December 2020

Energy Storage Technologies:
Challenges and Outlook

The Green Tank *Policy solutions for a sustainable future*

Energy Storage Technologies: Challenges and Prospects

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Please cite as:
TheGreenTank (2020) "Energy Storage Technologies: Challenges and Prospects"

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Executive Summary

The extensive use of Renewable Energy Sources (RES) is a key component of European energy and climate policy on the path to climate neutrality. However, given the stochastic nature of wind and solar technologies, and as the shares of renewables increase, so does the need for storage; the latter is vital in order to balance supply and demand of renewable electricity. For this reason, electricity storage technologies have acquired a key role in both the National Energy and Climate Plan for 2030, and the Long-Term Strategy of Greece for 2050.

This report presents the basic properties and associated advantages and challenges of the main energy storage technologies. Emphasis is placed on the two currently dominant storage technologies, namely pumped hydro energy storage (PHES) and batteries, as well as on two emerging technologies: thermal storage through the conversion of lignite and coal combustion plants; and hydrogen technologies, which are expected to be increasingly implemented in the future. Finally, an overview of the possibilities of financing energy storage infrastructure by the new Multiannual Financial Framework (MFF) 2021-2027 will also be presented.

Today, pumped hydro storage is -by far- the dominant storage technology worldwide. Its main advantages are technological maturity, rapid response to load changes, and relatively high efficiency scores of up to 80%. However, finding a suitable location and building the required infrastructure is difficult and time consuming. At the same time the construction process is accompanied by significant environmental impacts, such as the disturbance of species habitats – especially of aquatic ecosystems, deforestation, and large-scale vegetation removal.

Battery storage systems have very fast responses (of a few tens of seconds) and significantly higher efficiency rates, compared to pumped hydro storage technologies; certain new lithium-ion batteries have an efficiency of up to 96%. Batteries provide a range of energy services, such as black-start capability, peak shaving, frequency regulation, load levelling, and load following. The advances in related technologies together with increased demand, have led to a dramatic reduction in their costs, in the order of 87%, within the decade 2010-2019, with prospects of a further reduction, down to $61/KW by 2030. Another important comparative advantage of batteries is their short construction time, as illustrated by the iconic example of the Tesla system in Australia that was built in less than 100 days.

However, batteries have a short life span compared to other storage technologies. In addition, both the finite availability of raw materials for the manufacture of certain types of batteries (for instance lithium batteries) and the environmental impact of their end-of-life-cycle disposal dictate the development of recycling and reuse technologies and facilities. Furthermore, lithium-ion batteries are generally sensitive, wear relatively easily during use, and are bound by safety restrictions.

The conversion of lignite and coal combustion plants into thermal storage units of electricity coming from RES has an important advantage: it gives these retired plants and their extensive accompanying infrastructure a second life-cycle; thus, maintaining jobs in the lignite industry. Moreover, thermal storage media, such as salts or volcanic stones, have a low cost. Molten salts in particular are very durable and can be used for 35 consecutive years of charging/discharging cycles, while they have an alternative use as fertilizer components. An additional important advantage is the short installation period of approximately 18 months, which contrasts the much longer construction times of pumped hydro storage systems -especially when new reservoirs are required.

On the other hand, the combination of thermal storage technologies with lignite or coal combustion plants is new, and therefore, accompanied by various technical challenges; these mainly relate to the large capacity scale of the existing combustion plants. Furthermore, the total efficiency of such systems is in the order of 40-45%, thus, clearly lower than that of the two most common storage technologies, namely pumped hydro storage and batteries.

Finally, despite its great prospects of contributing to the decarbonization of many sectors of the economy, green hydrogen, namely hydrogen coming from RES, corresponds to only 1% of all hydrogen produced, mainly due to its high production cost. The remaining 99% comes from processes based on fossil gas or coal/lignite, and is therefore burdened by significant emissions of carbon dioxide. In addition, the current use of hydrogen in transport, buildings, and electricity generation is extremely limited. Hydrogen is mainly used in industry (refineries, high grade heat generation, ammonia & methanol production, and steel production process), without however contributing to the reduction of the carbon footprint of these industrial processes, as it is produced from fossil fuels.

In order for hydrogen to play a key role in the decarbonisation of the European economy, it is vital to establish long-term policies that will both stimulate demand for multiple applications simultaneously, and provide for research and development, so that green hydrogen production is rendered economically competitive.

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Introduction

Achieving climate neutrality by 2050 constitutes a central goal of the European Union; which is reflected in the new European climate law and will be implemented through the European Green Deal.

The extensive use of Renewable Energy Sources (RES) is a key component of European energy and climate policy on the path to climate neutrality. However, given the stochastic nature of wind and solar technologies, and as the shares of renewables increase, so does the need for storage; the latter is vital in order to balance supply and demand of renewable electricity. By providing these necessary services for periods ranging from a few hours to months, or even entire seasons, electricity storage technologies can support the complete decarbonization of electricity and other sectors of the economy.

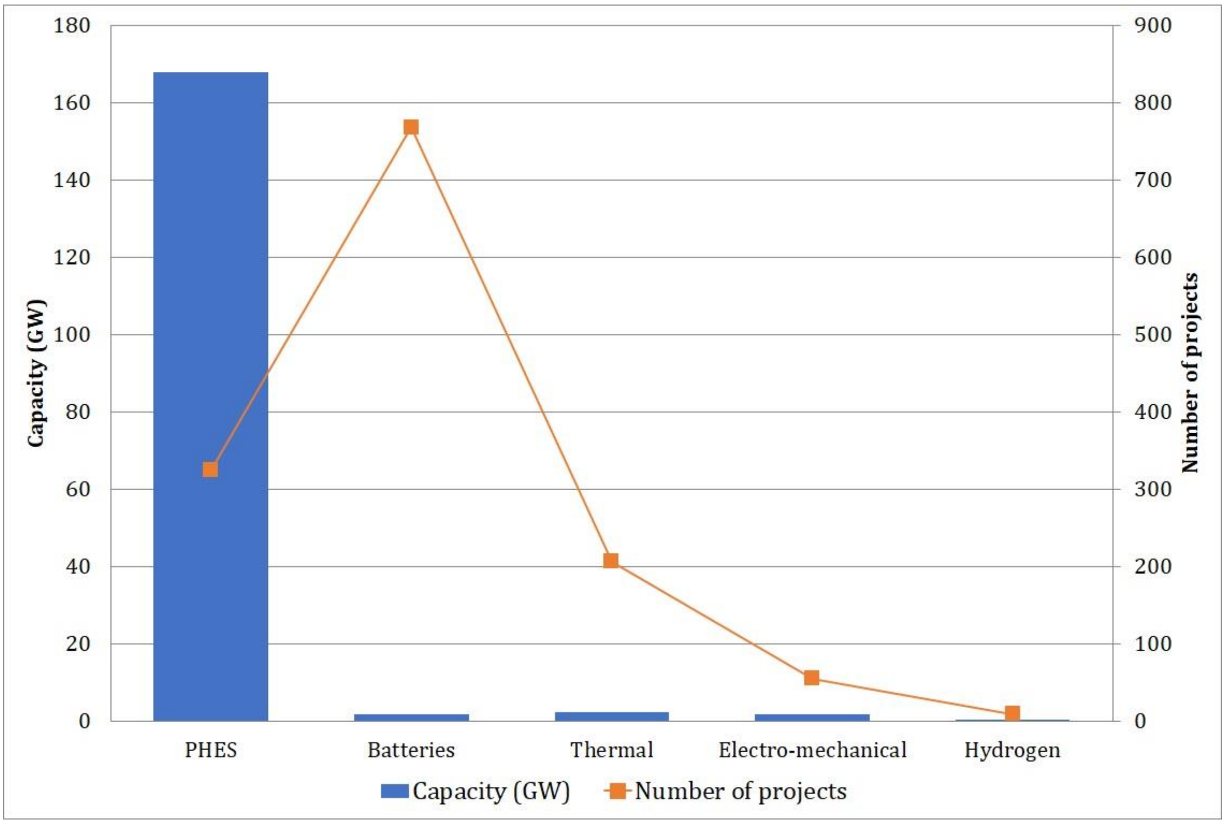

Figure 1: Global Storage capacity by technology[1]

According to the latest data of the US Department of Energy database[1], there are 1363 energy storage projects in operation worldwide, with a total capacity of 173.7GW. Pumped hydro energy storage (PHES) is by far the most widespread storage technology, accounting for 167.8 GW, or 97% of total global storage capacity. Thermal storage technologies come in second place with a share of merely 1.4%, or 2.4GW, while various electrochemical storage technologies (batteries) rank third, with a share of 1% and 1.79GW. In addition, there are several electromechanical storage systems, including compressed air systems, with a capacity of

[1]DOE OE Global Energy Storage Database, https://cutt.ly/ihENbfg

1.66GW, or 0.95% of global storage capacity; finally, the first 9 energy storage projects using hydrogen technologies were recently put in operation (Figure 1).

Currently, in the mainland network of Greece there are only two pumped hydro storage stations, in Thesavros (Drama) and Sfikias (Imathia), with a total capacity of approximately 700MW. In the non-interconnected network, on the islands of Tilos and Ikaria, there are two storage systems of a much smaller scale. Specifically, in 2018, the first RES hybrid system in the Mediterranean was put into operation on the island of Tilos; the system consists of a small 800KW wind turbine, a small 160KW photovoltaic and two standard NaNiCl2 batteries with a storage capacity of 2.8MWh[2]. In 2019, on the island of Ikaria, "Naeras" -a hybrid system by PPC Renewables- was put into operation, consisting of three (3) wind turbines with a total capacity of 2.7MW, two small hydroelectric systems (1.05MW and 3.1MW), and a total pumping capacity of 3MW[3].

The National Energy and Climate Plan (NECP) that was submitted to the European Commission in December 2019 provides for the construction of new pumped hydro storage systems with a total capacity of approximately 700MW by 2025, in order to promote the penetration of RES and increase their share of gross final electricity consumption to 61% by 2030. According to the NECP, in 2030, the total energy stored in all facilities, including small decentralized battery systems, could reach 2.2TWh[4].

In May 2020, a team led by S. Papathanassiou, Professor at the National Technical University of Athens (NTUA), completed a study on behalf of the Regulatory Authority for Energy (RAE), on the storage capacity ratio of PHES and medium and high-capacity batteries that is optimal in order to achieve both the NECP objectives and the maximum financial benefits. The study suggests that achieving a 60% RES penetration by 2030 will require 1.5-1.75GW of additional storage capacity, while, in order to maximize the benefits, 1-1.25GW of energy should be stored in PHES and 0.5GW in batteries[5].

These energy storage goals will have to be revised –and set higher- along with the entire NECP, as the latter is in line with the previous EU climate target, which is now under revision. Previously, the EU aimed at reducing greenhouse gas emissions by 40% by 2030, as compared to 1990 levels. However, the EU has now set a new, much more ambitious target of reducing emissions by 55% by the end of the decade. Achieving this target will require a much larger contribution of RES in electricity generation, which, in turn, will increase energy storage needs. In the case of Greece, the application of the scenarios formulated and analyzed in the relevant impact assessment study showed that, in order for the country to be compatible with the new pan-European climate target, the corresponding share of RES in gross final consumption should range between 83% and 88%[6], namely 22 to 27 percentage points higher than the current target of 61% set by the existing NECP. This level of RES penetration by 2030 will also require a

[2]https://tiloshorizon.eu/
[3]PPC Renewables (2019) "Naeras: Ikaria's hybrid energy system". https://cutt.ly/OhQ40iv
[4]Greek Ministry of Environment and Energy (December 2019), National Energy and Climate Plan https://cutt.ly/ChWwkun
[5]RAE Press Release (15.5.2020) "RAE conference on Energy Storage" https://cutt.ly/ohWrnuT
[6]Pantelis Capros, E3Modelling, Professor at NTUA (30.9.2020) "PRIMES MODEL SCENARIOS FOR THE EU'S GREEN DEAL" https://cutt.ly/VhWhn7e

significant increase in storage capacity; it is estimated that the latter will have to exceed 3GW by combining different storage options, including green hydrogen technologies.

Electricity storage technologies also play a pivotal role in Greece's Long-Term Strategy for 2050[7]. According to the two model scenarios that guide us towards achieving climate neutrality by the middle of the century (achieving a 95% reduction in greenhouse gas emissions in 2050 compared to 1990), storage capacity in 2050 will be between 8.5 and 28.1GW, while the corresponding amount of stored electricity will range between 22.4TWh and 42.4TWh per year.

All the above highlight the increasingly important role that energy storage technologies will acquire in the energy system of Europe, and Greece in particular, on the path to achieve climate neutrality. Therefore, understanding the main electricity storage technologies and their respective advantages and disadvantages is of particular importance.

In the following sections, we will present the basic characteristics of the two currently dominant storage technologies, namely pumped hydro energy storage and batteries; furthermore, we will discuss thermal storage and hydrogen technologies, two emerging technologies which are expected to gain larger shares in the future. Finally, an overview of the possibilities of financing energy storage infrastructure via the next Multiannual Financial Framework 2021-2027 will also be presented.

[7]Greek Ministry of Environment and Energy (2019) "Long term strategy for 2050" https://cutt.ly/vhWkL4M

Pumped Hydro Energy Storage (PHES)

Main Characteristics and Metrics

Pumped Hydro Energy Storage (PHES) technology first appeared in the 1890s in Italy and Switzerland[8]; the 1930s brought the first reversible water turbines that could function as both turbines and electricity storage pumps. These turbines had a decisive impact on the advancement of this technology, mainly in the USA and Japan, due to the growing need to manage the production of electricity from nuclear power plants. In Greece, the existing PHES stations in Thisavros (Drama) and Sfikias (Imathia) were constructed mainly in order to store electricity generated by lignite plants, when lignite had a dominant share in meeting electricity demand in the interconnected grid.

PHES is the most mature electricity storage technology; there are 325 such systems in operation worldwide with a total capacity of 167.8GW, which represents 97% of the 173.7GW of global total storage capacity. More than 75% of the world's PHES capacity is located in ten countries, and almost half of it (48.5%) is located in just three: China (31.4GW), Japan (27.4GW), and USA (22.6GW). The Member State with the highest PHES capacity in the EU-27 is Spain, which also ranks 4th in the world (8GW), followed by Italy (7.1GW), and Germany (6.5GW) (see Table 1)[1].

Table 1: Top 10 countries by PHES capacity

Country	**Capacity (GW)**
China	31.40
Japan	27.42
USA	22.56
Spain	8.00
Italy	7.07
India	6.77
Germany	6.53
Switzerland	6.43
France	5.81
Korea	4.70

The largest PHES system in the world is located in Bath County, USA, with a capacity exceeding 3GW; Canada has announced the construction of an even larger system, with a capacity of 4GW. The second and third largest systems are in China, with a power of 2.45GW and 2.4GW respectively, while the largest PHES system in the EU-27 is located in Spain and has a capacity of 2GW (see Table 2)[1].

[8]U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), https://cutt.ly/1hIukvq

Table 2: Top 10 PHES systems worldwide

Project	Country	Capacity (GW)
Bath County	USA	3.003
Huizhou	China	2.448
Guangzhou	China	2.400
Dniester	Ukraine	2.268
La Muela	Spain	2.000
Okutataragi	Japan	1.932
Kannagawa	Japan	1.880
Ludington	USA	1.872
Tianhuangping	China	1.836
Grand Maison Dam	France	1.820

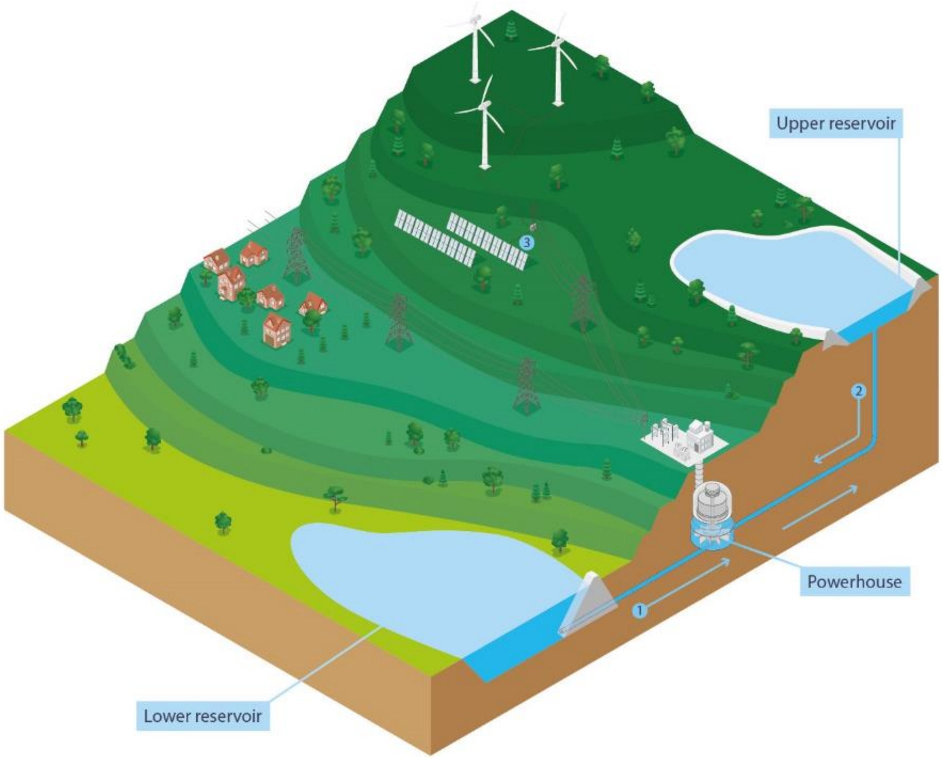

Figure 2: The principle of operation of a pumped hydro storage (PHES) system[9]

The principle of operation of PHES (see Figure 2) is based on the conversion of electricity into potential energy at the energy storage or "charging" phase, and its conversion back into electricity at the generation or "discharge" phase. Energy storage is achieved by pumping water, and electricity is generated by releasing that water into turbine units. The system consists of two reservoirs - the upper and the lower- with an adequate difference in elevation, and a suitable circuit of pipes for the circulation of water. In different versions of the system, it is possible to use a single pipeline in combination with the use of a reversible water turbine, as well as an auxiliary pumping station with a second pipeline. Furthermore, there is an interesting prospect in using the sea as a lower reservoir, as in the case of the Rance Tidal PHES station in France, which is also the first of its kind[10].

[9] International Hydropower Association, https://cutt.ly/khIyIne
[10] La Rance Barrage, https://cutt.ly/phIt5W6

In PHES systems, storage capacity is determined by the available water volume, combined with the exploitable elevation difference between the two reservoirs. The total efficiency of PHES systems can reach up to 80%[11] as, in a complete operating cycle, energy losses are encountered during both the pumping and the generation phase (hydroturbines-generators). Moreover, during long storage periods, efficiency is also affected by other types of losses, as, for instance, the evaporation of water from the reservoir.

Advantages and Challenges

An important advantage of PHES units is the rapid response and near immediate adaptation to load changes; for instance, the Dinorwig pumping station in northern Wales can handle a ~1.7GW load in less than 16 seconds[12]. This level of flexibility is in stark contrast to that of conventional thermal power plants, and particularly those nuclear and lignite-based, which have significantly worse response times (nuclear plants require 40 hours while lignite units require 6-10 hours for hot and cold reserves respectively)[13].

A major disadvantage of PHES lies in the difficulty in finding suitable areas for the construction of the two reservoirs and the one or two dams required. Moreover, both the location-finding process and the construction of these reservoirs is very time consuming –it can take up to 10 years- and expensive. Moreover, the construction process often has significant environmental consequences, such as deforestation and the removal of large amounts of vegetation before reservoir completion[14].

These disadvantages can be mitigated by utilizing reservoirs of existing hydroelectric dams. Converting pairs of hydroelectric dams into PHES systems requires the configuration of pumping pipelines and the installation of the necessary pumping systems; therefore, such projects have lower costs, are built faster, and have a much less severe environmental impact.

In the case of Greece, and according to the results of a study that was carried out for the Regulatory Authority for Energy[15], seven such pairs of PPC's existing hydroelectric power stations were identified; the latter would only require small interventions in order to be converted into PHES stations. The unit installation cost for a total additional pumping capacity of 400MW has been estimated at approximately 520€/KW. In fact, the findings of this study were incorporated in a report by WWF Greece that examined alternatives to the construction of "Ptolemaida 5", the new lignite plant in Greece, and potential uses for this additional pumping capacity that would result from the conversion of existing hydroelectric pairs. Specifically, that report showed that part of that capacity could be combined with photovoltaic and wind technologies, to form a hybrid system that can carry the base load of the new lignite unit during the entire year, and in fact, with a significantly lower levelized cost of energy (LCOE)[16].

[11] IRENA (2017). "Electricity storage and renewables: costs and markets to 2030" https://cutt.ly/QhpYlGW
[12] European Association for Storage of Energy, https://cutt.ly/IhU4Zrh
[13] Eurelectric.(2011). "Flexible Generation. Backing up Renewables", https://cutt.ly/ghU4CqZ
[14] Haisheng Chen, Yujie Xu, Chang Liu, Fengjuan He and ShanHu (2016) "Chapter 24 - Storing Energy in China—An Overview", Storing Energy, pages 509-527 https://cutt.ly/FhRYqRK
[15] Stefanakos, I. "An exploration of the possibilities to build new PHES units in mainland Greece". NTUA: Research Project 62/2423
[16] WWF Greece (2015) "Clean Alternatives to Ptolemaida V" https://cutt.ly/hhRUEUf

Batteries

Main Characteristics and Metrics

The first battery in the world was the Leyden jar. This device was discovered independently by German clergyman Ewald Georg von Kleist on October 11, 1745, and Dutch physicist Pieter van Musschenbroek at the University of Leiden between 1745 and 1746; the discovery was named after the city. The Leyden jar stores high voltage electrical charge from an external source between electrical wires on the inside and on the outside of a glass container. The first electrochemical battery was made by Italian physicist Alessandro Volta in 1800[17].The device consisted of a stack of copper and zinc trays separated by paper trays soaked in brine, and could produce a constant electrical current for a considerable period of time. However, the first widely used battery was the Daniell cell, discovered by British chemist John Frederic Daniell in 1836. Since then, battery technology has made a huge progress and is widely used in multiple applications.

The principle of operation of the battery lies in creating a potential difference (voltage) between two different elements (electrodes) immersed in an electrolyte solution. A battery consists of one or more electrochemical elements that convert the chemical energy contained in the battery materials into electrical energy through redox reactions[18].

The main technical characteristics that differentiate battery categories are: energy density, cell voltage, peak current, self-discharge rate, charging time, the temperature range within which the battery can operate safely, and the number of charging/discharging cycles before a significant portion of its nameplate capacity is lost.

A schematic diagram of the operation of a battery storage system is shown in Figure 3[19]. A battery cell consists of two electrodes of opposite charge: the anode and the cathode. These electrodes are immersed in an electrolyte, which can be in a liquid, solid, or viscous state. During the discharging phase, via an electrochemical reaction, the metal at the anode dissolves in the electrolyte in the form of anions, leaving electrons behind at the anode. These electrons flow from the anode to the cathode through the external circuit, thus generating a current. During the charging phase, the electrons move in the opposite direction, namely from the cathode to the anode. The voltage generated by a single cell is not enough to meet the requirements of most applications; therefore, many cells are connected in series, in order to produce the desired cell voltage output.

[17]"Biography of Alessandro Volta, Inventor of the Battery" https://cutt.ly/LhOZy6I

[18]Krivik, P. and Baca, P. (2013) Electrochemical Energy Storage, Energy Storage—Technologies and Applications, Ahmed Faheem Zobaa, IntechOpen.https://cutt.ly/ChOBfOM

[19]Hossain, E. et al., Energies (2020) "A Comprehensive Review on Energy Storage Systems: Types, Comparison, Current Scenario, Applications, Barriers, and Potential Solutions, Policies, and Future Prospects", https://cutt.ly/ghOBGzR

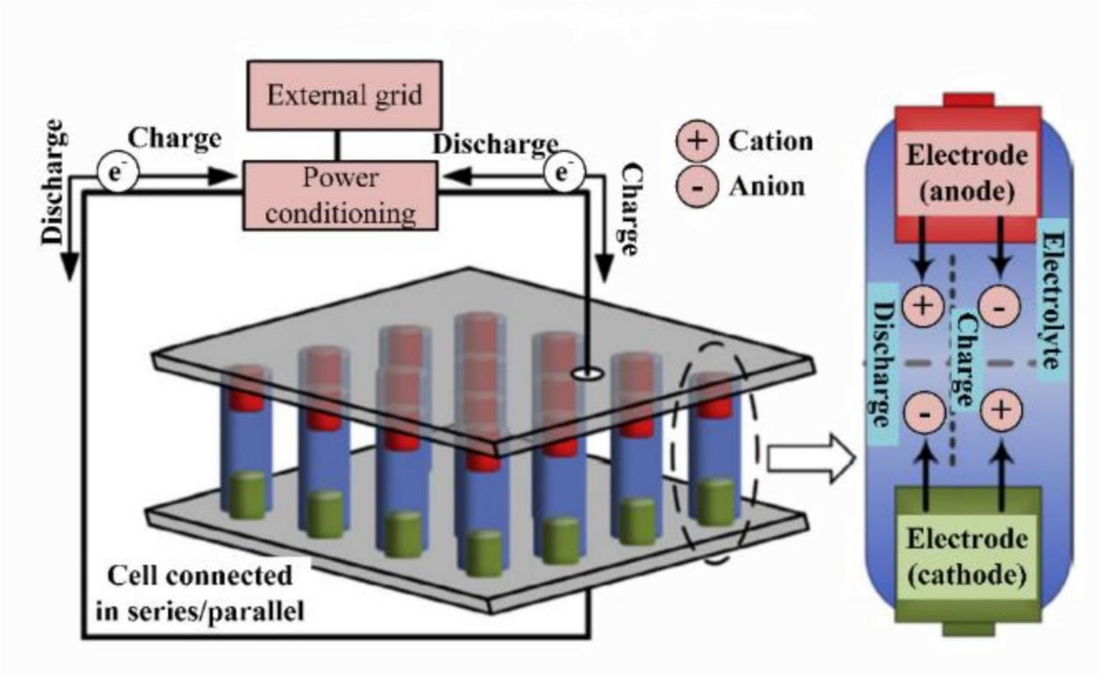

Figure 3: Principle of operation of a battery storage system[20].

According to the US Department of Energy database, there are currently 768 large-scale battery systems in operation worldwide, with a total storage capacity of 1.79GW; these technologies rank third among storage technologies, behind pumped hydro storage (168GW) and thermal storage (2.44GW). Lithium-ion batteries have the lion's share (74%) among individual battery technologies that vary in terms of chemistry, while sodium-based batteries come in a distant second place with 8.5%[1].

The Hornsdale Power Reserve plant in Australia was built in less than 100 days by Tesla[21] right next to the Hornsdale wind farm; as of 2017, it is the largest battery storage system worldwide, at 100MW and a storage electricity capacity of 129MWh. This system helps prevent load-shedding blackouts, and provides stability to the network in the event of a sudden drop in electricity generation from the wind farm or other network problems.

Despite their present-day relatively small capacity, there are great prospects of increasing the penetration of battery storage technologies, due to both the advancement of technology and the massive reduction of costs. According to the Bloomberg New Energy Foundation (BNEF), battery costs have declined by 86.8% in the last decade from $1183/KWh in 2010 to $156/KWh in 2019 (see Figure 4)[22]. This impressive drop can be attributed to the increase in the size of the batteries ordered, the large rise in the sales of electric cars (Battery Electric Vehicles - BEVs) and the increasing penetration of high energy density cathodes. The same research company predicts that in 2024, as demand will exceed 2TWh, the cost of batteries will plummet below $100/KWh, while in 2030 it will drop to $61/KWh. Moreover, the size of the battery market is projected to increase fivefold from 2019 to 2030, reaching $116 billion per year; this is projected to skyrocket the total installed capacity of batteries worldwide, including that of

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[20] Luo, X.; Wang, J.; Dooner, M.; Clarke, J. Overview of current development in electrical energy storage technologies and the application potential in power system operation.Appl. Energy**2015**, 137, 511–536

[21] https://hornsdalepowerreserve.com.au/

[22] Bloomberg NEF (December 2019) "Battery Pack Prices Fall As Market Ramps Up With Market Average At $156/kWh In 2019", https://cutt.ly/JhOT9Ye

electric vehicles, from 9GW in 2018 to 1095GW in 2040[23]. Continuing downward trends in costs and upward trends in battery penetration will be determined by the increase in energy density that allows the most efficient use of materials, the advancement of new silicon and lithium technologies for anode construction, and the development of new materials for cathodes.

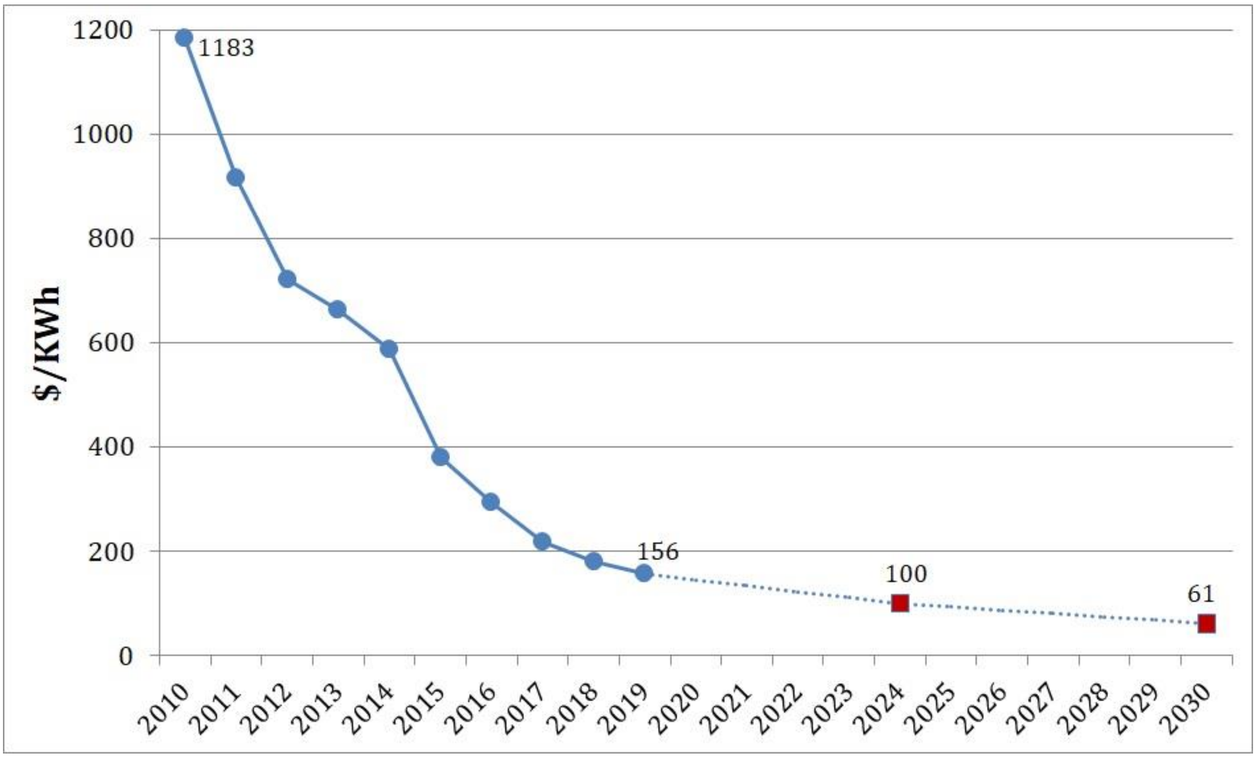

Figure 4: Battery costs for the period 2010-2019 and forecasts for 2024 and 2030[23]

Advantages and Challenges

One of the most important advantages of battery storage systems is their fast response time -in the order of a few tens of seconds- due to their lack of mechanical parts. They can also achieve significantly higher efficiency rates than pumped hydro storage technologies -up to 96% in the case of some of the latest lithium-ion batteries[24]. Another important comparative advantage is construction speed, as illustrated by the iconic example of Tesla's system in Australia. In addition, batteries provide a range of services, such as black-start capability, peak shaving, frequency regulation, and load levelling and following. Lithium-ion batteries in particular dominate the market today, and have a high energy density, a much lower rate of self-discharge compared to batteries of other technologies, and low maintenance costs.

However, the disadvantage of batteries lies in their short life span, compared to other storage technologies, as they lose a significant part of their nameplate capacity after a relatively small number of charging/discharging cycles. In addition, both the limited availability of raw materials for the manufacture of certain types of batteries (such as lithium batteries) and the

[23]Bloomberg NEF (July 2019)"Energy Storage Investments Boom As Battery Costs Halve in the Next Decade", https://cutt.ly/DhOCpwY
[24]Zachary Shahan, CleanTechnica (2015). "Tesla Powerwall &Powerpacks Per-kWh Lifetime Prices vs Aquion Energy, Eos Energy, &Imergy",https://cutt.ly/qhO4iHR

environmental impact of their end-of-life-cycle disposal dictates the development of recycling and reuse technologies. Industry analysts estimate that, by 2030, there will be 2 million metric tons of lithium batteries at the end of their life cycle; at the same time, it is estimated that, today, lithium batteries are recycled at a rate of only 2-3% in Australia and less than 5% in Europe and the US. In order to increase the overall use of batteries, recycling technologies need to advance; however, this means overcoming technical constraints, financial obstacles, and regulatory gaps[25]. In addition, lithium-ion batteries are generally sensitive, wear more easily than other batteries, and are also restrained by safety issues. Hence, manufacturers have to install a protective circuit in order to both limit the maximum voltage of each cell during charging and prevent a voltage drop during the discharging phase. Finally, their temperature has to be monitored in order to avoid extreme temperatures.

[25]Chemical and Engineering News (2019), "It's time to get serious about recycling lithium-ion batteries", https://cutt.ly/OhDsqLe

Thermal Storage

Electricity storage technologies in the form of heat (thermal storage) currently occupy the second place among all storage technologies, after PHES. Existing thermal storage systems have a total capacity of 2.3 GW worldwide; molten salts technology holds the largest share with 81.5%[1].

These technologies have been used for years in conjunction with solar thermal power systems, offering the latter flexibility in meeting demand even beyond the hours of high sunshine[26]. Solana in Arizona, USA, is globally the largest solar power plant that uses molten salt technology to store electricity. Solana was put in operation in 2013, has a total capacity of 280MW, and is designed to store energy for 6 hours. In conjunction with its storage system, it can supply the grid with 38% of its rated capacity during the course of a year; this utilization rate is significantly higher than that of both solar thermal systems without thermal storage and large-scale photovoltaics (20-25%)[27].

Conversion of Lignite and Coal Power Plants

It is important to mention the recent attempts of converting existing lignite or coal combustion plants into thermal storage systems for electricity generated from renewable sources. Electricity storage technologies have been dictated by the increased shares of RES in the energy system; however, the driving force behind the development of this type of conversion is the rapid decline in the share of lignite and coal in the European energy mix and the commitment by several EU Member States to completely phase out solid fossil fuels within the next decade. Based on the analysis by Ember, a British environmental think tank, the production of electricity from lignite and coal in the EU-27 declined by 32% in the first half of 2020, compared to the same period in 2019[28]. Furthermore, while the gross rated capacity of lignite and coal plants currently in operation in the EU is 136.5GW, the retirement of 71.2 GW has already been announced[29]. An analysis carried out by CAN Europe and Ember suggests that, according to the commitments made by the EU Member States in their National Energy and Climate Plans, in 2030 the net capacity of lignite and coal combustion plants will drop to 52.2GW[30], while many predict that the withdrawal rate of such plants will be much higher. Therefore, it is now certain that a very large part of the established network infrastructure will be rendered useless unless it can be repurposed in a sustainable way. Large power companies in Europe are moving in this direction with the aim of converting lignite and coal combustion units into thermal storage facilities for electricity generated by RES.

The operation of such systems involves three stages (see Figure 5). In the first stage, the electricity generated by RES systems is converted into heat using a resistance. In the second stage this heat is stored by increasing the temperature of a high heat capacity material. In the

[26] IRENA (2016) "The Power to Change: Solar and Wind Cost Reduction Potential to 2025", Bonn, International Renewable Energy Agency, https://cutt.ly/GhpIuVb

[27] Power (2014) "Top Plant: Solana Generating Station, Maricopa County, Arizona" https://cutt.ly/Ahdoth0

[28] Ember, July 2020, «Renewables beat fossil fuels: A half-yearly analysis of Europe's electricity transition», https://bit.ly/38uFNgH

[29]https://beyond-coal.eu/

[30] CAN Europe and Ember (2020) "Just transition or just talk?" https://cutt.ly/phdpmap

third stage, the stored heat is used to produce steam from water, which, in turn, moves the existing turbine of the unit, thus, generating electricity. As the original source of electricity is renewable, the same applies to the electricity that enters the grid during the "discharge" stage. In this way, it is possible for the previously polluting lignite and coal combustion plants to contribute to a clean energy system, free of greenhouse gas emissions.

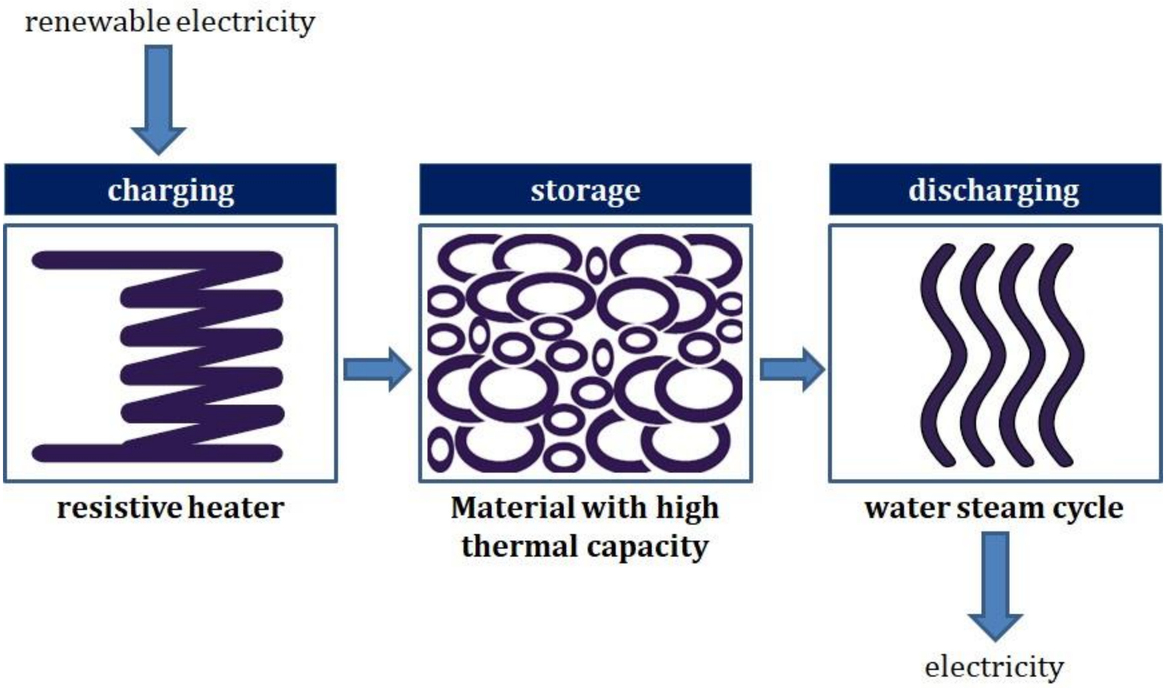

Figure 5: Principle of operation of a thermal storage system in combination with a lignite or coal combustion unit.

Volcanic Rocks

In 2011, Siemens-Gamesa embarked on the "Electric Thermal Energy Storage" (ETES) project to develop a thermal storage system, using low-cost volcanic rocks as a storage medium.

The first pilot system had a storage capacity of just 5MWh, was combined with a small 700KW steam turbine, and was put into operation in 2014. The success of the first project led to the development of a larger one in Hamburg, whose construction began in November 2017. The system was put into operation in 2019 and is able to store up to 130MWh of electrical energy drawn from the grid in the form of heat, for a period of one week. This thermal energy is converted back into electricity using a 1.4MW steam turbine, which can operate continuously for 24 hours. The system employs 1000 tonnes of volcanic stones to store electricity in the form of heat, at temperatures between 750°C and 800°C; this electricity is produced via an electrical resistance, and transported to the volcanic stones through special blowers. In addition to electricity, the unit can be "charged" directly with heat[31].

The conversion of electricity into heat is carried out with minimal losses (99% efficiency); however, electricity generation from stored heat is not expected to exceed an efficiency of 45%.

[31] NS Energy (2019) "Electric Thermal Energy Storage (ETES) System, Hamburg" https://cutt.ly/mhdHHyg

Finally, according to the company, the installation cost is 10 times lower than that of large-scale batteries[32].

The company expects that ETES will be available for commercial operation by 2022. By then, the storage will scale up to the level of a few GWh and the corresponding "discharge" capacity will exceed 100 MW; thus, the system will be ready to operate in conjunction with existing lignite and coal combustion plants[33].

Molten Salts

Molten salts are a more mature thermal storage technology, already used in conjunction with solar thermal systems. The salts commonly used in such storage applications are sodium nitrate and potassium nitrate, which have a high heat capacity and are commonly used as components of several fertilizers.

Figure 6 illustrates how a molten salts energy storage system can be combined with an existing lignite or coal combustion plant. Initially, the boiler of the combustion unit is replaced with a suitable heat exchanger, which can operate in combination with the two salt tanks (one of low and one of high temperature). As shown on the left, electricity from wind and/or photovoltaic systems is converted into heat through an electrical resistance; heat then raises the temperature of the salts to 600^{o}C, where they take on a liquid form. The stream of high temperature salts passes through the heat exchanger leading to the production of steam from the water stream, as the salts cool and end up in the low temperature salt tank. The next stages of the power generation process remain the same as in the lignite or coal combustion unit, as the generated steam is fed to the unit's turbine to generate electricity. The difference lies in the origin of the steam. In the case of the original combustion unit, steam was produced by the combustion of lignite or coal; in the case of the combustion unit combined with the molten salts storage system, the steam is produced by the heat of molten salts -a heat generated from stored wind or solar energy.

[32]Siemens-Gamesa (July 2018) "ETES-Energy storage to the next level", Presentation in the Working Group meeting of the Coal Regions in Transition Platform.https://cutt.ly/chdJ83j
[33]Siemens-Gamesa (2020) https://cutt.ly/7hdJTyT

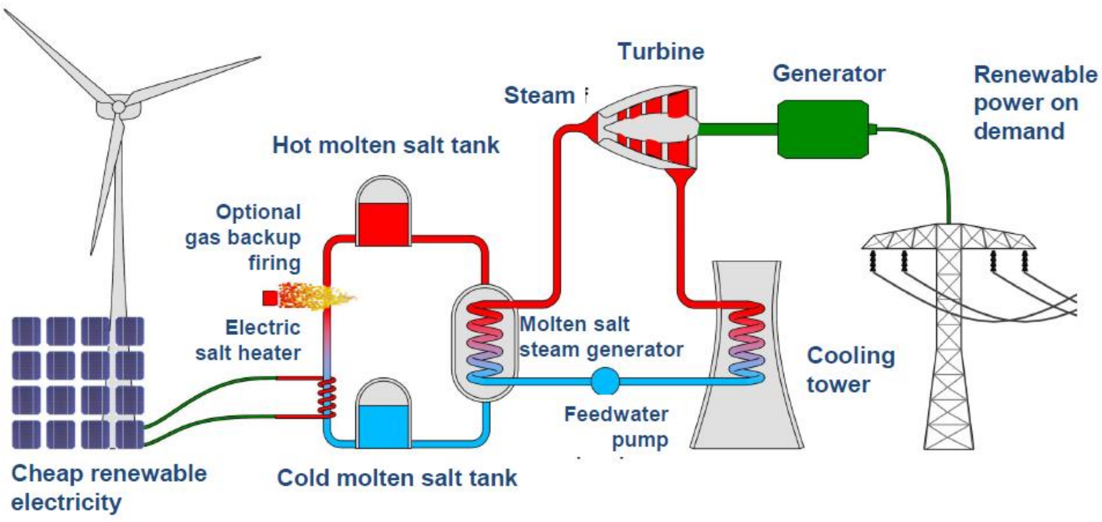

Figure 6: Principle of operation of a molten salts energy storage system in conjunction with an existing lignite or coal combustion plant[34].

The "Store 2 Power" project, which runs in Germany, applies the above technological model. The project aims to transform RWE lignite plants in North Rhine-Westphalia into molten salts energy storage plants, with a total efficiency of approximately 40%. The project is a collaboration among RWE (Europe's largest power company), the German Aerospace Center (DLR), and the University of Aachen[35].

This project has the full political support of Germany's largest political parties as the intention to convert existing lignite plants into energy storage plants had been included in the 2018 agreement of the German Cooperation Government parties[36]. In addition, the project was included in the proposals of the German Coal Commission that planned the phase out of lignite and coal by 2038, and was selected by the German Ministry of Economic Affairs and Energy in 2019 as one of the main projects of "Reallabore der Energiewende", Germany's program for energy transition[37]. The project was also included in the list of projects accompanying the recent German law[38] on lignite and coal phase-out by 2038, based on which 40 billion euros will be channelled to boost the economy of lignite areas in transition.

Similar projects for the conversion of lignite plants via molten salts technology are currently being discussed in other countries; for instance, in Chile, a collaboration is being formed among the country's Ministry of Energy, the German Ministry of the Environment, the German Aerospace Center (DLR), and GIZ GmbH, in the context of the decarbonization program of the Chilean energy sector[39].

[34] Michael Geyer, German Aerospace Center (DLR) (2019) "From Coal Age to StorAge", Webinar on Carnot Batteries
[35] En:former – RWE's energy blog, (2019) "Coal-fired power plant to be converted into heat storage facility" https://cutt.ly/0hQd9eA
[36] Koalitionsvertragzwischen CDU, CSU und SPD; (February 2018), https://cutt.ly/QhQfj6e (lines 3321-22)
[37] German Federal Ministry for Economic Affairs and Energy, Press Release (18 July, 2019), P.Altmaier: "AltmaierverkündetGewinnerimIdeenwettbewerb ,Reallabore der Energiewende" https://cutt.ly/BhQf6Y1
[38] Deutscher Bundestag: Bundestag beschließt das Kohleausstiegsgesetz; 3 July 2020; https://cutt.ly/dhQgfcY
[39] DLR, "Repurposing of existing coal-fired power plants into Thermal Storage Plants for renewable power in Chile" https://cutt.ly/DhQgLUM

Advantages and Challenges

The great advantage of converting lignite and coal combustion plants into thermal storage units for energy generated by RES is that these retired –previously highly polluting – units, along with their extensive infrastructure, are given a second life, and, in fact, one that is free of greenhouse gas emissions. Thus, lignite and coal plants can be employed to offer storage services, which are indispensable in an electricity system dominated by mature RES technologies.

The implementation of such conversions, which combines part of the combustion unit with a thermal storage system, will maintain jobs in the lignite industry, which is particularly important for lignite regions in transition. This conversion requires the installation of the molten salt tanks and the resistance used to convert electricity into heat, and the replacement of the old boiler with a suitable heat exchanger; otherwise, the operation and maintenance of the lignite unit remains the same.

Moreover, storage media, such as salts or volcanic stones, have a low cost. The molten salts are very durable and can be used for 35 consecutive years of charging/recharging cycles, while they have an alternative use as fertilizer components.

An additional important advantage is the short installation time. According to DLR experts, a 300MW lignite plant can be converted into a molten salt energy storage plant in approximately 18 months. In contrast, pumped hydro storage systems have much longer installation times, especially when new reservoirs are required.

On the other hand, the combination of thermal storage technologies with lignite or coal combustion plants is new, and, therefore, accompanied by various technical challenges, which are mainly related to the large size of the existing combustion plants. Moreover, the overall efficiency of such systems is 40%-45%, clearly lower than the efficiency of the two most common storage technologies, namely pumped hydro storage and batteries.

Another aspect that requires detailed investigation is the cost of electricity provided to the grid by such systems. In the case of Greece, DLR experts estimate that, if the cost of electricity from photovoltaics drops to 20€/MWh, then for a total efficiency of 40%, the cost of electricity delivered to the grid will range between 60 and 70€/MWh[40].

RWE, a pioneer company in thermal storage technologies, is already collaborating with PPC to build photovoltaics with a total capacity of 2GW in Western Macedonia [41]; therein lies an opportunity to expand this collaboration to include molten salt technologies. A relevant proposal for the conversion of lignite plants into molten salts energy storage facilities is included in the roadmap for the Region of Western Macedonia that was prepared by the World Bank team of experts and accompanied the Greek Just Transition Development Plan[42].

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[40] Michael Geyer (DLR), "From Coal Age to StorAge: Decarbonization and job securement by converting coal-fired power plants into storage plants for dispatch of renewable power", Athens, October 2019 (World Bank workshop)
[41]Kathimerini newspaper (1.9.2020) "RWE comes to Macedonia for a green investment" https://cutt.ly/0hQbsyW
[42] World Bank (2020) "A Road Map for a Managed Transition of Coal-Dependent Regions in Western Macedonia" https://cutt.ly/zhQbtpU and Press Release by the Greek Ministry of the Environment and Energy (3.10.2020) "Public consultation on the masterplan to phase out lignite"https://cutt.ly/0hQbgAV

Hydrogen

Hydrogen (H_2) is a high-density energy carrier that can serve as a means of storing electricity produced from renewable sources (RES) and, importantly, for long periods of time. Hydrogen technologies constitute the only storage technologies that can channel stored electricity to other end-use sectors, such as transport, buildings, industrial heat generation, chemical production, and electricity generation. Due to this very potential, hydrogen is considered to have a pivotal role in both the decarbonization of the entire European economy, and the central pan-European goal of achieving climate neutrality by 2050.

According to the latest available data worldwide (2019)[43], approximately 117 million tonnes (Mt) of H_2 are produced annually, 69 Mt in pure form and 48 Mt as by-products of synthetic gas processes, to be used either as fuel, or as a raw material for the manufacture of other products. The hydrogen produced is mainly used in oil refineries, (38 Mt), in the production of ammonia (31 Mt), heat (26 Mt), methanol (12 Mt), and steel (4Mt), while less than 0.01 MtH 2 are used as fuel for Fuel Cell Electric Vehicles (FCEV).

Virtually all hydrogen in pure form (69Mt) is produced from fossil fuels. Specifically, 76% comes from 205 billion cubic meters (bcm) of fossil gas (6% of global fossil gas end-use), while 23% comes from 107 Mt of coal and lignite (2% of world production). Less than 1% of the pure hydrogen produced worldwide comes from RES, via electrolysis. As a result, hydrogen production is currently responsible for the emission of 830 MtCO 2 per year (70-100 MtCO 2 by the EU), namely more than 9 times the total annual greenhouse gas emissions of Greece.

If hydrogen continues to be produced mainly from fossil fuels, as is the case today, it will not make a decisive contribution towards the goal of climate neutrality. It is evident that the production of green hydrogen must be increased. To this end, the European Commission proposed a new hydrogen strategy[44] with an objective to install at least 40 GW of electrolyzers in order to produce at least 10Mt of green hydrogen by 2030. In its vision for a climate neutral Europe in 2050[45], the Commission estimates that the share of hydrogen in the EU energy mix will increase from the current 2% (325 TWh) to approximately 13-14% by 2050; according to other scenarios, this share could rise up to 24%[46].

Hydrogen will also play a key role in Greece, according to the country's Long-Term Energy Strategy for 2050[47]. Based on the two scenarios that will render Greece near climate neutral by 2050 (greenhouse gas emissions in 2050 to be reduced by 95% compared to 1990), 15.7-33.1 TW of electricity will be stored in the form of hydrogen, with corresponding shares of 70%-78% of the country's total stored electricity. Moreover, the two most ambitious scenarios suggest

[43]IEA (2019). Report prepared for the G20, Japan. "The Future of Hydrogen: Seizing today's opportunities", https://cutt.ly/BdU7WnD
[44]European Commission (8.7.2020). "A hydrogen strategy for a climate-neutral Europe", COM (2020) 301 https://cutt.ly/FdIjrHk
[45] European Commission (2018) 773. "A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy". https://cutt.ly/gdIkB78
[46]FCH JU (2019) "Hydrogen Roadmap Europe".https://cutt.ly/pdSKYsn
[47] Greek Ministry of Environment and Energy (2019). "Long term strategy for 2050". https://cutt.ly/mdSCd9r

that the power of electrolyzers for hydrogen production will range from 4.3GW to 23.5 GW, occupying 51% to 84% of the total storage capacity of the country, respectively.

Production Methods

Hydrogen can be produced from a variety of raw materials and processes that have distinct climatic footprints. According to current terminology[48], when hydrogen is produced by coal or lignite gasification, it is called "black" or "brown"; it is called "gray" when it is produced by steam methane reform (SMR) based on fossil gas, or "blue" when SMR is combined with the capture and storage of the released carbon dioxide (CO_2). Finally, when the methane found in fossil gas is converted to hydrogen and solid carbon via pyrolysis, the hydrogen produced is called "turquoise". However, none of the above processes is climate neutral; climate neutrality can only be achieved when pure hydrogen is produced via water electrolysis, using electricity derived from RES. In this case hydrogen is characterized as "green".

Next, the three main methods of hydrogen production will be presented: Coal or lignite gasification, Steam Methane Reform (SMR) using fossil gas, and electrolysis. Other hydrogen production methods such as solar thermo chemical water splitting[49] or artificial photosynthesis[50], which employ direct use of solar energy, are still at a much earlier stage of research and development.

Gasification of Coal or Lignite

Lignite and coal gasification for hydrogen production is a mature technology that has been used for decades, particularly in China, in the chemical and fertilizer industry in order to produce ammonia. First, hydrogen is produced via the reaction of lignite or coal with oxygen and steam at high temperature and pressure, to form a synthetic gas consisting mainly of carbon monoxide (CO) and hydrogen, according to the reaction:

$$CH_{0.8} + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other products}$$

Following the removal of by-products from the synthetic gas, carbon monoxide reacts with steam through a water-shift reaction, producing additional hydrogen and carbon dioxide, according to the reaction:

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

There are 130 lignite and coal gasification units in operation worldwide, 80% of which are located in China. Production costs are low and range between \$1.2- \$2.2 per kilo of hydrogen, a price that is even lower than that of steam methane reform in certain world regions. However, this production method emits 19 kg of CO_2 per kg of hydrogen produced, which is more than twice as much as the steam methane reform process based on fossil gas[43].

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[48]Wood Mckenzie (2019). "Green hydrogen production: Landscape, projects and costs". https://cutt.ly/ydIpLX2
[49] C. N. R. Rao and SunitaDey (2017) "Solar thermochemical splitting of water togenerate hydrogen", Proceedings of the National Academy of Sciences, 114(51), 13385-13393 https://cutt.ly/Ad1K9gk
[50]University of Michigan (2018)."Harvesting clean hydrogen fuel through artificial photosynthesis", phys.org.https://cutt.ly/qd1Lyd9

Steam Methane Reform (SMR)

Most hydrogen is currently produced from fossil gas via the steam methane reform process (SMR). High temperature steam (700°C–1,000°C) reacts with the methane (CH_4) contained in fossil gas, in the presence of a catalyst and with the supply of energy, so as to produce synthetic gas (syngas), namely hydrogen, carbon monoxide, and a small amount of carbon dioxide, according to the following chemical reaction:

$$CH_4 + H_2O \rightleftharpoons CO + 3\ H_2$$

In phase two, carbon monoxide and steam react to produce additional hydrogen and carbon dioxide, according to the water-shift reaction that is also used when hydrogen is produced via lignite or coal gasification. In the final stage, carbon dioxide and excess substances are removed, leaving pure hydrogen.

At-present, the steam methane reform process has the lowest production costs compared to all others methods. Fuel cost has the largest contribution to the total costs (45% -75%). Consequently, in countries where fuel costs are low (Middle East, USA, Russia) the total cost is approximately $1/Kg$H_2$, while in Europe and China, where fossil gas is imported, the respective cost draws nearer to $1.75/Kg$H_2$. It is estimated that the combination of SMR with Carbon Capture and Storage technologies (CCS) will increase installation costs by 50%, fuel costs by 10%, while operating costs will double, due to the need to transport and store the CO_2 produced[43].

Despite the relatively low costs, every ton of hydrogen produced via the SMR process is accompanied by 9 tonnes of CO_2; thus, "gray" hydrogen is not expected to play a part in achieving the climate neutrality goal.

The amount of CO_2 released is reduced if the SMR process is combined with the capture and storage of the carbon dioxide produced. However, to date, and despite the maturity of SMR technology, a large-scale SMR-CCS system that can achieve CO_2 emissions reduction at high levels -in the order of 90%- has yet to be developed[51]; moreover, the greenhouse gas emissions related to the mining and transport of the fossil gas required for the hydrogen production via SMR, further burden the carbon footprint of this production method. Therefore, it remains questionable whether “blue” hydrogen will have an important contribution towards climate neutrality.

Electrolysis

Up until the 1950s, direct water electrolysis was widely used in hydrogen production. Today, however, only a small percentage of hydrogen is produced via this process, for applications that require a small volume of pure hydrogen, mainly because the cost of producing pure hydrogen via other methods is much lower. However, due to the large drop in the cost of RES and the

[51]IEAGHG Technical Report2017-02February (2017). “Techno-EconomicEvaluationof SMR Based S tandalone (Merchant) Hydrogen Plant with CCS”, https://cutt.ly/2dL4Xwp

unique potential of green hydrogen to contribute to the decarbonization of many sectors of the economy, there is now a strong interest in building integrated electrolyzers in conjunction with the exploitation of renewable energy sources. A study by the International Energy Agency (IEA), using 2018 data estimates the cost of green hydrogen production to be between $3 and $7.5 per kilo, while the cost of hydrogen production via SMR is between $0.9 and $3.2 per kg[43]. Recent research demonstrates that green hydrogen is already competing with gray in Texas and Germany in niche applications, but not on an industrial scale. Nevertheless, this is expected to change within a decade, as the cost of producing green hydrogen will fall to $2.5 per kg[52].

Electrolysis is the process of applying an electric current through water, in order to break it down into its components, namely hydrogen and oxygen gas, according to the reaction:

$$2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$$

When the electricity used for electrolysis comes from RES, then the hydrogen produced is called "green", as no greenhouse gases are emitted during the entire process. Electrolyzers consist of an anode and a cathode, and an electrolyte between them, namely a chemical that has the property of breaking down into positive and negative ions when dissolved in a solvent such as water. The type of electrolyte affects the electrolysis process; thus, electrolysis systems are divided into three categories[43] (See Figure 7).

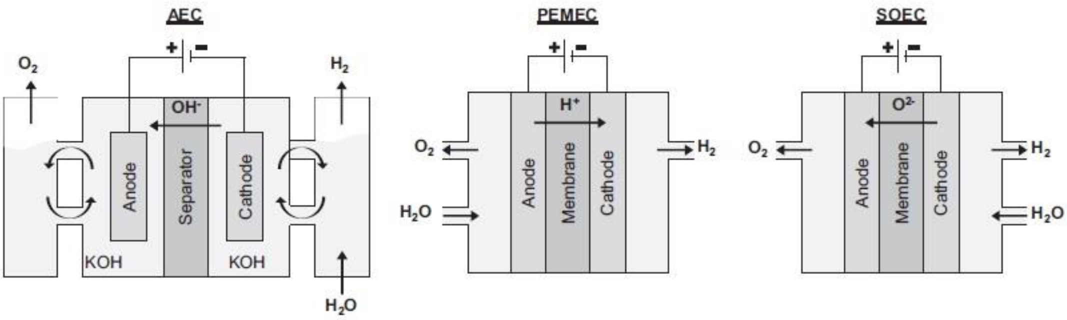

Figure 7: The principle of operation of the three main electrolyzer technologies for hydrogen production[53]

Alkaline Electrolyzers

Alkaline electrolysis is the most mature electrolysis technology, as it has been employed since the 1920s in order to produce hydrogen to be used in the fertilizer industry. Installation costs are relatively low, as no expensive materials are necessary for the process. The electrolyte here is usually a liquid alkaline solution of Sodium Hydroxide (NaOH) or Potassium hydroxide (KOH). The produced hydroxyl anions (OH^-) move from the cathode to the anode, while hydrogen is formed at the cathode.

Polymer Electrolyte Membranes (PEMs)

These systems were developed in the 1960s to overcome certain problems posed by alkaline electrolyzers. PEMs use pure water instead of an electrolyte solution, thus avoiding the sodium- or potassium- hydroxide recovery and recycling process, which is necessary in alkaline

[52]Glenk, G. and Reichelstein, S. (2019) "Economics of converting renewable power to hydrogen", Nature Energy, 4, 216-222.https://cutt.ly/fd1GnGh

[53]Schmidt et al. (2017) "Future cost and performance of water electrolysis: An expert elicitation study". International Journal of Hydrogen Energy, 42, 30470-30492. https://cutt.ly/ld1DTgY

electrolyzers. Also, PEMs are smaller in size and thus more suitable for installation in densely populated areas. On the other hand, they have a shorter lifespan and are clearly more expensive than alkaline electrolyzers, mainly due to the cost of membranes and the cost of electrodes' catalysts (palladium, iridium). The main difference between PEMs and alkaline electrolyzers is that the electrolyte in PEMs is not a liquid solution, but a specialty plastic polymer film. Water reacts at the anode to form oxygen, positively charged hydrogen ions (protons), and electrons. Electrons flow through an external circuit, while hydrogen ions selectively penetrate the electrolytic membrane towards the cathode, where they combine with electrons from the external circuit to form H_2 gas.

Solid Oxide Electrolyzer Cells (SOECs)
This is the least developed technology of all three, and is not yet commercially available. In these systems, the electrolyte is a solid ceramic material, which selectively conducts negatively charged oxygen ions (O^{-2}) when it is exposed to a high temperature (700°–800°C). The water in the cathode combines with electrons from an external circuit to produce hydrogen gas and negatively charged oxygen ions. The latter pass through a solid ceramic membrane and end up at the anode, where they are converted to oxygen gas and electrons, subsequently fed to the external circuit. SOECs can be employed for co-electrolysis, when supplied with water and carbon dioxide, in order to produce syngas. Nonetheless, their greatest comparative advantage is that they can function in reverse, namely as fuel cells, producing electricity from hydrogen. This increases the efficiency of the system, which can function as both an electricity storage unit and a grid balancer. On the other hand, the biggest challenge for the evolution of SOECs is their short lifespan, as there is a high rate of material wear, due to the very elevated temperatures required for this process.

Most experts believe that within the current decade, PEMs rather than alkaline electrolyzers will dominate the market, while high uncertainty characterizes the evolution of SOECs. In addition to the development of research concerning the different electrolysis technologies, a key factor to reducing their cost is the expansion of the hydrogen market.

Uses

It is predicted that the increase in RES penetration, together with the further development of energy storage technologies, will lead to the decarbonization of the electricity generation sector. However, the complete decarbonization of other sectors presents greater challenges, due to the difficulties in their full electrification. Green hydrogen technologies could override these obstacles, thus making a decisive contribution to the decarbonization of other sectors of the economy, such as transport, buildings, and industry. In addition, hydrogen-based technologies can also play an important role in electricity generation, by storing surplus electricity from RES and delivering it to the grid when there is high demand.

Transport
According to the latest available data (2018), the transport sector is responsible for 22% of total greenhouse gas emissions and almost 30% of EU-27 CO_2 emissions[54].

[54]EEA greenhouse gas - data viewer.https://cutt.ly/Kd13e2X

Road Transport

The development of electric mobility, accompanied by an increase in RES penetration, constitutes the main instrument for the decarbonization of road transport. However, increasing the penetration of Battery Electric Vehicles (BEVs) presents a number of challenges, such as high purchase costs, autonomy limitations, and long charging times. These difficulties can significantly delay the decarbonization of road transport. Faster and better results can be achieved by combining the development of battery-powered electric mobility with that of Fuel Cell Electric Vehicles (FCEVs). Similar to BEVs, FCEVs run on electricity and do not emit greenhouse gases during operation; they only emit water vapor. The difference between them lies in the source of electricity; in FCEVs, electricity is generated by the reaction of oxygen and compressed hydrogen within the hydrogen cell, while in BEVs, it is exclusively generated by a rechargeable battery.

Hydrogen cell electric vehicles have specific advantages over battery electric vehicles[46]:

- **Greater autonomy,** for up to 800km without the need to recharge. However, advances in battery technology are expected to alleviate this disadvantage of BEVs. Already today, there is a BEV model with nearly 650km of autonomy[55].
- **Faster charging time,** (up to 10-15 times) compared to BEVs, and comparable charging time to that of conventional vehicles. Therefore, in order to serve the same number of vehicles, hydrogen cell electric vehicles' refuelling stations require 10-15 times less space than the corresponding BEVs charging stations; this constitutes an advantage, particularly in densely populated areas, as well as on large highways.
- **Smaller size and weight.** Using the technology currently available, a battery suitable for a 40-tonne truck weighs approximately 3 tonnes, thus reducing the available load. No such issue arises with hydrogen cells, which, due to the higher energy density of hydrogen, are lighter than batteries, and therefore, more suitable for large vehicles, buses, and trucks.
- **Balancing demand.** FCEVs indirectly offer demand balancing services: their increased use can reduce the demand peaks created by the need to simultaneously charge a large number of BEVs at specific times of the day, especially in large cities.

However, FCEVs also have significant disadvantages:

- **Higher purchase cost.** Despite declining prices in recent years, the cheapest FCEV model currently available in the California, US market costs $57,500, while BEVs start at $30,700, excluding discounts and special incentives[56,57].
- **Lower efficiency.** As multiple energy conversions are necessary on the way from the energy source to the vehicle (well-to-wheel), FCEVs require more energy to travel the same distance as BEVs. Experts estimate that in order to be supplied with 60KWh, a BEV requires 70KWh of primary electrical energy generated by renewable sources (76% efficiency), while a FCEV requires 202 KWh (30% efficiency) (see Figure 8). However, it should be noted that FCEVs

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[55] '4 Wheels' magazine (16.6.2020) "647Km autonomy for the new Tesla Model S" https://cutt.ly/Rd0BWcU
[56]Community Environmental Council (2020), Fuel Cell Electric Vehicles.https://cutt.ly/Pd06CoT
[57] Roland Berger, FCH (2017) "Development of Business Cases for Fuel Cells and Hydrogen Applications forRegions and Cities" https://cutt.ly/dd2qVT5

have a higher degree of efficiency compared to conventional vehicles, as only 12%-30% of the energy contained in the fuel is used for vehicle movement[58].

- **Higher fuel cost.** This is due to both the current high cost of hydrogen production and the lower well-to-wheel efficiency of these vehicles, as compared to BEVs.
- **Double the cost to install refuelling stations**. Today the construction of a hydrogen refuelling station costs approximately €4000/vehicle, while the corresponding cost for BEV rapid charging stations is approximately €2000/vehicle. However, the expansion of the refuelling station network is expected to reduce construction costs, while the cost of BEV charging stations is expected to rise due to the saturation of local networks. It is estimated that, in the long run, the construction cost for both new hydrogen refuelling stations and BEV charging stations will balance out at €2500/vehicle[46].

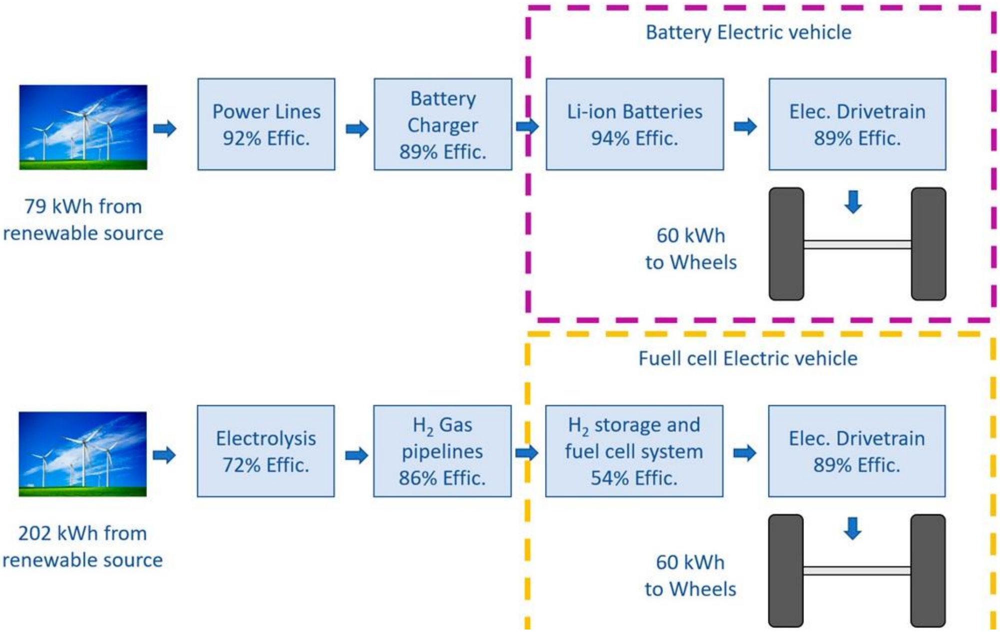

Figure 8: 'From well to wheel' energy route for Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs)[58].

Currently, there are 5 models of passenger FCEVs available, while hydrogen cell buses are already circulating in 14 European cities, such as Aberdeen, Antwerp, Cologne, London, Oslo, Riga, etc. In addition, hydrogen cell taxis are circulating in London, Paris, Brussels, and Hamburg. Twenty-five additional models of passenger FCEVs are expected to circulate within the next five years, while 3 companies (2 of which are in Europe) have announced the production of hydrogen cell trucks. Additionally, "H_2 BusEurope", a consortium of 6 companies that are active in the hydrogen chain, will finance the purchase of 600 new hydrogen cell buses by 2023 in the United Kingdom, Denmark, and Latvia utilizing Connecting Europe Facility funds[59].

[58]Eaves, S. & Eaves, J. (2004) "A cost comparison of fuel-cell and battery electric vehicles". J. Power Sources, 130, 208–212. https://cutt.ly/Hd0M84G

[59]H_2Bus, Press Release (3.6.2019). "Leading players enabling true zero-emission hydrogen solution for public transportation" https://cutt.ly/ld0uCeF

The development of hydrogen refuelling infrastructure has been slow. Currently, there are only 120 hydrogen refuelling stations for FCEVs across Europe (84 of which are in Germany[60]), in or around urban centers; several European countries have stated their intention to build a total of 750 additional stations in the next five years. Nonetheless, the comparison in infrastructure is overwhelmingly in favor of BEVs, as in Europe there are already more than 175,000 standard- and 19,500 fast-charging stations for BEVs (under and over 22KW respectively), and their growth rate in recent years has been exponential[61].

Rail Transport

Electrification is recommended for new railways, as well as existing ones. Hydrogen fuel cells constitute a promising technology to replace diesel as the main fuel for trains, thus contributing to the decarbonization of transport by rail. The relevant hydrogen refuelling infrastructure can be relatively easily and quickly developed on the existing rail network. The first pilot project to replace a diesel-powered train with a hydrogen-powered one is already in trial operation in Germany, as of September 2018[62], while similar additional projects have been announced in France[63], Austria[64], and the United Kingdom[65].

Maritime Transport

Hydrogen can play a particularly significant role in the decarbonisation of maritime transport, given that 90% of all goods are transported by sea, and these transports are responsible for 3% of global greenhouse gas emissions, and even exhibiting upward trends. As a result, in April 2018, the shipping industry committed to reduce emissions by at least 50% by 2050. Achieving this goal, considered by many ambitious, will require new ships, new engines and, above all, new fuels.

Hydrogen cells can be used in both marine and river transport to reduce the emission of CO_2 and other pollutants such as dust, nitrogen oxides, and sulfur oxides by conventional ships. Energy Observer[66], sailing under the French flag, is the first passenger ship with hydrogen cells. It produces the hydrogen it consumes to sail through seawater electrolysis and the combined use of wind, solar and hydroelectric energy; moreover, it is equipped with a lithium-ion battery for short-term storage of the generated electricity. In addition, two pilot projects involving hydrogen-powered ships are underway. The MARANDA project, launched in 2017, aims to build a 165KW hydrogen cell transmission system to power the electrical components of a ship that is conducting research in the icy Arctic. The FLAGSHIPS project concerns the use of 1MW hydrogen cells on both a riverboat and a ship carrying passengers and vehicles[67]. The interest in building large ships with hydrogen cells is on the rise. In September 2017, Viking Cruises, a Norwegian company, announced that it will build the first cruise-ship using hydrogen cells and liquefied hydrogen; this vessel will be 230 meters long with the capacity to accommodate 900

[60]Hydrogen Mobility Europe (19.5.2020). "Insight into the expansion of the HRS network" https://cutt.ly/Kd01DEB
[61]European Alternative Fuels Observatory.https://cutt.ly/od0yZFp
[62]Railway Gazette International (19.5.2020) "Hydrogen fuel cell train trials completed" https://cutt.ly/Cd2wO5n
[63]Railway Gazette International (10.12.2018) "SNCF to run fuel cell train in 2022" https://cutt.ly/2d2ulFD
[64] Railway Gazette International (2.3.2020) "ÖBB to test hydrogen multiple-units" https://cutt.ly/Td2uGcE
[65]BBC (27.2.2020). "Next stop, hydrogen-powered trains" https://cutt.ly/Xd2eymO
[66]https://www.energy-observer.org/
[67]FCH-JU. "Maritime Hydrogen: The next big wave" https://cutt.ly/ld2dSJx

passengers and 500 members of crew[68]. Finally, in April 2020, ABB signed a Memorandum of Understanding with Hydrogène de France (HDF) with the aim of developing hydrogen cells with a capacity in the order of MW, to be used in commercial vessels, such as containers and tankers[69].

Air Transport

The aviation industry is responsible for approximately 3% of the EU's total greenhouse gas emissions and for 2% of emissions worldwide; importantly, air transport emissions are on the rise. Annual emissions in 2017 were 60% higher than in 2005; moreover, it is predicted that without any measures, international aviation emissions will be three times higher in 2050 as compared to 2015[70]. In order to achieve climate neutrality, the European Green Deal has set a goal of reducing transport emissions by 90% compared to 1990 levels. Air transport must contribute to this goal; nonetheless, the decarbonization of this industry presents great challenges. The direct use of hydrogen as a fuel for small pilot aircrafts, such as the German four-seater HY4, is currently in the early stages of research[71]. Meanwhile, in September 2020 Airbus announced its intention to commercialize the first passenger aircraft to run entirely on hydrogen[72]. However, a more extensive use of pure hydrogen will require much further research and possibly major alterations to both aircraft design and airport infrastructure, with regards to fuel storage and refuelling facilitities. Several studies are being conducted on air transport electrification; nonetheless, here too, there are serious limitations related to battery weight and cost. The use of synthetic fuels containing green hydrogen and CO_2, in addition to biofuels, offers higher prospects: unlike pure hydrogen, synthetic fuels require no drastic changes in aircraft design or refuelling and storage infrastructure. However, they do not eliminate greenhouse gas emissions and their cost is currently 4-6 times higher than that of kerosene. Even in the long run, it is predicted that the cost of hydrogen-based synthetic fuels will not drop below 1,5 times the cost of conventional fuels. Therefore, it appears certain that their extensive use will lead to a significant increase in ticket prices[43].

Buildings

Due to the widespread use of fossil fuels, the energy consumed by buildings is responsible for 28% of the world's energy-related greenhouse gas emissions[73]. The electrification of heating, along with extensive use of heat pumps, in combination with the increased penetration of RES in the energy mix, constitutes the main instrument to decarbonize the building sector. However, the installation of heat pumps, especially in old buildings, is often accompanied by significant difficulties, while the complete electrification of heating in the building sector will lead to large fluctuations in electricity demand. Therefore, the combination of electrification and hydrogen technologies may prove to be ideal in order to meet the heating needs of buildings, while

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[68] Offshore Energy (29.9.2017) "Viking Cruises to Build World's 1st Hydrogen-Powered Cruise Ship?" https://cutt.ly/Zd2gotJ

[69]ABB Press Release (8.4.2020). "ABB brings fuel cell technology a step closer to powering large ships" https://cutt.ly/ud2fWSR

[70]European Commission."Reducing emissions from aviation".https://cutt.ly/zd3UAgl

[71]http://hy4.org/

[72] Airbus, (21.9.2020) "Airbus reveals new zero-emission concept aircraft" https://cutt.ly/phpzUq0

[73]Abergel et al. (2018) "Global Status Report - Towards a zero-emission, efficient and resilient buildings and construction sector" https://cutt.ly/xd86V9i (2017 data)

remaining on the path towards climate neutrality. Hydrogen can contribute to this direction in four ways. Particularly:

Hydrogen Blending

This method has the lowest cost, as it requires no changes to either the transmission network, the components, or the end-appliances. There are currently several pilot projects examining different percentages of hydrogen blending in fossil gas networks[74,75].

However, within the existing infrastructure, and in order to avoid problems of loss and leaking, ignition, flame stability, etc., the potential share of hydrogen that may be injected to the total transported gas lies between 5% and 20%. This approach shows limited potential with regards to achieving the climate neutrality goal. Moreover, even at these low rates, hydrogen blending is accompanied by significant disadvantages and technological challenges. More specifically, as the volumetric energy density of hydrogen is one third that of fossil gas, blending reduces the final energy content transported by a pipeline, and therefore final consumers will have to use larger quantities of gas to meet the same needs. It is estimated that blending at 3%, reduces the energy transported by a pipeline by 2%[76]. Additionally, hydrogen burns faster than methane, which is a key component of fossil gas, thus, increasing the risk of flame dispersion. The maximum rate of hydrogen blending in a network is determined by the technical limitations of the appliances connected to it; therefore, blending must be determined on a case-by-case basis. Finally, it is not possible to change the volume fractions of the injected hydrogen, as it will damage the appliances and components that are connected to the network.

Despite the above problems, hydrogen blending in existing fossil gas networks may, at an early stage, contribute to the development of hydrogen technologies. For instance, it is estimated that a 3% volume share of hydrogen in global fossil gas demand (approximately 3,900 billion cubic meters in 2018) would require almost 12 million tonnes of hydrogen. If this amount were to be produced by electrolysis, it would require approximately 100GW of electrolyzers with a 50% utilization rate. This in turn would reduce electrolyzer installation costs by approximately 50%[43], thus contributing to the reduction of the total cost of green hydrogen production.

Production of Synthetic Natural Gas (SNG)

Synthetic methane can be produced from green hydrogen and carbon dioxide via CO_2 capture, storage, or even utilization technologies (CCS/CCU), and be injected into the existing fossil gas network, or replace it completely, in order to meet the energy needs of buildings (see Figure 3 for the SNG production process). The advantage of this method lies in its compatibility with the existing network, components, and end-use devices; furthermore, due to the chemical affinity between fossil gas and synthetic methane, the aforementioned disadvantages of hydrogen blending can be avoided. However, despite decades of efforts, CCS/CCU technologies have not sufficiently matured, and the efficiency of the synthetic methane production process remains low, thus raising production costs. The 4-year STORE & GO demonstration project (2016-

[74]Engie, Press Release (8.11.2016). "The GRHYD demonstration project" https://cutt.ly/Cd4ryg5
[75]https://hydeploy.co.uk/
[76]Haeseldonckx, D. and W. D'haeseleer (2007), "The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market structure", International Journal of Hydrogen Energy, Vol. 32, Issues 10-11, pp. 1381–6. https://cutt.ly/Td4eve9

2020)[77] with the participation of 27 partners, aimed to address several of these challenges by assessing the effectiveness of three different synthetic methane production processes with a capacity of 200KW-1MW, with the methane produced being then fed into the existing fossil gas network. Despite the advantages of synthetic methane, as compared to clean hydrogen, the International Energy Agency estimates that injecting synthetic methane into fossil gas will remain more expensive[43].

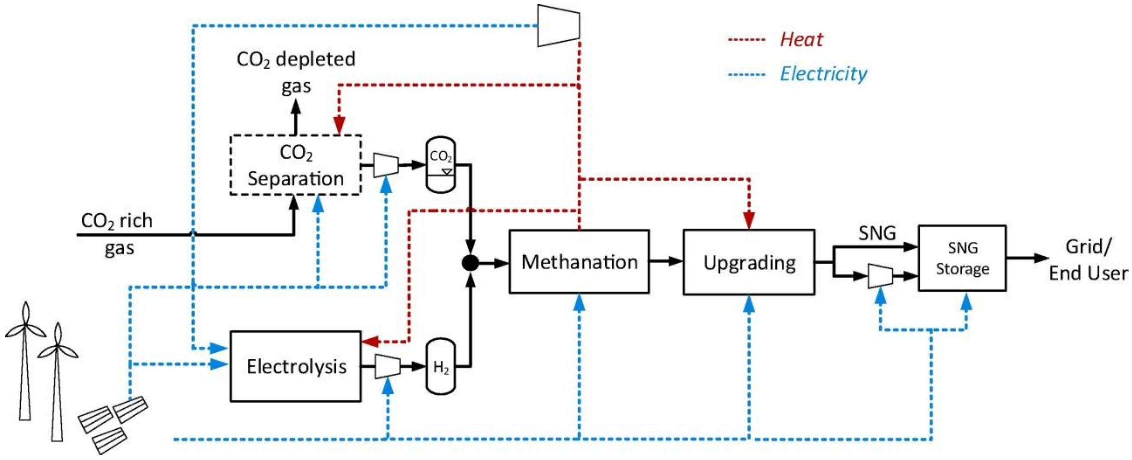

Figure 9: Flow chart of the production of synthetic methane from green hydrogen and CO_2 using CCS/CCU technologies[78]

100% Hydrogen Use

The problems that arise by hydrogen blending can be overcome if, in order to meet the needs of buildings, 100% pure hydrogen is used, rather than a mix of hydrogen and fossil gas. However, this would require the upgrade or even complete replacement of the steel used in the existing transmission pipes, with materials that do not corrode or allow hydrogen leaks, such as polyethylene and reinforced polymers. Moreover, most end-use appliances (boilers, hot water tanks, ovens) that are not designed to run on pure hydrogen would also have to be replaced[46]. The H21 Leeds City Gate project[79] plans to transform Leeds, UK, into a city that uses 100% hydrogen; the existing pipe network will be employed, as, in 2016, it was confirmed to be adequate for hydrogen transmission. In order to achieve the goal of 100% hydrogen, the project aims to produce 180 KtH_2/year by 2025, and 2,000 KtH_2/year by 2035. However, this hydrogen will not be "green", as it will be produced via SMR.

Hydrogen Cells for Buildings

Hydrogen can be used to meet the energy needs of buildings through integrated heat and power generation systems with hydrogen cells, thus completely freeing buildings of burners and boilers. Across Europe, there are currently approximately 3,000 such systems, and 25,000 additional ones are planned to be installed in 11 countries by 2021, with the support of various funding programs. In addition, certain countries provide special incentives to install hydrogen cell heat and power generation systems in buildings through state subsidies (Germany) or guaranteed prices (United Kingdom)[46]. However, this technology appears to be particularly implemented in Japan. ENE-FARM is a large-scale program that installed the first such system in

[77] https://www.storeandgo.info/
[78] Gorre, J et al. (2019) "Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage", Applied Energy 253 113594. https://cutt.ly/qd4uT2b
[79] https://www.h21.green/

2009; by 2017, 250,000 more had been installed in the country. The goal is to install 5.3 million such systems (10% of households) by 2050. Thanks to this program, the installation cost per unit declined by 70% in less than 10 years, and, specifically, from approximately $30,000 in 2009 to approximately $9,000 in 2018[80].

Industry

There is a wide range of existing or potential uses of hydrogen in industry, including: high grade heat generation at various stages of specific industrial processes; removal of various substances and mainly sulphur; treatment of heavy oil fractions in refineries; production of widely used chemicals, such as ammonia and methanol; and steel production, with the use of hydrogen as a reducing agent to replace carbon. If the hydrogen used in these varied processes is produced by electrolysis using power generated by RES, then it can make a decisive contribution to the decarbonization of the respective industries. Particularly:

High-grade heat generation

A significant part of the industry's greenhouse gas emissions is produced by the combustion of fossil fuels to supply heat to various processes, such as melting, gasification, drying, as well as to endothermic chemical reactions. Heat can be used either directly, as in an oven, or indirectly by generating steam and transporting it where heat is needed[43]. In processes that require low- and medium-grade heat, such as in the food and paper industries, electrification is the method of choice in order to phase-out fossil fuels. However, electric heaters have a reduced efficiency in generating heat higher than 400-500°C (high grade heat), which is required at various stages of the production process in the cement and steel industries.

Processes that require high grade heat in the cement and the iron and steel industries are responsible for 30% and 45%, respectively, of total greenhouse gas emissions[46]. This is due to heat being generated via the combustion of coal and lignite by 65%, fossil gas by 20%, oil by 10%, as well as small percentages of biomass and waste. In such processes, the combustion of hydrogen in specially designed burners, can replace the use of polluting fossil fuels; hydrogen is currently used, but on a very limited scale in processes that produce hydrogen as a by-product. In addition to the potential contribution of green hydrogen to the coal industry, the main advantage of using hydrogen –as opposed to electricity- to generate high grade heat is that no change in the existing infrastructure is necessary. Currently, hydrogen is barely used in industry for high grade heat generation, due to its high cost, compared to that of conventional fuels. A reasonable value for the cost of hydrogen that will trigger the desired fuel change in industries with processes that require high grade heat, is the sum of the price of fossil gas and the cost of CO_2 emissions in the European Emissions Trading Scheme (ETS).

Refineries

More than 50% of the pure hydrogen produced today (38Mt out of a total of 69Mt per year) is utilized in refineries whose purpose is to convert crude oil into various end-use products, such as mobility fuel or raw materials for petrochemical products (alkenes, aromatic hydrocarbons, etc.). However, as the hydrogen used in refineries comes from fossil fuels, rather than RES, it

[80]Nagashima (2018) "Japan's Hydrogen Strategy and Its Economic and Geopolitical Implications" https://cutt.ly/Id4abmN

results to the release of 230 $MtCO_2$ per year[43]; this highlights the need to improve green hydrogen production processes, so as to replace fossil fuels as production feedstock. The two main uses of hydrogen in refineries are hydrotreatment and hydrocracking.

Hydrotreatment is a catalytic process in which high-pressure hydrogen is introduced to remove impurities, such as nitrogen, oxygen, various metals and particularly sulfur, from liquid oil fractions[81]. This is why hydrotreatment is often referred to as desulfurisation. Today, refineries remove 70% of sulfur from oil. However, due to air pollution, the relevant legislation is expected to move towards requiring higher levels of desulfurisation. The International Energy Agency estimates that sulfur emissions from refinery products in 2020 will be 40% lower compared to 2005[82]. This estimate is primarily based on the new limit of 0.0015% set for fuel sulfur content in petrol and diesel vehicles in China, and the corresponding limit of 0.5% recently set by the International Maritime Organization (IMO) as of 2020. However, a strict legislation will also lead to an increased demand for hydrogen in refineries; the latter, therefore, constitute a market that can promote the production of green hydrogen, while reinforcing the development of the respective production technologies. Hydrocracking (pyrolysis) is a catalytic process through which the heavier fractions of oil are converted into products of higher value (light and medium fractions)[83]. Finally, in addition to hydrotreatment and hydrocracking, certain amounts of hydrogen that are not recovered are combusted, along with other gaseous by-products, in order to generate energy.

Ammonia:
Ammonia (NH3) is a chemical used, by approximately 80%, in the manufacture of fertilizers such as urea and ammonium nitrate, while the rest is used in the industries of explosives, synthetic fibers, plastics, nitric acid, and other special purpose materials, whose demand is growing. Ammonia is prepared from hydrogen and nitrogen according to the Haber-Bosch catalytic process:

$$3H_2 + N_2 \rightarrow 2NH_3$$

More than 31Mt of pure hydrogen per year are used to make ammonia. The average carbon intensity of that hydrogen is 2.4 $tCO_2/tNH31$, as 65% is produced via SMR and 30% via coal and lignite gasification. Demand for ammonia has been projected to increase by 1.7% each year from 2018 to 2030, reaching 39Mt in 2030[43]. In particular, the demand for fertilizers is expected to remain stable or even begin to decline in some areas after 2030; this is not the case for the ammonia used to produce other special purpose chemicals, as their demand will continue to show upward trends.

At present, the production cost of green ammonia remains significantly higher than that of ammonia manufactured using hydrogen produced via SMR, even when the latter is combined with CO_2 capture, storage and utilization technologies (CCS/CCU). A pilot project was recently announced in the Netherlands, funded by the Danish Energy Agency, where the Haber-Bosch process for the production of ammonia will employ green hydrogen produced by a solid oxide

[81] Ancheyta, J.et al (2016)."Hydrotreating of oil fractions" p 295-329.https://cutt.ly/6d4mj0s
[82] IEA (2018), World Energy Outlook 2018.https://cutt.ly/Ed4bK7y
[83] Bricker, M. (2014) "Hydrocracking in Petroleum Processing", Handbook of Petroleum Processing.https://cutt.ly/ed4mnNa

electrolyzer cell (SOEC) system and clean energy. This "green ammonia" production unit is expected to operate in 2025[84]. Assuming that the cost of installing electrolyzers declines by 50% and that electrolyzer efficiency increases by 15%, while the cost of fossil gas ranges from $3-10/MBtu, it is estimated[43] that electrolysis via RES for ammonia production will become economically competitive with SMR combined with CCS-CCU, at an electricity price of $15-50/MWh. Due to the number and complexity of interactions between the parameters that affect such comparisons, the above estimates, as well as others, are characterized by high levels of uncertainty and a wide value range for critical parameters (cost of electricity, cost of fossil gas, etc.).

Methanol

Methanol (CH_3OH) is a liquid chemical that serves as a key component in hundreds of chemicals that we use in our daily lives, and for several other purposes. Since the 19th century, methanol has been one of the most widely used chemical products of mankind. One third of the methanol produced goes into the manufacture of formaldehyde, which is then widely used as a raw material for the manufacture of resins, adhesives and various plastics; this is methanol's largest scale application. In addition, methanol is also widely used in the preparation of acetic acid, which in turn is used to produce polyester materials and PET plastics. Olefin (ethylene and propylene) production is one of the newest and fastest growing markets for methanol. Olefins constitute the basis of the plastics industry, and, until now, were mainly manufactured by cracking hydrocarbons, such as ethane and naphtha. Finally, the use of methanol for the production of aromatic hydrocarbons (benzene, toluene, xylene, etc.) is currently in its infancy.

In addition to being a raw material for the preparation of chemicals, methanol plays a part in the biological wastewater treatment process, acting as food for anaerobic bacteria. It is also used as a fuel for internal combustion engines of passenger cars, trucks, and buses. In fact, in China, methanol has a share of 7% among fuels used in road transport. Methanol is also being studied as a fuel for shipping, due to the recent tightening of legislation on fuel sulphur content and the fact that methanol does not contain sulfur. Furthermore, methanol is used in the manufacture of biodiesel and dimethyl ether (DME), which are substitutes for diesel. It is also now used in Direct Methanol Fuel Cells (DMFCs) to generate electricity following the release of hydrogen at the cell anode. Finally, and particularly in China, methanol is used as a combustion fuel directly in industrial boilers and domestic ovens[85].

There are currently 90 methanol plants worldwide with a production capacity of 110 million tonnes or 128 million cubic meters per year. Methanol is prepared from synthetic gas (syngas) at a pressure of 50-100atm and a temperature of 250°C, using a mixture of copper and zinc oxides as catalyst, according to the chemical reaction:

$$CO + 2\ H_2 \rightarrow CH_3OH$$

Today, the global demand for hydrogen for the purpose of methanol production amounts to 12Mt. However, as methanol demand shows an increasing trend of 3.6% per year, it is expected that by 2030 global hydrogen demand for methanol production will reach 19Mt[43].

[84]Ammonia industry (28.3.2019). "Green ammonia: HaldorTopsoe's solid oxide electrolyzer". https://cutt.ly/Dd4Q3NK

[85]Methanol Institute (2020) https://www.methanol.org

As in the case of ammonia, the vast majority of the hydrogen used to manufacture methanol is produced via fossil-fuel-based processes. It is estimated[43] that electrolysis via RES in the methanol production process will become economically competitive with SMR, in combination with CCS-CCU, at electricity prices of $10-65/MWh, and under the same assumptions as in the case of ammonia.

Steel

Steel plants in Europe are currently responsible for 4% of total EU CO_2 emissions and 22% of CO_2 emissions from all industries[86]. There are two main processes for steel production (see Figure 10). The first uses iron ore, which with the help of coke is converted into cast iron in blast furnaces (BF). Cast iron is then converted to crude steel with the introduction of oxygen in basic oxygen furnaces (BOF). This process currently has the largest market share in EU steel production, and emits 1.72t of CO_2 per tonne of steel produced, due to the extensive use of coal in the steel production process.

The second process involves recycling scrap instead of iron ore, which is converted to steel in electric arc furnaces (EAF); this process has the second largest market share and a much lower emission rate per unit, namely 0.3t of CO_2 per tonne of steel. Emissions depend on the electricity mix used in the electric oven. In theory, this process could allow steel production to be climate neutral; however, this is not possible due to both the low availability of scrap metal and the inability to produce high quality steel via this method.

One way to reduce CO_2 emissions by the first BF-BOF steel production process is to replace coal with biomass to obtain coke. This technique, which is still in research phase, will undoubtedly require significant investments in order to change the design of blast furnaces. An additional way to reduce emissions is to use carbon release and storage (CCS) technologies, in order to capture the CO_2 emitted by the BF-BOF process. However, CCS technologies have not yet proven their effectiveness, and depend on the availability of CO_2 storage facilities. Moreover, they require significant amounts of energy, and, therefore, have additional costs.

Finally, a third steel production method is the Direct Reduced Iron (DRI) process. Albeit currently holding a very small market share in the production of steel, this process has the greatest potential to decarbonize the steel industry, using only 4Mt of H_2 per year, both in pure and mixed form, for the reduction of iron ores. Via this process, the iron ore, either in the form of pellets or in the form of sinter, is directly reduced to iron in a shaft furnace or a fluidized bed, respectively, with the use of hydrogen instead of coke. The iron is then fed to the electric arc furnace (EAF) along with scrap metal, and converted to steel. The great advantage of the DRI-EAF technique is the possibility of zero CO_2 emissions, provided that the hydrogen used in the process comes from electrolysis, and that the electricity required for the entire process comes from RES. An additional advantage is the flexibility of feeding DRI directly to the electric furnace, which means that part of the existing steel industry infrastructure can be utilized in the DRI-EAF method. Obviously, the biggest disadvantage of the DRI-EAF process today is the high cost of green hydrogen production. It is estimated that, in order for this technique to become economically competitive, the cost of hydrogen must drop below €2/kg. Finally, there are

[86] Roland Berger (2020). "Europe's steel industry at a crossroads".https://cutt.ly/Id4O0CQ

currently several pilot projects in Sweden, Finland, Austria, and Germany, working to overcome certain technological challenges associated with the substitution of coke by hydrogen in the DRI-EAF process[46].

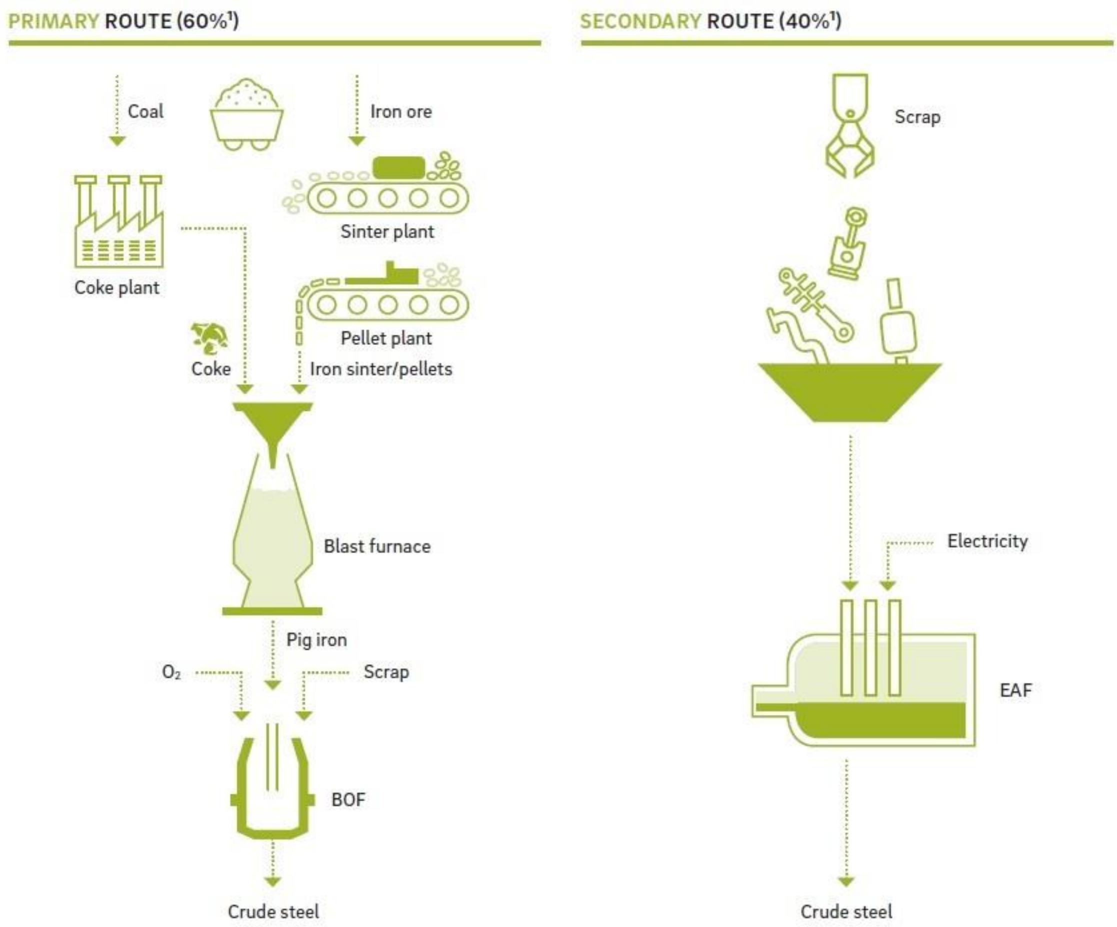

Figure 10: The two main steel production processes. The BF-BOF process of converting iron ore into cast iron in BF blast furnaces, followed by the conversion of cast iron into steel in basic oxygen blowing furnaces BOF (left) and the process of converting scrap metal into steel in electric arc furnace (AF)(right)[86].

Electricity Generation

Today, hydrogen has a negligible percentage (0.2%) in the production of electricity, dedicated to meet a small portion of electricity needs in refineries, steel and petrochemical plants. Nevertheless, this is likely to change in the future, as hydrogen is able to generate electricity continuously, without compromising the climate. Hydrogen can be used in electricity generation in two ways:

First, by replacing fossil gas as combustion fuel in conventional gas turbines or combined-cycle gas turbines (CCGT). However, most of the existing turbines can only handle small hydrogen shares (3-5%), while a few turbines can operate with shares of up to 30%[43]. An exception to the rule is the Fusina plant in Italy, which, as of 2009, is the only 100% hydrogen-powered electricity plant. The plant, owned by Enel, and with a total capacity of 16MW, produces approximately 60GWh per year, using hydrogen produced in the neighboring Porto Marghera petrochemical industry and the neighboring Polimeri Europa refineries. The plant has a special turbine that was manufactured by General Electric and is capable of using 100% hydrogen[87]. However, Fulvio Conti, the former director of Enel, reported in 2010 that the cost of the hydrogen-powered electricity plant was 5-6 times that of conventional units[88].

Despite the technical difficulties that exist today, the industry is optimistic and predicts that existing gas turbines will be converted to run on 100% hydrogen by 2030[89]. Indeed, HYFLEX POWER, the four-year Horizon 2020 project, is also moving in this direction. The project aims to convert a 12MWe combined heat and power (CHP) production unit that currently runs on fossil gas, so as to run on a hydrogen-fossil gas mix, with hydrogen shares of at least 80%, to even 100%. The unit is owned by Engie, and the turbine will be modified by Siemens, the project leader. Six other partners participate in the project, including the National Technical University of Athens (NTUA), which will carry out economic, social, and environmental assessments[90].

A second way of using hydrogen to generate electricity is via cells, which can achieve high efficiency levels, in the order of 60%, with no direct carbon dioxide emitted by the process. The operation of hydrogen cells can be viewed as the reverse of electrolysis: inside the cell, hydrogen is converted into water, electricity, and heat. However, the hydrogen fuel cell systems that exist today are much smaller in size than hydrogen fuelled turbine systems. There are only 70MW of hydrogen fuel cell systems worldwide, constituting only a small fraction of all fuel cells that, combined, reach a capacity of 1.6GW worldwide, and run on fossil fuels[43]. In addition, hydrogen cells have a much shorter lifespan than turbines (10,000-40,000 operating hours) and are more expensive. Under favorable assumptions, the cost of installing hydrogen cells is expected to drop to $425/KW by 2030, a fourfold decline from the current cost of $1600/KW[91].

In addition to research and various pilot projects, hope for reducing hydrogen-powered electricity generation costs comes from the ambitious goals set by Korea and Japan, with regards to the share of hydrogen in electricity generation. More specifically, Japan has set a goal of reaching 1GW of hydrogen-based electricity generation systems by 2030m which corresponds to an annual hydrogen consumption of 0.3Mt, and 15-30GW over a period of time, which corresponds to an annual consumption of 15-30 MtH_2. Korea is even more ambitious, aiming to reach 1.5GW and 15GW of hydrogen cells by 2022 and 2040, respectively[92].

Advantages and Challenges

Green hydrogen has great potential to contribute to the decarbonization of many sectors of the economy; however, today only 1% of the hydrogen produced comes from RES. The production of the remaining quantity is based on fossil gas and coal or lignite, and is, therefore, accompanied by significant CO_2 emissions.

[87]Power, (2009) "Enel's Fusina Hydrogen-Fueled Plant Goes Online".https://cutt.ly/ihpwuM3
[88]Reuters, (2010) "Enel to start major plant conversion to coal 2011".https://cutt.ly/hhpeiqd
[89]EUTurbines (2019), "The gas turbine industry commitments to drive Europe's transition to a decarbonised energy mix" (press release), 23 January 2019, https://cutt.ly/hhpthAM.
[90]Power (2020). "World's First Integrated Hydrogen Power-to-Power Demonstration Launched". https://cutt.ly/ShpibMy
[91]Bruce, S. et al. (2018), "National Hydrogen Roadmap", CSIRO, Australia
[92]Ministry of Economy, Trade and Industry of Japan (2017), "The Basic Hydrogen Strategy", https://cutt.ly/uhpk9A2.

In addition, the current use of hydrogen in transport, buildings, and electricity generation is extremely limited. The primary user of hydrogen is industry (refineries, high grade heat generation, ammonia & methanol production, and steel production processes); however, as the hydrogen used in these processes comes from fossil fuels, the carbon footprint of these industrial activities is not essentially reduced.

In order for hydrogen to assume a key role in the decarbonization of the European economy, it is necessary to establish long-term policies that will both stimulate demand for multiple applications simultaneously, and support research and development, so that green hydrogen production can become economically competitive.

Funding opportunities from the Multiannual Financial Framework 2021-2027

The Multiannual Financial Framework (MFF) is the multiannual budget of the European Union. The next programming period to cover the period January 1 2021 to December 31, 2027. It is based on the European Commission proposal that was presented in 2018[93] and is followed by a package of proposals covering the regulations and budgets of the different financing instruments and the EU's own resources. While initially foreseen that negotiations would have been completed already before the EU elections, this did not happen. Additional delays, political setbacks, and important changes[94], primarilry due to the annoucement of the European Green Deal[95] and the need to respond to the consequences of the COVID-19 pandemic[96], led the negotiations to continue until December 2020, when a political agreement at all levels was reached[97] and the final approval of the MFF of €1,074 billion by the Europen Parliament.[98]

Since the regulations regarding the MFF as a whole, as well as regarding specific funds had not been finalized when we were undertaking our analysis, we examined the potential financing opportunities for energy storage in the MFF -2021-2027, based on the provisions of the draft regulations as presented by the European Commission in 2018. Specifically, we reviewed all draft regulations to identify potential financing opportunities across MFF headings and funding instruments. Additionally we reviewed the funding opportunities offered by the Just Transition Fund, which is a new fund that was presented in early 2020. We have also taken into account revisions resulting from the EU Recovery Plan, since while being a stimulus package (Next GenerationEU) of €750 billion, it aims to support the EU re-build its economy and its green transition. The REACT-EU[99] financing instrument has not been analyzed, since, while it provides additional resources with a priority to operations contributing to the transition to a green economy, it in fact links to funding opportunities available in the 2014-2020 programming period. Finally, if a 2018 proposals has been withdrawn, we focus the examination on the more recent European Commission proposal.

[93] European Commission. 2018. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. A Modern Budget for a Union that Protects, Empowers and Defends – The Multiannual Financial Framework for 2021-2027. (COM(2018) 321 final). https://cutt.ly/7hOXxDO

[94] European Commission. 2020. Amended proposal for a Council Regulation laying down the multiannual financial framework for the years 2021 to 2027. (COM(2020) 443 final). https://cutt.ly/GhOXmzL

[95] European Commission. 2018. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions (COM 2019 640 final) https://bit.ly/2Jh8t2A

[96] European Commission. 2020. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions 'The EU budget powering the recovery plan for Europe' (COM(2020) 442 final). https://cutt.ly/2hOXbEr

[97] Council of the EU. 2020. Next multiannual financial framework and recovery package: Council presidency reaches political agreement with the European Parliament. Press Release. 10.11.2020. https://bit.ly/3as5UWA

[98] European Pariament. 2020. Parliament approves seven-year EU budget 2021-2027. Press Release. 16.12.2020. https://bit.ly/3h6eITb

[99] European Commission. 2020. Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) No 1303/2013 as regards exceptional additional resources and implementing arrangements under the Investment for growth and jobs goal to provide assistance for fostering crisis repair in the context of the COVID-19 pandemic and preparing a green, digital and resilient recovery of the economy (REACT-EU) (COM(2020) 451). https://bit.ly/345KJFS

For each of the funding instruments we identified a potential energy storage funding opportunity, we provide a short overview. Note that in our review, we included provisions for energy storage linked also to the transport sector, such as charging stations.

Our review concludes that there are several funding opportunities for energy storage, even if these are not always explicitly mentioned.

It should also be noted that the new MFF 2021-2027 includes a climate mainstreaming objective across all EU programmes. Specifically, this concerns a bidning commitment of 30% of the EU expenditure to climate objectives. In fact this percentage is larger than the initial 25% that had been proposed by the European Commission and emerged during the July 2020 meeting of the European Council, , demonstrating a strong commitment to the EU Green Deal. This objective does not apply equally across the funding instruments, as the percentage commitment of each fund varies.

Significant additional resources are expected to be mobilized towards the same climate and environment direction also from other sources, beyond the EU budget, based on the Sustainable Europe and European Green Deal Investment Plan[100] that was announced in January 2020. The European Commission estimated a 1 trillion investment towards the European Green Deal objectives. In this analysis, however, we focus only on the MFF resources and the EU Recovery Plan.

Table 3 presents in summary the financing instruments or programmes that potentially could provide resources for energy storage facilities, which are presented in the sub-sections that follow, as well as the total funds available per fund, as approved by the European Parliament on December 16, 2020. A short description of each one is presented in the following sub-sections.

Table 3: Energy storage financing opportunities from the MFF 2021-2027 (in ***italics*** the additions made in 2020)

Headline - Priority	**Funding Instrument / Programme**	**Total (billion euros)**
Heading I. Single Market, Innovation & Digital		**143,4**
1. Research & Innovation	Horizon Europe	84,9
2. European Strategic Investments	InvestEU Programme Connecting Europe Facility	9,4 18,4
Heading II. Cohesion & Values		**1 009,7**
5. Regional Development & Cohesion	European Regional Development Fund Cohesion Fund	200,4 46,6
6. Recovery and Resilience	*Recovery and Resilience Facility*	*672,5*
Heading III. Natural Resources & Environment		**373,9**
9. Environment & Climate Action	Programme for Environment & Climate Action (LIFE) *Just Transition*	4,8 17,5

[100] European Commission. 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Sustainable Europe Investment Plan - European Green Deal Investment Plan. COM(2020) 21 final). https://bit.ly/38cGIAP

Heading VI. Neighbourhood & The World		**22,7**
15. External Action	Neighbourhood, Development and International Cooperation Instrument (including external aspects of migration) Overseas Countries & Territories (including Greenland)	71,8
16. Pre-Accession Assistance	Pre-Accession Assistance	12,6

1. **Horizon Europe:** Horizon Europe[101] is the main financial instrument under the Research and Innovation headline of the MFF's Single Market, Innovation and Digital heading. Horizon Europe, investing in research and innovation, aims at strengthening the EU's scientific and technological bases in order to help tackle the major global challenges of our time and contribute to achieving the Sustainable Development Goals (SDGs).

Horizon Europe is structured around three pillars. Pillar II, which aims at tackling several global challenges, is based on five thematic clusters, including a cluster on climate, energy and mobility. Energy storage is listed as an area of intervention under this cluster, both on its own, as a separate area of intervention, titled as such 'Energy Storage' (4.2.9) and as part of selected areas of intervention; specifically the following: 'Energy Systems and Grids' (4.2.3), 'Building and Industrial Facilities in Energy Transition' (4.2.4), 'Industrial Competitiveness in Transport' (4.2.6), and 'Clean Transport and Mobility' (4.2.7).

Energy storage is also one of the areas to which the Joint Research Center (JRC) is expected to contribute towards. (6.2.2.4).

2. **InvestEU Programme:** The InvestEU Programme[102] is a new investment instrument, under the European Strategic Investments headline of the MFF Single Market, Innovation and Digital heading. InvestEU aims at mobilizing public and private financing to support EU policy priorities and strategic investments.

Following the COVID-19 pandemic and the announcement of the EU's Recovery Plan, the InvestEU proposed regulation was revamped. InvestEU is expected to support the financing of the EU recovery aiming at growth and employment in the EU economy, the sustainability of the EU economy and its environmental and climate dimension contributing to the achievement of the SDGs and the objectives of the Paris Agreement on Climate Change. As such it aims to support sustainable infrastructure and investments deemed as of strategic European importance.

While energy storage was not explicitly mentioned per se in the 2018 proposal, in the revised InvestEU 2020 proposal energy storage is mentioned explicitly under both sustainable and strategic infrastructure investments. Energy storage is also listed among the activities that are

[101] European Commission. 2018. Proposal for a Regulation of European Parliament and of the Council establishing Horizon Europe – the Framework Programme for Research and Innovation, laying down its rules for participation and dissemination. (COM(2018) 435 final). https://bit.ly/3qPcpZh

[102] European Commission. 2020. Proposal for a Regulation of the European Parliament and of the Council establishing the InvestEU Programme (COM(2020) 403 final). https://bit.ly/3814saG

eligible for the EU Guarantee foreseen in Invest EU, as well as potential projects to be included in the list of Important Projects of Common European Interest.

InvestEU aims contribute to the climate mainstreaming objective by setting to implementation partners a target of at least 60 % of the investment to be applied to the sustainable infrastructure policy window, which will be tracked based on Commission guidance.

3. **Connecting Europe Facility:** The Connecting Europe Facility (CEF)[103] supports specific cross-border projects under the European Strategic Investments headline of the MFF's Single Market, Innovation and Digital heading. CEF aims to support investment and cooperation to develop infrastructure in the transport, energy and digital sectors and connects the EU and its regions.

In order to support the decarbonization of the transport sector, the CEF may support actions to secure efficient and interconnected European-wide network; actions, such as the development of charging infrastructure (art. 9(2)a(ii & iii)), as well as actions specifically for smart, sustainable, inclusive, safe and secure mobility. Energy storage is explicitly referred to under the innovative energy infrastructure solutions (άρθ. 9(2)b(i, iii, iv)).

The number of CEF actions contributing to the smartening and digitalization of grids and increasing energy storage capacity, is one of the indicators that will be used to monitor the CEF's contribution to the 'security of energy supply objective'.

The CEF is expected to make a significant contribution towards the climate mainstreaming of the MFF as 60% of its total budget is to contribute to climate objectives.

4. **European Regional Development Fund and the Cohesion Fund:** The European Regional Development Fund (ERDF) and the Cohesion Fund (CF)[104] are two of the most important funding instruments of the EU. They fall under the MFF Cohesion and Values heading and its Regional Development & Cohesion headline. Contributing to the reduction of regional disparities, they affirm the principle of solidarity among Member States and European regions in line with the EU's cohesion policy. Specifically, the ERDF contributes to structural adjustment and economic transition, while the CF supports investments in environmental and transport infrastructure.

The ERDF and the CF support is to be concentrated on five specific objectives, among which three relate to energy storage, namely, a smarter Europe (PO 1), a Greener Europe (PO 2) and a more connected Europe (PO 3). The Cohesion Fund shall support PO 2 and elements of PO 3, all of which could relate also to energy storage.

Energy storage falls under the interventions that can be supported by both funds; hence contributing to the overall "Investment for jobs and growth" goal.

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[103] European Commission. 2018. Proposal for a Regulation of the European Parliament and of the Council establishing the Connecting Europe Facility and repealing Regulations (EU) No 1316/2013 and (EU) No 283/2014 (COM(2018) 438 final). https://bit.ly/3mbUTeh

[104] European Commission. 2018. Proposal for a Regulation of the European Parliament and of the Council on the European Regional Development Fund and on the Cohesion Fund (COM(2018) 372 final). https://bit.ly/3gExlxi

Potential energy storage projects could be financed under all three relevant policy objectives. Energy storage, however, is specifically listed as an intervention field dimension for ERDF and CF, under the Greener Europe (PO 2) policy objective, with code number 033 'Smart Energy Distribution Systems at medium and low voltage levels (including smart grids and ICT systems) and related storage (033). Other listed interventions that could potentially support energy storage systems include the following: Support to enterprises that provide services contributing to the low carbon economy and to the resilience to climate change (027), Clean urban transport infrastructure (073), Alternative fuels infrastructure (077), Multimodal transport (TEN-T) (078), Multimodal transport (not urban) (079), Seaports (TEN-T) (080), Other seaports (081), Inland waterways and ports (TEN-T) (082), Inland waterways and ports 9regional and local (083)

Among the 95 output, the 94 results and the 42 performance indicators for the ERDF and the CF, none of the indicators relates specifically to energy storage, with the exception of one output indicator, under the Greener Europe (PO 2) objective, which provides for metrics on alternative fuels infrastructures (refueling / recharging points) supported (RCO 59).

The ERFD and the CF are expected to contribute towards the climate mainstreaming of the MFF as 30% of the ERDF budget and 37% of the CF budget are to contribute to climate objectives.

5. **LIFE - Programme for the Environment and Climate Action:** The LIFE programme for Environment and Climate Action[105], although small in budget compared to other instruments that fall under the Natural Resources & Environment Heading of the MFF, is the only funding instrument dedicated specifically to environment and climate action headline. LIFE aims to contribute to the shift towards a clean, circular, energy-efficient, low-carbon and climate-resilient economy, including through the transition to clean energy, to the protection and improvement of the quality of the environment and to halting and reversing biodiversity loss, thereby contributing to sustainable development.

The LIFE financial instrument particularly aims to support demonstrating techniques and best practice that can be replicated and upscaled in larger programmes. In this context, energy storage project could be eligible for funding under the Clean Energy Transition sub-programme.

The proposed budget of LIFE for the Clean Energy Transition sub-programme is €1 billion. The exact percentage of the contribution of the LIFE budget towards the MFF climate mainstreaming objective is not provided as an EU climate marker system at an appropriate level of disaggregation, will be used by the Commission and updated annually. However, it is estimated that more that 60% of its budget will be directed to climate objectives.

[105] European Commission. 2018. Proposal for a Regulation of the European Parliament and of the Council establishing a Programme for the Environment and Climate Action (LIFE) and repealing Regulation (EU) No 1293/2013 (COM(2018) 385 final). https://bit.ly/2LvNHwU

6. **Just Transition Fund:** The Just Transition Fund (JTF) **[106]** is a new financing instrument aimed to support those regions that face economic and social challenges as a result of the transition towards a climate-neutral European economy by 2050. It is understood that the main focus will be on the coal regions in transition. While its resources are available to all Member States, criteria guide how the resources of the JTF will be allocated among Member States and regions.

While the JTF forms part of the Cohesion Policy, it is listed under the Environment and Climate Heading of the MFF. The JTF forms the main pillar of the Just Transition Mechanism which aims to mobilize additional funds via the InvestEU instrument and a public sector loan from the EIB.

Supporting the transition of economies away from fossil fuel dependent activities, the JTF gives priority to investments in climate and energy. While energy storage was not mentioned *per se* in the draft Regulation, it no doubt falls under investments in technology and infrastructure investments for affordable clean energy. In fact, it is now explicitly mentioned in the draft that emerged from the trilogue negotiations.

7. **Recovery and Resilience Facility:** The Recovery and Resilience Facility (RRF)[107] is a new instrument that was developed in response to the crisis created by the COVID-19 pandemic. It is to be implemented during the 2021-2024 period. The RRF will not only help address immediate economic and social challenges, but also support Member States in their long-term green and digital transitions so as to become more resilient and better prepared in the future. The RRF replaces the Reform Support Programme that was proposed in 2018.

Assisting Member States in their clean energy transition is among the central objectives of the RRF. The recovery and resilience plans of Member States are assessed with respect to their contribution to the green transition and the overall EU climate neutrality by 2050 objective and their response to resulting challenges. The plans are assessed as to the extent to which they are consistent with the National Energy and Climate Plans and the Just Transition Territorial Plans.

Next to the RRF a Technical Support Instrument[108] is foreseen to be available to all Member States, to support their reforms. In this context, technical support can be sought also for investments in energy storage.

The RRF is expected to contribute to the climate commitment, with 37% (compared to the initial 25%) of its burdget directed towards climate objectives.

8. **Neighbourhood, Development and International Cooperation Instrument (including external aspects of migration):** The Neighbourhood, Development and International

[106] European Commission. 2020. Proposal for a regulation of the European Parliament and of the Council establishing the Just Transition Fund (COM(2020) 22 final). https://bit.ly/3ndGTSA
[107] European Commission. 2020. Proposal for a regulation of the European Parliament and of the Council establishing a Recovery and Resilience Facility (COM(2020) 408 final). https://bit.ly/2LZad1z
[108] European Commission. 2020. Proposal for a Regulation of the European Parliament and of the Council establishing a Technical Support Instrument (COM(2020) 409 final). https://bit.ly/37dq7gN

Cooperation Instrument[109] falls under the EU External action programmes of the MFF 'Neighbourhood and the World' heading. It aims to uphold and promote the Union's values and interests worldwide, while addressing global challenges. The geographic programmes are listed in the Regulation as is a list of countries that are included in the Neighbourhood Area.

Energy and climate financing is available across geographic programmes and under the thematic programme of addressing global challenges under the Planet and Prosperity areas of intervention. Energy storage is not mentioned *per se*, however, investments in such operations can be eligible for support from the newly established integrated financial package capacity, the European Fund for Sustainable Development Plus (EFSD+) through the External Action Guarantee.

9. **Overseas Countries & Territories (including Greenland):** The Overseas Countries & Territories (OCT)[110] funding instrument is listed under the EU external action programme of 'Neighbourhood and the World' MFF heading. The instrument, which forms an integral component of the OCT Association Decision, applies to only to the overseas countries and territories.

Energy storage is one of the areas of cooperation in the association frameworks that can be developed in the field of environmental issues, climate change, oceans and disaster reduction. The EU may provide financial resources in order to achieve their overall objectives, and may contribute to specific actions.

10. **Instrument for Pre-Accession Assistance:** The Instrument for Pre-Accession Assistance (IPA III)[111] is the only financial instrument to offer pre-accession assistance under the 'Neighbourhood and the World' MFF heading. The Instrument aims to support candidate and potential candidate countries to comply with EU values and progressively align to the EU acquis.

It is worth noting that the IPA III will also be used to support the engagement of the EU in the Western Balkans. Assistance will be based on an EC drafted IPA programming framework. It is also an instrument to finance actions in Turkey, as well as Iceland.

Energy storage is not mentioned *per se*, in the regulation, which foresees support for climate change mitigation and the acceleration of the shift towards a low-carbon economy.

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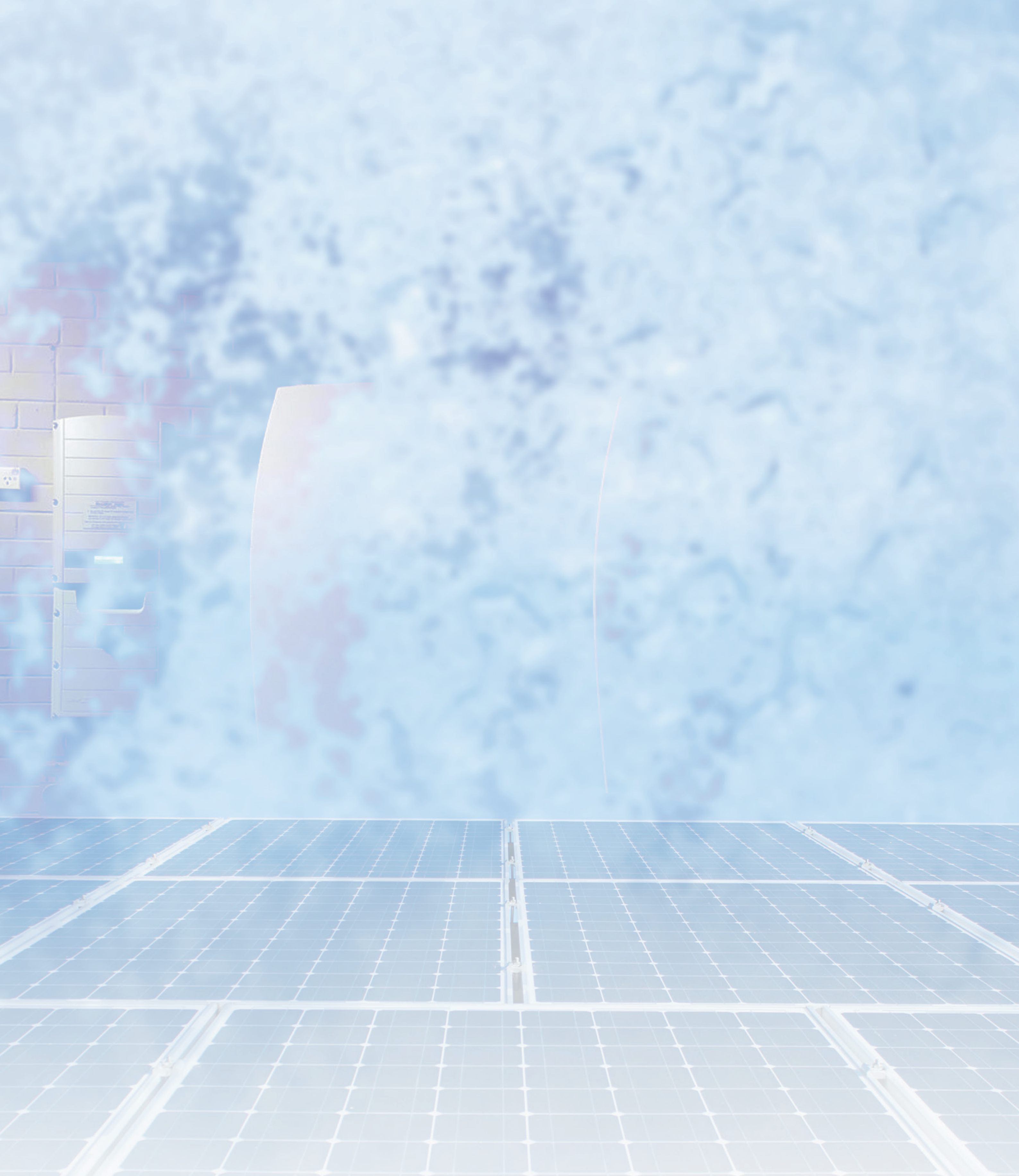
[109] European Commission. 2018. Proposal for a Regulation of the European Parliament and of the Council establishing the Neighbourhood, Development and International Cooperation Instrument (COM(2018) 460 final). https://bit.ly/3qSldh9

[110] European Commission. 2018. Proposal for a Council Decision on the Association of the Overseas Countries and Territories with the European Union including relations between the European Union on the one hand, and Greenland and the Kingdom of Denmark on the other ('Overseas Association Decision') (COM(2018) 461 final). https://bit.ly/37Ylkih

[111] European Commission. 2018. Proposal for a regulation of the European Parliament and of the Council establishing the Instrument for Pre-accession Assistance (IPA III) (COM(2018) 465 final). https://bit.ly/381r6Qx



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