ENERGY STORAGE AND ENERGY EFFICIENCY AS THE KEY ENABLERS OF GREATER USE OF RENEWABLE ENERGY IN ELECTRICITY CONSUMPTION

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Contents

Introduction 5

Chapter 1 11

Overview of energy storage technologies and the technology maturity concepts 11

1.1 Roles for storage in electricity systems 13

1.2 Smart grids as enabling technology 16

1.3 Technology maturity 18

1.4 Methodology 18

1.5 Future-oriented Technology Analysis (FTA) 22

Chapter 2 25

Energy storage technologies - the state of art 25

2.1 Mechanical energy storage 27

2.2 Thermal energy storage 33

2.3 Electrochemical storage 39

2.4 Chemical energy storage 52

Chapter 3 64

Energy efficiency and other enabling technologies for greater renewables integration into the grid 64

3.1 Available technologies and pathways for buildings decarbonization 69

3.2 Electrification 71

3.3 Building Energy Efficiency 73

3.4 Sector Coupling 77

3.4 Barriers and Challenges to Overcome for Sector Coupling 81

Conclusions 83

EXECUTIVE SUMMARY:

Renewable energy sources and increased energy efficiency are essential to achieve European Union's climate neutrality by 2050. There has been fast progress in the deployment of renewable energy technologies, several of which are now well established including solar (thermal and PV), hydro and wind technologies. However, recent developments in electric vehicle technology and policy targets in many countries may mean that renewables play a more indirect role in transport. Many future scenarios forecast a rapid expansion of electric (and sometimes hydrogen) vehicles, which could increase demand for renewables to generate clean electricity or hydrogen (UNCTAD, 2019)[1].

There is an increasing emphasis on the technical and economic challenges of integrating larger share of renewables into the electricity grid. Power grid operators must come up with innovative solutions to manage renewable capacity and adopt smart systems to balance supply and demand in the most efficient way possible. The optimal share of fluctuating renewable energy sources in the energy mix depends on various factors. The flexibility of the grid, the back-up capacity, the quality and capacity of the transmission system are some of the challenges. New approaches and enabling technologies are needed to go along with these new generating technologies in order to ensure the grid resilience. These technologies share the potential to facilitate and advance the deployment and use of renewable energy. The list of these enabling technologies is not complete but cover end-use technologies (EVs), energy storage and demand-side energy management technologies (e.g. energy management systems in the buildings). Multiple sources of flexibility are now available, including demand-side response programs, interconnectors, conventional generation and storage. One implication is that further increases in renewable electricity from variable technologies will partly depend on progress with developing and deploying these forms of flexibility.

With the increase in innovation and deployment of different renewable energy sources, there have been improvements in the utilization of these energy sources. Some of these improvements include integration of electric vehicles into the power grid, enabling digital technologies in energy systems and developments in electricity storage technologies.There has been minimal linkage between the transportation and electric power sectors until recently (IEA, 2017)[2]. Integration into smart infrastructures, such as vehicle-to-grid integration, is an emerging technology with a lot of potential[3]. There is growing interest in developing vehicle-to-grid systems that provide systems with a bi-directional electricity flow between a vehicle and the power grid. There is possibility of using electric vehicles as storage devices, with the potential of selling electricity back to the grid during peak demand while the vehicles are not being used.

There is an important potential for convergence of electricity systems with digital and information technologies. Such technologies may have a crucial role in enabling a system in which demands can flexibly respond to the conditions of the grid. Smart power grids can match

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[1] United Nations Conference on Trade and Development (2019). "The role of science, technology and innovation in promoting renewble energy by 2030". UNCTAD, United Nations, Geneva, 2019.

[2] International Energy Agency (2017). "Vehicle-grid Integration: A Global Overview of Opportunities and Issues". OECD/IEA.

[3] Vehicle-to-grid (V2G) describes a system in which plug-in vehicles (PEV) sell demand response service to the grid.

and integrate intermittent sources of electricity such as solar and wind power. This technology accompanied by advanced grid management systems enable smooth integration of renewable energy sources into existing power grids, optimizing distribution and minimizing wastage Digital technologies are also relevant to buildings which account for more than 50 percent of electricity demand. Technological innovations are transforming buildings into active participants in the energy ecosystem. Smart buildings, equipped with sensors, energy management systems and internet-connected devices can optimize energy consumption, monitor and control renewable energy generation, and even participate in demand response programs.

Energy storage systems play a critical role in mitigating the fluctuation by storing the excess generated power and then making it accessible on demand. Today, there exist multiple storage technologies and solutions that are able to compensate for the intermittent nature of variable renewable sources, namely electrochemical-, electrical-, thermal-, and chemical energy storage. Recent years have also seen advances in a range of storage technologies, including new chemistries for lithium-ion batteries with the aim to improve performance and reduce dependence on elements with constrained supply chain. In addition, new approaches to thermal storage for electricity and chemical storage (e.g. the production and storage of hydrogen that can be used to generate electrity) can complement the existing technologies. Taking into consideration all these developments, battery deployment will need to scale-up significantly between now and the end of the decade to enable achieve the agreed energy and climate goals. Therefore, there is also a need for advances in other types of heat or energy storage that can operate over longer timespan (IRENA, 2017)[4].

Renewables can play a larger role in primary energy supply when the delivery of energy services is more efficient. As the renewables share increases in the energy mix, less primary energy is required for provision of the same level of energy services. Consequently, distributed renewable energy coupled with energy efficiency improvements reduces peak electricity demand while simultaneously minimizing transmission losses and bottlenecks. As shown in recent analysis by the International Energy Agency (IEA) renewable energy investments allow efficient buildings to be powered more easily, especially when these renewables are not grid-connected (IEA, 2017)[5]. Efficent buildings combined with on-site renewable energy generation reduce end-use demand, grid congestion and losses, as well as fuel transportation costs.

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[4] IRENA (2017). “Electricity storage and renewables: costs and markets to 2030”.

[5] International Energy Agency (2017). “Renewables 2017: Analysis and Forecasts to 2022”. OECD/IEA.

Introduction

As Europe accelerates its ambition to achieve climate neutrality by 2050[6], the electricity sector particularly, is making great efforts in reducing greenhouse gas emissions by replacing fossil fuel generation with renewable sources of energy. Governments and cities have introduced regulations and incentives to accelerate the shift to sustainable mobility. Transport currently accounts for more than a quarter of the European Union's greenhouse gas emissions and this figure continues to rise as demand grows and other sectors reduce their emissions. Several key actions are put forward at the European Union level to facilitate the uptake of clean vehicles and alternative fuels, to promote a shift to more sustainable transport modes[7]. Regulators worldwide are defining more stringent emissions targets. The European Union presented its *„Fit for 55"* program, which seeks to align climate, energy, land use, transport, and taxation policies to reduce net greenhouse gas emissions by at least 55% by 2030. Decarbonization of the energy system will require a massive transformation in the way energy is generated, transported and used. As more and more countries respond to climate change and announce their commitments to Net Zero[8], supporting mechanisms and measures continue to increase. Photovoltaic and wind technologies play a key role in the shift towards green growth, a low-carbon economy, and a greater share of renewables in the energy mix.

Renewable generation is often variable, increasing grid volatility and decreasing system inertia when it comes from distributed sources (e.g. solar and wind energy). New approaches and enabling technologies are needed to go along with these new generating technologies to ensure the grid resilience. Overall, enabling technologies comprise both the physical infrastructure and the automation technology required to support, for example greater systems integration, data collection and dissemination of system resources, as well as effective and efficient demand response. This can also enhance the function and efficiency of energy systems and thereby facilitate greater deployment and use of renewable energy. These technologies present significant opportunities to bring additional benefits by creating new venues for renewable energy in buildings, industry and transportation sectors.

Enhanced environmental responsibility and the fact that fossil fuels are limited induce alternative mobility concepts like electro-mobility[9] and carbon dioxide reduction in terms of lowering fuel consumption. From a European perspective, electro-mobility has been identified as a crucial element of the shifting process to low-carbon transportation, which represents almost 25% of the European Union greenhouse emissions. For example, electrification of vehicles not only reduces local air pollution, but also allows rapidly growing renewable power technologies to replace fossil fuels in a sector where renewables, except biofuels were barred

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[6] The European Commission has adopted a set of proposals to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. See also European Commission (2021). „Delivering the European Green Deal: On the path to a climate-neutral Europe by 2050".

[7] Such as rail and inland waterways, combining various transport modes through a journey –and cycling, walking and public transport in urban areas.

[8] Net Zero – a target of completely negating the amount of greenhouse gases produced by human activity, to be achieved by reducing emissions and implementing methods of absorbing carbon dioxide from the atmosphere.

[9] E-mobility is the principle of using electric propulsion for a wide range of transportation types.

from entry. New concepts for energy storage have to be developed and integrated into the car structure (Burstein & Leal-Arcas, 2023)[10].

Electrical energy storage is now becoming the integral part of the power generation infrastructure. This technology is highly required to balance supply and demand. However, when both demand and supply are continously fluctuating, the grid faces several problems in managing the power generation and distribution according to the demand. The grid balance can also be achieved through the use of different storage technologies that absorb energy and store it for a period of time before releasing it to supply energy or power services. Many analysts confirm that by 2040, 40 terawatt –hours (TWh) would be required[11].

An energy storage system will enable *smart grid concepts*, which is one of the encouraging technologies in the future. Eliminating the fluctuations related with power production, energy storage systems might facilitate the integration of renewable energy systems. The rapid growth and high penetration of digitalization has caused profound changes in energy sector[12]. It reduces energy consumption, decreases energy intensity and optimizes energy infrastructure. The mediating effect suggests that digitalization has a significant indirect impact on energy by promoting technological innovation. Intelligent power networks, or smart grids[13], are urgently required to integrate the growing number of distributed energy sources and generators into the energy system. They coordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders to operate all parts of the system as efficiently as possible.

For decades, electricity needs have been adequately met by traditional national grid model, which is conceptually quite simple. A small number of large-scale fossil fuel- or sometimes nuclear – power stations deliver power over long distances to where it is needed: homes, commercial- and retail premises, factories, hospitals, schools, and many other environments. Typically, a distinction is made between transmission (*transmission grid: high and extra high voltage*) and distribution (distribution grid: *lower voltage*), where different wiring and cabling systems come in the picture. The purpose of an electrical grid is to make sure that electricity is always provided when and where needed, without interruption – and herein lie many challenges, where a smart grid can already offer solutions/answers.

The future electricity system needs to become much more flexible than it is at present to accommodate the rising share of renewables. The need for flexible high-capacity energy storage in the power system will grow as renewable energy consumption rises over 80% (Kaushik et al., 2022)[14]. Flexibility in power systems refers to its ability to ensure a supply-demand balance, maintaining continuity in unpredictable scenarios. Weather variations contribute to the intermittent nature of electricity generation from some type of renewable

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[10] B.Burstein, R.Leal-Arcas (2023). “Energy decentralization and energy transition in Slovakia”. Chapter 24.5 Electric mobility. In *Electricity Decentralization in the European Union* (Second Edition), 2023.

[11] International Renewable Energy Agency (2017). “Electricity Storage and Renewables: Costs and markets to 2030”, IRENA, 2017.

[12] With the wave of information revolution, digitalization refers to a series of economic activities that use information and knowledge as key production factors.

[13] Smart grids is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users.

[14] E.Kaushik, V.Prakash, O.P.Mahela, B.Khan, A.El-Shahat, A.Y.Abdelaziz (2022). “Comprehensive Overview of Power Systems Flexibility during the Scenario of High Penetration of Renewable Energy in Utility Grid”. In *Energies* **2022**, 15, 516.

sources, such as solar and wind energies. With the increasing integration of unpredictable renewable sources into the power grid, the challenge has grown in importance and complexity. In this effort, grid-scale energy storage is recognized as an imperative component of the energy transition, with both International Energy Agency (IEA) and World Energy Forum (WEC) estimating that meeting global energy targets will require a world energy storage capacity in excess of 250 GW by 2030[15].

Energy storage is a process of converting the electrical energy to another storable form and then converting the stored energy to electricity during the time of need. In order to cope with the intermittency of renewable energy sources and to ensure a proper balance between energy generation and demand, energy storage systems (ESSs) are regarded as the most realistic and effective choice, which has great potential to optimize energy management and control energy wastage. These systems can be classified based upon their specific function, speed of response, duration of storage, and form of energy stored. Existing definitions generally compare energy storage systems according to size and discharging duration (AFRY, 2022)[16]. The categories of short, medium and long duration storage are separated by overlapping boundaries, which are influenced by factors such as a technology's capabilities, energy system needs and market arrangements as seen in Figure 1.

Figure 1. Adapted from the study "Renewable Energy Storage Roadmap" by Australia National Science Agency, March 2023.

Storage type	Duration
Short	Storage less than 4 hours
Medium	Storage between 4 and 12 hours
Long intraday	Storage between >12 and 24 hours
Long multiday	Storage between >24 and 100 hours
Seasonal	Storage more than 100 hours

Short duration storage technologies are suited to discharging energy over a 0-4 hour output timeframe. Batteries (mainly lithium-ion) have been successfully developed for example in the United Kingdom to provide services for the electricity system over seconds, minutes and hours (usually one or two at most)[17]. Medium duration storage assets are designed to help balance daily discrepancies between electrical supply and demand (4-12 hours), and multiday variation in wind generation (12-200 hours). Long duration options (over 200 hours) could store energy over weeks, months, seasons and years. These help to balance inter-seasonal variation in heating and cooling demand and address system resilience challenges in the power sector, such as wind droughts or interconnector failure (electricity supply connections between grids. Long duration storage will need to be deployed at the larger grid scale to address these challenges.

In order to have a more comprehensive overview of energy storage technologies, it is important to categorize different types of energy storage systems based on their formation and

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[15] World Energy Council (2016). "Energy Storage: Shifting from cost to value – wind and solar applications". See also International Energy Agency (2019). "Tracking energy integration".

[16] AFRY (2022). "Benefits of Long Duration Electricity Storage: A Report to BEIS". See also P. Denholm et al. (2021). "The Challenge of Defining Long-Duration Energy Storage", p.1-23.

[17] National Grid ESO (2022). "Future Energy Scenarios: July 2022", pp. 1-237.

composition materials. These systems may be divided into 5 main categories such as chemical, electrochemical, electrical, mechanical, and thermal storage. These technologies can be implemented on large and small scales in distributed and centralized manners through the energy system. While some technologies are mature or near maturity, most are still in the early stages of development and will require additional attention before their potential can be fully realized. Next generation storage technologies need to keep pace with rapidly rising demand, which is projected to double as building and transport industries electrify; address the challenge of diverse geographical and end use contexts. The complications associated with the uncertainty surrounding energy market design, infrastructure availability, and technology costs are the other aspects to consider.

Due to the large variety of available energy storage systems with various applications, numerous authors have reviewed ESSs from various angles in the literature. However, the types of energy storage systems addressed in the reviews are often limited. Some assessments, for example, focus solely on electrical energy storage systems, without mentioning thermal or chemical storage systems at all. There are only a few reviews in the literature that cover all the major ESSs. Luo et al[18] provided an overview of several electrical energy storage technologies as well as detailed comparison based on technical and economic data. The efficiency of the system mainly depends upon the identification and implementation of the right system based on the parameters such as storage capacity, cost, reliability, size and lifetime.

Based on the estimates of the European Association for Storage of Energy (EASE, 2022)[19], energy storage power capacity requirements at EU level will be approximately 200 GW by 2030. This is focusing on energy shifting technologies and including existing storage capacity of approximately 60 GW in Europe, mainly pumped hydro energy storage. Unlike many other forms of energy storage and generation, batteries are particularly valuable because they provide flexibility. Based on the IEA's recent report (2024)[20] „*Batteries and Secure Energy Transitions*" the energy sector accounts for 90% of overall battery demand. In 2023 alone, battery deployment in the power sector increased by more than 130% year-on-year basis, adding a total of 42 gigawatts to electricity systems globally. By 2050, it is estimated at least 600 GW of energy storage will be needed in the energy system. This is based on the needs in terms of bi-directional contribution from Power-to-X solutions (i.e. for energy shifting), estimated approximately around 435 GW[21].

Governments and private utilities globally have been working on energy storage technologies for a long time. The United States of America has positioned large-scale energy storage technology as an important supporting technology to revitalize the economy, realize the new Deal for Energy, and ensure national energy and resource security. Large-capacity energy storage technology has been listed as the highest priority demand technology in the Grid

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[18] X.Luo, J.Wang, M.Dooner et al (2015). "Overview of current development in electrical energy storage technologies and the application potential in power system operation". In *Applied Energy* **137** (2015), pp. 511-536

[19] EASE (2022). "Energy Storage Targets 2030 and 2050. Ensuring Europe's Energy Security in a Renewable Energy System".

[20] International Energy Agency (2024). "Batteries and Secure Energy Transitions". IEA/OECD, Paris.

[21] Power-to-X means converting power into something else. For example, power can be converted via electrolysis into hydrogen, which can be used directly or in combination with other elements for production of fuels or chemicals.

2030 plan (Reihani et al., 2016)[22]. Similarily, Japan has also positioned energy storage as a safeguard technology for its nuclear energy post-abandonment strategy (after the Fukushima nuclear meltdown) and promoted the application of the energy storage market through subsidies (Li et al., 2018)[23]. Additionally, Europe has over time supported energy storage technology as a strategic new industry in the energy sector (Geth et al., 2015)[24]. China does not yet have a specific policy or large-scale use of energy storage (O'Meara, 2020)[25]. However, it is critical period of energy and economic development transformation, as the proportion of renewable energy in increasing, which has an increasingly significant impact on grid reliability, grid peaking, and unit energy efficiency, thus energy storage will have a great market demand and necessity.

However, energy storage is used not only in extensive energy systems, but also in the automotive industy (electric vehicles), military industry (radio communication, drones), emergency systems (lighting) and in consumer devices (power tools, laptops, smartphones, etc)[26]. Storage of renewable energy is essential to ensure access to secure, reliable and affordable energy as countries transition to net zero. The effectiveness of energy storage facility is determined by how quickly it can react to changes in demand, the rate of energy lost in the storage process, its overall capacity, and how quickly it can be recharged.

As extreme weather exacerbated by climate change continues to devastate infrastructures in many countries, government officials have become increasingly mindful of the importance of grid resilience. Energy storage helps provide resilience since it can serve as a backup energy supply when power plant generation is interrupted. For example, in the case of Puerto Rico, USA, where there is minimal energy storage and grid flexibility, it took approximately a year for electricity to be restored to all residents (U.S. Department of Energy)[27]. The international Energy Agency (IEA) estimates that, in order to keep global warming below 2 degrees Celsius, the world needs 266 GW of energy storage by 2030, up from 176.5 GW in 2017[28]. Under current trends, Bloomberg New Energy Finance forecasts that the global energy storage market will hit that target, and grow quickly to a cumulative 942 GW by 2040 (representing 620 billion USD in investment over the next two decade)[29].

The research methodology of this study uses a synthesis of review articles and industry interviews. Several studies have addressed the technical and economic aspects of energy storage technologies. Most of these studies reviewed the technical characteristics, the sizing of various energy storage systems, and challenges related to their applications. These studies help

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[22] E.Reihani, S.Sepasi, L.R.Roose, M.Matsuura (2016). "Energy management at the distribution grid using a Battery Energy Storage System (BESS). In *International Journal of Electrical Power & Energy Systems* **2016,** 17, pp. 337-344.

[23] Y.Li, W.Gao, Y.Ruan (2020). "Performance investigation of grid-connected residential PV-battery system focusing on enhancing self-consumption and peak shaving in Kyushu. Japan". In *Renewable Energy* **2018**, 127, pp.514-523.

[24] F.Geth, T.Brijs, J.Kathan, J.Driesen, R.Belmans (2015). "An overview of large-scale stationary electricity storage plants in Europe: Current status and new developments". In *Renewable Sustainable Energy Review* **2015**, 52, pp.1212-1227.

[25] S. O'Meara. "China's plan to cut coal and boost green growth". In *Nature* **2020,** 584, S1-S3.

[26] Olabi et al (2022). "Battery energy storage systems and SWOT (strengths, weakness, opportunities, and threats) analysis of batteries in power transmission. In *Energy* **2022**, 254, 123987.

[27] "Energy Storage: The Key to a Reliable Clean Energy Supply". U.S. Department of Energy.

[28] International Energy Agency. "Energy Storage Tracking Clean Energy Process".

[29] "Energy Storage is a 620 Billion USD Investment Opportunity to 2040". Bloomberg New Energy Finance.

to realize technical properties, such as efficiency, energy and power densities, depth of discharge to determine the size of energy storage technologies for renewable sources like solar and wind (Rahman et al., 2020)[30]. Another source of information is secondary articles related to innovations in the power sector. The main goal of the study is to introduce different options for technology maturity assessment. This is very important as many energy storage technologies at this point are near maturity, which means that different pilot projects are necessary for technologies' improvements.

The study "*Energy storage and energy efficiency as the key enablers of greater use of renewable energy in electricity consumption*" consists of three chapters and its structure is the following. **Chapter 1** provides an overview of energy storage technologies and the technology maturity framework. **Chapter 2** is dedicated to energy storage technologies and gives its state of the art. **Chapter 3** addresses energy efficiency and smart grids as the key enabling technologies for integrating bigger share of renewable sources of energy into the grid.

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[30] M.M.Rahman, A.O.Uni, E.Gemechu, A.Kumar (2020). "Assessment of energy storage technologies: A review". In *Energy Conversion and Management*, Volume 223, 1 November 2020.

Chapter 1

Overview of energy storage technologies and the technology maturity concepts

Meeting greenhouse gas (GHG) emission reduction targets will require multidimensional approach to decarbonizing all GHG-contributing sectors. Net emissions of carbon dioxide (CO_2) by human activities - including not only energy services and industrial production but also land use and agriculture – must approach zero in order to stabilize global mean temperature. Governments all over the world have introduced a variety of international, regional and national targets and timetables for climate change mitigation for achieving net zero CO_2 emissions from 2035 to 2050 and beyond. Indeed, international climate targets, such as avoiding more than 2 degrees Celsius of mean warming are likely to require an energy system with net-zero (or net-negative) emissions later this century (Rogel et al., 2015)[31].

Achieving very low economy-wide CO_2 emissions will require all sectors to achieve significant reductions of emissions. Energy services, such as heating, cooling and lighting may be relatively easy to decarbonize by electrification and renewable energy generation. On the other hand, the other sectors such as aviation, long-distance transport, shipping and production of carbon-intensive materials (e.g. steel and cement) are relatively difficult to decarbonize. Since fossil fuels mainly in the form of coal and coke, are used in conventional steelmaking in considerable quantities, shifting to non-fossil fuels is an important step for decarbonization. Hydrogen is one way for steel industry to decarbonize. In this process, fossil fuels, such as coal, are replaced with green hydrogen that is produced from renewable energy and water. In Europe, there are already several projects – Hybrit and H_2 Greensteel for example that aim to replace fossil fuels with green hydrogen, while in the USA, Massachusetts Institute of Technology (MIT) is developing direct electrolysis from iron ore. In both cases, the electricity used would be renewable sources, ensuring sustainability and zero emissions during the process (Iberdola, 2024)[32].

A successful transition to a future net-zero emissions energy system is likely to depend on large amounts of inexpensive, emissions free electricity, as well as mechanisms to quickly and cheaply balance large and uncertain time-varying differences beween demand and electricity generation. Most studies conclude that the path to very low economy-wide emissions involves decarbonizing the power sector and replacing decarbonized electricity for fossil fuels as much as possible in transportation, industry, and buildings (MIT, 2022)[33].

Decarbonization of power systems typically involves two strategies: (1) improving the energy efficiency of the existing system and (2) replacing carbon-intensive generation sources with low- or zero-carbon generation sources such as renewables, nuclear, and power plants

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[31] J.Rogel et al. (2015). “Zero emission targets as long-term global goals for climate protection”. In *Environmental Research Letters* **10,** 105007. See also S.Davis, N.S. Lewis, M.Shaner et al (2018) “Net-zero emissions energy systems”. Review, University of California, Berkeley.

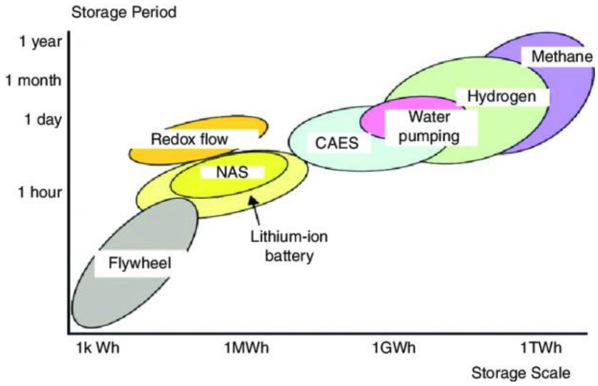
[32] Iberdola (2024). “Green steel: a material ready for industrial decarbonization and widening the horizons of electrification”. R&D, Green hydrogen.

[33] Massachusetts Institute of Technology (2022). “The Future of Energy Storage. An interdisciplinary Study”. MIT Energy Initiative, June 3, 2022.

with carbon capture and storage (CCS). The electricity grid is a complex system in which power supply and demand must be equal at any given moment. Historically, supply has been adjusted to meet changes in demand, from the daily pattern of human activity to unexpected changes such as equipment overloads, wildfires, storms, and other extreme weather events (Jafari et al., 2022)[34]. Therefore, the key challenge of integrating increasing share of renewables into the power system, is to balance the supply and demand together with low-carbon flexible generation technologies and transmission network expansion.

Reliable electricity could also be achieved through energy storage technologies that play an important role in this balancing process and helps to create a more flexible and reliable grid system. Electricity storage can provide a source of reserve power, as well as absorb excess electricity. These capabilities are crucial for balancing the grid and ensuring that frequency remains within a stable operating range of 50 Hertz, as well as providing other ancillary services.

Figure 2. Schematic illustration of various energy storage technologies



Source: Adapted from the article “Hydrogen technologies and developments in Japan” by Ida & Sakata (2018)[35].

Increasing penetrations of intermittent renewable energy sources (e.g. photovoltaics and wind energy) have increased the need for energy storage technologies to accommodate daily periods of overgeneration and peak loads. Electric energy storage is definitely not a new topic. The initial application of pumped hydroelectricity storage occurred in the late 19th century in Europe and in 2020 pumped hydro storage still accounted for around 99% of total grid-scale electricity capacity globally[36]. Global recognition of the need to mitigate damages from the climate change by dramatically reducing economy-wide emissions of greenhouse gases, most importantly carbon dioxide (CO_2), is the main cause of increased interest and investment in energy storage.

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[34] M.Jafari, A.Botterud, A.Sakti (2022). “Decarbonizing power systems: A critical review of the role of energy storage”. In *Renewable and Sustainable Energy Reviews*, Volume 158, April 2022.

[35] S.Iida and K.Sakata (2018). “Perspective: Hydrogen technologies and developments in Japan”. In *Clean Energy*, 2018, pp. 1-9.

[36] International Energy Agency (2021). “Pumped storage hydropower storage capability by countries, 2020-2026”. IEA, 01 December 2021.

Previous studies have suggested that the decreasing costs of batteries and associated technologies may enable battery systems to meet the short-term needs of the grid with high penetrations of intermittent renewable energy systems. Large scale renewable energy storage is a relatively young technology that has rapidly grown with an increasingly global demand for more energy from sources that reduce the economies' contribution to greenhouse gas emissions. While several forms of energy storage are commercially available, new long-term and short-term storage concepts are continually being developed and improved upon to decrease capital costs and increase energy conversion efficiencies. However, recent studies have shown that long-duration energy storage (days to months) will be needed to accommodate 100% renewable (or carbon-free) energy generation. Consequently, long-duration energy storage will be needed to increase the security and resilience of the electrical grid in the face of increasing natural disasters and intentional threats.

Electrification of the energy mix is both a need and reality. Produced from low-carbon energy sources, it helps reduce the dependence on fossil fuels. According to the IEA's Net Zero Emissions by 2050 scenario, the share of electricity in total final energy consumption must increase from around 20% in 2022 to over 27% by 2030. This volume growth comes together with not only new uses (in particularly for electric vehicles) but also new modes of production (carbon-free). However, carbon-free electricity production comes with great variability, both in terms of demand and production sources. For example, in France in 2019, wind power fluctuated between 46.7 GW and 0.4 GW and solar power 1.3 GW and 33.6 GW. The capacity to store energy partly conditions the energy transition's success[37].

Rapid growth of energy storage technologies has been accompanied by cost reductions globally. Simultaneously, the penetration of variable renewable energy resources has grown; the cost of lithium-ion (Li-ion) batteries has declined rapidly. The cost declines of lithium-ion batteries are largely due to their development and use outside the electricity system, particularly in electric vehicles (EVs). Recent years have also seen advances in a range of storage technologies, including new chemistries for lithium-ion batteries that aim to improve performance and reduce dependence on elements with constrained supply chains. In addition, new approaches to thermal storage for electricity and chemical storage (e.g. via the production and storage of hydrogen that can be used for generating electricity). Therefore, the study looks at potential benefits from similar cross-sector couplings for two other storage technologies: thermal energy storage and hydrogen storage.

1.1 Roles for storage in electricity systems

Energy storage services can be classified in four categories: energy arbitrage, ancillary services, transmission and distribution infrastructure services, and customer energy management services. This section provides definitions and examples of services that can be provided by storage (based on the definitions used by the IEA's *Technology Roadmap: Energy*

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[37] International Energy Agency (2023). "Global Energy and Climate Model: Net Zero Emissions by 2050 Scenario (NZE) ".

Storage (2014)[38]). In reality, a single energy storage technology or several storage technologies may support multiple services.

The easiest way to optimize energy round trip efficiency[39] is **energy arbitrage**. It is about buying electricity when prices are low and using (or selling it) when rates are the highest. The goal of energy arbitrage is to optimize the use of energy assets, such as generation facilities, storage systems, or demand response programs in order to maximize financial returns. Battery technology has evolved rapidly in recent decades as innovations like lithium-ion batteries, such as those used in electric cars, and emerging solid-state batteries become more affordable and more common. Battery storage systems, such as lithium-ion batteries or flow batteries, are increasingly used for energy arbitrage purposes. Demand response programs enable energy consumers to adjust their electricity consumption in response to price signals or grid conditions. By participating in demand response initiatives, consumers can leverage energy arbitrage opportunities to reduce their energy costs and earn incentives by curtailing or shifting their electricity usage during peak periods. The speed at which batteries can deploy and absorb electricity makes them useful grid assets. However, every very large battery setups can only discharge power for around two hours. If, for example, the wind dropped off for a long period the grid needs a longer duration supply of stored power (Drax, 2022)[40].

Lithium-ion batteries, are currently dominant storage technology for large scale plants to help electricity grid ensure a reliable supply of renewable energy due to their cost-effectiveness and high efficiency. Battery pack prices have fallen fast, down 89% since 2010, according to the estimates of the research compnay BloombergNEF (BNEF), making their deployment increasingly cost effective. In California, batteries are being installed to replace gas-fired power plants to provide power when the grid is under strain. In Australia, massive batteries are being built at the sites of soon-to-close or shuttered fossil fuel power plants.

At remote sites, energy storage can provide energy security and reduce on-site fuel consumption. The battery maker Saft offers an energy storage system that can be shipped by road or sea in 20 feet standardized containers that includes the heating, ventilation, and air conditioning (HVAC) system, air ducting, fan, and control room. In the desert of Western Australia, Saft commissioned a 13MW/4MWh energy storage system in May 2020 as part of Australia’s largest renewable energy microgrid. The system that powers the Agnew gold mine, includes 4 MW of solar, 18 MW of wind, and 21 MW of gas and diesel-fired generation (Energy Monitor, 2021)[41].

Energy storage assets that provide **ancillary services** to the bulk power system deliver power for short durations but require faster response times (from less than a second to minutes). Ancillary services refer to functions that help grid operators maintain a reliable electricity system. This type of services maintain the proper flow and direction of electricity, address imbalances between supply and demand, and help the system recover after a power system event. In systems with significant variable renewable energy penetration, additional ancillary

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[38] International Energy Agency (2014). “Technology Roadmap: Energy Storage”. IEA.

[39] Round-trip efficiency (RTE) is the ratio of the energy output to the energy input of an energy storage system over a complete charge-discharge cycle. It measures how much energy is retained or lost by the energy storage system during the storage process.

[40] Drax. “Storage solutions: 3 way energy storage can get the grid to net zero”, 28 February 2022.

[41] J.Gerdes (2021). “The role of battery storage in the energy transition”. In *Energy Monitor,* Newsletter, 07 April 2021.

services may be required to manage increased variability and uncertainty. There are two broad categories of ancillary services: (1) Frequency related[42] and (2) Non-Frequency related (e.g. reactive power and voltage control and congestion management. Ancillary services can include synchronized regulation, contingency reserves, black-start regulation and flexibility reserves.

Frequency regulation is the use of storage to dampen fluctuations caused by momentary differences between power generation and load demand. This is often performed automatically on a minute-to-minute, or shorter basis. Frequency regulation services aim is to maintain the frequency of a grid by continously balancing demand and supply. In North America this frequency is 60 Hertz, in Europe and many other parts of the world it is 50 Hertz. The frequency is kept at 50 Hz by having electricity supply and demand and trying to plan by predicting how much supply and demand exists. If necessary, adjustments can be made. This can be done by either increasing demand, supply or utilizing batteries to work in both directions. It is crucial as deviations of 0.2 Hz above or below 50 Hz (in Europe) may lead to blackouts. However, if there are still deviations from the balance after planning, balancing services can be purchased to restore the balance. There are four main methods to regulate a grid's frequency:

(1) **Generation control**: generation can be adjusted to maintain the grid's balance. In case the frequency is too low, generation is increased or the other way around if the frequency is too high (generation is reduced);
(2) **Demand response**: demand can be adjusted to maintain the grid's frequency. Demand response requires demand-side flexibility, i.e consumers that can be controlled to reduce (i.e load shedding) on inrease their demand;
(3) **Energy storage**: energy storage can adjust both, demand and supply. If more supply is needed storage is discharged. If more demand is needed storage is charged;
(4) **Balancing energy**: In some countries, balancing energy is obtained via a market-based on an auction to reduce the costs. In Europe, balancing energy is divided into three options. First, Frequency Containment Reserve (reaction time is less than 30 seconds). secondly, Automatic Frequency Restoration Reserve (less than 5 minutes) and thirdly, Manual Frequency Restoration Reserve (less than 15 minutes).

Voltage support is the provision or absorption of reactive power to the grid to maintain acceptable voltage. Transmission and distribution operators must inject appropriate amounts of reactive power into the grid due to resistive losses along transmission and distribution lines and due to consumption of reactive power by consumers. Voltage support is required on the bulk electric system so that acceptable voltage is provided at each distribution substation connecting to the transmission system. It is also required on the distribution system so that the distribution utility can maintain acceptable voltage to customers.

Black start capability refers to a power station's ability to restart without relying on the transmission network in the event of a wide-area power system collapse. This entails isolated power stations being started individually and gradually reconnected to one another to form an interconnected system again. It is used when the grid experiences a blackout and must be restarted from scratch. As such, black start is a critical resource for maintaining the

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[42] Inertia, Frequency Containment Reserve (FCR), and Automatic Frequency Restauration Reserve (aFRR).

reliability and resilience of the electric power system and is central to system restoration and recovery plans for system operators.

In large power grids, black-start service comes from generators that can be started from an on-site auxiliary generator – without help from external power supplies. Microgrids can provide local reliability and resilience through local generation[43]. Microgrids insulate local customers from the effects of outages on the larger grid and can be used to start a system from the bottom up. Microgrids that are connected to one another and the larger grid need to be able to switch to „*island*“ mode seamlessly to insulate themselves during widespread disruptions such as blackouts and cyberattacks (NREL, 2024)[44].

The transition of the energy and transportation sectors toward a higher share of renewable energies leads to a growing number of volatile electricity producers. This forces the Transmission System Operators (TSOs) to frequently make use of **flexibility reserves.** On the other hand, this also leads to an increasing number of flexible producers and consumers in the household sector (also referred to as „microsystems“). They can also participate in the flexibility markets. For this purpose, the individual flexibility potentials of the microsystems Photovoltaic (PV), Battery Storage Systems (BSS), heat supply (heat pump and electrical heating elements) and Electric Vehicles (EVs) have been identified to average flexibility profiles (Dörre el, 2021)[45]. The abovementioned authors investigated the future flexibility potential of Germany’s household sector, in particular for single-family and twin homes in 2025 and 2030 with the assumption that households primarily optimize their self-consumption. The results indicated that the household sector can contribute considerably to system stabilization with an average potential of 30 GW negative and 3 GW positive flexibility in 2025. In 2030, the relevant flexibilities potentially increase to 90 GW and 30 GW respectively. This indicates that considerable flexibility reserves could be provided by single-family and twin homes in future.

1.2 Smart grids as enabling technology

In the energy sector, digitalization is playing an important role in the smart electric grid. Intelligent power networks, or smart grids[46], are urgently required to integrate the growing number of distributed energy sources and generators into the energy system. Smart grid is defined as an intelligent network based on new technologies, sensors and equipment has to manage wide energy resources and to enhance the reliability, efficiency and security of the entire energy value chain (Wang, 2013)[47]. The goal of a *smart grid* is to make the distribution

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[43] A microgrid is a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid.

[44] National Renewable Energy Laboratory (2024). “Grid Modernization: Black Start”, NREL, USA.

[45] E.Dörre, S.Pfaffel, A.Dreher, P.Girón, S.Heising, and K.Wiedemann (2021). „Flexibility Reserve of Self-Consumption Optimized Energy Systems in the Household Sector”. In *Energies,* **2021**, 14 (11), 3017. Frauenhofer Institute for Energy Economics and Energy System Technology, TransnetBW GmbH.

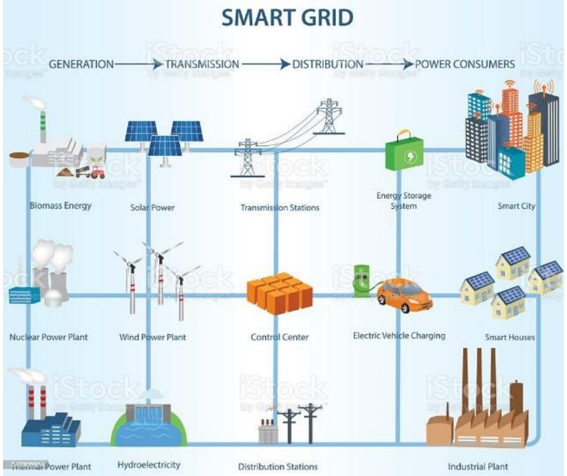
[46] Smart grids is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users.

[47] W.Wang, Z.Lu. “Cyber security in the smart grid: survey and challenges”. In *Computational Networks* 2013, volume 57, pp. 1344-1371.

of electricity more efficient, reliable, and sustainable. As more renewable energy is added to the grid, smart grids will play a greater role in balancing demand and supply of electricity.

Smart grids as a concept – became known over a decade ago and are essential in the digital transformation of the electricity sector. Big data analytics and IoT technologies are important technology drivers in smart grids whereby analytics shift to the edge, as in edge computing. Traditional electricity grids had almost no storage capabilities; they are demand-driven and have a hierarchical structure. The main advantage of smart grids is the ability to better integrate renewable energy resources into the system and supervise energy consumption and production due to bi-directional flow of energy and data between power generation, distribution and consumption. Power generation is the first step in smart grid value chain, it includes power sources such as nuclear, hydropower and renewable and it relies on wide area monitoring and control technologies to communicate with the next step called power distribution. Later, it is based on proximity network that connects consumers with the electricity grid and transmits data using advanced metering infrastructure. Power consumption is the last step on smart grid value chain and it involves the users of electricity, both residential and industrial.

Figure 3. Smart grid concept



Source: iStock, 2016

The world's electricity systems face a number of challenges, including aging infrastructure, continued growth in demand, the integration of increasing numbers of variable renewable energy sources and electric vehicles. *Smart grids* allows for two-way communication between the utility company and the consumer, and it enables the integration of renewable energy sources, such as wind and solar power into the grid. The digital IoT technology that supports two-way communication between the utility and its customers, and the sensing along the transmission lines, makes the grid smart. Like the internet, the smart grid will become an integrated system of controls, computers, automation, analysis, and new technologies and equipment. These technologies will work with the smart electrical grid to respond digitally to quickly changing electric demand. The electricity market, the consumption of electricity, regulations, and demands of various stakeholders and the very production of electricity are all changing. Therefore, smart grid initiatives exist across the globe, albeit sometimes with different approaches and goals.

In 2024, we can expect to see continued growth in the development of smart grids globally. Governments, utilities, and other stakeholders are likely to continue to invest in the development and deployment of these technologies as they become more cost-effective and widely available.

1.3 Technology maturity

The acquisition and development of emerging technologies has demonstrated to be an effective booster for expanding new technological capabilities, strategic options, gaining improved efficiency and responding to the competitive environment (Mortara and Ford, 2012)[48]. Technology can be acquired in a number of ways, understanding the various options available and deciding which might be best in particular circumstances might be challenging.

The technology acquisition is by nature technology transfer, the aim of which is to transform inventions and scientific outcomes into new products and services that benefit society. Technology transfer is a collaborative process that involves data, designs, inventions, materials, technical knowledge or intellectual property. The technology to be acquired typically will require further development. Its level of „maturity“ may range from something that is simply a new scientific phenomenon right through to a technology that is almost market-ready.

Maturity is a stage in the technology life cycle where technology is highly competitive and it can (safely) be integrated into products or processes. The technology life cycle is a model that describes the different stages that a technology goes through from its initial development to its eventual decline. There are typically four stages in the technology lifecycle: the innovation, the growth stage, the maturity stage, and the decline stage. There are various ways of measuring the maturity of a technology.

1.4 Methodology

With significant improvements in energy technology field for the past decades, it is important to include level of technology maturity, as well as priorities in research and development in the domain, when it comes to selecting storage technology for energy systems. Emerging renewable energy technologies face many challenges to get to market, including high up-front capital requirements, long payback periods, regulatory uncertainty, and perceived risks of new solutions.

1.4.1 Technology Readiness Level (TRL) and Commercial Readiness Index

The Technology Readiness Level (TRL) index is a globally accepted benchmarking tool for tracking progress and supporting development of specific technology through the early stages of the technology development chain. In the 1980’s the National Aeronautics and Space

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[48] L.Mortara & S.Ford (2012). “Technology acquisition: a guided approach to technology acquisition and protection decisions”. University of Cambridge, Institute for Manufacturing, Cambridge.

Administration (NASA) released a seven level Technology Readiness Level (TRL) metric to assess the risk related with technology development[49]. By the 1990's this metric had evolved into the nine levels that exist today and has become widely used across NASA as a systematic metric/measurement system to assess the maturity of a particular technology and to allow consistent comparison of maturity between different types of technologies (Sauser et al., 2006)[50]. In 1999, the U.S. Department of Defence (DoD) elaborated a similar TRL concept. While the use of TRL is similar in both NASA and the DoD, there is a slight variation in the interpretation of TRL in these two organizations. For example, NASA specified that technologies should mature until a TRL 6 before a mission can assume responsability for the technology (Shishko et al., 2003)[51] then DoD respectively states that a technology should reach the equivalent of TRL 7 before they are included in a weapons system program (GAO, July 30, 1999)[52].

Figure 4. Technology Readiness Levels

TRL	**Definition**
9	Actual System Proven Through Successful Mission Operations
8	Actual System Completed and Qualified Through Test and Demonstration
7	System Prototype Demonstration in Relevant Environment
6	System/Subsystem Model or Prototype Demonstration in Relevant Environment
5	Component and/or Breadboard Validation in Relevant Environment
4	Component and/or Breadboard Validation in Laboratory Environment
3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept
2	Technology Concept and/or Application Formulated
1	Basic Principles Observed and Reported

Source: Adapted from the conference paper by Saucer et al (2006) "From TRL to SRL: The Concept of Systems Readiness Levels". Conference on Systems Engineering Research, in Los Angeles, CA, Paper 126.

The development of TRL moved beyond its current nine levels (see Figure 4) and entered into a more dynamic metric for assessing technology and has been a part of numerous NASA and DoD focused research efforts. The TRL tracks a product's development from basic scientific discovery, through demonstration in various settings, and ending when the technology is validated at full scale in an operational development. This approach is the most common terminology used by the U.S. federal government to describe technology maturity but its focus on technology rather than market adoption means it is not always the best fit for private sector funders to assess the maturity of a technology.

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[49] The TRL methodology was developed by Stan Sadin with NASA in 1974.

[50] B.Sauser, D.Verma, J.Ramirez-Marquez, R.Gove (2006). "From TRL to SRL: The Concept of Systems Readiness Levels". Conference on Systems Engineering Research, in Los Angeles, CA, Paper 126.

[51] Shishko, Ebbeler, and Fox (2003). "Nasa Technology Assessment Using Real Options Valuation". In *Systems Engineering* 7, No 1 (2003): 1-12.

[52] GAO (1999). "Better Management of Technology Readiness Development Can Improve Weapon System Outcomes". In *The Defence Acquisition System*, edited by United States General Accounting Office: GAO/NSIAD-99-162, July 30, 1999.

Technological readiness level (TRL) and commercial readiness index (CRI) are essential component with regard to the new technologies. Since 1990s it has been applied in various industries to provide a measurement of technology maturity. This concept has also been used in the energy sector. For example, Electricity Supply Board (ESB) and Vattenfall proposed that TRLs should be not only be defined in terms of technology's readiness to convert ocean wave energy and export it to the grid, but also address the project lifecycle requirements such as operational and supply chain readiness, risk and cost reduction (Bertram et al., 2020)[53].The Australian Renewable Energy Agency (ARENA) also uses the TRL index in the Emerging Renewables Program to help applicants in the early stages of technology development identify the stage ofdevelopment of their particular innovation (ARENA)[54].

While the majority of technology risk is retrieved through the TRL 1-9 framework there is often significant commercial uncertainty and risk remaining in the demonstration and deployment phase. New technology and/or entrants entering the market typically supplied by proven incumbents and financed by capital markets that are often risk adverse, face a multi-faceted range of barriers during the commercialization process. This in especially relevant in the context of renewable energy where capital cost and therefore access to capital is a key barrier to accelerating deployment.

Historically, the majority of support for the development of renewable energy technologies has been through the provision of upfront capital grants. Upfront grants can be useful in assisting companies with acquiring funding for their projects, especially where they are small-scale and the state funding covers most of the costs. Although the TRL concept is appropriate to help minimize technological uncertainties, there are often commercial or financial uncertainties characterizing new programs and technologies entering the market. Undestanding the policy and market conditions that enable renewable energy technologies to get to the market – or hinder them from doing so – is necessary for effective policy making. However, beyond technical development, emerging renewable energy technologies need to prove their commercial viability.

This study applies principles in market dynamic analysis and literature review to address driving factors in the energy storage market. Within the framework of product life cycle, the stages of entry, exit, growth and innovation of all energy storage types are examined (Klepper, 1996)[55]. The technology maturity curve as seen in Figure 5 is depicted by assessing two parameters for each storage technology: technology readiness level (TRL) and stage of market development. The TRLs are a type of measurement system used to assess the maturity level of a particular technology. There are nine TRLs, where TRL 1 is the lowest and TRL 9 is the highest (European Commission 2014)[56]. Based on the description of the levels, the TRL of each storage technology is recognized by investigating different reviews on energy storage

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[53] D.V.Bertram, A.H.Tariqhaleslami, M.R.Walmsley, M.J.Atkins, G.D.E. Glasgow (2020). "A systematic approach for selecting suitable wave energy converters for potential wave energy farm sites". In *Renewable and Sustainable Energy Reviews*, Volume **132**, October 2020.

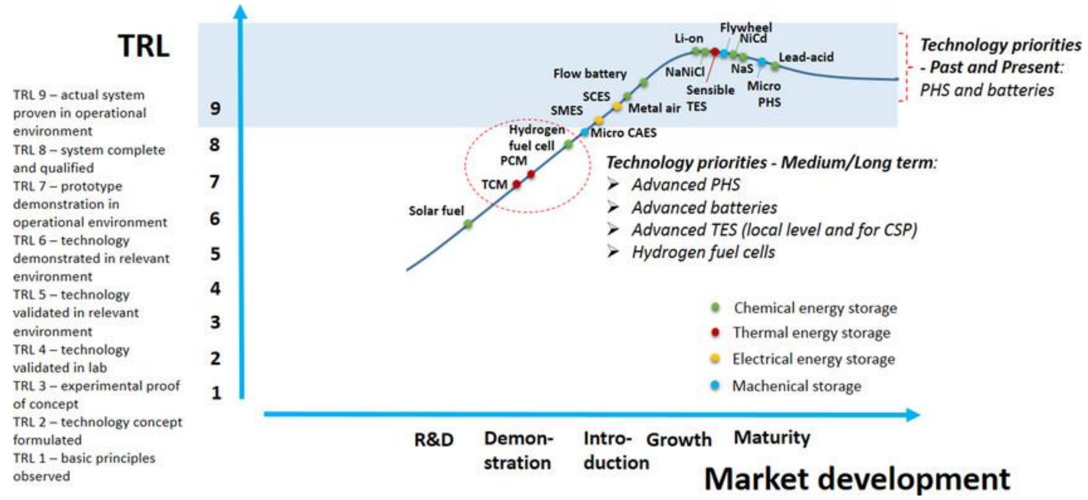
[54] Australian Renewable Energy Agency. "Emerging Renewable Program use of TRL".

[55] Klepper, S. (1996). "Entry, exit, growth, and innovation over the product life cycle". In *American Economic, Review* **86**, 562.

[56] European Commission (2014). "Horizon 2020 – Work Program 2014-2015 General Annexes G – Technology Readiness Levels (2014).

technologies where the current state of technology development is marked; in case there are several references, the more recently released one is chosen.

Figure 5. Technology maturity curve of energy storage technologies for small scale energy systems



Source: Adapted from the article „A Review on technological maturity of small-scale energy storage technologies“ by T.T Ngyen et al (2017) in *Renewable Energy and Environmental Sustainability*, 2, 36 (2017).

Another accepted process that can be used for benchmarking the commercial maturity of new technologies is the commercial readiness index (CRI). The CRI was developed by the Australian Renewable Energy Agency (ARENA) to evaluate the commercial readiness level of renewable energy technologies. The CRI begins once the technology is at the stage where there is research to prove that it is feasible in the field (TRL 2). The CRI extends to when the technology or application is being commercially deployed and has become a bankable asset class.

Figure 6. CRI

6	Bankable asset class
5	Market competition. Driving widespread development
4	Multiple Commecial Applications
3	Commercial Scale Up
2	Commercial Trial, small scale
1	Hypothetical Commercial Proposition

Source: Australian Renewable Energy Agency. “Emerging Renewable Program use of TRL”.

Indicators

Status Summary Level	**Descriptions**
6	**“Bankable” grade asset class** driven by same criteria as other mature energy technologies. Considered as a “Bankable” grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake
5	**Market competition driving widespread deployment** in context of long-term policy settings. Competition emerging across all areas of

	supply chain with commoditization of key components and financial products occurring.
4	**Multiple commercial applications** becoming evident locally although still subsidized. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support.
3	**Commercial scale up** occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publicly discoverable data driving emerging interest from finance and regulatory sectors.
2	**Commercial trial:** Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.
1	**Hypothetical commercial proposition.** Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims.

1.5 Future-oriented Technology Analysis (FTA)

The FTA term was first used in 2004 in the title of the seminar on *New Horizons and Challenges for Future-Orienated Technology Analysis: New Technology Foresight, Forecasting and Assessment* organized by the Institute for Prospective Technological Studies (IPTS). The FTA concept was defined as the so-called „umbrella“ that covered a number of different methods of technology analysis in the field of technology foresight, technology forecasting and technology assessment (Cagnine et al., 2008)[57]. It helps decision-makers to anticipate and deal with transformations. The following sections will examine the most notable FTA methods regarding technology maturity assessment. Over time, FTA started to be treated as a kind of future management concept.

1.5.1 Technology Forecasting

Technology forecasting methods were an early attempt to assess technology maturity. Due to the increasing importance of technology, the analysis and forecasting of technology trends and futures becomes more important. Despite the fact that precise predictions are impossible, technology forecasting provides useful insights that are urgently needed. Its goal has been to determine the most feasible alternatives in technology development (Roper et al., 2011)[58]. The technology forecasting methods have been divided into 5 blocks: (1) environmental scanning; (2) expert opinion, (3) trend analysis and statistical methods; (4) modeling and simulation; (5) scenarios and roadmapping. These methods are ideal when evaluating one technology against other. However, they fall when assessing the overall level of risk that comes with it. As new methods were developed, attempts were made to overcome

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[57] C.Cagnin, M.Keenan, R.Johnston, F.Scapolo, R.Barre (2008). “Future-oriented technology analysis: strategic intelligence for an innovative economy”. Springler, Berlin.

[58] S.Roper, P.Micheli, J.H.Love, P.Vahter (2011). “The roles and effectiveness of design in new product development: A study of Irish manufacturers”. In *Research Policy*, Volume 45, Issue 1, February 2016, pp. 319-329.

this restriction. However, the current capacities of obtaining information, communicating and processing data have fundametally changed the application and possibilities of the methods. Additionally, new methods derived from the existing ones have emerged.

1.5.2 Life Cycle Analysis (LCA)

Traditionally, the technology assessment literature uses metrics such as Technology Readiness level (TRL, Mankins, 2009)[59] and Manufacturing Readiness Level (MRL, GAO, 2010)[60] to describe the maturity of technology and its related production infrastructure, where the lowest levels represent fundamental laboratory based research and development, and the highest of full-scale commercialized technology. Manufacturing Readiness Levels are a method for understanding the maturity of a manufacturing process readiness similar to how TRL are used to understand technology maturity. MRLs allow engineers to have a consistent datum of reference for understanding manufacturing maturity evolution. The MRL concept was developed by the U.S. Department of Defence to assess the maturity of a manufacturing process throughout its conception, development, deployment and support progression phases. MRLs ar based on a scale from 1-10, with 10 being the most mature.

Consequently, when a technology concept is conceived and validated (TRLs 1-4), it belongs to the emerging stage. When it is prototyped and launched (TRLs 5-8), it pertains to the growing stage. Finally, when the techology flourishes (TRL 9), it is considered mature. The satuarated stage not include TRLs, since this stage –where competitive potential is lost – goes beyond TRL intended assessment.

However, the markets into which technologies are deployed may also be characterized by different levels of maturity. Markets comprise the context into which a technology is deployed; the diffusion of technology is reflected via transactions in the market. Markets have a size (e.g. number of passenger vehicles sold per year), a composition (market share of different technologies) and are affected by consumer behavior (Bergerson et al.,2020)[61]. Technology development is a mixture of inheritance and innovation that follows certain rules along a technology trajectory. This trajectory charts a technology's evolution and is among the best supporting data for decision making.

Technology life-cycle analysis is one of the foundational topics in the field of technology management, is of vital importance for describing the evolutionary path of technology. LCA looks for ways to match to the life cycle stages. However, it typically tries to employ qualitative methods. Having no repeatable frameworks, forecasting advances were almost impossible, and the limits of each stage were not well defined – which dimmed objectivity from the assessment (Reinhart and Schindler, 2010)[62].

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[59] J.C.Mankins (2009). "Technology readiness assessments: a retrospective". Acta Astronaut 65 (9), pp. 1216-1223.

[60] GAO (2010). "Best Practices. DOD Can Achieve Better Outcomes by Standardizing the Way Manufacturing Risks Are Managed". April 2010/

[61] Bergerson et al (2020). "Life cycle assessment of emerging technologies". In *Journal of Industrial Ecology,* Volume 24, Issue 1: Life Cycle Assessment of Emerging Technologies, February 2020.

[62] G.Reinhart, S.Schindler (2010). "A strategic evaluation approach for defining the maturity of manufacturing technologies". In *World Academy of Science Engineering Technologies* 47 (4), pp. 730-735.

1.5.3 TRL-FTA Hybrid Model

TRL and FTA methodologies have proven to be symbiotic. The TRL offer a solid maturity index, however the means to determine them rely almost entirely on expert assessment. The FTA expands the techniques for determinig maturity, yet it is usually based on LCA, whose stages and transitions are not as well established as TRLs.

In 1997, Watts and Porter published an attempt to link the technology life cycle stages to specific bibliometric indicators. The technology life-cycle is a model that describes the different stages that a technology goes through, from its initial development to its eventual obsolence. The model can help understand the technology and its processes, anticipate future trends, and make strategic decisions. The typical stages of the technology life-cycle are research and development, growth, maturity, and decline.

It is a particularity of the energy sector that technologies from a diverse range of sectors of the economy are used in the extraction, conversion, and end-use of energy. Therefore, most energy innovations are not developed by energy companies but enter the sector in the form of specialized equipment or innovative fuels from other sectors. The best examples can be solar panels, gas turbines and biofuel conversion technology. Empirical research shows that long-term patterns in the process and focus on innovation often referred to as „technology life-cycles“, differ across these sectors (Huenteler et al., 2016)[63].

The concept of technology substitution through either sustained or disruptive innovations has become prominent in academia and in practice (Christiansen et al, 2015)[64]. A sustaining innovation is a strategic and incremental improvement process that organizations use to maintain their competitive edge. Sustaining innovation strives to create products that perform better and are of higher quality than those that already exist. Disruptive innovations, on the other hand, aim to create „good enough“ products. Innovative solutions eventually disrupt an existing market and value network.

It should be highlighted that while the concept of disruptive technology is widely used, *„disruptive innovation“* is a more useful concept as few technologies are intrinsically disruptive. It is the business model and not the technology that enables and creates the disruptive effect. A key to disruptive innovation is that, opposed to sustaining innovation, it does not occur with established competitiors. Disruption refers to a process whereby a smaller company with fewer resources is able to successfully challenge established incumbent businesses. An example of disruptive innovation is how when Apple introduced the iPod, the company brought together a strong technology with groundbreaking business model.

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[63] J.Huenteler, T.S.Schmidt, J.Ossenbrink, V.H.Hoffmann (2016). “Technology life-cycles in the energy sector – Technological characteristics and the role of deployment for innovation”. In *Technological Forecasting and Social Change*, Volume 104, March 2016, pp. 102-121.

[64] C. Christiansen, M.Raynor, and R.McDonald (2015). “What is disruptive innovation”? *Harvard Business Review,* Volume 93 No 12, pp. 44-53.

Chapter 2

Energy storage technologies - the state of art

Grid integration and energy storage are the two mostly used solutions, which can enhance the renewables-based power system performance. Energy storage systems in conjunction with the renewable energy resources can provide some environmental, technical, and financial benefits to a power system. This kind of technologies can reduce the overall greenhouse gas emissions and enhance the reliability of renewable power generation systems. Many of the novel ideas described in this chapter are based on existing technologies, but taken a step further in technology development or hybridized with other types of energy storage. As a result, the main focus of future technologies' research and development should be dedicated to cost effective implementation of energy storage systems in renewable power generation.

Figure 7. Comparison of different energy storage technologies

Energy storage system	Power rating	Discharge time	Deployment time	Life time Efficiency
Pumped hydro energy storage system	100-4000 MW	1h-24 h	30 years	70-85%
Flywheel energy storage system	>750 kW	Milliseconds to 40 minutes	20 years	90-95%
Compressed air energy storage system	50-300 MW	1h-24h	30 years	70-80%
Battery	<50 MW	Sec-hours	5-10 years	80-90%
Hydrogen	<250 kW	14h-24h	10-20 years	20-50%
Supercapacitor	< 100kW	Milliseconds to minute	10,000 cycles	90-95%
SMES	10 kW-10 MW	Milliseconds to seconds	30 years	80-90%

Source: Adapted from the article „Overview of energy storage technologies for renewable energy" by N.Barah & O.Husev, September 2015[65].

Different types of storge technologies are theoretically and operationally available to solve the renewables fluctuations problem. A variety of parameters can be used to develop a control scheme or compare the storage system characteristics with other alternative storage systems. Cost, efficiency, energy density, life cycle, and environmental impact are some examples of these parameters. Energy density can be defined as the amount of energy that can be supplied from a particular storage device or technology per unit weight. The energy density determines the quantity of the energy that the device can deliver or can store energy. The first key parameters when comparing different storage technologies are usually the gravimetric storage capacity and volumetric energy density.

Gravimetric energy density, sometimes referred to as specific energy, is the available energy per unit mass of a substance. It is typically expressed in Watt-hours per kilogram (wh/kg), or Megajoules per kilogram (MJ/kg). The gravimetric energy density gives the energy content of a fuel in terms of storage and handling of the substance. It can be considered as a

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[65] N.Barah & O.Husev (2015). "Overview of Energy Storage Technologies for Renewable Energy". In *International Journal of Innovative Science, Engineering & Technology,* Volume 2, issue 9, September **2015.**

more precise definition of energy density[66]. However, gravimetric energy density is not only used for fuels; it can also be used to define battery capacity. The term can be particularly useful when talking about materials that need to be stored based on weight, such as batteries in vehicles.

Volumetric energy density is the amount of energy stored in a given system or region of space per unit volume. It is typically expressed in watt-hours per liter (Wh/L) or megajoules per liter (MJ/L). This kind of energy density is an important factor for the performance of batteries and electric vehicles. In order to choose a storage technology for an application, the geographical characteristics of the implementation site, the application size, and the availability of renewable sources of energy are key parameters that should be considered. Therefore, a detailed economic and technical performance assessment is necessary for the energy storage comparison. Consequently, no unique storage technology can be considered as the best option for all energy storage purposes.

Figure 8. Volumetric and gravimetric energy densities of common fuels.

Fuel	**Gravimetric Energy Density (MJ kg^{-i})**	**Volumetric Energy Density (MJ L^{-})^{i}**
Hydrogen (liquid)	143	10.1
Hydrogen (compressed 700 bar)	143	5.6
Hydrogen (ambient pressure)	143	0.0107
Methane (ambient pressure)	55.6	0.0378
Natural Gas (Liquid)	53.6	22.2
Natural Gas (compressed 250 bar)	53.6	9
Natural gas	53.6	0.0364
LPG propane	49.6	25.3
LPG butane	49.1	27.7
Gasoline (petrol)	46.4	34.2
Biodiesel oil	42.2	33
Diesel	45.4	34.6
Kerosene	46.4	36.7

Source: Adapted from the article “Hydrogen as an energy carrier: Prospects and Challenges” by Mazloomi & Gomes. In *Renewable and Sustainable Energy Reviews* 16 (5) (**2012**).

According to the way of energy stored, the energy storage technologies can be classified into five major categories, i.e. chemical, electrochemical, electrical, mechanical, and thermal. As shown in Figure 2, drawn from several sources, the relative benefits and drawbacks of technologies are broadly consistent. The advantages of mechanical solutions, in general, are their low cost, long lifetime, long duration, and low technology risk. The challenges in some cases have been associated with round-trip efficiency[67], costs and siteability. Alternatively, energy storage systems can be classified according to the field of application and power rating:

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[66] Energy density is used to describe the energy of a substance per volume or per mass. In contrast, gravimetric energy density or specific energy are only used to describe energy per unit mass of a substance.

[67] The round trip efficiency (RTE) of an energy storage system is defined as the ratio of the total energy output by the system to the total energy input to the system, as measured at the point of connection. It varies widely for different storage technologies.

Figure 9. Types of energy storage systems

Category	Application	Power rating
Small scale	Mobile devices, electric vehicles, satellites	< 1 MW
Medium scale	Office building, remote communities	10-100 MW
Large scale	Power plants	>300 MW

Source: Adapted by the article „Modern Mechanical Energy Storage Systems and Technologies" by Mallick et al. (2016)[68].

Among several energy storage methods, thermal energy storage (TES) appears as one of the emerging technologies that can bridge the intermittency gap in renewables such as solar energy, energy saving and the promotion of environmental aspect. TES systems consist of a thermal energy storage medium (*heat and/or cold*) kept for a defined period to use it when and where it is needed. The applications of these systems are in the building sector (*air conditioning, thermal comfort, domestic hot water*), and industrial sector (chemical industry, food industry, etc.) It is worth highlighting that the estimated annual energy saving potential in the European Union is 7.5% due to these technologies. In terms of environmental savings, the annual potential CO_2 emissions were reduced by about 5.5% in the EU. Later 90% of the CO_2 emissions mitigation is expected by 2050 (according to the International Renewable Energy Agency (IRENA)[69] through the application of these systems. Since then, these systems have received particular attention through an economic and environmental analysis in several sectors[70].

2.1 Mechanical energy storage

Mechanical energy storage, which is based on the direct storage of potential or kinetic energy, is probably one of the oldest energy storage technologies along with thermal storage. Mechanical storage refers to systems that use gravity, acceleration or compression to store kinetic energy, which can generate electricity upon release. Unlike thermal storage, mechanical energy storage enables the direct storage of excess energy. An attractive feature of the various types of mechanical storage is the simplicity of the basic concept. The challenge in developing mechanical storage systems is often the limited storage density, which is lower than most other energy storage concepts.

Mechanical energy storage technology can be divided into kinetic energy storage technology (such as flywheel energy storage[71]), elastic potential energy storage (such as compressed air energy storage), and gravitational potential energy storage technology. In the category of mechanical energy storage, pumped hydro and flywheels make up the overwhelming majority of commercially implemented energy storage technology solutions.

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[68] K.Mallick, A.Sengupta, S.Das, S.Chattaraj (2016). "Modern Mechanical Energy Storage Systems and Technologies". In *International Journal of Engineering Research & Technology* (IJERT), Volume 5, Issue 2, February **2016**.

[69] International Renewable Energy Agency (2018). "Global Energy Transformation: A Roadmap to 2050". IRENA.

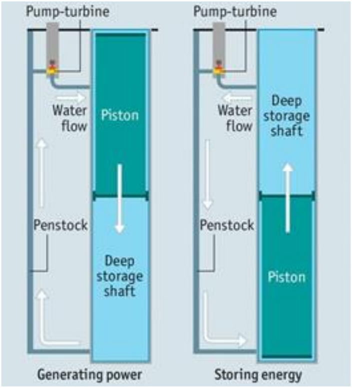
[70] International Renewable Energy Agency (2020). "Innovation outlook: Thermal energy storage". IRENA.

[71] One of the energy storage methods used by establishing a motor and generator system before chemical storage technologies. Energy is stored rotatable in a rotating mass. When energy is needed, electrical energy is provided by coupling the rotating mass with the generator.

The only other mechanical storage concepts are at the developmental stages and they primarily include the storage of gravity-based potential energy and buoyancy-based potential energy.

Gravity energy storage technology has been used for a long time. The gravitational potential energy is stored by absorbing power to drive the electrochemical equipment to lift the height of the weight when there is power surplus in the power grid and lowering the weight to return power to the grid when there is a power shortage in the power system as shown in Figure 10. In addition, gravity storage will be built using methods and techniques already known from the mining and tunneling industry. Still construction, maintenance and site-related aspects must be considered.

Figure 10. Showing the mechanism behind storing electricity using gravity



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Source: Gravity Power (2024).

Mechanical energy storage systems that used pumped storage (PHES) or compressed air storage (CAES) differ significantly from flywheel storage systems. In the short-term range, the capacity and power of flywheel storage systems fall between electric storage systems and batteries. They have considerably higher capacities, but only slightly longer discharging durations than electric storage systems. There are a range of application areas for flywheel energy storage systems. They are used as phase shifters to provide short circuit capacity in the electricity network, for example, or for recuperating braking energy in the transport sector.

2.1.1 Pumped hydro energy storage

Pumped hydro storage system (PHES) is a mature technology with efficiency, long storage period, and relatively low capital cost per unit energy. It is a form of clean energy storage that is ideal solution for electricity grids reliant on solar and wind power. This technology absorbs surplus energy at times of low demand and releases it when demand is high. Pumped storage hydropower is the world’s largest battery technology, accounting for over 94% of installed global energy storage capacity. The International Hydropower Association (IHA) estimates that pumped hydro projects globally store up to 9,000 gigawatt hours (GWh) electricity[72]. Multiple studies have identified vast potential for pumped storage

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[72] International Hydropower Association (2024). “Pumped hydro: Water batteries for solar and wind power”. IHA

sites globally and there is increasing research on possibilities for retrofitting disused mines, underground caverns, non-powered dams and conventional hydroplants.

The working principle of pumped hydroelectricity energy storage system is the same as the hydro electric power plant. Internationally, PHES is a commercially competitive technology deployed extensively across the world (TRL 9/CRI 4-6). Medium- and long-duration large-scale grid-connected systems are commercially competitive (TRL 9/CRI 6), whereas small-scale systems are undergoing supported commercial deployments (TRL 9/CRI 4-6).

This storage technologies work in a reverse way than that of the traditional hydropower generation plant. There are two types of pumped hydro storage system according to their installation sites - underground and over ground (conventional). Conventional pure pumped hydro system make use of two reservoirs at different elevations – an upper storage reservoir providing head to the hydro power turbine and another to collect water back into the upper reservoir using surplus electricity during off period hours.When electricity is needed, water is released back to the lower pool, generating power through turbines. During the off-peak hours the surplus power is used to pump and store water in the high reservoir to the low reservoir which in turns the turbine to produce electricity. The efficiency ranges between 70-85% (Duke University, 2022)[73]. PHES operations and technology are adapting to the changing power system requirements due to variable renewable energy sources. Variable-speed and ternary PHES systems[74] allow for faster and wider operating ranges, providing additional flexibility. The major difference between a ternary plant and other types of pumped storage plants is that the ternary plant can simultaneously operate both the pump and turbine. All other pumped storage plant designs operate either in a generating mode or a pumping mode, and the shaft rotates in opposite directions in these two modes. The ability of the pump and turbine to operate simultaneously provides added flexibility in the plant's operation.

The major drawback of this technology lies in the scarcity of available sites for two large reservoirs and one or two dams. Long lead-time (typically 10 years) and high cost for construction and environmental issues (removing trees and vegetation from the large amounts of land prior to the reservoir being flooded (Hino & Lejeune, 2012)[75]. Pumped hydroelectric storage (PHES) and compressed air energy storage (CAES) provide alternative means for utility-scale power storage. The selection of one over the other depends on several factors, including geological features locally.

Figure 11. Compressed air energy storage versus Pumped hydroelectric storage

Technology	**Pro arguments**	**Counter arguments**
Compressed Air Energy Storage (CAES)	-High capacity; -Lower storage cost; -Fast start-up; Turbine power entirely available	-Natural caverns required for large power plants
Pumped Hydroeletric Storage (PHS)	-Mature technology; -Very high capacity	-Higher capital cost; -Not suitable in flat regions

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[73] C.J.Yang (2022). "Pumped Hydroelectric Storage". Center on Global Change, Duke University, USA.

[74] A ternary pumped storage system consists of a separate turbine and pump on a single shaft with an electric machine that can operate as either a generator or a motor.

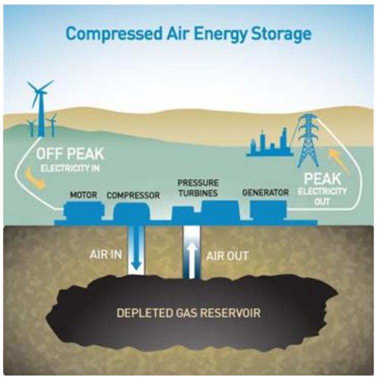
[75] T.Hino, A.Lejeune (2012). "Hydropower" in Comprehensive Renewable Energy, 2012.

2.1.2 Compressed air storage system

Compressed air energy storage (CAES) is a key technology as large scale grid storage is expected to be a major source of power system reliability. According to the report prepared by the U.S. Department of Energy (DOE) „Energy Storage Grand Challenge“, among all energy storage technologies, compressed air energy storage offers the lowest total cost for large-scale application (over 100 MW and 4 hours)[76]. Based on the U.S DOE report, CAES can potentially be installed at approximately 60 GWh in 2030. Amongst all different types of energy storage approaches, CAES system offers many competitive features such as large power and energy capacity, high cycle lifespan, and fast response time. This feature makes CAES systems particularly suitable for energy storage purposes in the electric grid.

In the manufacturing industry, compressed air is broadly applied. It is used either as energy carrier for various processes like drilling or carving or it serves as a process fluid carrier e.g. for cleaning or varnishing. Either way, compressed air is generated almost exclusively on site by employing electrical energy. In Germany, for example, currently 16 TWh are consumed annually to provide compressed air for industrial purposes (Budt et al., 2016)[77].

Figure 12. Compressed air energy storage.



Source: U.S Department of Energy (2024)

The concept of CAES can be dated back to 1949 when Stal Laval filled the first patent of CAES which used an underground cavern to store the compressed air. It is derived from the gas-turbine cycle, in which the compressor and turbine operate separately. As shown in Figure 12, CAES decouples the compression and expansion cycle of a conventional gas turbine into two separated processes and stores the energy in the form of the elastic potential of compressed air. In low demand period, energy is stored by compressing air in an air tight space (typically 4.0-8.0 Mpa) such as underground cavern. During charging, air is compressed and stored with additional electricity, and the compression heat is stored in a thermal energy storage unit for future use. During discharging, air is released, either heated by burning fuel or stored thermal energy to generate electricity. Compressed air is stored in underground caverns or up ground vessels.To extract the stored energy, compressed air is drawn from the storage vessel, mixed with fuel and combusted, and then expanded through a turbine. The turbine is connected to a generator to produce electricity. The waste heat of the exhaust can be captured through a

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[76] V.Viswanathan, K.Mongrid, R.Franks, V.Li, V.Sprenkle (2022). “Grid energy storage technology cost and performance assessment”. Report, U.S. Department of Energy.

[77] M.Budt, D.Wolf, R.Span, J.Yan (2016). “A review on compressed air energy storage: basic principles, past milestones and recent developments”. In *Applied Energy*, Volume 170, 15 May **2016**, pp. 250-268.

recuperator before being released to the atmosphere.This technology has somewhat lower capacities than pumped storage plants over durations of a day. Like pumped storage systems, compressed air storage systems are bound to specific geographical sites (Stadler & Sterner, 2018)[78].

Adiabatic compressed air energy storage (ACAES) is frequently suggested as a promising alternative for bulk electricity storage, alongside more established technologies such as pumped hydro and high-capacity batteries. An Adiabatic Compressed Air Energy Storage is an energy storage system based on air compression and air storage in geological underground voids. During operation, the available electricity is used to compress air into a cavern at depths of hundreds of meters and at pressures up to 100 bar. The heat produced during the compression cycle is stored using Thermal Energy Storage (TES), while the air is pressed into underground caverns. When the stored energy is needed, this compressed air is used to generate power in a turbine while simultaneously recovering the heat from the thermal storage.

There are two major barriers to implementation of CAES: the reliance on favorable caverns and the reliance on fossil fuel. Advanced CAES systems that eliminate the use of fossil fuels have been developed in recent years, including isothermal CAES (ICAES), underwater CAES (UWCAES), Liquid Air Energy Storage (LAES) and supercritical CAES.

In an Isothermal Compressed Air Energy Storage (**I-CAES**) system, energy is stored by compressing air from the atmosphere to a high pressure, and subsequently regenerated by expanding the compressed air back to atmospheric pressure. Both processes are to occur at nearly constant temperature. Generally, the round-trip efficiency and energy density if ICAES range from 66.0% to 96.0%. This provides the best efficiency and energy density. As a grid scale long duration storage approach, I-CAES can be configured so that it does not have a carbon footprint, and can be sited everywhere. Supercritical CAES (**SC CAES**) combines the features of both ACAES and LAES (Liquid Air Energy Storage)[79]. The concept of SC CAES developed by Chen et al[80], utilizes the supercritical characteristics of fluids (air, temperatures above 132 K, and pressures above 3,79 Mpa) to enhance the overall system performance. During charging, air is pressurized and cooled to a liquid state, and a regulator valve or Cyro turbine is utilized to decrease the pressure and temperature. In turn, Underwater CAES (**UW-CAES**) stores compressed air deep in water to create hydrostatic pressure. UW-CAES includes some facilities above water and storage vessels. In an underwater vessel, the compressed air is stored at approximately the same pressure as the hydrostatic pressure in the surrounding water, so the water provides the reaction to the pressure of the compressed air and the storage vessel can be very low in cost (Pimm & Garvey, 2022)[81].

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[78] I.Stadler, M.Sterner (2018). “Urban Energy Storage and Sector Coupling”. In *Urban Energy Transition*, Second Edition, **2018**.

[79] Liquid Air Energy Storage (LAES) is a class of thermomechanical energy storage that uses the thermal potential stored in a tank of cryogenic fluid.

[80] S.Zhang, W.Cheng (2022). “China’s energy transition pathway in a carbon neutral vision”. In *Engineering* **2022**, 14, pp. 64-76.

[81] A.Pimm, S.D.Garvey (2022). “Underwater compressed air energy storage”. In Storing Energy (Second Edition), pp.157-177.

Liquid Air Energy Storage (**LAES**) concept was first proposed by Smith at the University of Newcastle in 1977 for electricity peak shaving[82]. Researchers in academia and industry have studied the fundamentals and applications of LAES. During charging, the purified air is compressed via multistage compression, cooled by the stored cold energy, and recirculating cold air. The air then flows through a cryoturbine or Joule-Thompson throttling valve and becomes liquid air ,which is stored in a cryogenic tank (ca 78K and near-ambient pressure). The compression heat was stored for future use. Liquefying air reduces the air volume by factor of 700. The charging process is closely related to th liquefaction industry and usually involves conventional air liquefaction technology. During charging, a subcritical operating pressure of approximately 0.6-1.0 Mpa.

Technical maturity of CAES is roughly classified into three levels: R&D, demonstration and development and commercialization. It can be highlighted that ACAES technology is the most mature among all these advanced CAES systems, as some commercial demonstrations have been constructed and connected to the grid. LAES and UWCAES technologies are less mature, as only megawatt-level demonstrations have been developed, and related companies have announced the development of large-scale systems. ICAES, SC-CAES, and RES-CAES systems are mainly under theoretical study, and experiments have been conducted. All these theoretical and experimental studies have proven their feasibility and application potential.

2.1.3 Flywheel

As a counterpart of today's electrical network, there is a high demand for reliable, cost effective, long lasting, and environmentally sound energy storage systems to support a variety of energy storage applications. With advances in materials technology, bearings, and power electronics, the technology of flywheels for energy storage has significantly developed. Flywheels with the main attributes of high energy efficiency, and high power and energy density, compete with other storage technologies in electrical energy storage applications, as well as in transportation, military services, and space satellites (Liu & Jiang, 2007)[83]. With storage capabilities of up to 500 MJ and power ranges from kW to GW, they perform a variety of important energy storage applications in a power system. The most common applications of flywheels in electrical energy storage are for uninterruptible power supplies (UPS) and power quality improvement. For these applications, the electrochemical battery is highly mismatched and suffers from an insufficient cycle life, since the number of cycles per day is usually too high (Bender, 2015)[84].

The flywheel energy storage system is one of the oldest energy storage methods and serves as an efficient method of bulk energy storage. Flywheel systems are made up of a rotating cylinder, a bearing system, a motor or generator and a container to house the flywheel. Amount of energy stored in disk or rotor is directly proportional to the square of the wheel speed and rotor's mass moment of inertia. When power is required, flywheel uses the rotor's inertia and converts stored kinetic energy into electricity. To charge this device, energy is used

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[82] E.M.Smith (1977). "Storage of electrical energy using supercritical liquid air". In *Proc Inst Mechanical Engineering* **1977**, 191 (1), pp. 289-298.

[83] H. Liu, J.Jiang (2007). "Flywheel energy storage – An upswing technology for energy sustainability". In *Energy Building*, **2007**, 39, pp. 599-604.

[84] D.Bender (2015). "Flywheels". Sandia Report, Sandia National Laboratories, Albuquerque, ME, USA.

to power a motor which spins the disc, and the disc remains spinning until the energy is needed. At that point, the disc is allowed to turn a generator, which produces electricity. The speed of the flywheel increases during charging and decreases during discharging. Based on the speed of the rotating flywheel the system can be classified as Low speed and High speed device. The low speed type is designed to operate below 10,000 RPM and the high speed type can operate above 10,000 RPM.

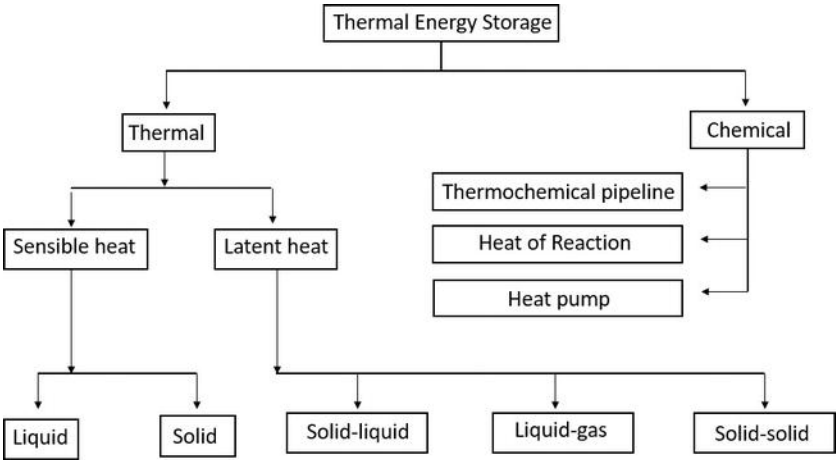
Recent advances in power electronic conversion and control technology resulted in the DC (direct current) flywheel energy storage system. The flywheel can be used as a substitute for batteries. Though the initial cost of installation of the flywheel is higher it has no environmental impacts like the battery energy storage which are toxic. As well flywheels are not as adversely affected by temperature changes, can operate at a much wider temperature range, and are not subject to many of the common failures of chemical rechargeable batteries. Depending on winding losses, bearing losses and cycling process, the round trip efficiency of flywheel is modules varies from 80% to 85%. In addition, they have high energy density as compared to the other energy storage systems. The main advantage of flywheel energy storage is long life and low maintenance costs.

2.2 Thermal energy storage

Thermal storage is increasingly important due to the demand-supply challenge caused by the intermittency of renewable energy and waste heat dissipation to the environment. The gap between the energy demand and supply can also be caused by the difference in the energy availability time and consumption, the difference in enegy cost at peak hours, and the distance between the energy source and consumption site. At present, thermal energy storage systems (TES) are prevalent and are applicable in engineering solutions such as integrated renewable energy systems and shifting peak load energy demand to off-peak.

Thermal energy storage is subdivided into the sensible and latent types as seen in Figure 13. For the sensible storage, it is the storage material that preserves its condition as a solid or a liquid. The stored energy is manifested through a sensible increase in temperature of the material. On the other hand, latent storage is mainly dependent on phase change from solid to liquid and the other way round. Phase change materials (PCMs) change their phase at constant temperature (melting or solidification temperature).

Figure 13. Different thermal energy storage systems



Source: Adapted from the book „Latent Heat Storage: An Introduction“ by Hebatallah Teamah.

Basically, thermal energy storage is a technology that stocks thermal energy by heating or cooling storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. Thermal energy systems (TES) are particularly used in buildings and in industrial processes. It also offers flexibility and services to facilitate the management of future electricity supply and demand challenges. The storage and release of energy can be accomplished by using storage media with high heat capacity, high latent heat or phase change materials (PCMs)[85].

Storage density, in terms of the amount of energy per unit of volume or mass, is significant for optimizing solar ratio (meaning how much solar radiation is useful for the heating/cooling purposes), efficiency of appliances (solar thermal collectors and absorption chillers), and energy consumption for space heating/cooling room consumption. Therefore, the possibility of using phase-change materials (PCMs) might be able to increase the energy density of small-sized water storage tanks, reducing solar storage volume for a given solar fraction or increasing the solar fraction for a given available volume (Medrano et al., 2009)[86].

Advantages of using TES in an energy system include an increase in overall efficiency and better reliability that can lead to better economics, reductions in investment and running costs, and fewer carbon dioxide emissions (Dincer & Rosen, 2011)[87]. Solar thermal systems, unlike photovoltaic systems, are industrially mature and utilize a major part of the Sun's thermal energy during the day. At the same time, it does not have enough thermal backup to continue operating during the low or no solar radiation hours. TES is becoming particularly important for electricity storage in combination with concentrating solar power (CSP) plants where solar heat can be stored for electricity production when sunlight is not available.

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[85] Phase changing materials (PCMs) are materials for thermal energy storage. They can undergo phase transitions (changing from solid to liquid or vice versa) while absorbing or releasing large amounts of energy in the form of latent heat.

[86] M.Medrano, M.O.Yilmaz, M.Noque's, M., I.Martorell, J.Roca, L.F.Cabeza (2009). "Experimental evaluation of commercial heat exchangers for use as PCM thermal storage systems". In *Applied Energy* **2009,** 86, 2047-2055.

[87] I.Dincer, M.A. Rosen (2011). "Thermal Energy Storage: Systems and Applications". UK, 2011, John Wiley & Sons.

By means of energy storage, intermittent solar energy is able to not only meet the demands of space heating and domestic water supply but also to offer a high grade heat source all year around regardless of timing or seasonal constraints. Using excess heat collected in the summer to compensate for the heat supply insufficiency during the wintertime is the concept of seasonal thermal energy storage, also called long-term heat storage. Seasonal storage is more complex and costly than the short-term energy storage. The main difference between the two systems is the size and volume of the storage (Jurigova & Chmurnyi, 2016)[88]. Although seasonal storage has greater potential in practical applications, it is more technologically challenging than short-term storage. It requires large storage volumes and has greater risks of heat losses, and the material chosen for implementation must be economical, reliable and ecological. Over recent decades, related studies addressing diverse applications and storage mechanisms have been carried out globally (Dincer & Rosen, 2010)[89]. The concept of seasonal storage is not only used in district heating (Schmidt et al., 2006)[90] but also in greenhouses for space heating (Alkilani et al., 2011)[91] because heating for the plants during winter nights consumes a large portion of heat input in agricultural greenhouses.

TES technology is established and economically feasible, where the USA and Canada have used short-term thermal energy storage and long-term thermal energy storage (which can involve (PCMs) since the 1980s (Dincer & Rosen, 2021)[92] . Various obstacles hinder TES adoption, including high initial costs, poor infrastructure, and lack of experience, which make decison-makers only consider using TES for ice storage in air-conditioning buildings. However, recent years, have seen significant interest in TES systems, and efforts were made to reduce costs and improve performance by focusing on technologies with local experience and keeping systems as simple and possible.

2.2.1 Physical principles of thermal energy storage

Thermal energy systems units can be classified into different types according to various characteristics. They store heat or cold for later use and are classified into sensible heat storage, latent heat storage, and thermochemical heat storage. Sensible heat storage systems raise the temperature of a material to store heat. In turn, latent heat storage systems use phase change materials (PCMs) to store heat through melting or solidifying. Thermochemical heat storage systems store heat by breaking or forming chemical bonds. The choice of TES system depends on factors such as the specific application, desired operating temperature, storage duration, and efficiency. Figure 14 shows basic advantages and disadvantages of different technologies of thermal energy storage.

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[88] M.Jurigova, I.Chmurny (2016). “Systems of Sensible Thermal Energy Storage”. In *Applied Mechanics and Materials,* Volume 820 (2016), pp. 206-211.

[89] Dincer & Rosen (2010). “Thermal Energy storage Systems and Applications”. Second Edition, August 2010.

[90] Schmidt et al. (2006). “Seasonal Thermal Energy Storage in Germany”.

[91] Alkilani (2011). “Single-pass solar air heater integrated with PCM unit”.

[92] I.Dincer, M.A. Rosen (2021). “Thermal Energy Storage: Systems and Applications”. Third edition, edited by John Wiley & Sons, Hoboken, NJ, USA, 2021.

Figure 14. Advantages and disadvantages of different methods of energy storage

Method	Advantages	Disadvantages
Sensible	Cheap, reliable, long life, non-toxic materials	Low energy density, self-discharge
Latent	Isothermal, some materials are cheap and abundant, non-toxic materials	Many materials are flammable or corrosive, may occur phase separation
Chemical	High energy density, no self-discharge	Low power, low thermodynamic efficiency.

Source: Adapted from the article „Systems of Sensible Thermal Energy Storage“ by Jurigova & Chmurny (2016).

Sensible heat

Sensible heat storage is a relatively mature technology that has been deployed in a wide range of high-temperature industrial applications. For liquid sensible heat storage media, materials with low melting temperatures, higher decomposition temperatures and low costs are preferred. This heat storage is the simplest method based on storing thermal energy by heating or cooling a liquid or solid storage medium (e.g. water, sand, molten salts, or rocks), with water being the cheapest option. The energy involved in the change of its temperature is called sensible heat. Then the material is thermally isolated from the environment, until it is necessary to release the heat. The unit storage capacity depends on heat capacity of the material and temperature at which it is stored. Sensible thermal storage options include storing heat in liquids such as molten salts and in solids such as concrete blocks, rocks, or sand-like particles. The most popular and commercial heat storage medium is water, which has a number of residential and industrial applications. Underground storage of sensible heat in both liquid and solid media is also used for typically large-scale applications.

The sensible heat of molten salt is used for storing solar energy at a high temperature, termed *molten-salt technology*. Molten salt can function as a large-scale thermal storage method that would allow other energy sources, such as nuclear and solar, to become feasible in smoothing out the fluctuations in demand. Molten nitrate salt (60% sodium nitrate, 40% potassium nitrate) is being used in commecial concentrated solar plants (CSP) around the world to provide gigawatt-hours of thermal energy storage. Concentrating solar power, also known as solar thermal electricity, is a commercial technology that produces heat by concentrating solar irradiation. The high temperature heat is typically stored and subsequently used to generate electricity via a steam turbine (Rankine cycle)[93]. The different high-temperature TES options include solid media (e.g. regenerator storage), pressurized water (or Ruth storage), molten salt, latent heat, and thermochemical energy storage(Bauer et al., 2020)[94].

Electrically heated regenerator storage has recently received significant attention for applications in storage power plants, electrothermal energy storage and Brayton based pumped thermal electricity storage due to the feasibility of converting excess electricity into heat and

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[93] Rankine cycle system consists of a pump, boiler, turbine, and condenser. The pump delivers liquid water to the boiler, the boiler heated by the solar heat converts water to superheated steam. In turn, steam is used to run the turbine, which powers the generator.

[94] T.Bauer, C.Odenthal, and A.Bonk (2020). “Molten Salt Storage for Power Generation”.

storing it cost effectively at various temperature levels. This heat is then reconverted by a power cycle to produce electricity on demand (Forsberg et al., 2017)[95]. In turn, pumped-thermal electricity storage (PTES) based on reversible (Joule-) Brayton cycle is a promising grid-scale energy storage technology, which working principle is to store electricity in the form of high-grade thermal energy. This energy storage technology offers the advantages of geographical independence, high energy density, and low-cost.

Latent heat

Latent heat storage involves storing heat in a phase-change material that utilizes the large latent heat of phase change during melting of a solid to a liquid. This thermal energy storage technology leverages phasechanges in materials like paraffins and salts for energy storage used in heating, cooling, and power generation. It relies on the absorption and release of heat during phase change, the efficiency of which is determined by factors like storage material and temperature (Mselle et al., 2022)[96]. While having high energy density and efficiency, latent heat storage is hampered by costs and maintenance demands.

Theoretically, the phase change material has a phase change point when the phase transition happens in a certain temperature range instead of one exact point (Socaciu, 2012)[97]. In practice, the phase change temperatures and enthalpy of a certain phase change material during the process are measured by a device called differential scanning calorimeter. When testing with differential scanning calorimeter, a net dynamic heating power will be input to the tested sample to make its temperature increase at a constant rate. The value of this net dynamic heating power is recorded and finally plotted in the form of differential scanning calorimeter curves. The reference materials used during differential scanning calorimeter testing's are those with the constant heating or cooling rate, as well with the constant specific heat capacity (e.g, alumina and indium metal)[98].

Materials must be chosen according to the phase change – a liquid to a gas, or solid to a liquid. Phase change materials are either packaged in specialized containers such as tubes, shallow panels, plastic bags, or contained on conventional building elements (wall board, ceiling) or encapsulated as self-contained grains.That is done basically for the reason that the chemicals in some phase change materials separate and stratify when in their liquid state, phase change materials have not always re-solidified properly. As the temperature drops, these materials do not completely solidify, reducing their capacity to store latent heat. These problems have been addressed by packaging phase change materials in thin or shallow containers.

In this context, latent heat thermal energy storage system employing phase change material (PCM) is the attractive one due to high energy storage density with smaller

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[95] C.W.Forsberg (2017). "Converting excess low-price electricity into high-temperature stored heat for industry and high-value electricity production". In *Electricity Journal*, 30 (6), **2017.**

[96] B.D.Mselle et al. (2022). "A detailed energy analysis of a novel evaporator with latent thermal energy storage ability". In *Applied Thermal Energy*, 201 (2022).

[97] L.Socaciu (2012). "Thermal Energy Storage: An Overview". In *Acta Technica Napocensis*, Technical University of Cluj-Napoca, Series: Applied Mathematics and Mechanics, Volume 55, Issue IV, 2012.

[98] V.V.Tyagi, D.Buddhi (2008). "Thermal cycle testing of calcium chloride hexahydrate as a possible PCM for latent heat storage". In *Solar Energy Materials & Solar Cells*, Volume 92, pp.891-899, 2008.

temperature difference between storing and releasing functions. PCMs are generally possessed with low thermal conductivity, which leads to decreased rates of heat storage and extraction during melting and crystallization process (Jesumathy, 2018)[99].

Thermochemical energy storage

Thermochemical energy storage utilizes a reversible chemical reaction and takes the advantages of strong chemical bonds to store energy as chemical potential. Compared to sensible heat storage and latent heat storage, this theoretically offers higher energy density with minimum energy loss during long-term storage due to the temperature-independent means of storage. Thermochemical energy storage technologies are mainly divided into two groups: (1) thermochemical sorption storage system; and (2) chemical reaction storage system (thermochemical without sorption). Thermochemical sorption storage commonly focuses on low-grade heat, while thermochemical without sorption storage are more used for relatively higher temperature application.

Storage based on thermochemical reactions has also higher thermal capacity than storage based on sensible heat. As compared to other thermal storage technologies (e.g. sensible and latent energy storage technologies), thermochemical thermal energy storage has higher storage densities, making them more suited for applications where storage space is restricted or cost-prohibitive.

Thermochemical systems without sorption are based on reversible reaction of two separate chemical substances where a high amount of energy is generated because of an exothermic synthesis reaction (Yu, Wang and Wang, 2013)[100]. In a sorption process, heat is stored by breaking the binding force between the sorbent and the sorbate in terms of chemical potential (Chang et al., 2013)[101]. While sorption storage can only work up to temperatures of about 350°C, thermochemical systems without sorption can operate at higher temperatures and offer higher energy storage densities. Due to the capability of the sorption systems to conserve the heat energy at ambient temperature as long as desired without heat losses, thermochemical heat storage has become a widely researched technology for seasonal energy storage at low temperature (for application in buildings).

The selection of a thermal energy storage system for a specific application depends mainly on storage duration, costs, supply and utilization temperature requirements, storage capacity, heat losses and available space. Simultaneously, TTES technologies are commonly used for seasonal or long-term storage projects due to their potential advantage of low energy loss during the storage process. However, thermal heat storage technologies (THS) suffer from several challenges in terms of the availability of suitable materials to store energy with low

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[99] P.S.Jesumathy (2018). “Latent Heat Thermal Energy Storage System”. 01 August 2018.

[100] N. Yu, R.Z. Wang & L.W. Wang (2013). “Sorption thermal storage for solar energy”. In *Progress in Energy and Combustion Science*, pp. 489-514.

[101] M. H. Chang et al. (2013). “Design and experimental investigation of calcium looping process for s 3-kWth and 1.9-MWth facilities”. In *Chemical Engineering and Technology*, vol 36, Issue 9, pp 1525-1532.

heat losses, fast reaction kinetic, cost, good cyclic stability, and complex maintenance (Gude, 2018)[102].

2.3 Electrochemical storage

The electrochemical storage of energy has become essential in assisting the development of electrical transport and use of renewable energies. Clean energy storage devices, such as batteries, fuel cells, and electrochemical capacitors, have been recognized as one of the next-generation technologies in this field. Supercapacitors utilize the separation of charges on the electrode surfaces to electrostatically store energy. They feature a high power density, rapid charging and discharging rates, and long cycle life. They are utilized frequently in renewable energy systems and hybrid electric vehicles. However, supercapacitors have certain limitations. Namely, they are unable to store as much energy per unit volume as other energy storage systems.

Battery storage technologies, unlike other storage technologies, are more suitable for renewable energy sources because of a simple and efficient way of electrical energy storing. This kind of energy storage systems provide an effective strategy for improving the reliability and utilization of power grids. For example, the energy company Vatenfall in its Haringvliet hybrid energy park in the Netherlands combines the three technologies of battery, wind and solar for the first time (Vattenfall, 2024)[103]. Technologies based on supercapacitors and Lithium-sulfur (Li-S) batteries are still in the early stages of development for use in several applications that demand high energy and power density, including space and electric vehicles. Despite the successful commercialization of Lithium-ion batteries (LIBs), there is still significant scope for improvement in terms of low-cost novel material combinations and safety issues.

Batteries can be located in a range of areas and installed in small or large quantities for different uses. For example, a large number of batteries installed together, known as grid-scale or large-scale battery storage, can act as a large-scale power generator connected into the electricity transmission system. Smaller-scale batteries can be installed in homes to provide back-up power, but can also be operated as a collective in what is called Virtual Power Plant (VPP). Lithium-ion batteries, which have become common power sources in the portable electronic market since their first commercialization in the early 1990s, are the primary candidates for energy storage systems. The introduction of Lithium-ion batteries (LIBs) into the automotive market as the battery of choice for powering hybrid electric vehicle (HEVs), plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) could reduce dependence on fossil fuels. Lithium, the primary ingredient in LIBs, is unevenly distributed within the Earth’s crust. However, the increasing demand for lithium related to these new applications is expected to rise significantly. This all makes the use of lithium in the aforementioned applications very costly and difficult.

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[102] V.Gude (2018). Energy Storage for Desalination”. In *Renewable Energy Powered Desalination Handbook: Application and Thermodynamics,* 2018 Chapter 10.

[103] Vattenfall (2024). “Battery storage systems”.

Simultaneously, Sodium, the fourth most abundant element on earth, has a seemingly unlimited distribution (Llave et al., 2016)[104]. Supplies of sodium-containing precursors are vast, with 23 billion tons of soda ash located in the United States alone. The abundance of resources and the much lower cost of trona (about 135-165 USD per ton), from which sodium carbonate is produced, compared to lithium carbonate, provide a compelling rationale for the development of SIBs to be used as alternatives to LIBs. As an alternative to lithium is needed to realize large-scale applications, SIBs have attracted considerable research attention in recent years. This kind of batteries were initially studied when the development of LIBs began in the 1970s and 1980s, but due to rapid advances in the development and success of commercial applications of LIBs, SIBs were largely abandoned. For these reasons, sodium-ion batteries are proposed to compete with lithium-ion batteries, due to their lower price and the apparition of new materials for high-voltage and high capacity systems. However, they maintain some common problems of safety and recyclability, as well as the necessity of specific electrodes with high Na storage, still in the first stages of development.

2.3.1 Battery Energy Storage Technologies

Batteries are the oldest form of electricity storage as they store electrical energy in chemical form, and their properties depend primarily on the type of materials used, and manufacturing processes. They are made of stacked cells wherein chemical energy is converted to electrical energy and vice versa. The desired battery voltage as well as current levels are obtained by electrically connecting cells in series and in parallel. The batteries are rated in terms of their energy and power densities. Some other important features of a battery are efficiency, life span (stated in terms of number of cycles), operating temperature, and energy density (Divya, Østergaard, 2009)[105]. Battery energy storage system provides a great number of applications in the power system, including frequency control, voltage support, power support, energy shifting, etc. The frequency control service is one of the most favorable applications for grid-connected battery energy storage systems (BESS), which is used to restore the grid frequency in the event of disturbance by extractig or injecting frequency-dependent power.

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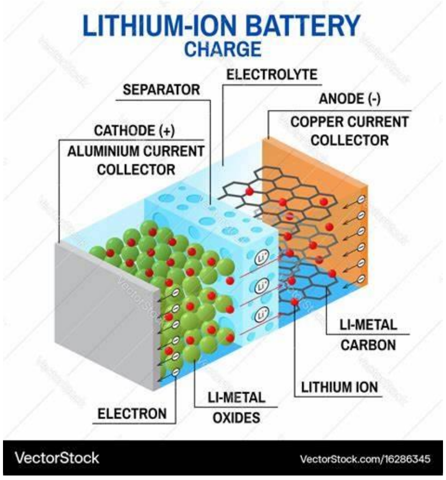
[104] E. de la Llave, V.Borgel, K.J.Park, J.Y Hwang, Y.K.Sun, P.Hartmanm, F.F.Chesneau and D.Aurbach. In *ACS Applications of Material Interfaces*, **2016**, 8, pp. 1867-1875.

[105] K.C.Divya, J.Østergaard (2009). “Battery energy storage technology for power systems – An overview”. In *Electric Power Systems Research* 79 (2009), pp. 511-520.

Figure 15. Lithium-ion battery diagram



Source; VectorStock, 2018.

Several types of rechargeable systems exist, from the mature lead acid to different newer technologies at various developmental stages. Primary batteries are „single use“ and cannot be recharged, whereas the second type is rechargeable and is called a secondary battery. Primary and secondary batteries utilize the chemical components built into them, whereas fuel cells have chemically bound energy supplied from the outside in the form of synthetic fuel (hydrogen, methanol or hydrazine). Secondary batteries are also known as rechargeable batteries because their electrochemical reactions are electrically reversible. Li-ion battery is a typical example of secondary battery. This type of batteries use intercalated lithium compounds as electrode materials. Cathode materials, such as lithium cobalt oxide ($LiCoO_2$), lithium manganese oxide ($LiMn_2O_4$) and lithium iron phospate ($LiFePO_4$), have been used in commercially available batteries. The dominant anode material used in Li-ion batteries is graphite.

Lead-acid batteries are commercially mature in their applications and much work has been done over the decade regarding their development. They have a low cost for their high performance and they are easily recycled. However, their usable capacity decreases when high power is discharged. For this reason, lead-acid batteries have a limited depth of discharge. They have a typical cycle life of approximately 1500 cycles at 80% depth of discharge (Antonucci, 2011)[106].

Lead acid represent more than 90% of the whole batteries market. This battery technology is based on positive and negative electrodes submerged into electrolyte which is a combination of sulfuric acid and water, using lead dioxide as a positive electrode and lead as a negative electrode (Šimič et al., 2021)[107]. At present, typical lead batteries for transportation have a polypropilene external case, high performance separators based on glass fibre, polyethylene or polyvnyl chloride matrices, thin grids with extremely low antimony content or

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[106] V.Antonucci (2011). “Electrochemical Energy Storage”. In *Energy Storage in the Emerging Era of Smart Grids*.

[107] Z.Šimic, D.Pelin, D.Topič (2021). “Battery energy storage technologies overview”. In *International Journal of Electrical and Computer Engineering Systems*, April **2021**.

based on lead, calcium, tin alloys. The effect of additives has been explored and optimized, allowing to reduce or cancel the necessity of maintenance.

The continuous development of lead-acid battery has brought along significant improvements in its capabilities, resulting in low costs and high reliability. However, the main drawback remains, its low energy density due to the high density of lead. Lead-acid batteries have ability to perform a deep discharge when it is required and the main problem with lead-acid batteries is that battery performance largely depends on temperature. The more advanced lead battery uses carbon additives in the negative electrode in order to increase its life-time; this type is still at developmental stage.

Lithium-ion (Li-ion) technology is one of the most advanced battery technologies widely used today. Generally, a lithium ion battery is a device able to convert chemical energy to electric energy and the other way round, through electrochemical reactions (oxidation/reduction) between the active materials (anode/cathode) that have a potential difference in the presence of an electrolyte. A Lithium ion battery (LIB) is composed of three main components: two electrodes with different electrical potential, and a separator, which electrically isolates the electrode from each other and allows the Li ions to migrate between the electrodes.

LIBs offer valuable properties, i.e., long cycle life, high energy density, reasonable production cost, and the ease of manufacturing flexible designs. Although, developing anode materials for lithium ion batteries with higher performance and competitive price is still the main hurdle to reduce weight and improve the performance of this type of batteries. Early in 1991, Sony introduced the first lithium ion battery to the market in which graphite was used as active anode material due to its abundance, low production cost, and reasonable theoretical capacity (Broussely et al., 1999)[108]. This event drew the attention of many researchers and motivated them to do extensive work to improve the performance of lithium ion batteries. However, using cathode as anode material is accompanied by several drawbacks. It suffers from severe structure collapse and exfoliation over cycling that originally starts with the formation of solid electrolyte interface followed by rapid capacity fading. The low operating voltage of approximately 0.1 V vs Li/Li^+ is another problem. Such a low potential allows for lithium electroplating at the electrode surface which requires using other materials for safety issues (Madian et al., 2017)[109]. Moreover, the use of a graphite-based anode is particularly restricted to low-temperatures. However, the hybrid electric vehicles (HEVs) and electric vehicles (EVs) are usually charged/discharged at high current rates over a wide temperature range (-30°C to +60°C), where the application of graphite is not suitable and does not meet the EVs requirements. Therefore replacing graphite with another material becomes necessary. A variety of materials have been proposed as promising candidates for the negative electrode in lithium ion batteries including lithium-metal alloys, aluminium, gallium, and lead.

One of the most successful Li-ion cathode formulas developed to date is obtained by combining nickel, manganese, and cobalt. Lithium-Nickel-Manganese-Cobalt-Oxide abbreviated as NMC has become the cathode powder to develop batteries for power tools, e-

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[108] M.Broussely, P.Biensan, B.Simon (1999). “Lithium insertation into host materials: The key to success for Li ion batteries”. In *Electrochim. Acta* **1999,** 45, pp.3-22.

[109] M.Madian, A.Eychmüller, and L.Giebeler (2017). “Current Advances in TiO_2-Based Nanostructure Electrodes for Higher Performance Lithium Ion Batteries”.

bikes and other powertrains. It delivers strong overall performance, excellent specific energy, and the lowest self-heating rate of all mainstream cathode powders, which makes it the preferred option for automotive batteries. As well, Lithium Iron Phosphate (LFP) is a popular, cost-effective cathode material for lithium-ion cells that is known to deliver excellent safety and long life span, which makes is particularly well-suited for specialty battery applications requiring high load currents and endurance. Discovered by University of Texas researchers in the mid-90s, LFP cathode offers several key advantages including a high current rating, long cycle life, and superior thermal stability, which makes it one of the safest and most abuse-tolerant cathode material options available to manufacturers. On the other hand, LFP delivers a lower nominal voltage, which results in lower specific energy when compared to other cathode materials on the market. Consequently, LFP batteris tend to have a higher self-discharge than other Li-ion battery types.

Besides lithium-ion batteries, the lithium-sulfur (**Li-S**) batteries have attracted great attention as the next generation rechargeable batteries due to its high theoretical energy density capacity, environmental sustainability, and cost-effectiveness. The lithium-sulfur battery uses a lithium metal anode but with composite sulfur cathode that is paired with an organic liquid-sulfide electrolyte. The sulfur cathode is often blended with either graphite, graphene, or even silicon in some cases. It has potential to achieve 1675 mAh/g and 2500 Wh/kg or 2800 Wh/L at the material level which translates into about 400-600 Wh/kg at the cell level.

Lithium-Sulfur (Li-S) batteries have been considered as a promising storage system from the ealy 1960s. Sulfur is low cost material and abundant in nature. It has a high theoretical gravimetric capacity, high energy and high volumetric density. The Li-S battery offers many challenges that have to be overcome before full commercialization of stable cells wih high gravimetric energy density. The major issues are lithium polysulfides' transport towards the anode, the so-called lithium polysulfides shuttle mechanism and the cells' self-discharge, which causes capacity decay (Dominko &Vizintin, 2023)[110]. Although, recently, Lyten, a California, U.S.-based supermaterials application company and the leader in lithium-sulfur battery technology announced that it is consistently surpassing 90 percent yield from its automated production line, confirming the manufacturability of its lithium-sulfur battery utilizing sulfur cathode and lithium metal anode. Lyten's lithium-sulfur battery has the potential to be a key ingredient in enabling mass-market EV adoption globally[111].

Lyten's lithium-sulfur battery chemistry utilizes no NMP (N-metryl-2-pyrollidone) in the cathode manufacturing process, eliminating the potential health, safety, and environmental impacts of the highly toxic solvent standard in today's lithium-ion batteries. Additionally, the lithium-sulfur battery cell has proven to be highly tolerant to metallic contamination (that is problematic in case of the leading battery chemistries (NMC and LFP[112]).

Nickel-cadmium (Ni-Cd) batteries are widely used in the automotive industry, in electric vehicles, aviation, emergency systems (lighting), and military equipment (radio

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[110] R.Dominko, A.Vizintin (2023). In *Comprehensive Inorganic Chemistry* III (Third Edition).

[111] "Lyten Achieves Manufacturing Milestone: Now Producing Lithium-sulfur Batteries at Greater Than 90% Yield". Press release, 14 may 2024.

[112] LFP is a type of lithium-ion battery using lithium-iron phosphate as the cathode material, and a graphite carbon electrode with a metallic backing as the anode. Due to its low cost, high safety, low toxicity, long cycle life and other factors, LFP batteries are finding a number of roles in vehicle use, utility-scale stationary applications, and backup power.

communication). This kind of batteries are direct competitors with lead-acid batteries since they offer similar technical characteristics, but with superior cycling abilities and energy density. They are characterized by an energy density of about 50-60 Wh/kg, and the nominal voltage of one cell is 1.2 V . Like all the batteries described earlier, they contain two electrodes, out of which the anode is made of metallic cadmium, while the cathode is made of nickel oxide. The electrolyte in such a battery is a 20-30% aqueous solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH).They are also characterized by a high number of charging and discharging cycles, from several hundred to several thousand, depending on the design.

An important advantage of the considered batteries is their high resitance to shocks and vibration as well as low costs. However, scientific research is also being carried out focusing on the problem of recycling and the recovery of cadmium from the batteries mentioned above. Despite their superior cycling characteristics and energy density, NiCd batteries have their drawbacks. The batteries are constructed from highly toxic materials and suffer from „memory effect“, which requires that the battery be fully charged even after a partial discharge. This technology is in use for a long time in applications that require a long battery life and in difficult environmental conditions because this battery technology is cheap and robust.

Nickel-metal hydride (Ni-MH) technology is based on the negative electrode made from hydrogen absorbing alloys, which have the possibility to absorb releasing hydrogen, and the positive electrode made from nickel oxy-hydroxide. There is a separator, which separates positive and negative electrodes to prevent shorting between electrodes. Electrolyte used in this technology is potassium hydroxide (KOH). There is a current collector made of metal, which minimizes the internal battery resistance. To release gases produced during the over changing or shorting there is a self-sealing safety vent. Similarly with Ni-Cd batteries this type of batteries have also the so-called “memory effect”, which consists in reducing the capacity if the battery is charged before it is completely discharged. Therefore, it is recommended that Ni-MH batteries be fully discharged before charging (Detka & Górecki, 2023)[113].

For Ni-MH batteries, the chemistry at the positive electrode is the same in the Ni-Cd battery. The advantages if Ni-MH batteries include a higher energy density (60-120 Wh/kg) than in the case of Ni-Cd batteries; they are characterized by half the operating time on a single charge as compared with Ni-Cd batteries. These batteries are safe for the environment and are characterized by the ability to operate in a wide temperature range, i.e., from 5℃ to 60℃. However, the significant disadvantage of this type of batteries are certainly lower capacity compared with lithium-ion batteries, high voltage instability when charging, which requires precise charging control, and tendency to self-discharge, which means that they must be recharged every few months, even if not used.

At present, Ni-MH batteries have achieved an annual worldwide production of over 1 billion cells. This type of batteries have been recently used in many electric car applications since they do not have oxide properties and have better performance (Aktaş & Kirçiçek, 2021)[114]. This technology has been used in several applications such as energy storage for smart

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[113] K.Detka, K.Górecki (2023). “Selected Technologies of Electrochemical Energy Storage – A Review”. In *Energies* **2023,** 16, 5034

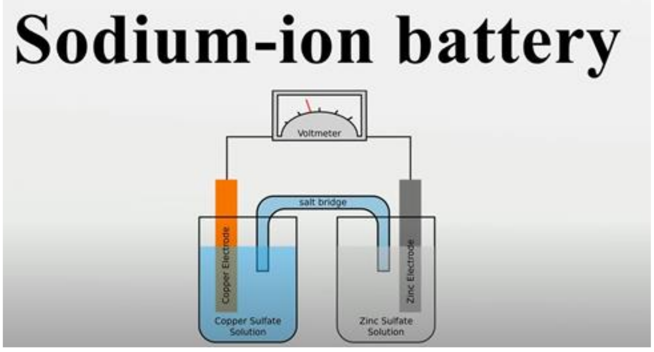
[114] A.Aktaş, Y.Kirçiçek (2021). “Solar Hybrid Systems and Energy Storage Systems”. In *Solar Hybrid Systems*, **2021**.

energy systems, robust battery systems that work at high temperatures, hybrid electric cars and public transport.

Sodium-sulfur (NaS) batteries have attracted attention due to the wide availability of sodium and its stable operation in all temperature levels. Sodium provides an electrochemical reduction potential of – 2.71 V versus standard hydrogen electrode. When sodium is coupled as an anode with an appropriate cathode material, it is capable of giving a cell voltage >2V. The combination of high voltage and low mass leads to the possibility of employing sodium as anode material in rechargeable battery for obtaining high specific energy. Sodium-sulfur (NaS) and sodium-ion batteries are the most studied sodium batteries by the researchers' worldwide (Kumar et al., 2017).

Sodium battery technology has its origins in the 1960s. By the late 1970's a variety of developers had advanced sodium-sulfur technology for applications ranging from satellite communications to large stationary power. It is one of the most suitable for use in energy storage systems due to its high energy density. The major components of the Na-S cell are solid ceramic electrolyte of ß-alumina and electrodes of sodium and sulfur in liquid state. A Na-S battery assembly consists of three major subsystems: a large number of electrically and mechanically interconnected cells, a thermal enclosure maintaining a temperature in the range 300-350 ℃ and a heat management system for initially heating and removing waste heat from battery.

Figure 16. Sodium-ion battery



Source: University of Houston (2022).

Due to the advantages of long service life, high changing efficiency and high energy density, high-temperature sodium-sulfur battery systems have been used in stationary energy storage systems. However, in order to maintain the molten conductive state of the two poles, a high operating temperature is required. These high temperatures limit their energy efficiency and create safety concerns, although research is focusing on developing room temperature sodium-sulfur batteries. The high operating temperature not only causes a loss of electrical energy, but also may cause the failure of the solid electrolyte, which causes explosions and fires due to contact between the cathode and the anode. These problems limit the wide application of high temperature sodium-sulfur batteries (Wang et al., 2020)[115].

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[115] Y.Wang, D.Zhou, V.Palomares, D.Shanmukaraj, B.Sun, X.Tang, C.Wang, M.Armand, T.Rojo, G.Wang (2020). "Revitalizing sodium-sulfur batteries for non-high temperature operation: A crucial review". In *Energy & Environmental Science* **2020,** 13, pp.3848-3879.

Redox flow batteries (RFBs) are electrochemical devices halfway between secondary batteries and fuel cells. The energy is stored in two electrolytes, separated by an ion exchange membrane. There is no electrochemical reaction between the electrolytes and the electrodes. They can supply power as long as they are supplied with electrolytes.

A typical RFB usually has two electrolyte tanks for energy storage, a cell or several cells (stack) for the electrochemical reaction and pumps for the flow of the electrolyte between the tanks and the stack. The difference between RFB technology and other battery systems is that in RFBs, the energy is stored in electrolyte solutions, and the redox pair concentration and the volume of the electrolytes determine the system capacity. Consequently, the power and the capacity are separated and offer flexibility to build battery systems under different working conditions.

RFBs can be classified by active species or solvent (aqueous and non-aqueous, respectively). In the discharge mode, an anolyte solution flows through a porous electrode and reacts to generate electrons, which flows through the external circuit. The charge-carrying species are then transported to a separator (typically an ion-exchange membrane), which serves to separate the anolyte and catholyte solutions. RFB classification can be carried out according to the structure of the cell or according to the type of redox couple used, as indicated in the figure 17.

Figure 17. Main redox couples used in flow batteries

Redox couples	**Redox reaction**	**E^0 (V)**	**Electrolyte**
All vanadium	Anode: $V^{2+} \longleftrightarrow V^{3} + e^-$ Cathode: $VO_2^+ e^- \longleftrightarrow VO^{2+}$	1.4	H_2SO_4/H_2SO_4
V-polyhalide	Anode: $V^{2+} \longleftrightarrow V^{3+} + e^-$ Cathode: $\frac{1}{2} Br_2 + e^- \longleftrightarrow Br^-$	1.3	VCl_3-HCl/NaBr-HCl
Fe/Cr	Anode: $Fe^{2+} \longleftrightarrow Fe^{3+} + e^-$ Cathode: $Cr^{3+} + e^- \longleftrightarrow Cr^{2+}$	1.2	HCl/HCl
Br/polysulphure	Anode: $2S_2^{2-} \longleftrightarrow S_4^{2-} + e^-$ Cathode: $Br_2 + 2e^- \longleftrightarrow 2 Br^-$	1.5	$NaS_2/NaBr$
H_2/Br_2	Anode: $H_2 \longleftrightarrow 2H^+ + e^-$ Cathode: $Br_2 + 2 e^- \longleftrightarrow 2Br^-$	1.1	PEM^+ - HBr
Zn/Br	Anode: $Zn \longleftrightarrow Zn^{2+} + 2 e^-$ Cathode: $Br_2 + 2 e^- \longleftrightarrow 2Br^-$	1.8	$ZnBr_2/ZnBr_2$
Zn/Ce	Anode: $Zn \longleftrightarrow Zn^{2e} + 2 e^-$ Cathode: $2Ce^{4+} + 2 e^- \longleftrightarrow 2Ce^{3+}$	2.4	CH_3SO_3H/CH_3SO_3H

Source: Adapted from the article by Leung et al., (2012). "Progress in redox glow batteries, remaining challenges and their applications in energy storage". In *RSC Adv* 2012, 2 pp. 10125-10156.

There is conceptual difference between power and energy properties. Namely, the delivered power depends upon electrodes dimension and number of cells, whereas the volume of the reservoirs that contain the electrolytes flowing through the cells determines the storage capacity. For a given power absorption, the energy capacity can be increased by introducing more electrolyte (using more capacious reservoirs). Therefore, flow batteries are particularly advantageous for long-term applications, when several hours of storage are required. The recharge capacity is equivalent to the rapidity of refilling; therefore, this kind of battery appears particularly promising for mobile applications. In comparison with other types of batteries, redox systems have an outstandingly long life and no operative limitations (e.g. no “memory effects” or problems connected with discharge).

Vanadium-redox flow battery (VRFB) is one of the most promising electrochemical energy storage systems that are suitable for a wide range of renewable energy applications. This technology has been successfully implemented in a number of field trials and demonstration projects around the world. The main drawback of this technology is that it suffers from low energy density that limits its use to stationary applications. Therefore, extensive research is being carried out to improve its energy density and enhance its performance to enable mobile applications while simultaneously trying to minimize the cost by using cost effective stack materials (Parasuraman et al., 2013)[116].

The particularity of redox flow batteries is that the active species are dissolved in liquid electrolytes, with the reaction occurring in the solid-liquid interface between the active solution and an inert electrode, as a difference with other batteries as Li-ion batteries or solid-state batteries, where the reaction takes place in the solid electrodes. This technology has a long lifetime, very fast response time and long storage time that is ideal for long-term energy storage. Power and energy of VRFB are independent, power depends on the number and size of the cells and energy depends on the available electrolyte, respectively tank size.

A zinc-bromine flow battery (ZBFB) is a type of redox flow battery in which a large part of the energy is stored as metallic zinc, deposited on the anode. For these reasons, the total energy storage capacity of this system depends on both the size of the battery (effective electrode area) and the size of the electrolyte storage tanks. Therefore, in this type of battery, the capacity and power are not totally decoupled (Jimenez-Blasco et al., 2021)[117]. During charge, the electrolyte is pumped into the cell, where bromine gas is formed in the cathode part due to the oxidation of the bromide, while in the anodic part, the zinc ions are reduced into metallic zinc and is deposited on the surface of the electrode. Bromine has limited solubility in water, so a bromine complexing agent is added to the electrolyte to capture the bromine formed and prevent its evaporation (the boiling point of bromine is 58.8).

The energy efficiency of this battery is around 70%, and it offers one of the highest voltages of the redox pairs used in flow batteries (1.8 V), releasing two electrons per atom of zinc. In having such a high density, the weight and cost are reduced for the same storage capacity as a similar battery. However, as bromine is a highly toxic compound to inhale or

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[116] A.Parasuraman, T.M.Lim, C.Menictas, M.Skyllas-Kazacos (2013). “Review of material research and development for vanadium redox flow battery applications”. In *Electrochimica Acta*, Volume 101, 1 July 2013, pp. 27-40.

[117] U.Jimenez-Blasco, E.Moreno, M.Colera, P. Diaz-Carrasco, J.C.Arrebola, A.Caballero, J.Morales, O.A.Varga. “Enhanced Performance of Zn/Br Flow Battery Using N-Methyl-N-Propylmorpholinum Bromide as Complexing Agent”. In *International Journal of Molecular Sciences* **2021**, 22, 9288.

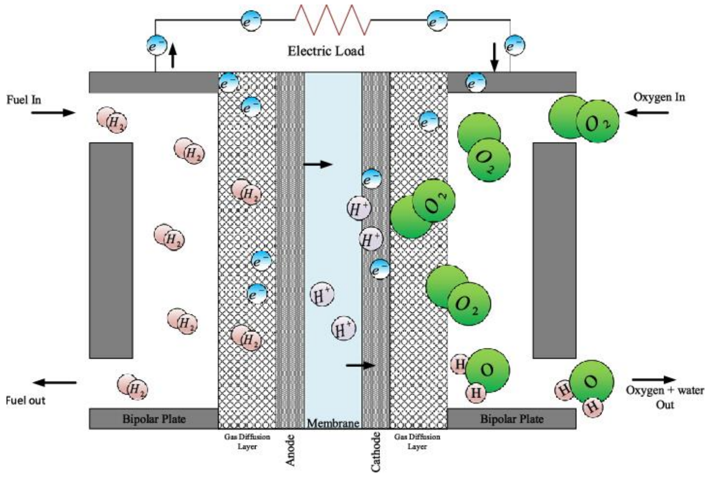
absorb, it is necessary for a complete bromine capture process to take place within the cell. This is essential for the safety and efficiency of the system (Zhang et al., 2013)[118].

2.3.2 Fuel Cells

A fuel cell is energy conversion device that converts the chemical energy of a fuel gas directly to electrical energy and heat without the need for direct combustion as an intermediate step, giving much higher conversion efficiencies than conventional thermochemical methods They can operate at higher efficiencies than combustion engines and can convert the chemical energy in the fuel directly to electrical energy with efficiencies capable of exceeding 60%. In addition, fuel cells have lower or zero emissions compared to combustion engines. Hydrogen fuel cells can emit only water, addressing critical climate change challenges as there are no carbon dioxide emissions.

A fuel cell stack consists of several individual cells combined in series to provide the requisite voltage for a given application. Each fuel cell in the stack contains two electrodes – a positive cathode (where the reduction occurs and a negative anode (where the oxidation occurs). The energy producing reactions take place at the surfaces of the electrodes. Each individual pair of electrodes is separated by an electrolyte (either in solid or liquid form). This electrolyte carries electrically charged particles (ions) between the electrodes. The rate of a given reaction can be increased with the help of a catalyst such as platinum or nickel.

Figure 20. A typical structure of Proton Exchange Membrane Fuel Cell



Source: Adapted from the article „Adaptive Control of Membrane Conductivity“ by Farcaş and Dorbra (2014)[119].

Present materials' science has made the fuel cells a reality in some specialized applications. By far the greatest research interest globally has focused on Proton Exchange Membrane (PEM) and Solid Oxide cell stacks. PEMs are well advanced type of fuel cell that are suitable for cars and mass transportation. The classification of fuel cells is complicated, as

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[118] L.Zhang, H.Zhang, Q.Li, Y.Cheng. "Development of carbon coated membrane for zinc/bromine flow battery with high power density. In *Journal of Power Sources* **2013**, 227, pp.41-47.

[119] Farcaş and Dorbra (2014). „Adaptive Control of membrane Conductivity". In *Procedia Techno*logy 12 (8), pp. 42-46.

they can be classified by operating temperatures, electrolytes, and fuels. Based on the differences in electrolytes, fuel cells can be commonly dividied into:

- polymer membrane fuel cells (PEMFC),
- alkaline fuel cells (AFC),
- solide oxide fuel cells (SOFC),
- phosphoric acid fuel cells (PAFC),
- high temperature molten carbonate fuel cells (MCFC),
- direct methanol fuel cells.

If classified by temperature, AFC and PEMFC belong to low temperature fuel cells (less than 100℃), PAFC belongs to medium temperature fuel cells, while SOFC and MCFC belong to high temperature fuel cells. Different types of fuel cells differ in output, operating temperature, electrical efficiency, and typical application. In addition, the operating temperature of the fuel cells and the rate of the ion transfer also depend on the properties of the electrolytes. Appropriate high temperatures can improve cell efficiency and thus reduce material costs (Hossain et al., 2017)[120].

Figure 21. Comparison of fuel cells

Cell type	**Fuel**	**Electrolyte/membrane**	**Temperature (Celsius)**	**Generated Voltage (V)**	**Electrical Efficiency (%)**
AFC	Hydrogen	Aqueous solution of potassium hydroxide	90-100	1.0	60
PAFC	Hydrogen	Liquid phosphoric acid	150-200	1.1	>40
SOFC	Hydrogen, carbon monoxide, methane	Solid zirconia with an admixture of yttrium oxide	600-1000	0.8-1.0	35-43
MCFC	Hydrogen. Methane, carbon monoxide	A mixture of molten sodium and/or potassium carbonates	600-700	0.7-1.0	45
PEMFC	Hydrogen	Solid polymer, perfluorosulfonic acid	50-100	1.1	53-58
DMFC	Methanol	Solid polymer membrane	60-200	0.2-0.4	40

Source: Adapted from the article „Case Study: Fuel Cells“ by LibreTexts Chemistry, 2024.

The operating principles of fuel cells are similar to those of batteries, i.e., electrochemical combination of reactants to generate electricity. It is a combination made of gaseous fuel (hydrogen) and an oxidant gas (oxygen from the air) through electrodes and via an ion conducting electrolyte. In fuel cells, pure hydrogen or a mixture of hydrogen with other gases is the most often used fuel. The efficiency of fuel cells largely depends on the type of the fuel used. In typical solutions, it assumes values in the range from 35% to 60%.

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[120] S.Hossain et al. (2017). “Review of proton conducting electrolytes for clean energy and intermediate temperature-solid oxide fuel cells”. In *Renewable Sustainable Energy Review* 79, pp. 750-764.

Fuel cells are unique in terms of the variety of their potential applications; they can use a wide range of fuels and feedstocks and they can be potentially used in multiple applications, providing power across different sectors, including transportation, industrial buildings and long-term energy storage for the grid in reversible systems (U.S Department of Energy, 2024)[121].

In the alkaline fuel cell (**AFC**), the electrolyte is a water solution of potassium hydroxide. This type of fuel cells consume hydrogen and pure oxygen, to produce potable water, heat, and electricity. They are among the most efficient fuel cells, having the potential to reach 70%. NASA has used alkaline fuel cells since the mid-1960s, in the Apollo-series missions and on the Space Shuttle. AFC is characterized by high sensitivity to carbon dioxide, which reduces the amount of hydroxyl group ions during a chemical reaction, and thus the degradation of such a cell. In order to avoid the destruction of the cell, an auxiliary carbon dioxide air purification system and pure oxygen supply are often used. In addition, the electrolyte used in these cells is corrosive, which shortens its life.

Phosphoric acid fuel cells (**PAFC)** are a type of fuel cell that uses liquid phosphoric acid as an electrolyte. They were the first fuel cells to be commercialized. Developed in the mid-1960s and field-tested since the 1970s, they have improved significantly in stability, performance, and cost. PAFC have developed more slowly than other fuel cells due to the low conductivity of acid. Phosphoric acid fuel cell technology has widespread commercial use in many countries, especially in hospitals, residences, and schools. The efficiency of this type of fuel cell has reached 40% in electricity generation and 85% in cogeneration applications. Due to its high operating temperature, it has the potential to provide hot water, as well as electricity, depending on the need for electricity and heat energy.

The proton exchange membrane fuel cell (**PEM**) is unusual in that its electrolyte consists of a layer of solid polymer which allows protons to be transmitted from one face to the other. It basically requires hydrogen and oxygen as its inputs, though the oxidant may also be ambient air, and these gases must be humidified. It operates at a low temperature because of the limitations imposed by the thermal properties of the membrane itself. The operating temperatures are around 90℃. The PEM can be contaminated by carbon monoxide, reducing the performance by several percent for contaminant in the fuel in ranges of tens of percent. It requires cooling and management of the exhaust water in order to function properly.

There are a number of companies involved in manufacturing PEM, Ballard are probably the leaders, though companies such as DeNora in Italy and Siemens are progressing fast. The main focus of current designs is on transport applications, as there are advantages to having a solid electrolyte for safety, and the heat produced by the fuel is not adequate for any form of cogeneration. Daimler-Benz has taken a high profile in developing cars powered by Ballard fuel cells, while Toyota has recently presented a vehicle that is using a fuel cell of their own design. Other car manufacturers, including General Motors and Ford, are actively engaged in similar developments. It seems to be that there is a strong possibility of using the PEM in very small scale localized power generation, where the heat could be used for hot water or space

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[121] U.S Department of Energy (2024). "Fuel Cells". Hydrogen and Fuel Cell Technologies Office.

heating (Hydrogen Central, 2021)[122]. There is also a possibility of a heater/chiller unit for cooling in areas where air conditioning is popular.

Molten carbonate fuel cell (MCFC) is one of the most promising high efficiency and sustainable power generation technologies. In the molten carbonate fuel cell, the electrolyte consists of a molten mixture of potassium carbonate and lithium carbonate to transport carbonate-ions from the cathode to the anode. The operating temperature is about 850°C which allows nickel to be used as catalyst material. Oxygen and carbon dioxide are fed to the cathode and fuel to the anode of the fuel cell. The key electrochemical reaction at the cathode is the reduction of oxygen and reaction with carbon dioxide to form carbonate ions that are transported through the molten electrolyte and converted back to carbon dioxide at the fuel cell anode. Since the earliest days of development, nickel oxide (NiO) has been the material of choice for the cathode. It meets all the essential needs of the MCFC cathode except for that it slowly dissolves in the electrolyte. Unlike many other types of fuel cells, MCFCs are capable of internal reforming, whereby they convert other fuels to hydrogen directly. Simultaneously, MCFCs have several significant advantageous characteristics. Basically, they are more resistant to impurities than other fuel cell types. Therefore, MCFCs can use gases derived from coal or carbon oxides as fuel.

Unlike the first generation utility-type fuel cells, the molten carbonate systems operate at sufficiently high temperatures so that natural gas, and other fuels can be reformed internally yielding the H_2 consumed by the cells. It allows the transport of carbonate ions. MCFCs could work with an efficiency of up to 60% reaching an operating power of 100 MW. Using waste heat from the system, fuel efficiency can be as high as 85%, a value above performance in PAFCs, PEMFCs, another clear comparative advantage. In this regard, MCFCs compete very well with PAFCs, PEMFCs and other types of fuel cells, because they do not require an external reformer to convert other types of fuels into hydrogen.

Solid Oxide Fuel Cells have emerged as a high temperature fuel cell technology. promising devices towards highly efficient power generation from chemical energy. SOFCs differ in many respects from other fuel cell technologies. Solid oxide fuel cells have three main components: anode, cathode and electrolyte. The anode and cathode have a relatively high porosity, which allows gasses to pass through them. The cathode side receives oxygen (from air), and the anode receives fuel (e.g. hydrogen or its mixture with carbon monoxide if hydrogen is derived from a hydrocarbon fuel source).

The electrolyte is SOFC's is a solid, ceramic inorganic oxide, generally yttria-stabilized zirconia, rather than a liquid electrolyte, and require operation at elevated temperatures, typically 750-1000°C. Operating at very high temperatures make them ideal for combined heat and power systems, using high-grade waste heat, whereas, home applications can replace boilers for heating. This type of fuel cells can already run on fuels like natural gas and biomethane, which are converted to hydrogen in the fuel cell's reformer. The high operating temperature allows internal reforming, promotes rapid electrolysis with non-precious materials, and produces high quality by-product heat for co-generation.

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[122] Hydrogen Central (2021). "This is how Daimler began with fuel cell research for mobile applications 30 years ago". 1 March 2021.

This technology can be used in a wide range of applications for both domestic and industrial sectors, from distributed power/CHP generation to light traction vehicles. The SOFCs have high fuel flexibility, low emission and relatively low operating costs. However, the main drawbacks of this technology are the high costs of manufacture and the rapid deterioration of the fuel cell performance (Nguibous Batista, 2023)[123].

Fuel cells is a prominent technology for indirect electrification through renewably produced methanol to overcome the inherent disadvantages of batteries in transportation applications. The Direct Methanol Fuel Cells (**DMFC**) is a device that generates electrical energy using methanol and oxygen. In contrast to indirect methanol fuel cells, where methanol is reacted to hydrogen by steam reforming, DMFCs use a methanol solution (usually about 3% in mass) to carry the reactant into the cell. Common operating temperatures are in the same range 50 to 120°C, where high temperatures are usually pressurized. These cells have advantages such as high density environmentally friendly products, and they are lightweight. In DFMC, the slow reaction of the anode and the cathode creates a problem with energy conversion. Platinum is the most used catalyst, but it undergoes CO poisoning due to methanol passing through the anode and provides low activity for the oxygen download reaction. In DMFC, it is important to absorb methanol to the surface of the electrode in the fuel cell. When methanol is fed with water in the anode, it prevents thermal management problems better than other fuel cells.

In principle, the structure of DMFC is similar to that of a battery. It also has an anode and cathode that are separated by a membrane. By means of an electrochemical reaction, the direct methanol fuel cell converts the fuel, i.e, methanol into electricity in combination with oxygen, producing only waste heat, waste vapor and a small amount of carbon dioxide as waste products of the combustion process. The main advantages of the direct methanol fuel cell are clear. Direct methanol fuel cells like all fuel cells work without moving parts. As compared to combustion engines, they are not only very silent, but also require less maintenance. A more efficient version of a direct fuel cell would play a key role in the theoretical use of methanol as a general energy transport medium, in the methanol economy.

It is considered as a promising power source for the next-generation portable electronics, owing to its characteristics such as a high energy density, convenient refuelling of liquid fuel, and ambient operation conditions. However, there still remain several critical problems to be overcome in order to commercialize the DMFC system as a real power source.

2.4 Chemical energy storage

Nowadays chemical energy storage systems are very popular due to long-time energy storage capability. They are classified into two categories well known as hydrogen and biofuels. The hydrogen storage system is one of the emerging storage techniques to store the energy for long-term with a flexible energy carrier. Hydrogen can be pressed, hydrated, or stored in a solid or liquid state in fuel cells, and industrial and transport applications but a major challenge related to hydrogen is its production and storage. The conversion of sunlight into

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[123] C.T.Nguimbous Batista, R.Steinberger-Wilckens (2023). “33rd European Symposium on Computer Aided Process Engineering”. In *Computer Aided Chemical Engineering*, 2023.

fuels and chemicals is an attractive prospect for the storage of renewable energy. Photo-electro catalytic technologies (e.g., solar fuels) represent a pathway by which solar fuels might be realized. However, there are numerous scientific challenges in developing these technologies. These include finding suitable materials for more efficient catalysts for both water splitting and the production of fuels.

The energy stored as chemical energy can be exploited in several final uses, which can be thermal, fuel for mobility applications, re-conversion to electricity, or synthesis of liquid fuels or chemicals. This concept, which integrates several energy sectors by means of hydrogen as an intermediate energy vector, is known as *sector coupling*, and it is the driving force of the rising interest in hydrogen technologies because of its high decarbonizing potential. It is about connecting the energy sector with the industry, transport, and building sectors and then optimizing them together. Apart from the power sector, heating, cooling and transport are other areas in which fossil fuels are to be gradually replaced with renewables. Renewables can be used directly to heat buildings or by using electricity from renewables to bring the energy transition into other sectors. For example, in the heating sector it will enable replacing oil and gas-fired heating systems with electric systems powered by renewable energy. Power-to-heat technologies can be combined with heat storage units and programmed to absorb electricity from the grid at times when a lot of electricity is being generated. Power-to-gas allows energy from electricity to be stored and transported in the form of compressed gas, often using existing infrastructure for long-term storage. Both of these technologies are dealt with in the next chapter.

There are four major chemical storage technologies in the form of ammonia, hydrogen, synthetic natural gas, and methanol. Currently, the most promising solution for large-scale energy storage is chemical storage, which is possible by generating hydrogen (H_2), ammonia (NH_3) or carbon-based synthetic fuels (though other options also exist). Synthetic or carbon-neutral fuels capture CO_2 in the manufacturing process. In this way, this greenhouse gas becomes a raw material, from which gasoline, diesel, and substitute natural gas can be produced with the help of electricity from renewable sources. The electricity demand for the production of these fuels increases from H_2 and NH_3 to carbon-based gases and liquid fuels. An additional advantage of such synthetic fuels is the relative ease of adapting existing and proven technologies for their transport, storage and use. Nevertheless, all alternative fuels are currently significantly more expensive than fossil energy. This remains the major economical obstacle for implementing non-fossil carbon neutral and carbon free technologies (Lauf & Zimmermann, 2021)[124].

The use of ammonia and hydrogen as fuel or energy storage has been attracting a lot of attention in recent years. Hydrogen has great potential, however, issues associated with hydrogen storage and distribution are currently impeding factors for its implementation. On the contrary, the infrastructure and distribution systems currently in place are far more compatible with ammonia. Additionally, from the point of view of physical properties, ammonia can be easily liquefied at room temperature at about 10 bar or at minus 33 under ambient pressure, which is similar in properties to LNG thus offering easy transportation or

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[124] Dr J. Lauf, Dr R.Zimmermann. "Connecting production facilities and transport infrastructure for creating robust and carbon-neutral sector-integrated energy systems". In *Energy Highlights*, No 17, **2022,** NATO Energy Security Center of Excellence.

storage in the liquid phase. Overall, ammonia seems a very promising energy storage medium and carrier, but most of the ammonia produced globally is used for fertilizers. Hydrogen energy storage is another form of chemical energy storage in which electrical power is converted into hydrogen. Its production through water electrolysis is a promising approach since it leads to the production of sustainable fuel that can be used directly in hydrogen fuel cells or to reduce carbon dioxide in chemicals and fuels compatible with the existing infrastructure for production and transportation (Vasconselos & Lavoie, 2019)[125].

The production of ammonia (NH_3) via the Haber-Bosch process requires H_2 and N_2. Industrial ammonia production plants may use compressed ambient air (78% N_2 content) or for generating high purity N_2 via air separation technology. For H_2 as source material several options are available:

(1) Typically produced by steam reforming of fossil fuels at Haber-Bosch plants, releasing huge amounts of CO_2. However, only when the NH_3 is further processed into urea, the CO_2 is used in the production process.

(2) H_2 production from the electrolysis of water is currently used in countries with large amounts of cheap electricity. However, both production pathways mentioned above are very cost intensive.

(3) The usage of waste H_2 from industrial chemical production seems to be very promising option as well.

In the Netherlands, waste from H_2 from a "Dow Benelux" has no usage for the waste H_2. Dow Benelux outlined its plants to reduce current CO_2 emissions from its Terneuzen, the Netherlands, on its path to achieve net-zero emissions by 2050. The hydrogen would be used as a clean fuel in the production process. The CO_2 would be captured and stored until alternative technologies develop (Moares, 2021)[126] The ammonia produced by utilizing renewables via the Haber-Bosch process could help reduce above vast emissions in the ammonia industry.

Green ammonia has very good energy storage properties to solve the problem of electricity storage for renewable energy plants, like wind farms and photovoltaic solar systems. Ammonia can be produced at these sites to mitigate this issue by utilizing excess renewable energy. Most of the efforts in advancing the research on the use of green ammonia for energy storage is concentrated in Europe, with notable projects in countries like Australia, the USA, and Japan. In 2020, Siemens launched its green ammonia energy storage demonstrator in the UK. The demonstrator uses renewable power to make ammonia, a compound traditionally used to boost crop fields, by combining hydrogen, extracted from water and nitrogen from air. The ammonia is stored in a tank and converted back into electricity when either needed, through traditional combustion methods or by "cracking" it into nitrogen and hydrogen. In the latter

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[125] Bruno Rego de Vasconselos and Jean-Michel Lavoie. "Recent Advances in Power-to-X Technology for the Production of Fuels and Chemicals". In *Frontiers in Chemistry,* 5 June, **2019**, https://doi.org/10.3389/fchem.2019.00392

[126] R.Moares. "Dow Benelux to Build Green Hydrogen Plant in the Netherlands". In *Industry Europe*, 01 July 2021.

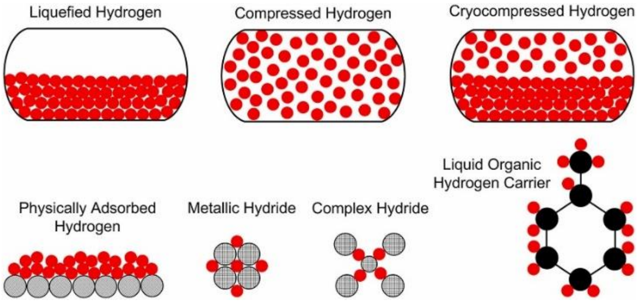
method, the hydrogen can then be used in hydrogen fuel cells to power devices such as electric vehicles (Power Technology, 2020)[127].

2.4.1 Hydrogen storage

Hydrogen has emerged as a promising and sustainable energy carrier, offering a clean and efficient alternative to fossil fuels. However, one of the key challenges in harnessing hydrogen's potential lies in its storage. The need for hydrogen's potential in Europe was estimated at some 72 terawatt hours by 2030 (Stargate Hydrogen, 2023)[128]. Therefore, efficient hydrogen storage is essential for its reliable use in various applications, from powering industries, fuel cell for vehicles to integrating renewable energy sources.

The produced hydrogen can be used for mobility, heating, power or industrial applications. However, due to the volatile nature of renewable energies, the energy availability and energy demand are not in synchronous mode. Therefore, efficent energy storage of hydrogen for mobile (road-bound, railroad, waterborne etc.) as well as stationary (from large-scale power plants to industrial housing) applications in the energy and industy sector is essential. Although hydrogen has the highest energy density per unit mass of any fuel, its low volumetric mass density at ambient temperature and pressure correspondingly results in a rather low energy density per unit volume.

Figure 22. Different methods for hydrogen storage



Source: Adapted from the article "Hydrogen storage methods: Review and current status" by M.R.Usman[129].

Today, hydrogen is stored either gaseous at high pressures (CHH_2) or in its liquid form (LH_2). However, CGH_2 requires energy for the compression of hydrogen, whereas enormous amount of energy is also needed for liquefaction of hydrogen for storage. Furthermore, even with very good isolation boil-off losses occur in LH_2 tanks over time due to heat from the environment. Absorption storage with metal-organic frameworks (MOF) has recently attracted attention in the field of hydrogen storage. MOFs consist of inorganic clusters or metal ions combined with organic molecules (ligands). However, the low absorption temperatures (approximately - 196℃) creates a challenge for practical applications. Another way to store hydrogen is via chemical reactions of LOHCs (liquid organic hydrogen carriers), but high

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[127] "Could Ammonia be the next key player in energy storage?" In *Power Technology*, February 6, **2020.**

[128] "Hydrogen Storage Solutions: Innovations and Advances". 04 December 2023.

[129] M.R.Usman (2022). "Hydrogen storage methods: Review and current status". In *Renewable and Sustainable Energy Reviews*, vol 167, October 2022.

temperatures are required to release hydrogen. Salt caverns and natural gas pipelines (direct hydrogen injection or natural gas injection upon methanation) are options for large scale storage. The natural gas pipelines can also serve for transportation of the hydrogen/natural gas.

Figure 23. Hydrogen storage technologies

Source: Adapted from the article „Recent developments in state-of-the-art hydrogen energy technologies – Review of hydrogen storage materials“ by Nagar et al 2023[130].

Storing hydrogen in the form of organic fuels including methane and methanol, is considered carbon-free, as these materials involve carbon in their molecules. Among reformed organic fuels, ammonia is also considered promising for storing hydrogen due to its high hydrogen density (17.8 wt%), availability of infrastructure, wide possibility for utilization (with and without decomposition), and good storability (liquefaction at pressure of 0.8 Mpa and temperature of 20°C). However, ammonia faces several challenges, including high energy demand during its synthesis, narrow flammability range (15.15-27.35% and 15.95-26.55% in dry and 100% relative humidity of air), relatively higher apparent toxicity[131].

The use of hydrogen as a fuel in a hydrogen economy is an attractive alternative to the current fossil fuel economy for reasons beyond climate change mitigation. As a fuel hydrogen has a gravimetric energy density, which is about 2.5-3 times higher than the most commonly, used fossil fuels today (see figure 8). Considering end-user application within a vehicle or industrial power generation facility, for every kilogram of hydrogen burnt, the use of stored hydrogen generates up to 2.5 to 3 times more energy than conventional fossil fuel. However, hydrogen has a much lower density than most fossil fuels and as such for the same phase, its volumetric density is lower than what is achievable with fossil fuels. This imposes volumetric sizing challenges on any media storing hydrogen. In a developed hydrogen economy, hydrogen is expected to be used both for the stationary as well as for the on-board purposes[132]. Hydrogen

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[130] R.Nagar, S.Srivastava. S. L. Hudson, S.L.Amaya, A.Tanna, M. Sharma, R.Achayalingam, S.Sonkaria, V.Khare, S.S.Srinvasan (2023). “Recent developments in state-of-the-art hydrogen energy technologies – Review of hydrogen storage materials”. In *Solar Compass*, Volume 5, March **2023**.

[131] Approximately three orders of magnitude higher than methanol.

[132] Mainly transportation sector: industries including automobiles, aerospace, unmanned aerial systems and hydrogen tanks used throughout the hydrogen supply chain.

storage for a stationary application is far less challenging than for an on-board application. The increasing development of light and heavy fuel cell vehicles is expected to drive the development of on-board solid-state hydrogen technologies. For the stationary applications, the weight of the storage system that is gravimetric hydrogen density is less of a concern than the volume of the storage system or volumetric hydrogen density.

Liquid hydrogen

Among the above-mentioned hydrogen storage systems, liquid hydrogen is considered promising in terms of both gravimetric and volumetric hydrogen densities, high hydrogen purity and the possibility for low-pressure storage. This form of hydrogen was initially produced in 1898, and its application as a rocket fuel was adopted at the beginning of the 1950s. As the demand for aerospace and other applications is increasing, the production of liquid hydrogen also grows. Moreover, the rapid growth of various hydrogen applications, including fuel cell based power generators and vehicles, require high purity of hydrogen on a large-scale basis, which can be provided by liquid hydrogen-based storage and transportation (Yin & Ju, 2023)[133].

Liquid hydrogen and ammonia are considered promising storing methods, considering their hydrogen storage density and utilization. Liquid hydrogen is light and has fewer potential risks as compared with gas in terms of storage pressure. However hydrogen liquefies at 20.25K, thus storage vessels require sophisticated insulation techniques to minimize unavoidable heat transfer leading to hydrogen loss via boil-off. Like gaseous hydrogen, liquid hydrogen is odorless, tasteless, and colorless. The main characteristics of liquid hydrogen distinguishing it from gaseous hydrogen are its very low temperature and liquid phase. The liquid phase leads to a significantly higher density (approximately 848 times of gaseous hydrogen). The properties of liquid hydrogen are shown in Figure 24.

Figure 24. Physical properties of liquid hydrogen

Properties	**Value**
Density (kg/m^3)	70.85
Volumetric energy density (kWh/L)	2.36
Gravimetric energy density (kWh/kg)	33.3
Heat of evaporation (kJ/kg)	446
Heat of ortho- to para-hydrogen (-253°C) kJ/kg[134]	703

According to Wijayanta et al (2019)[135], liquid hydrogen is the most economically competititve when high-purity hydrogen is required during utilization. In addition, liquid hydrogen remains highly competitive compared to ammonia in many carbon-neutral

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[133] L.Yin, Y.Ju. “Review on the design and optimization of hydrogen liquefaction processes”. In *Frontiers Energy* **2020**, 14, pp. 530-544.

[134] Hydrogen has two different spin isomers that possibly co-exist; they are ortho- and para-hydrogen. This phenomenon was initially observed in 1912 during experiments using hydrogen at low temperatures.

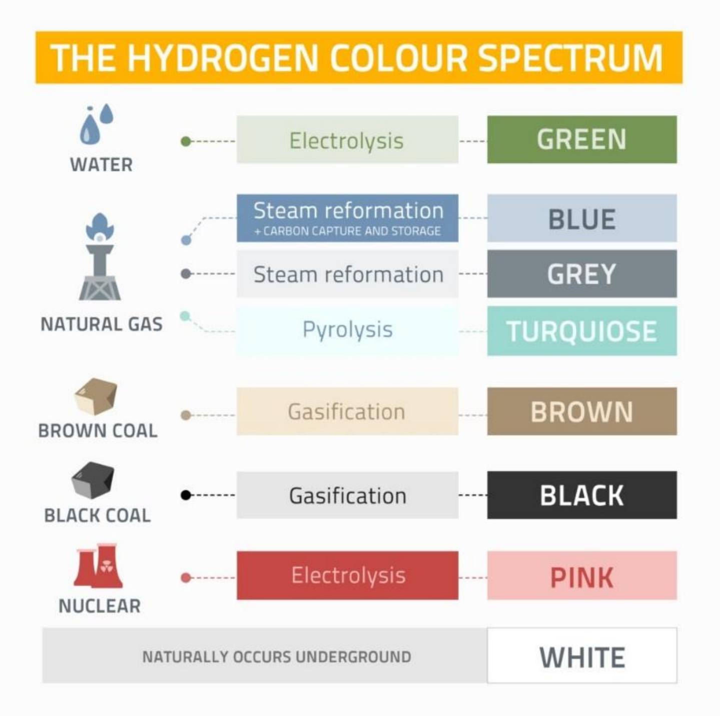
[135] A.T.Wijayanta, T.Oda, C.W.Purnomo, T.Kashiwagi, M.Aziz (2019). “Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review”. In *International Journal of Hydrogen Energy* **2019**, 44, pp. 15026-15044.

applications. Liquid hydrogen is predicted to be applicable for advanced applications demanding high gravimetric energy density, such as maritime and aviation.

Hydrogen can be produced from various primary energy sources, including conventional fossil fuels, renewable energy sources, and surplus energy (heat and electricity) as seen in Figure 25. This conversion can be conducted through electrochemical (electrolysis), thermochemical (gasification, pyrolysis, steam reforming, and chemical looping) and biological processes (fermentation, bio photolysis, and microbial electrolysis). Fossil-based hydrogen is produced from conventional steam methane reforming (SMR) or coal gasification representing currently the primary sources of global hydrogen production. Long seen as a key element in global decarbonisation, green hydrogen has emerged the limelight as an accelerant for the energy transition, with the potential onshore only superseded by what might be achieved offshore, where hydrogen could be produced, stored and shipped to landfall for industrial use and in the future become a fuel for zero-emission shipping.

The produced hydrogen is then liquefied before being loaded for transportation. Various transportation options are available, such as sea tankers, trucks and railway tankers. Transportation covers long-distance international shipping and domestic distribution. In the utilization sites, liquid hydrogen is unloaded and regasified before being distributed to small-scale consumers.

Figure 25. Classification of hydrogen production method



Source: Adapted from the article “True Colours: What do the different colours of hydrogen mean?” In *What is Watt* (Stanley Company) (2024)?

Compressed hydrogen

Compressed hydrogen gas (CGH_2, CH_2) is one of the most established methods of gaseous hydrogen storage. Compressing gas is the process of applying an external force, which minimizes the distance between gas particles, therefore forcing the system to occupy less volume. This is attractive since many particles can exist in a reasonably sized tank. At room temperature and atmospheric pressure, 4 kg of hydrogen occupies a volume of 45 m^3, which corresponds to a balloon with a diameter of 5 m. Compression is required to store and transport the gas.

The hydrogen density stored in its compressed form depends strongly on the storage pressure. Typically, at pressure of 10 MPa, the volumetric density of the storage hydrogen is 7.8 kg-H_2/m^3 (temperature of 20°C). It increases to 39 kg-H_2/m^3 when the pressure is increased to approximately 69 MPa. A hydrogen tank is a specialized container designed to store hydrogen in either gaseous or liquid form. The construction of a hydrogen tank must meet stringent physical requirements based on the pressure and temperature of storage. This has led to continuous innovation in the design and manufacturing of these tanks. One of the key innovations in this area is the development of advanced composite materials for high-pressure storage tanks. These materials offer higher strength and improved safety compared to conventional steel tanks. Hydrogen fuel tanks are used in a variety of applications, including fuel cell and electrolyzer systems, rockets, and space flight.

The use of hydrogen as a fuel source is becoming increasingly popular due to energy transition. However, the safe and efficient storage of hydrogen is a major challenge. Hydrogen storage as compressed gas have challenges related to the energy requirement due to its low specific gravity. Furthermore, there are some material challenges related to the materials of the storage tanks. Storing hydrogen in the liquid form requires a 64% higher amount of energy than that needed for high-pressure hydrogen-gas compression, where hydrogen does not liquefy until -253°C, and cooling that is an energy-intensive process (Ni, 2006)[136].

Compressed hydrogen gas storage system consists of two main components: the storage means and the compressor used for reaching the storage pressure. Due to properties of materials, investment costs, and safety issues, storing large quantities of compressed hydrogen gas at pressures exceeding 200 bar have many hindrances. The work needed for compressing gases is based on gas nature and the thermodynamics behind the compression process. Hydrogen require a significantly larger amount of energy to be compressed to the same pressure than helium and methane, which is mainly due to its extremely low density (Bossel & Eliasson)[137].

Some metals are subject to embrittlement caused by hydrogen absorption and dissociation at surfaces of those materials, which reduce the strength and durability of the material. Suitable materials that are mostly used for the pressure cylinders are austenitic stainless steel[138], aluminum and copper alloys, which are known for their resistance and opposition to effects of hydrogen at ambient temperatures. Many other materials such as alloy

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[136] M.Ni (2006). "An overview of hydrogen storage technologies". In *Energy Exploration and Exploitation*, 24 (3), June 2006, pp.197-209.

[137] U.Bossel, B.Eliassen (2003). "Energy and the hydrogen economy".

[138] Austenitic stainless steels are non-magnetic stainless steels, which have large immunity to corrosion and known for their formability.

or high strength steels are prone to embrittlement[139], and their usage should be avoided in hydrogen storage applications. Compressed hydrogen is adopted in many applications, including vehicles, hydrogen refueling stations, and other industrial purposes. To achieve a high density, advanced materials for vessels are required, such as carbon fiber and glass-fiber reinforced plastics. However, due to manufacturing limitations, the vessel size is also limited. Consequently, due to its high pressure, the permeation of hydrogen gas (permeated hydrogen gas amount) to the vessel wall become larger leading to higher risk of accelerated embrittlement.

Metal hydrides

Metal hydrides are compounds of one or more metal catons (M^+) and one or more hydride anions (H^-). When pressurized, most metals bind strongly with hydrogen, resulting in stable metal hydrides that can be used to store hydrogen conveniently on board vehicles. The most common examples of metal hydrides include aluminum, boron, lithium borohydride and various salts. These complex metal hydrides are often soluble in ethereal solvents. Metal hydrides can be liquids or powders that are usually stored in tanks at approximately 1 MPa. As the pressure is reduced or the temperature is increased (between 120°C and 200°C) hydrogen is released. The metal hydride can be recharged without the use of high pressure compressed gas or cryogenic liquid.

Metals hydrides storage has a low risk of accidental leaks since hydrogen is stored within the metal hydride crystal and requires energy to be released. In addition, the energy spent in storing hydrogen using metal hydrides is about half as much as that of compression (70 MPa) and about a sixth as much as that of liquefaction. Thus, the CO_2/kg of hydrogen is the lowest of any storage method due to the low storage and release energies involved (Profio et al., 2009)[140]. However, there are some challenges as well. Metal hydride storage has a relatively high energy density by volume, but a relatively low energy density by weight (kWh/kg). This results in metal hydride storage tanks that are about four times heavier (250-300 kg) than gasoline tanks. Even with improvements in metal hydride technology, storage tanks are currently too heavy for use in passenger vehicles and are limited for use in other applications.

Low and high temperature metal hydrides are another storage option showing in theory high storage capacities. Although, thermal management and packing limitations greatly decrease these values. In addition, the limited reversibility of the hydrogen storage, decomposition of the storage material and slow reaction kinetics are challenges to be tackled by further research. Many research activities are currently taking place, focusing on finding new metal hydrides that will meet the needs of industry and how the present metal hydrides could be modified to improve their present characteristics.

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[139] Embrittlement is the loss of the material ductility, which is the ability of material to be subjected to plastic deformation before becoming brittle.

[140] P.Di Profio, S.Arca, F.Rossi, M.Filipponi (2009). "Comparison of hydrogen hydrates with existing hydrogen storage technologies: Energetic and economic evaluations". In *International Journal of Hydrogen Energy* **34** (22), November 2009.

One of the most commonly discussed disadvantage of metal hydrides for storage compared to CGH_2 and LH_2 are the long filling and extraction times due to slow kinetics. The kinetics strongly vary from material to material and depend on material properties as well as operating conditions (Nguyen & Shabani, 2021)[141]. However, for interstitial hydrides the intrinsic kinetics itself are rarely the limiting factor of the reaction. The heat transfer or contamination in the hydride material usually limits the filling/extraction time.

Liquid Organic Hydrogen Carrier (LOHC)

Hydrogen can be transported via long distances based on Liquid Organic Hydrogen Carriers (LOHC), a technology that has shown great potential for efficient and stable hydrogen storage and transport. Such a transport is carried out based on two-step cycle: (1) loading/ storage of hydrogen (hydrogenation) into the LOHC molecule and (2) unloading/release of hydrogen (de-hydrogenation). During the storage period, hydrogen is covalently bound to the respective LOHC. Since the optimal LOHC is liquid at ambient conditions and show similar properties as crude oil based liquids, it can easily be handled, transported and stored

This technology allows for safe and economical large-scale transoceanic transportation and long-cycle hydrogen storage liquids are derived from non-renewable fossil fuels through costly refining procedures, resulting in unavoidable contamination. Biomass holds great promise for the preparation of LOHCs due to its unique carbon-balance properties and feasibility to manufacture aromatic and nitrogen-doped compounds. According to the recent studies, almost 100% conversion and 92% yield of benzene could be obtained through advanced biomass conversion technologies, showing great potential in preparing biomass-based LOHCs (Chou et al., 2023)[142].

2.4.1 Solar fuels

Solar energy driven processes with H_2O and CO_2 as basic feedstocks can produce „solar fuels“ that could substitute their fossil based counerparts. These „renewable fuels“ could potentially play a key role in future energy systems, both as a storage medium in the power sector and as an energy carrier in e.g. the transport sector, or deliver fundamental building blocks for the chemical industry. Although solar energy technology research has primarily focused on the electricity sector, electricity accunts for only one-third of total primary energy consumption. Solar energy can also be converted to fuels, which continue to dominate the energy consumption. Solar fuels could diversify fuel supply and increase the sustainability of overall energy system. They could also use existing fuel infrasruture for a huge range of applications. These fuels could be stored for hours, days, months, or longer. Solar fuels could be transported anywhere, making them a valuable and flexible resource for a more reliable power grid. Thus, solar-to-fuel conversion will play an increasingly important role in creating storable, transportable alternatives to high energy density fossil fuels.

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[141] H.Q.Nguyen, B.Shabani (2021). “Review of metal hydride hydrogen storage thermal management for use in the fuel cell systems”. In *International Journal of Hydrogen Energy* 46 (62) (**2021**).

[142] C.Chou, K.Wu, B.Luo, H.Zhang. “Hydrogen storage by liquid organic hydrogen carriers: Catalyst, renewable carrier, and technology – A review”. In *Carbon Resources Conversion* 6 (**2023**), pp. 334-351.

Solar energy can be used to convert basic chemical feedstocks such as carbon dioxide and water into clean alternative fuels that offer greater grid stability, energy security, and environmental benefits. *Solar fuels* technologies use sunlight, water, carbon dioxide, and nitrogen from the air to produce fuels that can readily be used in the existing energy infrastructure. Solar fuels technologies are analogous to natural photosynthesis – plants make fuels (biomass) from sunlight. However, the fastest growing crops store less than 1% of the sunlight they receive as biomass. To be compatible with current infrastructure, the primary biomass made by plants – lignocellulose – must be converted into ethanol, biodiesel, or gasoline. Converting crops to fuels raises significant land-use concerns, specifically with regard to trading food for fuel. The Lewis Group at California Institute of Technology has led the development of solar fuels technologies that produce hydrogen gas directly from sunlight and water. Carbon-containing fuels such as natural gas (methane) or liquid fuels such as methanol or ethanol might be produced from sunlight, water, and carbon dioxide. Ammonia for use as fertilizer in agriculture can be made indirectly from solar hydrogen or directly as a solar fuel from sunlight, water, and nitrogen in the air.

One possible approach to producing solar fuels is „artificial photosynthesis“ that works similarly to natural photosynthesis in plants, by using only water, carbon dioxide, and sunlight to generate fuel. Options for solar fuels could include processes to make hydrogen as a fuel buy using solar energy to split water, or to produce alcohols such as ethanol and methanol by using solar energy to reduce carbon dioxide with hydrogen, or to create less-conventional fuels such as ammonia and hydrazine by using solar energy to reduce nitrogen with hydrogen.

The replacement of fossil fuels by solar fuels, e.g., solar hydrogen and solar metals, is a long-term goal. It requires the development of novel technologies and it will take the time before these methods are technically and economically ready for commercial applications. In an optimistic scenario, analysis indicates that competivity could be reached between 2025 and 2048 for all renewable energy production pathways for hydrogen, syngas, methanol, and diesel. Two techniques yield break-even costs before 2050 even in a conservative base case scenario: H_2 production through electrolysis and diesel production by Fischer-Tropsch synthesis. Both processes use solid oxide electrolysis, which profits from rapid cost reductions and high efficiency (Detz et al., 2018)[143]. Similarly, to e-fuels, solar fuels are not yet available on the market. Sunny regions offer ideal conditions for the production of solar fuels, in particular deserts and semi-arid regions with high solar radiation. The solar heat generated during the day can be stored by inexpensive thermal energy storage to enable round-the clock production of fuels. Storage makes solar fuel plants self-sufficient and independent from any grid, giving them the potential to be scaled quickly and broadly. A number of prototypes have been demonstrated but at present stage, these cannot compete with existing energy technologies nor provide long-term stability.

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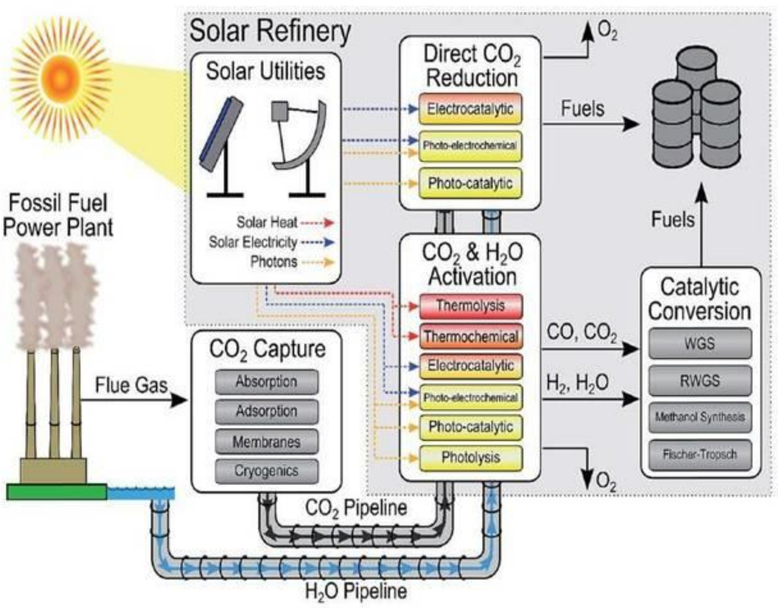
[143] R.J.Deetz, J.N.H.Reek and B.C.C van der Zwaan (2018). “The future of solar fuels: when could they become competitive?” In *Energy & Environmental Science*, Issue 7, **2018**.

Figure 24. Sun-to-Liquid production of solar fuels



Source: Adapted from the article “A general framework for the assessment of solar fuels technologies” published in Energy & Environmental Science, Issue 1, 2015.

Chapter 3

Energy efficiency and other enabling technologies for greater renewables integration into the grid

Energy efficiency and decarbonization are important elements of climate mitigation. Energy efficiency is a cost-effective means of decarbonizing the power sector, and it is believed to be repositioning itself globally as "the first fuel" (OECD/IPEEC)[144]. Economy-wide analysis suggests that energy efficiency improvements (including end-use efficiency of production and structural change of economy) determine emissions reductions short to medium term while decarbonization becomes more important in the long-term. Decarbonization is the power sector can play a pivotal role in cost-effective, economy-wide emissions reductions, given that deep emissions reductions are projected to be more expensive in other sectors. Doing so will not only involve adding more renewable energy, but also strengthening transmission infrastructure, moving away from fossil-based resources and enhancing demand response and load shifting programs. In the future energy system, energy efficiency must take center stage. In order to meet ambitious climate goals, energy efficiency, bigger integration of renewables and electrification are needed.

Power sector can be divided into supply side, demand side and power grid according to transmission process. The CO_2 emissions of power sector are concentrated in supply side, where fossil fuels burn. Unreasonable utilization in demand side and losses in power grid would increase energy consumption in supply side, which also indirectly contributes more carbon CO_2 emissions. Due to sharp increase in global energy consumption, it is currently quite challenging to manage problems such as controlling power loss, dependability, and efficiency and security challenges. A "*smart grid*", which combines self-monitoring, self-healing, adaptive, and islanding mode mechanisms, has been suggested to allow for energy transit from the point of production to the site of consumption to solve these problems (Xu et al., 2016)[145].

Electrical energy management is used to reduce energy expenses and alter the load profile on both the supply and demand sides. The objective of supply management (SSM) is to make energy generation, transmission, and distribution more operationally effective. Supply side management has many advantages, such as maximizing customer value by ensuring efficient energy production at the lowest practical cost, satisfying demand for electricity without the need for new infrastructure, and limiting environmental impact.

Demand side management (DSM) is a strategy used by electricity utilities to control demand by encouraging consumers to modify their level and pattern of electricity usage. DSM can be described as programs, actions, and technologies on the demand-side of electricity that seek to reduce or manage electricity consumption to either minimize the expenditure of power system or help to achieve policy objectives such as carbon emissions reduction (Warren,

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[144] OECD/IPEEC (2016). "G7 Hamburg initiative for Sustainable energy security. Analytical report on instruments for energy efficiency".

[145] G.Xu, W.Yu, D.Griffith, N.Golmie, P.Moulema (2016). "Toward integrating distributed energy resources and storage devices in smart grid". In *Institute of Electrical and Electronic Engineering* (IEEE) Internet of Things Journal 4 (1), pp. 192-194.

2014)[146]. From the view of cleaner production, a reduction in electricity demand due to efficiency minimizes the environmental impacts (e.g. climate change) of electricity consumption associated with a specific production level. In this regard, promoting DSM through policy instruments can help reduce the carbon intensity of the electricity sector.

A review articles published in the last two and half decades reveals a significant dichotomy in the classification of DSM measures. The first set of studies categorized DSM into two distinct parts – energy efficiency (EE) and demand response (DR) (Olkonnen et al., 2017)[147]. The second strand of literature contests the idea of merging EE and energy conservation (EC) into one. They instead opted for (EC) as a new classification (Linares & Labandeira, 2010)[148] . It is argued that while energy efficiency, demand response, and energy conservation have the same policy goal of reducing electricity consumption, they differ in approaches towards achieving it. Lastly, a number of scholars refer to the on-site storage and generation as the fourth category of DSM (Warren, 2018)[149].

Energy conservation and efficiency may be related, but they have distinct definitions in the energy domain. Energy conservation involves using less energy by adjusting behaviors and habits. Energy efficiency, on the other hand, involves using technology that requires less energy to perform the same function. Energy-saving light bulbs, large household appliances, smart thermostats[150] are all examples of technology that can be energy efficient. With increasing electricity demand and the need for power sector's decarbonization, many countries have accelerated efforts toward conserving energy through dedicated policy measures (Loi & Loo, 2016)[151]. Eight types of policy instruments found in energy conservation literature cut across all six policy categories with price-based (33%) as the highest, followed by incentive-based (27%), regulatory (20%), voluntary, customer education and community-based policies all account for 20% (ibid, 2016). Energy conservation measures are typically driven by advancements in technology whereby equipment and energy consuming devices become more energy-efficient and cheaper over time. A clear example of this trend is the proliferation of LED technology (Light emitting diodes). This technology requires less power for the same equivalent light output as traditional fluorescent and compact fluorescent lights (CFL).

Demand response (DR) involves shifting or shedding electricity demand to provide flexibility in wholesale markets, helping to balance the grid. It is based on two main mechanisms: price-based programs (or implicit demand response) and incentive-based programs (or explicit demand). Price-based programs use price signals and tariffs to incentivize consumers to shift consumption. Incentive-based programs, on the other hand, monetize flexibility through direct payments to consumers who shift demand in a demand-side response

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[146] P.Warren (2014). "A Review of demand-side management policy in the UK". In *Renewable and Sustainable Energy Review* 29, pp. 941-951.

[147] V.Olkonnen et al., (2017). "Benefits of DSM measures in the future finnish energy system". In *Energy* 137, pp. 729-738.

[148] P.Linares & X. Labandeira (2010). "Energy efficiency: Economics and policy". In *Journal of Economic Surveys* 24 (3), pp. 573-592.

[149] P.Warren (2018). "Demand-Side Policy: Global evidence base and implementation patterns". In *Energy and Environment* 29 (5), pp. 706-731.

[150] A smart thermostat is a WIFI enabled device that automatically adjusts heating and cooling temperature settings in the home for optimal performance.

[151] T.S. Loi & L.L. Loo (2016). "The impact of Singapore's residential electricity conservation efforts and the way forward. Insights from the bounds testing approach". In *Energy Policy* 98, pp. 735-743.

program (IEA, 2022)[152]. The electric power industry considers demand response programs as an increasingly valuable resource option whose capabilities and potential impacts are expanded by grid modernization efforts. For example, sensors can perceive peak load problems[153] and utilize automatic switching to reduce power in strategic places. European markets have been increasing demand response capacity since 2020, with some countries launching their first auctions or diversifying their portfolio of demand-side resources.

Distributed energy resources[154] and connected devices have the potential to contribute significantly to demand response, reduce peak demand and support net-zero pathways, if coupled with smart meters and digital management systems that allow the aggregation of and remote control of smaller and more numerous resources. The Net Zero Emissions by 2050 Scenario, around 250 GW of demand response capacity is in buildings and another 50 GW comes from electric vehicles[155]. Some countries, such as France, Italy, the Netherlands and the USA are increasing experimentation around electric vehicle-to-grid (V2G) charging, which technically allows vehicles to input electricity into the grid.

A decarbonized grid is crucial for the energy transition. To cope with the growing infeed of intermittent renewables, the transmission and distribution network needs modernization, expansion, and improvements in efficiency as well as stability. There is no one-size-fits-all method to reducing carbon emissions and increasing renewable energy in the grid. Decarbonization is happening in many ways in the grid – from introducing new technology through to transitioning to LED streetlights. Renewable energy generation is on the rise, with more wind and solar farms being connected to the grid.

The acceleration of the electrification trend is increasingly viewed as inevitable. As many state and local governments seek to accelerate decarbonization, low-carbon electricity is increasingly viewed as the “preferred fuel”. Efforts to electrify power grids are driven by multiple of factors, ranging from technological innovations in end-use technologies, connectivity, and digitalization, and policy objectives such as climate emissions reductions, and resilience. Developments in end-use technology and connectivity, together with changing grid characteristics (especially the integration of renewable sources that are clean, but less predictable and flexible), have enhanced the value proposition for demand-side management tools.

Power grid is not only a bridge connecting supply side and demand side physically, but also an important medium of achieving mitigation benefits of both sides. The essential aim of grid management is to match supply and demand. *Smart grids* technologies help to achieve this goal by allowing control from demand side (which is impossible to attain via conventional/classical control models, which rely exclusively on supply modulation)[156]. *Smart girds* incorporate the more recent advances in information and communication technologies

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[152] International Energy Agency (2022). “Demand Response: Technology deep dive. More efforts needed”.

[153] Peak load is the time of high demand the opposite of which is baseload, the minimum level of electricity demand over a period of 24 hours.

[154] Distributed energy resources (DERs) refers to often smaller generation units that are located on the consumers’ side of the meter. Examples of DERs that can be installed include rooftop solar photovoltaic units, wind generating units, battery storage and microgrids.

[155] IEA (2022). ““Demand Response: Technology deep dive. More efforts needed”.

[156] Smart grid is an electricity network uses digital and other advanced technologies to monitor and manage the electricity transmission from all generation sources to meet the varying electricity demands of end-users.

(ICT) to gather and consolidate the relevant information from all the players in the energy chain –from producer to consumer (Alotaibi et al., 2020)[157]. *Smart grid* is also considered as a way to reduce energy consumption, improve the electricity network efficiency, and manage renewable energy generation. With the development of smart grid and ultra-high voltage grid (UHV), losses decreased considerably[158]. Thereby, power grids show greater mitigation potential compared with other energy transmission methods.

However, the decarbonization of the energy sector brings along several challenges and the interdependence between the secondary energy carriers and end-use energy sectors[159] should not be underestimated[160]. Secondary energy sources, also known as energy carriers, are generated by transforming primary energy sources like solar, wind and hydro energy. They transmit usable energy from one point to another. Common examples of secondary energy sources are petrol, hydrogen and electricity. One of the challenges of decarbonizing the power sector is sufficiently reducing greenhouse gas (GHG) emissions while ensuring reliability, security and affordability. Generally, most renewable power generation produces CO_2 during the process of manufacturing equipment and consumables, but no direct CO_2 emissions arise during power generation process. As a result, it can be seen as near-zero carbon dioxide emissions.

The European Union is committed to cutting greenhouse gas emissions by 40 percent compared to 1990 levels by 2030, and in California, New Jersey and New York, utilities are required to have 50 percent electricity from renewables by 2030. Although there are also some challenges that come together with growth of renewable energy generation. It gives rise to grid integration costs and new grid planning requirement. Two principles are required to manage clean-generation technologies: flexibility and resiliency. Some electricity markets, particularly in parts of the USA, Germany and the UK, have already started to recognize, to varying degrees, flexible and resilient electric resources. Battery energy storage and distributed resources are two possible categories of competitive options. Greater interconnection of regional power grids would be beneficial to decarbonizing electric power. This would create more opportunities to add solar and wind generation where the best solar, wind resources are available, and to send the power they generate to other areas. However, this would require a significant buildout of transmission infrastructure, something that is extremely difficult due to high costs, disputes over who will pay for the lines and who will benefit financially.

On the other hand, harmonization between energy production and demand is becoming increasingly difficult to achieve, as the contribution of renewable energy sources is becoming more important. Unfortunately, the profile of renewable energy generation is rarely in phase with demand, giving rise to supply deficits and excesses. Renewable energy production fluctuations can be balanced with enough storage capacity. Unfortunately, viable solutions for

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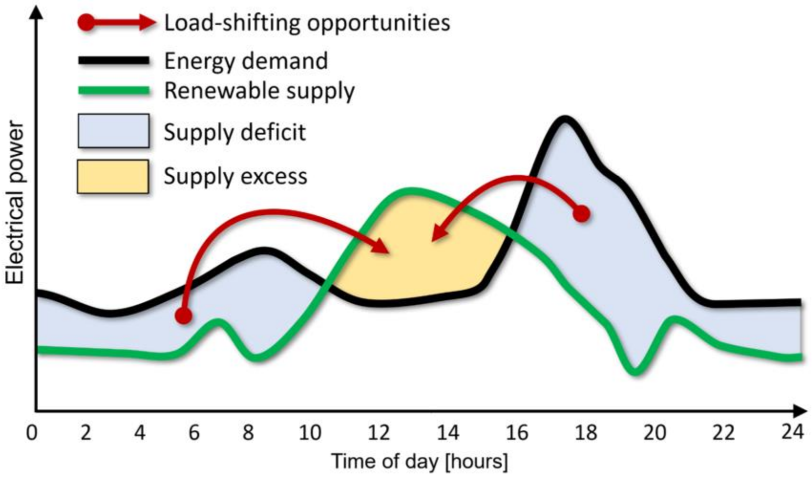
[157] I.Alotaibi, M.A. Abido, M.Khalid, A.V.Savkin. “A Comprehensive Review of Recent Advances in Smart Grids: A Sustainable Future with Renewable Resources”. In *Energies* 2020, 13, 6269.

[158] Ultra-High Voltage (UHV) cabling has been proposed in conjunction with other smart grid technologies to make electrical cable systems more amenable to renewable energy sources.

[159] An energy end-use is simply a category of energy use within a building (i.e. interior lighting, exterior lighting, space heating, space cooling, pumps, fans, receptacles, service hot water.

the needed storage capacity are still lacking. Hence, the importance of increasing the ability to control the grid from the demand side as seen in Figure 25 (Rodriquez et al., 2022)[161].

Figure 25. Typical daily renewable supply and demand profiles, and load shifting opportunities



Source: Adapted from the article "The Load Shifting Potential of Domestic Refrigerators in Smart Grids: A Comprehensive Review" by Rodriquez et al., 2022

Simultaneously, the impact on grid stability must be taken into consideration, as the connected renewable energy may bring fluctuations into the grid. Grid flexibility refers to the ability of supply and demand, or both, to adjust to balance the system to achieve a desired outcome, such as keeping prices low or minimizing GHG emissions. For example, wind and solar energy bring along fluctuations on a daily and seasonal basis. When the proportion of wind energy is too large, it leads to strong fluctuations in power grid. Demand flexibility can be facilitated either by technology (e.g. smart thermostat that can ramp up and down based on total supply and demand) or though behavior change (e.g. pricing programs that incentivize customers to use less electricity during peak demand times). Resources that can ramp up and down quickly, such as natural gas peaker plants or grid-connected batteries enable supply flexibility. Both demand and supply flexibility are likely to be necessary to help balance a decarbonized grid. Grid flexibility can offer the chance to avoid new investments in transmission infrastructure. Utilities can choose to invest in alternatives, such as batteries deployed in the transmission or distribution system, distributed generation, energy efficiency upgrades or demand response efforts.

Decarbonization of the power sector is a goal in and of itself. However, making the power sector more environment friendly will also help other sectors. Electrification of some end-use sectors (e.g. transportation, buildings and industrial sectors) is a key strategy for decarbonizing those sectors. Increased electrification also increases overall electricity demand and the scale of the power system that needs to be decarbonized. This would include siting and interconnecting new renewables and storage at a rate three to six times greater than recent levels, which would set the stage for doubling or tripling the capacity of transmission,

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[161] L.S. Rodriquez, D.L. Marquez, J.A. Ferreira, V.A. Ferreira Costa, N.D. Martins, and F.J. Neto Da Silva. "The load Shifting Potential of Domestic Refrigerators in Smart Grids: A Comprehensive Review". In *Energies* **2022**, 15, 7666.

upgrading the distribution system, building new pipelines and storage for hydrogen and CO_2 (NREL, 2022)[162].

However, electrification will only help deep decarbonization efforts if the electric power sector decarbonizes as well. Therefore, the electric power sector may need to grow capacity or increase efficiency as it decarbonizes. This will occur while the sector also changes in other ways, including the development of increasingly complex networks of supply and demand, new demands for bi-directional flow of power, grid infrastructure development and increasing digitalization of power technology. These will all present new challenges for the electric power sector to overcome (CSIS, 2022)[163]. Considering all the aspects, it is worth taking more system-level approaches to allow for parallel decarbonization of the power sector and other sectors. The European Union considers this approach "*sector coupling*" and recent research indicates that it could contribute 60 percent of the European Union's intended emissions reductions by 2050 (Bloomberg NEF, 2020)[164].

3.1 Available technologies and pathways for buildings decarbonization

Sustainable energy transition or low carbon transition has four major dimensions: decarbonization, electrification, efficiency, and digitalization. Decarbonization and decreased use of energy are already well-established dimensions of the sustainable energy transition. Decarbonization of the energy sector is led by the solutions like renewable and low-carbon technologies, electric mobility, carbon capture and storage, hydrogen and fuel cells. Decreased use of energy through energy conservation and management is critical to energy sustainability. Distributed generation or decentralized energy systems are becoming popular globally to help cost effective and efficient supplies of energy. Digitalization of energy systems is also deemed an important aspect of future energy systems. The international Energy Agency (IEA) regards energy digitalization as important to help improve productivity, accessibility, cost-effectiveness, and overall sustainability of future energy systems (IEA, 2017)[165].

Adjusting energy use patterns, potentially changes the CO_2 emissions in buildings, which makes buildings critical in decarbonization. In addition to adopting behind the meter DERs[166], buildings are not only energy consumers, but also energy generators. Using electricity generated by *behind-the-meter* DERs will further support decarbonization. Relevant to the energy industry, photovoltaics and supporting technologies are proliferating, as are business models to deploy *behind-the-meter* photovoltaics. Storage technology, and particularly strides in lithium-ion batteries, is improving and prompting innovations in other technologies,

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[162] National Renewable Energy Laboratory (2022). "Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035".

[163] S.Naimoli, S. Ladislaw (2022). "Climate Solutions Series: Decarbonizing the Electric Power Sector". CSIS, 2022.

[164] "Electrification Can Cut Emissions of Transport, Buildings and Industry in Europe by 60% by 2050", Bloomberg NEF, February 11, 2020, https://about.bnef.com/blog/electrification-can-cut-emissions-of-transport-buildings-and-industry-in-europe-by-60-by2050/

[165] IEA (2017). "Digitalization and Energy". Technical Report, International Energy Agency. Available online: https://www.iea.org/reports/digitalization-and-energy

[166] Behind the meter refers to the energy systems located on the customer's side of the utility meter. These systems could include solar panels, battery storage, or energy efficient appliances.

including mobile devices, the Internet of Things (IoT), electric vehicles and artificial intelligence (AI) for optimizing battery usage.

Two recent trends – the increase in *behind-the-meter* generation and the rise of storage can lead to important and substantial shifts in thinking and utilization of *behind-the-meter* DERs. Bolstering *behind-the-meter* storage resources is ensured by EV technology, which is changing the landscape for automakers and regulators. Technologies advancing blockchain and the IoT can boost investment in EV infrastructure. For example, a charging station could be leased to an EV driver by way of an efficient blockchain-facilitated transaction that is communicated through IoT devices and mobile communication networks.

Global warming will itself result in more electricity demand, as previously moderate regions require air conditioning to minimize heat stress. Energy efficiency must remain a top priority for zero carbon buildings, even with a decarbonized energy supply. It also reduces the total cost of future grid infrastructure to meet increased demand. While passive measures, such as increased insulation and higher efficiency equipment, can reduce overall electricity demand, active efficiency measures including automated demand response and dynamic energy optimization can provide demand flexibility to match intermittent renewable generation.

Digitalization is an important enabler of energy efficiency and demand flexibility in buildings. These “*smart buildings*” benefit from advanced sensing and controls, systems integration, data analytics and energy optimization to actively reduce energy use and demand while also improving occupant comfort, health productivity and facility resilience. Embedding these digital capabilities in “*smart*” equipment and appliances can provide additional benefits including improved reliability and remote management in addition to energy and emissions reductions.

The potential energy savings from smart buildings is significant. A study by the American Council for an Energy-Efficient Economy (ACEEE) shows that just by monitoring and automating three things – HVAC systems[167], lighting and window shading – can result in energy savings of 30-50%[168] . Basic automated building controls can save 10-15% of energy in commercial buildings. More advanced functionality, such as demand-controlled ventilation, can save additionally 5-10% in energy. Integrating systems together can yield incremental energy savings of 8-18% over basic HVAC (heating, ventilation and air conditioning) and lighting control. Energy decarbonization has boosted the sector due to continuous entry of new energy sources and new players in energy market. Electricity systems of future will have to consider other actors, such as smart transport and services, which will not be liabilities but participants and assets that will become quick, real-time boosters of these systems. High congestion rates due to more vehicles on the road have brought the need for an improved transportation system to the forefront. Intelligent transportation systems apply a variety of technologies to monitor, evaluate, and manage transportation systems to enhance efficiency and safety.

Technological solutions are not the main challenge for transforming the buildings sector. Various technologically mature options to decarbonize heating and cooling are already available, including energy efficient building envelopes, heat pumps, and on-site renewables.

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[167] HVAC refers to heating, ventilation and air conditioning systems.

[168] “Energy saving in smart buildings”, 05 June 2023. Market Overview, Smart Building EMEA.

The most appropriate technological strategy depends on the climate conditions, building purpose, and existing infrastructure. In many cases, heat pumps are the best option for thermal energy supply, while district heating or cooling is a proven approach in densely populated areas. Renewable hydrogen is unlikely to play a significant role as a transition fuel or to replace gas given its high costs and high-expected level of competition for supply from hard-to-decarbonize sectors. Smart controls can help to ensure electricity use is efficient and to integrate new demand into the grid. Nevertheless, production markets for key technologies are well established. Some improvements in the efficiency of equipment are still possible but the bigger challenge is the actual uptake of zero carbon technology and implementation of energy efficiency measures. Accelerating uptake is dependent on many other factors, including regulation, finance and actors (Climate Action Tracker, 2022)[169].

The energy and carbon emissions of existing buildings have been a major concern for a long time. Although building equipment, appliances, and other technologies have greatly improved energy efficiency, the buildings in which they are installed have been remarkably resistant to major change. Although, not many buildings are able to make this transition, and the pace of change is very low. Strategies such as switching from fossil fuels to cleaner energy sources or improving energy consumption to prevent expensive grid peaks cannot be readily applied to most buildings. Therefore, it is not surprising that the new buildings can achieve low or zero-carbon targets easier than existing buildings. However, the situation for existing buildings is much more complicated.

3.2 Electrification

Buildings use about 120 exajoules (EJ) of energy globally per year, about 30% of global final consumption (IEA, 2018)[170]. The electrification of energy consumption, primarily in buildings, will soon play a fundamental role as it represents a valid solution for increasing energy security and decarbonize the EU building sector. In buildings, electrification involves substituting electric technologies for combustion-fueled technologies for end uses where other fuels are being used – most notably space heating and water heating. Promising energy system benefits of electrification include greater flexibility for managing electric loads, opportunities to provide additional ancillary services to the grid, and valuable synergies with electric vehicles, demand response, and distributed generation and energy storage.

Building electrification known as *beneficial electrification* – describes the shift to using electricity rather than burning fossil fuels like oil, gas and coal for heating. It is an attractive alternative at present as fossil-powered appliances and equipment already have viable electric substitutes. Building electrification is gaining momentum, as the electricity grid is getting greener. The power sector is currently undergoing a period of unprecedented transformation. Increasing the use of local resources such as domestic fossil fuels, hydropower, wind, solar and battery storage – all to meet higher demand due to electrification – can reduce dependence on imported liquid fuels and improve energy security through greater decentralization. As states,

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[169] Climate Action Tracker. “Decarbonizing buildings: Achieving zero carbon heating and cooling”, March 2022.

[170] IEA (2018). “World Energy Balances 2018, https://webstore.iea.org/world-energy-balances-2018. Accessed 19 May 2023.

cities and even individual buildings set decarbonization goals; it is worth looking at how buildings contribute to carbon emissions – and how they contribute to solutions.

The early value seen in beneficial electrification and its technical potential has been borne out by two recent developments: improved technology for heat pumps, electric vehicles and other technologies, and advances in battery and charging technologies. Driven, in part, by market pressure for electrification there have been recent advances in heat pump technology, allowing buildings in colder climates to leverage the refrigeration cycle to move more efficiently heat their facilities, resulting in efficiencies 1.5 to 3 times that of electric resistance heat. However, it is important to understand that heat pump technology is not a "drop-in" replacement for gas-fired heat. In addition, energy efficiency and demand-response technologies are reducing power demand, while inexpensive renewables are reducing the carbon intensity of the electric grid. Incentives and funding programs to replace on-site fossil fuel equipment with electric equipment are growing rapidly.

In buildings, electric alternatives exist for all major energy end uses. Space heating with electric heat pumps is economically viable in a wide variety of buildings today. Electrified buildings and industrial end uses provide synergetic opportunities for electric vehicles (EVs) and distributed storage. For example, a microgrid for a future corporate building campus could feature onsite solar PV, flexible loads such as electrified water heating, pre-cooling of buildings, and employee-parked electric vehicles providing flexible charging and/or discharging, all networked in a way that would minimize grid purchases of electricity, especially during high-demand time periods – and grid-based demand charges (Deason et al., 2018)[171].

EVs might also be considered as battery storage systems on wheels. By using bi-directional chargers, idle EVs can function in aggregate as giant grid batteries and provide services used by network operators to stabilize electricity grids. This can engender added revenues, or by timing when to charge and discharge, simply lower the cost of buying energy from the grid. The values of such services depend on the power capacity of the batteries and the local electricity markets they participate in, and vehicle-to-grid (V2G) pilots are at present underway. For example, OVO Energy in the UK is commercializing its own software platform to take distributed storage resources, including solar-plus storage systems and V2G-enabled EVs and aggregate these various units to operate as a virtual power plant. Recently, the UK government granted funding to a series of V2G projects to demonstrate different commercial deployments of this technology. Including V2G bus fleets and a pilot involving domestic consumers (Innovate UK, 2017)[172].

Cities are working to reduce private vehicle use and congestion by offering greater support for alternative mobility modes like bicycles. Paris announced it will invest more than 300 million USD to update its bicycle network and convert 50 kilometers of car lanes into bicycle lanes. Industry players are accelerating the speed of automotive technology innovation as they develop new concepts of electric, connected, autonomous, and shared mobility. Electrification will play a key role in the transformation of the mobility industry and presents

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[171] J.Deason, M.Wei, G.Leventis, S.Smith and L.Schwartz (2018). "Energy Analysis and Environmental Impacts Division Lawrence Berkeley National Laboratory". Electricity Markets and Policy Group, Berkley Laboratory.
[172] Innovate UK (2017). "Innovation in Vehicle-to-Grid (V2G) Systems: CR&D -2017 Competition Results".

major opportunities in all vehicle segments, although the pace and extent of change will differ (McKinsey & Company, 2021)[173].

3.3 Building Energy Efficiency

Buildings energy efficiency is one of the traditional criteria for evaluating the performance of buildings. Energy use intensity reflects the annual energy consumption per area in buildings and is one of the key metrics to evaluate buildings energy efficiency. Building assets (e.g. envelope; lighting; heating, ventilation, and air-conditioning (HVAC) systems; and service water heating) are the main contributors to building energy efficiency (ASHRAE, 2023)[174]. Energy efficiency refers to the ability of a structure or system to perform its function using as little energy as possible. That it is why improving energy efficiency is a crucial strategy for building decarbonization, as it significantly reduce the carbon emissions associated with the operation and use of buildings.

Certain building energy codes and standards are used to regulate building designs to improve building energy efficiency. The ANSI/ASHRAE/IES Standard 90.1 [175] and International Energy Conservation Code (IECC) are two popular building energy codes of this kind.[176] In addition, there are advanced codes, which provide higher requirements, such as the ANSI/ASHRAE/IES Standard 189.1[177] and Advanced Energy Design Guides[178]. In many countries, energy efficiency of buildings falls under the jurisdiction of the federal states. Different standards cover different regions, climatic conditions, and different types of buildings, such as residential or simple buildings, commercial buildings and more complicated high-rise buildings. The importance of energy efficiency requirements in building codes or standards extends beyond their role in new buildings. Building codes and efficiency standard often serve as the efficiency target for refurbishment or other improvements of existing buildings. Buyers and renters of buildings or units will often compare new and existing buildings. With increased interest, for efficiency will foster higher requirements in building codes therefore spur the demand for refurbishment or general improvements of existing buildings (IEA, 2008)[179].

Considerable efforts have been made to enhancing energy efficiency in order to minimize the carbon footprint. Numerous studies have evaluated the energy savings potential from energy efficiency measures (EEMs) to reduce the energy consumption of residential and

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[173] McKinsey Center for Future Mobility (2021). “Why the automotive future is electric: Mainstream EVs will transform the automotive industry and help decarbonize the planet”. September 2021.

[174] ASHRAE. “Building EQ”. The American Society of Heating, Refrigerating and Air Conditioning Engineers. Available online: https://www.ashrae.org/technical-resources/building-eq

[175] ANSI/ASHRAE/IES “Standard 90.1” (2022). The American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[176] International Code Council (2021). “International Energy Conservation Code (IECC)”.

[177] “ANSI/ASHRAE/IES Standard 189.1” (2023). The American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[178] ASHRAE. “Advanced Energy Design Guides”. The American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[179] IEA (2008). “Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings”.

commercial buildings. Numerous EEMs have been proposed and promoted to be effective in enhancing energy efficiency as well as indoor environmental quality (IEQ) of the built environment. New buildings have a wide range of opportunities to achieve net zero energy building designs since they can easily adopt most of the EEMs. While existing buildings offer significant energy saving opportunities as they represent a large share of the building stock, special attention should be paid when considering energy efficiency retrofits for historic buildings to reduce energy use and maintain thermal comfort while preserving their heritage value.

A considerable set of energy efficiency measures has been reported in the literature. Enhancing the performance of the building shell has been one of the earliest remedies considered to reduce energy consumption. For example, increasing insulation levels or thermal mass for shell dominated structures (Cuce, 2018)[180]. There are many ways to improve the energy efficiency of a building, including:

1. **Upgrading insulation:** adding or upgrading insulation in a building's walls, ceiling, and floors can help to reduce heat loss in the winter and heat gain in summer, which can significantly reduce energy consumption for heating and cooling.
2. **Sealing air leaks: Air leaks, or drafts, in a building** can allow heat to escape in the winter and hot air to enter in the summer, increasing energy consumption for heating and cooling. By sealing these leaks, we can reduce energy consumption and improve the overall energy efficiency of the building.
3. **Installing energy-efficient appliances and lighting:** Replacing old, inefficient appliances and lighting with newer, more energy-efficient models can significantly reduce a building's energy consumption.
4. **Upgrading to a more efficient heating, ventilation, and air conditioning (HVAC systems):** Building's HVAC system is responsible for heating, cooling, and ventilating the building, and upgrading to a more efficient system can significantly reduce energy consumption.

Some of the proposed measures can be easily applied to the existing buildings while others require deconstructive means. Moreover, a lot of emphasis has been given to enhancing the efficiency of HVAC systems (heating, ventilation and air conditioning) since space heating and cooling comprise a large share of total energy consumption. The energy efficiency levels could be at the system, or control levels (Roth & Reyna, 2019)[181].

Lighting and equipment are major energy consumers, especially in commercial buildings. Their energy efficiency aspects focus on improving the efficiency of the systems and developing control strategies that can reduce the time of usage. For example, numerous studies revealed that the use of light emitted diode (LED) lamps could significantly reduce energy consumption as compared to other lighting types.

Furthermore, occupancy behavior is a critical factor that influences energy consumption in buildings. To improve energy efficiency, it is essential to integrate both

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[180] E. Cuce. "Accurate and reliable U-value assessment of argon-filled double windows: A numerical and experimental investigation". In *Energy Build*, **2018**, vol 171, pp. 100-106.

[181] A.Roth, J.Reyna (2019). "Grid Interactive Efficient Technical Report Series: Whole Buildings Controls, Sensors, Modeling, and Analytics". US Department of Energy, Office of Energy Efficiency.

behavioral change interventions, such as raising awareness and providing feedback on energy use.

3.3.1 Smart buildings concept

The concepts of *smart buildings* and *smart grids* have gained attention in publications concerning energy efficiency, emission reduction goals and other climate change related topics. Smart buildings are a reality increasingly present in cities around the world. This concept refers to a building that has several interconnected technology systems that work together and adjust to the needs, with integrated resource management, providing benefits to the user, owner and the environment. The above-mentioned systems are installed and operate independently in common building; but in smart buildings, they are planned and coordinated together, in a single consolidated way.

The concept of *smart buildings* is not new, but it has evolved mainly due to the development of new technologies, which, when incorporated, enable more intelligent resources and processes, which expand the building's capacity to operate in a more efficient, flexible, interactive and sustainable way. The concepts "*smart city"* and "*smart buildings*" emerged in the 1980s and evolved similarly. When analyzing the literature on smart cities, the approaches can be grouped in two phases. The first, from the end of the 1980s, focused mainly on the role of information technology and innovation, while the prevailing studies aimed at making digital, technological, and cyber cities and buildings. The second, from the end of the 1990s, with comprehensive approach emphasizing more and more the role of user interactions, with a focus on improving the quality of life and sustainability (Wong et l., 2005 & Baŝić et al., 2019)[182]. Smart buildings use emerging technologies such as the Internet of Things (IoT), augmented reality and artificial intelligence, among others, to provide solutions to long standing challenges of inefficiency in building design and performance and lack of productivity and security in buildings (Gansah et al., 2020)[183].

Automation was one of the first features incorporated into smart buildings, enabling the centralization, monitoring, and control of several services such as heating, ventilation and air conditioning (HVAC), elevators access control, light, water and power systems, in a shared network that can be automatically managed and remotely observed by internet, besides providing a comfortable working environment for users. The incorporation of new technologies such as ICT was significant progress, although it also increased the risks related to resilience and cyber security arising from the merge of the building systems with computer technologies.

The above-mentioned elements interlinked together form a complex solution that collects and analyzes building operation data in real time and improve building upkeep and maintenance as well as the experience of its occupants. For example, smart hospitals can bring better treatment outcomes, enhanced staff productivity, and cost-effectiveness, as proven by the Ankara City hospital, Türkiye, or the Sint-Maarten Hospital in Mechelen, Belgium. These hospitals are intelligent ecosystems with a central building management platform that controls the subsystems. Smart building hardware and software are used to lower infection risks,

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[182] J.K.W. Wong, H.Li; S.W. Wang. "Intelligent building research: A review". In *Automated Construction*, 2005, 14, pp 143-159. See also S. Baŝić, N.V. Strmo, and M.Sladoljev. "Smart cities and buildings". Gradevinar 2019, 17, pp. 949-964.

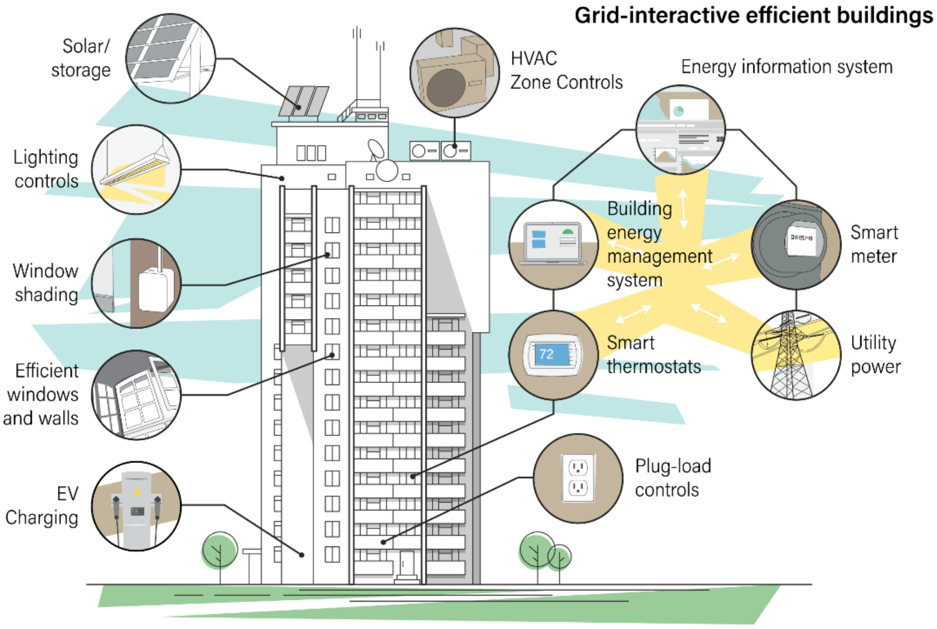
[183] F.A. Gansah et al (2020). "Underlying indicators for measuring smartness of buildings in the construction industry". In *Smart and Sustainable Built Environment*.

optimize the use and maintenance of medical equipment, facilitate patient and visitor registration, provide individual comfort setting for patients, and improve energy use. In addition, smart buildings provide considerable solutions to the challenges faced by the construction companies, which are not limited to inefficiency of energy, poor indoor air quality and cost of operations using data from sensors installed into the building to enhance building management.

The ambitious objectives of the Green Deal require buildings to not only be smart to reduce their energy use and improve the wellbeing of occupants, but also be able to interact with the energy grids through which buildings and other energy consumers are interconnected. To enable these interactions and unlock the potential of flexibility markets, electrical and thermal networks should also improve their levels of smartness. In addition to the interaction between "individual" buildings, it is possible to include a collective of formally related buildings, such as condominiums or university campuses, in which internal networks connect the building systems to single building automation system (BAS). However, the connection to the city's smart infrastructure is essential. For example, with regard to the electricity consumption, smart buildings can individually manage their consumption based on information received from the smart grids. While collectively, from the interaction between buildings, network stabilizing "micro-networks" can be created primary sources, compensating for fluctuations in supply and reducing overall energy demand.

Most of the buildings stand to benefit enormously from smart, connected technologies. Smart buildings, also known as Grid-interactive efficient buildings are designed to avoid the high costs and disruptions associated with peak demand and grid stress. Through clean, on-site power generation and innovative efficiency measures, it enables to reduce the carbon footprint of the building sector largely.

Figure 26.



Source: Adapted from the article "Grid-interactive Efficient Buildings Are the Future, And Utilities Can Help Lead the Way" The American Council for an Energy-Efficient Economy (ACCEE), 2019

More utilities in the USA are also adopting programs to promote smart buildings, which will be critical to the grid of the future. Some programs focus on energy savings and others on demand flexibility. These buildings are increasingly important. For example, they can help utilities adapt to rapid changes in the grid, including the adoption of technologies like electric vehicles, and heat pumps, as well as new energy policy directions like beneficial electrifications. They also deliver substantial energy and emission reductions by using efficient materials and equipment. They can also act as resources to the grid, by using less overall energy than a normal building and strategically shifting or reducing energy consumption during peak times.

These type of buildings use smart controls, sensors and analytics to communicate with the electrical grid, reducing the amount of energy they require during periods of peak demand. This capability is used to optimize buildings and distributed energy resources to maintain the comfort of the building occupants, lower utility bills, and reduces grid system costs. A recent study of the U.S. Department of Energy (DoE) estimated that by 2030, smart buildings could save up to 18 billion USD per year in power system costs and cut 80 million tons of carbon emissions each year (U.S. Department of Energy, 2021)[184].

3.4 Sector Coupling

Various attempts have been made to address the challenges related to the integration of renewable energy sources into the grid. However, most of them focus on improving efficiency, prediction accurancy and control performance within the power system. Recently, a new approach was proposed to enlarge the domain of the problem and solve it altogether with other energy sectors. Energy sources mainly considered for interaction with the power system include heat, hydrogen and gas (Ramsebner et al., 2021)[185]. For example, IRENA defines *„sector coupling*“ as the process of integrating various energy sources in order to match demand and supply through the process of co-production, co-consumption and transformation. The sector coupling is also called Power-to-X and the authors of Sterner and Sprecht[186] included gas, liquid, and chemicals in the definition.

The concept of sector coupling means that the electricity sector would become the central pillar of the energy system, supplying the other sectors – heat, mobility and industry – with energy in various ways. Sector coupling plays a significant role in the energy transition. By connecting the different sectors, new highly efficient technologies can be used. As a result, scarce resources can either be better utilized or energies can be generated in a renewable way and used sensibly. The electricity from renewable energy sources can provide heating services through various sector coupling technologies, such as heat pumps and electric resistance boilers, and to replace fossil fuels and fossil fuels-based electricity. Electrolysis and

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[184] “DOE’s National Roadmap for Grid-interactive Efficient Buildings”. May 18, 2021

[185] J.Ramsebner, R.Haas, A.Ajanovic, M.Wietchel (2021). “The sector coupling concept: A critical review”. Wiley Interdisciplinary Rev. Energy Environment, **2021,** 10, e396.

[186] M.Sterner, M.Sprecht (2021). “The History and Results of Developing a New Concept”. In *Energies* **2021**, 14, 6594.

methanization are indirect means for applying electricity to produce green hydrogen or methane for industry, residential use and transport.

3.4.1 Components of Sector Coupling

In recent years, an increasing number of countries have committed to achieving net zero emissions. There is a growing interest to pursue electrification-centered decarbonization strategies for other end-use sectors where emissions reduction has been slow. In the so-called consumption sectors of industry, transport and buildings, there has been little progress in decarbonization. So far, a considerable amount of fossil fuels has been used in these sectors, and CO_2 emissions are consequently high. At the same time, direct electrification may be practically challenged for some of these end-uses, e.g., in the case of heavy-duty transport where volumetric energy density and refueling time are the main drivers for fuel choice. In this context, hydrogen (H_2) and hydrogen derived energy carriers are expected to play significant roles in the decarbonization of difficult-to electrify end-uses in these sectors. Decarbonizing these sectors via electricity or H_2 could potentially enable a more integrated energy system with potentials for cost-savings through increased asset utilization[187]. The key advantage of sector coupling is that it gives the extra flexibility from end-use sectors to accommodate variable renewable energy resources directly or indirectly via hydrogen.

Power-to-Hydrogen

The European Union is promoting hydrogen as enabling energy carrier that may account for up to 20% of energy and especially fulfill between 20% and 50% of transportation demands[188]. To implement this shift, Power-to-Hydrogen and Hydrogen-to-X technologies have attracted significant interest as they transform renewable power directly into green hydrogen, which can be stored and transferred more readily than other fuels for several end-uses.

Considering this context, hydrogen could have significant potential as an energy carrier in several sectors as being a universal energy source that can be produced from multiple feedstocks by all countries. The ability to store larger amounts of electricity for longer periods can form a supply chain of production, storage, transportation and consumption. In this way, it can be linked to various industries and can be used as a fuel for vehicles, trains, and ships, so the potential value of hydrogen sector is high. Many countries have recognized its value have presented visions and roadmaps for the “hydrogen economy”, and the hydrogen sector is forming an independent ecosystem.

However, hydrogen accounts for 2% of the EU’s energy mix, even though 95% of its production is still based on fossil fuels. In this context, hydrogen has the potential to play a pivotal role in the industry of the future due to its versatility and sustainability as a source of energy. It can be used as fuel for vehicles, including cars, buses, and airplanes. Hydrogen fuel

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[187] DNV GL (2020). “Creating an interconnected decarbonized energy system benefiting industry, the power sector and society”. DNV GL, report.

[188] European Commission (2022). “Renewable hydrogen to decarbonize the EU’s energy system”. 15 November 2022.

can be produced during surplus of intermittent renewable electricity and stored for use during peak and when the variable renewable disappears (Palys and Daoutidis, 2020)[189]. Hydrogen can also be processed into synthetic fuels sources of energy like ammonia and methanol.

Nevertheless, the production process used in its production determines the overall lifecycle emissions of hydrogen. As at the end of 2021, almost 47% of the global hydrogen production is from natural gas, 27 % from coal, 22% from oil (as a by-product) and only around 4% comes from electrolysis. The main method of hydrogen production is by steam methane reforming where hydrogen is made by chemical reaction between steam and methane. About 6.6-6.9 tons of CO_2 are emitted by of this process to produce one ton of hydrogen (Bonheure et al., 2021)[190]. Carbon capture process can then be used to remove a large percentage of the CO_2 produced making the process cleaner. Although the overall carbon footprint of hydrogen as a fuel is yet to be fully established, it remains a cleaner fuel than natural gas, biogas or methane (Griffiths et al., 2021)[191].

Research and development are encouraged to develop hydrogen electrolyzers for use in large-scale production of hydrogen for power generation completely. Hydrogen produces intense heat suitable for industrial production of steel, cement, glass, and chemicals. Therefore, hydrogen can act as a clean fuel in the steelmaking, can act as a clean energy carrier and simultaneously as low-carbon catalyst in place of coke (Blank and Molly, 2020)[192]. The main limitation of hydrogen as an energy carrier is high storage and distribution costs since it is explosive and occupies a large volume. The gas also brittles pipes hence it needs special handling facilities which have to be developed (Griffiths et al., 2021)[193].

Power-to-Heat

In many industrialized countries, decarbonizing the heating sector is a precondition for achieving ambitious climate policy targets; in particular, space-heating accounts for substantial fractions of final energy demand. Heating and cooling applications are among the largest consumers of energy. Although some countries use renewables and waste to generate process heat for industries, and solar thermal and geothermal systems to generate space heating and cooling, the majority of heating needs are still met by fossil fuels. In Europe, for example,

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[189] M.J.Palys and P.Daoutidis (2020).”Using Hydrogen and Ammonia for Renewable Energy Storage: A Geographically Comprehensive Techno-Economic Study. In *Computational Chemical Engineering* 136, 106785.

[190] M. Bonheure, L.A. Vanderwalle, G.B. Marin, and K.M.V. Geem (2021). “Dream or Reality? Electrification of the Chemical Process Industries. In *Chemical Engineering Progress* 117 (7), pp. 37-42. Available: https://www.aiche.org/resources/publications/cep/2021/march/dream-or-reality-electrification-chemical-process-industries

[191] S.Griffiths, B.K.Sovacool, J.Kim, M.Baszilian, and J.M.Uratani (2021).”Industrial Decarbonization via Hydrogen: A Critical and Systematic Review of Developments, Socio-Technical Systems and Policy Options”. In *Energy Res Social Sciences* 80, 1022208.

[192] T.K.Blank and P. Molly (2020). “Hydrogen’s Decarbonization Impact for Industry”, in *Near-Term Challenges and Long-Term Potential*. Rocky Mountain Institute, NY.

[193] S.Griffiths, B.K.Sovacool, J.Kim, M.Baszilian, and J.M.Uratani (2021).”Industrial Decarbonization via Hydrogen: A Critical and Systematic Review of Developments, Socio-Technical Systems and Policy Options”. In *Energy Res Social Sciences* 80, 1022208.

approximately 75% of annual heating and cooling requirements are met by fossil fuels, while only 19% is generated from renewable energy (European Commission, 2019)[194].

Power-to-Heat is a term used to generally describe a process of converting excess power into thermal energy in terms of sector coupling (reverse process is also possible)[195]. Its principle is simple; electric current is converted into heat with an efficiency of nearly 100%. In order to prevent excess power from going unused, it can be converted into heat through power-to-heat systems and fed into the grid. Although, it should be highlighted that the heat and electricity sectors have many interfaces, among them, combined heat and power (CHP) uses the heat discarded in the process of generating electricity. Combined Heat and Power is the simultaneous production of electricity and heat usually in the form of hot water or steam from a primary fuel such as natural gas. Electricity is generated on site by using natural gas to drive an alternator connected to a turbine or engine. The heat from the exhaust gases generated by the turbine or engine is harvested to provide steam or hot water for the production processes. In this manner, CHP achieves 65-75% efficiency and is involved in both the power system and district heating (Noreika et al., 2013)[196].

Electrification of heating can help decarbonize the sector when the extra load is supplied with renewable electricity and smartly managed. Power-to-heat systems can help integrate greater shares of variable renewable resources by using heat pumps and electric boilers as a source of demand-side flexibility in power systems. These electric loads can be used to reduce curtailment of surplus renewable generation to load shift to coincide with renewable energy generation, and to provide grid services.

Power-to-heat systems can be used both in the low-temperature range as well as in the high-temperature range (steam). Electric boilers use electricity to heat water, which is then circulated through pipes or disseminated with fan coils to provide space heating, or stored in hot water tanks for later use. Heat pumps use electricity to transfer heat from the surrounding heat sources (air, water, and ground) to buildings. Immersion heaters or heating elements are used mostly in the decentralized low-temperature range, while electrode steam boilers are used in the high-temperature range. The generation of process steam of up to 30 bar is technically possible by means of an electrode steam boiler .the saturated steam generated in this way can be superheated to higher temperatures by means of a downstream electrode flow heater and thus, also fulfill higher requirements with regard to the steam generation (GETEC, 2024)[197].

The surplus power can be supplied to the heat network and processed at the heat demand point, or it can be utilized as a heat energy storage. The physical principles of thermal energy storage are touched upon in Chapter 2[198].

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[194] European Commission (2019). "Heating and cooling".

[195] Renewable power-to-heat refers to technologies that use renewable electricity to generate useful heat for buildings or industrial processes (via heat pumps or electric boilers).

[196] M. Noreika, K.Downes, O'Leary, and J.Stitcher"CHP implementation: Designing Combined Heat & Power Financial Incentives and Eligibility Requirements for Non-Residential Demand-Side Management Programs". In Proceedings of the 2013 ACEEE Summer Study on Energy Efficiency in Industry, Niagara Falls, USA, 23-26 July 2013, pp.1-11.

[197] GETEC (2024). "Our power-to-heat concept" (Accessed 08 April 2024).

[198] Thermal energy storage can be classified into three types: (1) sensible heat, (2) latent; and (3) chemical. Each of them has advantages and disadvantages.

Power-to-Gas

The development of renewable energy projects is increasing in number, which results in either the production of excess electrical energy that cannot be sent to the electrical grid for a number of reasons due to the longer distance from the existing electrical grid or excess production at the time when the demand is low. As renewable sources of energy, such as wind and solar photovoltaics, become increasingly more vital to support global carbon footprint reduction goals, innovative energy solutions are required to match unpredictable supply and demand. Power-to-gas (P2G) is the process of converting surplus renewable energy into hydrogen gas through Proton Exchange Membrane (PEM) electrolysis technology. The hydrogen can then be injected into the natural gas grid. In doing so, the hydrogen can displace natural gas, reducing greenhouse gas emissions and reliance on high-carbon fuels. P2G is an effective means of transitioning to a “greener” natural gas mix.

The excess renewable electricity can therefore be used to produce hydrogen via water electrolysis ($2H_2O \rightarrow 2H_2 + O_2$), which is considered a renewable electricity storage route. One of the emerging processes for conversion of the CO_2 into solar fuels is the synthetic natural gas production, which enables the storage and transportation of renewable energy in an efficient manner. Power-to-gas (P2G) concept will likely play an important role in the challenge of long-term and large-capacity renewable energy storage. It is because it has significant advantages as compared to other technologies.

Natural gas is used in various industries, including CHP, air conditioning/heating, vehicles, and industry, due to widespread network and high energy density. Methane, which makes up most of the natural gas (70-90%), can be obtained from natural sources or produced through Power-to-Gas. Most process steps within a Power-to-Gas system are not new and are mostly mature and already part of the conventional energy system, for example, pipeline transportation of gaseous energy carriers. Electrolysis, however, needs to be fit to the requirements of Power-to-Gas because renewable electricity are only temporarily available. P2G also supports the anaerobic digestion process, where microorganisms are broken-down to organic matter to produce fuels. With the addition of hydrogen, the process (also known as methanization) greatly improves conversation rates of carbon dioxide to biomethane (from 60% to 95%). Hydrogen generated via PEM water electrolysis technology is key to transforming surplus electricity generated from renewables into storable methane that can be utilized within the traditional national gas grid.

3.4 Barriers and Challenges to Overcome for Sector Coupling

To address the various challenges posed by the widespread integration of renewable energy into the grid, sector coupling is being considered as a technical solution. The sectors involved include electricity, heat, gas, and hydrogen, with the electricity sector serving as the center and other sectors mentioned above acting as buffers for surplus power and mitigating curtailment through energy conversion and long-term storage. Improving energy efficiency and increasing the share of renewables in the electricity sector is key to achieving a carbon- neutral power system.

There are several challenges that should be addressed in order to fully implement sector coupling. Technologies related to sector coupling are often not fully developed, and large-scale integration can be successful only if it is cost-effective. For example, the production of hydrogen is currently limited by the size of available electrolyzers. At the same time, the hydrogen sector lacks a supply network, and faces challenges in terms of efficiency, technical standards, and supply chain optimization. Economically, the price of renewable energy should be competitive with traditional power sources in order to support the transition towards carbon-neutral power systems. While the cost of renewables has decreased in recent years, it still varies significantly by country, and many countries subsidize renewables. Without price competitiveness, the reliance on fossil fuels would continue, and the goal of carbon-neutral power systems and sector coupling may not be possible.

Alongside regulatory and commercial initiatives, replacing fossil fuels with green electricity is another major hurdle. At present, the energy use heating and transport still accounts for 44% of all global carbon dioxide emissions. In order to achieve climate goals, it is important to generate sufficient energy from renewables but also to electrify consuming sectors. The high emissions of transport and heating imply that current climate goals cannot be achieved without significant transformation of these sectors. Electrification is the first step, as neither transport nor heating cannot become carbon neutral if based on fossil fuels. Increases in demand and supply side flexibility will be the key to account for higher demand and intermittent supply. A decentralized approach with greater integration of energy resources will become more important to lower pressure on the grid and avoid the need for costly new infrastructure. Smart energy solutions will maximize both user comfort and savings.

Operation and market are other big barriers to the integration between electricity and other sectors. Electricity, gas and heat networks have been operating independently for a long time; each sector has its own operator, and the exchanges between sectors have not been considered. Cooperation between multiple system operators is important for smooth operation; however, the existence of a single integrated operator discourages other sector operators to invest. Therefore, a theoretical approach is needed to increase the utility of all sector operators. What makes cooperative control between operators more difficult is the different supply characteristics and load profiles.

In many countries and regions, large-scale power systems are the standard. Microgrids (MG) are considered one of the most promising solutions to integrate renewable distributed generation into the electric power system. During the last decade, the microgrid concept has been studied and developed and nowadays it is becoming a reality. MG is a small-scale power system that can realize supply-demand balance of electricity within a certain demand area. Due to its friendliness to renewable energy sources and its high resilience to disasters, it has attracted much attention from a commercial perspective. Diaz et al[199] proposed a centralized control architecture for coordinated control of distributed renewable energy sources and loads in islanded mode. It was experimentally verified that stable supply could be continued by controlling multiple storage batteries and renewable sources to shift loads. Microgrids can also supply heat energy, taking advantage of the characteristics of small-scale systems. The operational cost can be further reduced by combining the supply of heat and power.

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[199] E.Bullich-Massagué, F. Dias-González, M.Aragüés-Peñalba, F.Girbau-Llistuella, P.Olivella-Rossell (2018). “Microgrid clustering architectures”. In *Applied Energy*, Volume 212, 15 February 2018, pp. 340-361.

Conclusions

Energy storage systems help mitigate the uncertainty related to the electrical load in the power network. To incorporate energy storage systems to the grid, it is essential to understand their technical parameters as well as their economic and environmental performance. This study provided a review of the current status of energy storage technologies along with their technical characteristics and operating principles. It was highlighted that each of the considered methods of storing this energy (batteries, fuel cells and supercapacitors) has specific features that determines the scope of its applications.

There is a pressing need to decarbonize the energy sector to limit the effects of climate change. Energy storage is an enabling technology for rapid acceleration in renewable energy deployments. It enables flexibility to ensure reliable service to customers when generation fluctuates, whether over momentary periods through frequency regulation or over hours, by capturing renewable generation for use during periods of peak demand. Progress in the integration of renewable energy requires both significant increases for storage on the grid and the development of new types of energy storage that can ensure reliability over days and seasons. Continued investment in research, development, and deployment of long-term energy storage technologies is crucial to enable electric grid decarbonization.

In addition to the main pillars of decarbonization such as energy efficiency, renewables, low-emission fuels, there are also crosscutting enablers such as innovation, international collaboration and digitalization that accelerate progress in energy transition. Most industrial greenhouse gas emissions are linked to energy use. Using energy more efficiently can reduce energy use, associated emissions, and energy costs. That is why energy efficiency should be the first step. Buildings are currently responsible for 39% of global energy related carbon emissions (New Buildings Institute, 2024)[200][199] above. Therefore, the built environment sector has a vital role to play in responding to the climate change impacts. Electrification of the buildings and transportation is widely considered the best path in the quest to decarbonize and reach net-zero emissions by 2050. The electricity sector is regarded as the one where decarbonization will be achieved first, compared to the other sectors. Sector coupling options, in which a future increased share of the heat and buildings, transportation and industry sectors will be electrified, make the decarbonization of the electricity sector more urgent.

The reliance of the major energy intensive building (HVAC and water heating) energy systems on working fluids that are fast being phased out further exacerbates the challenge of supplying these needs using carbon-neutral sources. Thus, continuous modification of the composition of the electricity grid for rapid increases in carbon-free generation, reduction in the dependence on electricity of end uses that are thermal in nature, and development of new HVAC and water heating technologies are all required in a carefully trajectory to allow countries to reach the goal of carbon neutrality by 2050.

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