy storage in European district heating systems is still limited.

4.8. Use case: Organic Redox Flow Batteries

By 2040, Austria's electricity system is largely renewable based, with PV and wind complementing hydropower and electricity demand rising to around 145 TWh per year due to electrification. In this system, the main challenge shifts from generation capacity to balancing prolonged periods of renewable surplus and deficit. Organic redox flow batteries (ORFBs) address this challenge by providing large-scale, long-duration, and sustainable electricity storage that complements hydropower and short-duration batteries and supports system stability.

In the 2040 system, ORFBs are installed at strategic grid locations such as renewable generation hubs, industrial demand centers, and transmission – distribution interfaces. Energy is stored in liquid organic electrolytes held in external tanks, while electrochemical stacks determine power output. This decoupling allows storage capacity to be expanded as renewable generation grows. ORFBs absorb renewable surpluses over multiple hours or days and supply electricity during extended low-generation periods, which reduces curtailment and relieves pressure on transmission infrastructure on the other hand.

APG's ZusammEn 2040 scenarios show that long-duration storage becomes essential once variable renewables dominate the system. ORFBs are assumed to provide 8 – 24 hours of storage with high cycle stability and moderate efficiencies, optimized for frequent deep cycling. Their organic electrolytes support long lifetimes and reduce dependence on critical raw materials.

Example Calculation (Illustrative, System Day 2040): A regional ORFB installation supports a high-renewables grid area on a typical summer day:

- Installed power: 10 MW
- Energy capacity: 160 MWh (16 hours: 8 hours PV, 8 hours wind)
- Renewable surplus absorbed: app. 160 MWh
- Energy delivered during evening and night: app. 110 MWh (at 70 % round-trip efficiency)

The installation smooths residual load over the day, reduces PV and wind curtailment and supports secure system operation during renewable lulls.

In a 2040 context, ORFBs bridge the gap between short-term balancing and seasonal storage. They enable higher renewable penetration without excessive grid expansion, improve system resilience, and offer a scalable storage option that grows with the energy system. Their safety characteristics allow deployment close to both generation and demand.

The system role of ORFBs depends on further technological maturation, proven long-term electrolyte stability, and integration into energy system planning. Effective coordination with hydropower operation, grid development and demand-side flexibility is essential to fully realize their potential.

4.9. Use Case: Virtual Batteries for Energy Communities

Virtual batteries represent a key innovation for enabling energy communities to operate efficiently in an increasingly decentralized and renewable-based energy system. Instead of relying on a single, large, physical storage device, a virtual battery aggregates the flexibility of many distributed assets into one coordinated system. Through intelligent forecasting and optimization algorithms, these diverse units collectively behave like a unified storage resource: they charge when excess renewable energy is available and prices are cheap by storing energy, and they discharge in periods of scarcity and prices are high. For energy communities, this means that locally generated electricity, particularly from rooftop photovoltaic installations, can be used more effectively, self-consumption can be raised, and grid interactions can be reduced. Even without installing additional physical storage, the community gains through smarter coordination.

Moreover, virtual batteries create meaningful opportunities for people living in urban apartments to participate directly in the energy transition, even if they do not have access to private rooftop photovoltaics or dedicated onsite storage.

Instead of requiring individual assets, the virtual aggregation of flexible household technologies, such as controllable appliances, thermal storage devices, or electric vehicle charging, allows apartment residents to contribute to and benefit from a shared flexibility pool. In this way, not only a single building, but entire clusters of residential units become part of a coordinated virtual storage system that responds collectively to system conditions. This inclusive approach reflects the insights of the ZusammEn2040 initiative, which highlights the essential role of distributed household level flexibility across all settlement types, including densely populated urban areas, in ensuring the cost-efficient integration of renewables and maintaining system stability.

In the Austrian context, the importance of such decentralized flexibility becomes particularly clear when viewed the ZusammEn2040 initiative of Austrian Power Grid. This initiative constructs a high-resolution digital twin of the Austrian and European energy system, integrating regional renewable potentials, technological developments, demand projections, and cross sectoral energy flows. Its modelling results show that the electrification of heating, mobility, and parts of industry, together with the rapid expansion of photovoltaic and wind generation, will significantly increase both temporal variability and spatial heterogeneity in electricity flows. As a result, the system will require far more flexible resources to maintain stability, avoid peak loads, and enable economically optimal operation. Virtual batteries directly address these needs by providing a distributed flexibility mechanism that can be activated at the local level while still contributing to system level efficiency.

Within this framework, virtual batteries can help mitigate some of the most critical challenges identified in the ZusammEn2040 modelling. For example, in regions with high PV penetration, midday generation peaks often exceed local demand, leading to curtailment or increased stress on distribution grids. A virtual battery absorbs these peaks by shifting consumption to times of excess generation, preventing unnecessary feedin and reducing the need for network reinforcement. In the evening, when demand rises and renewable production declines, the same coordinated assets reduce their consumption or activate previously stored energy, thus smoothing the load profile. This aligns with the modelling insight that flexibility from household level and community level technologies, such as heat pumps, thermal storage, and electric vehicles, is essential for the cost-efficient integration of renewables and for maintaining security of supply. Virtual batteries also enhance resilience by making energy communities more independent from short-term fluctuations and reducing exposure to high market prices during peak demand periods.

Another key connection lies in sector coupling, which is central to the future Austrian energy system as envisioned in ZusammEn2040. Heat pumps, powertoheat applications, and electric mobility are not only major drivers of future electricity demand but also significant sources of controllable flexibility. Virtual batteries orchestrate these sectors coupled technologies so that they operate synergistically: thermal storage can absorb renewable surpluses, electric vehicle charging can be shifted to optimal times, and commercial or industrial loads can adapt to system conditions without compromising service quality. In this role, virtual batteries become both an operational tool for local energy optimization and a structural element supporting the broader system transition that ZusammEn2040 outlines.

Overall, virtual batteries allow energy communities to actively participate in the energy transition by unlocking latent flexibility, improving the integration of renewable generation, and contributing to the stability and cost efficiency of the national electricity system. They translate the high-level modelling insights of ZusammEn2040 into practical, on the ground solutions that empower communities while supporting Austria’s path toward a climate neutral, resilient, and intelligently coordinated energy future.

5. Conclusions and Recommendations

This chapter synthesizes the key findings of the PESTEL analysis and assesses their implications for the energy storage sector in Austria. By integrating political, economic, social, technological, environmental and legal perspectives, it highlights the main opportunities and challenges shaping the development of energy storage technologies and markets.

Based on these findings, chapter 4 presents targeted recommendations to support Austria's alignment with European developments, strengthen competitiveness, and enable a sustainable energy transition. It summarizes the main PESTEL insights, discusses their implications for Austria and outlines prioritized recommendations.

5.1. Political Perspective

From a political perspective, the successful integration of energy storage into Austria's 2040 power system requires a stable and a well-coordinated policy framework that strengthens resilience on the one hand, while preserving market dynamics on the other hand. In light of increasing geopolitical uncertainties, establishing secure and diversified supply chains for key energy technologies becomes not only a necessary, but even more a strategic priority. Therefore, critical components of storage and flexibility technologies should increasingly be developed and manufactured within Europe to reduce external dependencies and to be less exposed to geoeconomic disruptions.

At the same time, regulatory processes must be streamlined to accelerate the deployment of storage and renewable technologies. However, accelerated deployment must follow coordinated and system-oriented growth pathways. Uncoordinated expansion of individual technologies, such as excessive photovoltaic capacity without corresponding flexibility, can lead to system imbalances, including extreme price fluctuations (e.g., negative prices), ultimately increasing overall system costs and reducing efficiency. In this context, the government should act as a coordinating entity that defines clear strategic direction and system boundaries, while maintaining sufficient entrepreneurial freedom for market participants. Still, a more pragmatic and accelerated approach is needed to build-out infrastructure. Global geopolitical disruptions (lethal conflicts around certain bottlenecks or just trade wars) conflicts are affecting energy imports in an unprecedented way and impose significant economic costs.

5.2. Economic Perspective

From an economic perspective, the effective integration of storage into Austria's future energy system depends critically on undistorted and transparent price signals across the entire value chain. Wholesale electricity price signals should be consistently passed through to all consumers, enabling flexibility to be activated where and when it provides the highest system value. Only if consumers and aggregators are exposed to real-time scarcity and surplus signals, storage assets across residential, commercial, industrial applications operate system-optimal. Broad or prolonged price interventions at the retail or wholesale level weaken these signals, reduce incentives for demand response and storage operation, and ultimately distort the development of viable use cases. Such interventions risk misallocating capital, delaying innovation, and skewing the expansion paths of competing storage and flexibility technologies in ways that are not system-optimal. At the same time, a purely laissez-faire approach is insufficient where technologies are system-relevant in the long run but not yet market-competitive.

In such cases a coordinating role of the state is justified, not to replace market mechanisms, but to guide them. This includes ensuring that growth trajectories of different storage technologies evolve in a coordinated and system-friendly order, aligned with renewable generation expansion, grid development, and sector coupling needs. The role of the state can thus be described as follows: setting clear rules, allowing prices to guide day-to-day decisions, while correcting structural gaps that the market alone cannot efficiently address.

Therefore, another recommendation is to expand the wholesale price signals to all relevant consumer and flexibility segments through dynamic tariffs, time-variable network tariffs and market-based flexibility products. Price caps, subsidies and set prices should be avoided wherever possible, as they undermine the economic rationale for storage use cases and lead to inefficient technology selection. Flexibility should earn its value in the market by responding to real system conditions rather than regulatory interventions. Where specific storage technologies are not yet economically viable but are required for future system stability, security of supply, or decarbonization objectives, targeted and temporary public support is desired. Such support should be explicitly time-limited, technology-specific only where necessary and designed to phase out automatically once economic viability is reached. Conversely, if a technology does not demonstrate a credible future system need it should neither be shielded from market signals nor supported through subsidies. This approach ensures that public funds are used efficiently, preserves market-driven innovation, and enables a cost-effective transformation of the Austrian energy system toward 2040.

5.3. Socio-cultural Perspective

From a socio-cultural perspective, the success of Austria's energy transition depends not only on technical feasibility and cost efficiency, but also on perceived legitimacy and fairness at the local level. While representative surveys indicate generally high public support for renewable energy projects local resistance remains a relevant constraint. Opposition tends to emerge where projects are perceived as externally imposed, where landscape and land-use impacts are concentrated locally, or where affected stakeholders have limited influence over planning decisions. Consistent with energy justice research, procedural, distributive, and recognition of justice, as well as trust in developers and public authorities, are key determinants of social acceptance. These factors shape the "social licence to operate" for infrastructure such as wind farms, grid expansions, and energy storage assets. Within Austria's multi-level governance system, municipalities play a central role as intermediaries, influencing local narratives, mediating conflicts, and affecting permitting and implementation outcomes.

To address these socio-cultural challenges, Austria should systematically integrate participation and local value creation into energy storage and renewable deployment strategies. Early-stage co-design processes, rather than one-way information provision, can strengthen procedural justice and reduce conflict. Standardized benefit-sharing mechanisms, such as municipal revenues, community funds, or local electricity price reductions, can improve perceived fairness by linking projects to tangible local benefits. Furthermore, existing frameworks for energy communities (EAG, ElWOG) should be leveraged to expand participatory ownership models, enabling citizens, small and medium sized enterprises (SMEs), and municipalities to jointly generate and store energy.

Complementary financial participation schemes, such as equity shares or project-based bonds, can help retain regional value creation and stabilize long-term acceptance. Finally, transparent communication through trusted local intermediaries remains essential to build credibility and minimize implementation risks.

5.4. Technological Perspective

From a technological perspective, current discussions are strongly centered on battery storage in combination with photovoltaics or wind farms, driven by declining costs and rapid deployment. Battery systems are highly effective for short-term flexibility, including intraday balancing, peak shaving and decentralized optimization. However, their technical characteristics limit their role in addressing seasonal storage needs. Pumped hydro storage, a traditional pillar of Austria’s energy system, is currently being expanded mainly through capacity uprating and efficiency improvements rather than the construction of new large reservoirs. While this strengthens short-term system services, it does not substantially increase stored energy volumes, which are essential for shifting renewable energy from summer to winter. Thermal storage in district heating systems can contribute to flexibility by storing surplus energy over days to several weeks, thereby reducing short-term mismatches between supply and demand and supporting system integration of renewables. However, such systems do not provide true seasonal storage across multiple months at large energy volumes. Hydrogen was long regarded as the technological option for seasonal energy storage, but has recently lost momentum due to efficiency losses, high costs, and slow market development. Nevertheless, some form of long-term energy storage remains indispensable for managing seasonal imbalances. Technologically, this implies that Austria will require a complementary portfolio of storage technologies, clearly differentiating between short-term flexibility and long-term energy shifting.

Based on these technological considerations, it is recommended that storage policy in Austria explicitly distinguishes between short-term flexibility technologies and long-term or seasonal storage solutions. Batteries should continue to be deployed through market-driven mechanisms, as they already respond effectively to price signals and local optimization incentives. However, system planning should avoid the assumption that battery storage alone can solve all challenges. For seasonal balancing, policy frameworks should prioritize technologies that can deliver large energy volumes at low cost per stored megawatt-hour, such as pumped hydro with expanded storage capacity and thermal storage integrated into district heating networks. Hydrogen-based solutions should be supported selectively and, in a technology-neutral manner. Importantly, technological support mechanisms should remain conditional on demonstrated system value and phased out once alternatives become more efficient. A coordinated, technology-neutral approach ensures that Austria retains the ability to shift energy from summer to winter while avoiding premature commitments to technologies that may not deliver long-term system benefits.

5.5. Ecological Perspective

From an ecological perspective, energy storage in Austria must be assessed through a system-wide and lifecycle-based approach.

Environmental impacts differ significantly across technologies and occur at all stages of the lifecycle, including resource extraction, infrastructure development, operation, and end-of-life management. Electrochemical batteries, while highly efficient and essential for short-term flexibility, are associated with upstream environmental burdens related to critical raw materials such as lithium, cobalt, and nickel. In contrast, mechanical storage technologies, including pumped storage hydropower, gravity storage, and flywheels, offer long lifetimes and low operational emissions but can involve land use, ecological disruption, and construction-related impacts, particularly in sensitive environments. For long-duration storage, hydrogen provides a key option for seasonal balancing, yet its ecological performance depends on renewable electricity input and is affected by conversion losses across the value chain. Thermal energy storage, particularly in district heating systems, represents a comparatively resource-efficient solution where it enables the use of surplus renewable energy or waste heat. Additional technologies such as compressed air energy storage and organic flow batteries further diversify the environmental profile, with varying trade-offs related to material use, infrastructure requirements, and technological maturity. Overall, no storage technology is environmentally neutral. The central challenge for Austria is therefore to allocate technologies according to their system function, ensuring that each application is served by the solution with the lowest total environmental impact.

Therefore, Austria should establish lifecycle-based environmental assessment as a central guiding principle for energy storage policy, planning, and investment decisions. Given the fundamentally different environmental profiles of storage technologies, deployment strategies should be clearly aligned with specific system functions, ensuring that short-term, medium-term, and seasonal flexibility needs are covered by the most environmentally appropriate solutions. To achieve this, policy frameworks should systematically integrate comprehensive environmental criteria into permitting, public support schemes, and infrastructure planning. These criteria should include lifecycle greenhouse gas emissions, land use, biodiversity impacts, water consumption, and material criticality, as well as the potential for reuse and recycling. In parallel, circular economy approaches, including second-life applications, design-for-reuse, and high-quality recycling, should be strengthened to reduce resource dependency and overall environmental pressure. Furthermore, environmental impacts should be minimized by prioritizing system integration and optimization of existing infrastructure, such as upgrading current hydropower assets, integrating storage into district heating systems, and utilizing brownfield locations where feasible. This approach reduces land use, limits ecosystem disruption, and enables faster deployment of storage capacity. Overall, Austria should pursue a technology-neutral but impact-oriented policy approach, ensuring that each storage application is matched with the solution that delivers the required system service with the lowest total environmental footprint. Such a portfolio-based strategy enables the expansion of storage capacity in line with climate targets while safeguarding ecological integrity and strengthening long-term system resilience.

5.6. Legal Perspective

From a legal perspective, the effective integration of energy storage into Austria's 2040 energy system depends on a coherent and forward-looking regulatory framework aligned with evolving EU legislation. In particular, recent initiatives such as the Renewable Energy Directive (RED III), the Electricity Market Design Reform, and the Clean Energy Package provide an important foundation for integrating storage as a key flexibility asset.

However, national implementation must ensure that storage is clearly defined and consistently treated across all regulatory domains, avoiding ambiguity between its roles as generation, consumption, or network asset.

A key priority is to eliminate regulatory barriers that hinder the deployment and operation of storage systems. This includes addressing issues such as double charging of grid fees, unclear tariff structures, and limited access to multiple revenue streams. In line with EU internal market rules, storage assets should be enabled to participate fully and non-discriminatorily in all relevant markets. Furthermore, permitting procedures must be significantly streamlined to meet the accelerated timelines required by the energy transition. The implementation of RED III provisions on "go-to areas" and simplified permitting for renewable and related infrastructure should be extended to storage technologies where appropriate. Reducing administrative complexity while maintaining environmental and legal safeguards is essential to unlock timely investments. At the same time, state aid frameworks, particularly under the EU Climate, Energy and Environmental Aid Guidelines (CEEAG) should be used in a targeted and proportionate manner to support system-relevant storage technologies that are not yet commercially viable. Such support must remain in technology-neutral where possible, time-limited, and designed to phase out as market competitiveness is achieved, to preserve market integrity. Finally, strong alignment with European network codes, cross-border market integration rules, and evolving flexibility of market designs is essential. A harmonized legal framework across Member States reduces regulatory uncertainty, facilitates cross-border investments, and ensures that storage contributes efficiently to system stability, security of supply, and decarbonization objectives within an integrated European energy market.

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