Carbon benefits of different energy storage alternative end uses. Application to the Spanish case.

Yolanda Lechón[a]*, Carmen Lago[a], Israel Herrera[a], Ana Rosa Gamarra[a], Alberto Pérula[a,b].

[a] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT). Energy Systems Analysis Unit. Avda. Complutense n. 40, 28040, Madrid (Spain)

[b] Department of Land Morphology and Engineering, Universidad Politécnica de Madrid, Madrid, Spain

yolanda.lechon@ciemat.es; carmen.lago@ciemat.es; israel.herrera@ciemat.es; anarosa.gamarra@ciemat.es; alberto.perula@ciemat.es

* = corresponding author details: yolanda.lechon@ciemat.es

Highlights

- The largest benefits are obtained using the stored energy in transport applications
- Using the stored energy in the power sector is also an option with high benefits.
- The use of batteries behind the meter would have low or no benefits in the future.
- Using electricity to produce heat leads to low GHG emission avoidance benefits.
- A specific storage strategy must be formulated for each particular case.

Abstract

Variable renewable technologies are characterized by a large degree of intermittency due to their natural variability, creating a need for exploiting a range of sources. In this context, the use of energy storage systems is often proposed. There are different ways to store and use the overproduced electricity from these technologies. This paper aims to evaluate the global warming emissions savings obtained from storing the surplus electricity from the variable renewable technologies in the Spanish market and later using it in different end use applications, both for the present day and the 2030 time horizon. First, a review of the life cycle assessments of different energy storage technologies published in the scientific literature is performed. Then, selected values from this review, adapted to the emission intensity of variable renewable electricity stored in Spain, are used to compute GHG savings from storing and using this electricity for different end uses. Results show that the highest benefits in terms of GHG emissions avoidance would be obtained in transport applications and in the power sector. However, as the electricity mix becomes decarbonized, the use of batteries behind the meter would lead to no GHG emissions avoidance. Using electricity to produce heat leads to low GHG emission avoidance benefits that will reduce over time. Benefits will improve in time for the chemical sector, as there are few alternatives to decarbonize this sector. A specific storage strategy must be formulated for each particular case.

Keywords: Energy storage systems; Decarbonization; Variable renewable electricity technologies;

Word count: 7102

Abbreviations:

ACAES: Adiabatic compressed air energy storage

CAES: Compressed air energy storage (Diabatic)

~~ACAES: Adiabatic compressed air energy storage~~

CCS: Carbon capture and storage

CCUS: Carbon capture technologies and their use

CO_2eq: Carbon dioxide equivalent

CSP: Concentrated solar power

DAC: Direct air capture

DME: Dimethyl ether

ESS: Energy storage systems

ETES: Electro-thermal energy storage

EU: European Union

EV: Electric vehicle

GHG: Greenhouse gas emissions

HD: Heavy duty

IEA: International Energy Agency

IRENA: International Renewable Energy Agency

LAES: Liquid air energy storage

LCA: Life cycle assessment

LH-TES: Latent heat - Thermal storage systems

NECP: Integrated National Energy and Climate Plan

NGCC: Natural gas combine cycle power plant

OME: Oxymethylene ether

P2Chem: Power to chemicals

P2hHeat: Power to heat

P2Mob: Power to mobility

P2Power: Power to power

P2X: Group of technological pathways to convert power in a variety of products, processes, technologies and applications

PCM: Phase change materials

PHS: Pumped hydro storage

PV: Photovoltaic

SMES: superconducting magnetic energy storage

SH-TES: Sensible heat - Thermal storage systems

TES: Thermal storage systems

UK: United Kingdom

USA: United States of America

V2G: Vehicle to grid

VRES: Variable renewable energy sources

1. Introduction

The need for a fast, efficient and coordinated response to the challenge of decarbonization has fostered the development of plans and strategies at the European and national levels. In the European Union, the ambition of becoming climate neutral by 2050 has been reflected in the European Green Deal [1] and the European Climate Law [2]. To that end, the EU is committed to the revision of its climate, energy and transport related legislation under the so-called "Fit for 55 package proposal [3] that aligns to the EU's target of reducing net greenhouse gas emissions by at least 55% by 2030. As for renewables, the package includes a proposal to increase the current EU-level target of at least 32% of renewable energy sources in the overall energy mix to at least 40% by 2030.

An important part of this renewable energy production will come from variable renewable energy sources (VRES), such as those using wind and solar resources. VRES are characterized by a large degree of intermittency due to the natural variability of climatic factors, such as air temperature, wind velocity and solar radiation [4]. The increasing penetration of these technologies in the electricity systems, in transition to decarbonisation, and the fact that the electricity demand not always fits the VRES production profile leads to situations of oversupply, in which electricity from VRES has to be curtailed. The term "curtailment" has emerged from the practice of not using available renewable energy output [5]. This temporal mismatch between VRES production and demand observed during the day is exacerbated by the behind-the-meter VRES (mainly photovoltaic (PV)) production systems, that leads to the appearance of the so called "duck curves" in the neat load curves. Another problem associated with the high penetration of renewable energy in electricity systems is associated with system frequency regulation (being frequency the extent to which supply and demand are in balance). Traditionally, conventional power generation technologies are often used to adjust production to the demand [6], leading to unwanted carbon emissions. To effectively manage large-scale VRE systems, a drange of sources need to be exploited. In this context, the use of energy storage systems (ESS) is often proposed, together with demand side management, increased interconnections and sector coupling measures [7].

In the case of Spain, the country has recently published the Spanish Storage Strategy, envisaging storage capacities of 20 GW by 2030 and reaching the 30 GW by the year 2050 (starting from the 8.3GW of capacity available today). The Strategy's ambition is to provide flexibility to the system and stability to the grid, especially taking into account the extensive planned deployment of renewable energy in the country, aligned with the goal of climate neutrality by the year 2050 [8].

The foreseen objectives on renewables were previously established in the Integrated National Energy and Climate Plan 2021-2030 (NECP)[9]. According to this Strategy, the planned storage capacity deployment would contribute to the decarbonisation of the electricity system and, simultaneously, avoid the loss of the surplus of clean energy provided by VRES by storing it for later consumption.

There are different ways to store and use the overproduced electricity from VRES. Figure 1 shows different options using different ESS and applying the stored energy to different purposes. The stored energy can be used to produce electricity again at peak times or to provide electricity grid regulation services (P2Power). It can also be used for mobility uses, either in the form of electricity for electric or hybrid vehicles or in the form of synthetic fuels (P2Mob). Stored electricity can be used to produce H_2, and this H_2, in combination with captured CO_2, can be used to produce synthetic chemicals, which can be an alternative to the conventional production of chemical compounds (P2Chem) or synthetic fuels to be used in transport, electricity or heat applications. Electricity stored in the form of heat can be used in thermal end use applications (P2Heat).

The environmental benefits will be different, depending on the environmental impacts of the conventional production processes of these services (reference scenario in Figure 1, outside the dotted line),. The quantification of these benefits will make it possible to identify those end uses in which the environmental benefits are maximized. This analysis will also provide the basis for prioritizing the use of those forms of storage whose environmental benefits are most interesting.

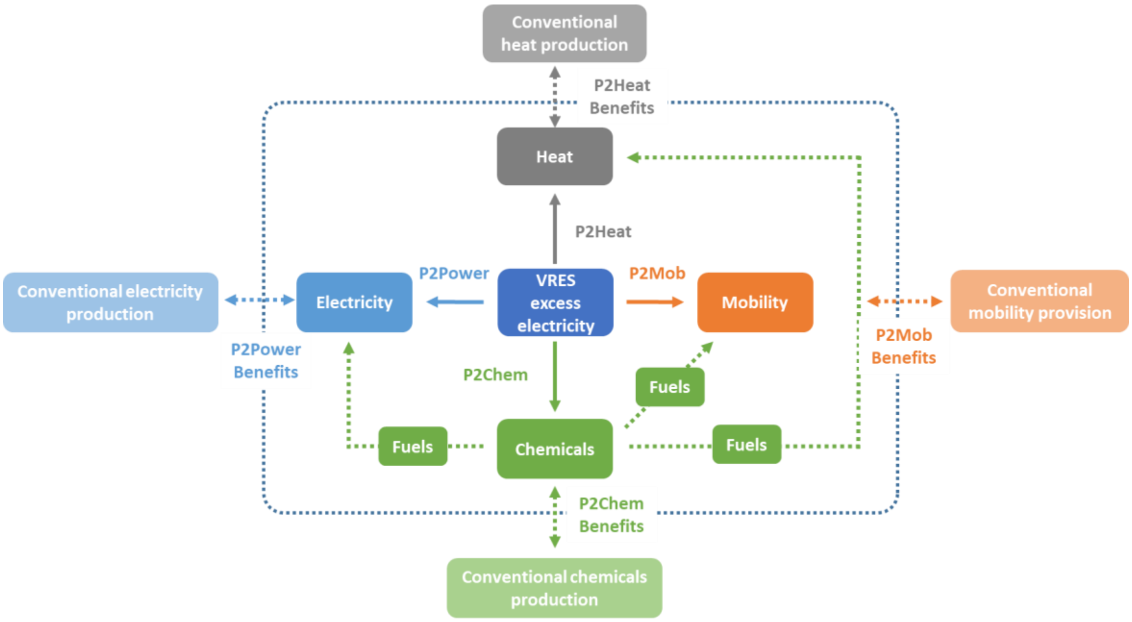

Figure 1. Options for the storage and use of surplus electricity from VRES. End-use applications: P2Power (Power to Power), P2Mob (power to mobility), P2Heat (power to heat) and P2Chem (power to chemicals). Conventional scenarios (outside the dotted line) represent the reference scenarios of the conventional production chain.

There are several technologies for storing electricity. Pumped hydro systems (PHS) is the most used storage system around the world, reaching 96% of the total capacity (197 GW) in 2017. PHS is followed by thermal storage systems with a capacity of 3.3 GW, batteries with 1.9 GW and other mechanical storage systems with 1.6 GW (flywheels- 0.9 GW and compressed air energy storage or CAES-0.6 GW) [10].

In terms of storage efficiency, there are also differences between the available technologies. The efficiency varies from 50% to 100% in the case of flywheels [11–16]. The efficiency of mechanical storage varies between 50% and 95%, with the highest values corresponding to PHS. Electrochemical storage efficiency ranges between 60% and 95% considering all the different types of batteries, with the best figures found for $NaNiCl_2$ and Li-ion technologies. Electrical storage has two differentiated ranges: 60-65% for capacitors and 85-95% for superconducting magnetic storage (SMES) and supercapacitors. Chemical storage provides the lowest efficiency values, ranging from 24% to 40% in the case of H_2 and 36% for synthetic methane, and 18% for synthetic natural gas. The efficiency of thermal energy storage system ranges from 50% to 90% for latent heat storage, reaching the highest values in the case of thermal chemical systems, with efficiencies in the range of 75% to 100%. In terms of costs, a comparison between ESS is difficult, due to the associated uncertainties (overall efficiency, fuel and emission costs for CAES, lifetime and life cycle numbers, discharge time and replacement period) and also to cost parameters (interest rate and electricity prices). The effect of uncertainties can affect the results by 5–17% [12]. ESS that are subject to significant replacement costs (e.g. Ni-Cd, VRFB and lead batteries) during the lifetime are more sensitive to the interest rate, while ESS systems with the lowest efficiencies are more sensitive to electricity prices (e.g. H2 based storage).

The cost structure of the different ESS technologies varies from technologies whose costs are dominated by power costs to technologies that are dominated by energy costs [17]. According to a recent review [18], sensible heat thermal storage (SH-TES), PHS and CAES are storage technologies whose costs are dominated by power costs. Power costs of SH-TES vary from 3650 to 7900 $/kW, PHS power costs vary from 500 to 4300 $/kW and CAES power costs vary from 400 to 1620 $/kWh. At the other end, there are technologies, such as SMES and flywheels, whose costs are dominated by energy costs. Energy costs of SMES can be as high as 10854 $/kWh, while flywheel energy costs vary from 500 up to 14000 $/kWh.

According to [12], PHS and underground CAES would be the most cost efficient technologies for bulk energy storage, with levelized costs of electricity (LCOE) of 120 €Euros/MWh and 134 €Euros/MWh respectively for the delivered electricity, while aboveground CAES offers the most cost-efficient option for transmission and distribution services with an LCOE of 202 €/MWh for this application. The evolution of the costs of the different ESS technologies has been analysed in the literature. According to [19], most ESS technologies will experience decreasing cost trends with increasing cumulative installed capacity. The cost reductions are expected to be the highest for alkaline electrolysis and for Li-ion batteries and lowest for mature technologies such as PHS and lead-acid batteries.

Different storage options are usually compared by their electricity production efficiency or costs in power to power (P2Power) applications, but there are few studies that look at the broader spectrum of possible storage end use applications and at other benefits. A comparison of different energy storage options using Life Cycle Assessment (LCA) and measuring fossil depletion and global warming avoided impacts of different applications can be found in [20]. The authors concluded that the highest reduction of global warming and fossil depletion impacts came from using surplus power in heat pumps with hot water storage, battery electric vehicles and electrical energy storage systems (pumped hydro storage, compressed air energy storage and redox flow batteries).

As the electricity system and the end use sectors become more decarbonized, relative benefits of alternative uses of the stored electricity could change. A greater penetration of renewable technologies in the electricity system produces an increasingly lower carbon footprint of the reference system (conventional electricity production in figure 1). Thus, electric applications could see their emissions savings reduced. As the passenger vehicle fleet incorporates more and more electric and low carbon emission vehicles, the use of the surplus electricity to power electric vehicles or to produce fuels for passenger transport becomes less attractive. In contrast, using surplus electricity for decarbonizing more difficult sectors, such as heavy duty (HD) transport or industry, could maximize the benefit.

This paper aims to evaluate the global warming emissions savings obtained by storing VRES surplus electricity from the Spanish market and using it in different end use applications, both for the present day and for the 2030 horizon. First, a review of the life cycle assessments of different energy storage technologies published in the scientific literature is performed. Then, selected values from this review, adapted to the emission intensity of VRES electricity stored in Spain, are used to compute GHG savings from using this electricity in different end uses.

2. Material and methods

2.1. Review of LCA studies for ESS alternatives

LCA is a process that evaluates the environmental burdens associated with a product, system or activity, identifying the energy and material flows and releases into the environment. It includes the entire life cycle of the product, from raw material extraction, through processing of materials, transportation, use and disposal at the end of the product's life. LCA determines the environmental impacts taking into account different impact categories (climate change, resource depletion, acidification, eutrophication, human health, toxicity, biodiversity, etc.). According to the ISO 14040 standard, LCA should include several steps: 1) Goal and scope; 2) Inventory analysis; 3) Impact assessment; 4) Interpretation of results [21,22].

Although LCA is a robust methodology, there are several parameters that can make the comparison between different studies difficult. Among those factors, the ones that stand out are the definition of system limits, the type of LCA applied (attributional versus consequential), the phases included in the analysis (cradle to gate, cradle to grave, etc.), the impact assessment models used to calculate the environmental impacts, and its different units of measurement, as well as the various hypotheses and assumptions. The global warming category is usually quantified using the IPCC methodology [23], therefore allowing the comparison between studies in most of the cases. However, for the other impacts (acidification, eutrophication, human toxicity, eco-toxicity, mineral and metal resources, particulate matter formation and so on), comparisons are, in many cases, impossible to make. For this reason, the present study analyses the environmental benefits of energy storage systems ESS, used to store surplus VRES production, in terms of their decarbonisation potential.

There are different classifications of ESS. We used five main groups [24]: *chemical storage* in the form of hydrogen and other synthetic chemicals; *electrochemical storage* in batteries; *electrical storage*, including superconducting magnetic energy storage (SMES); *mechanical storage*, such as pump storage, compressed air storage (CAES) and flywheels; and *thermal storage*.

2.1.1. Chemical storage

In this case, energy is stored in the chemical bonds of atoms and molecules that is eventually released in a chemical reaction. In this context, the focus is on H_2 production via water electrolysis and the subsequent production of synthetic fuels such as methane, syngas, methanol and ammonia. The review of the LCA literature on H_2 production via electrolysis has revealed that electricity supply is the main source of GHG emissions while the contribution of the electrolyser (around 4% of total emissions) and the compression and storage stage is relatively small (around 18% of total emissions). Production of H_2 using renewable electricity renders very low GHG emissions, ranging from 0.003 to 0.06 kg CO_2eq/MJ fuel [25–27], while, if electricity derived from fossil fuel is used, emissions can be as high as 0.2-0.3 kg CO_2eq/MJ fuel [25,28,29].

In recent years, the progress of carbon capture technologies and their use (CCUS) has made available a new way of supplying carbon as a raw material for the production of synthetic fuels. For this, the captured CO_2 is made to react with the hydrogen produced from renewable sources, allowing the synthesis of synthetic fuels. According to [30] the marginal supply of CO_2 would come, in the short term, from fermentation, bioenergy, H_2 production and ammonia production. For the long-term scenario, the marginal supply of CO_2 would come from the production of ammonia, iron and steel, ethylene and cement. Furthermore, CO_2 could be obtained from the atmosphere by the so-called direct air capture (DAC) [31]. The CO_2 footprint from the cradle to the door is negative. According to [31], it ranges from -0.95 to - 0.59 kg of CO_2eq/kg of CO_2 obtained under current conditions and from -0.99 to - 0.98 kg of CO_2eq/kg of CO_2 in a low carbon economy. The study by [30] provides values of the carbon footprint of the marginal supply of CO_2 in a current scenario and in a long-term scenario. In the short term, the carbon footprint is −0.80 kg of CO_2eq/kg of CO_2 captured (which agrees with previous results). However, in the long term the authors report a smaller negative footprint (−0.34 kg of CO_2eq / kg of CO_2 captured).

Using the H_2 produced from surplus electricity from VRES and CO_2 captured in industrial installations, synthetic fuels can be produced. In Table 1~~Table 1~~, the GHG emissions reported in the literature for the conversion of H_2 obtained from electrolysis using renewable electricity and captured CO_2 into synthetic fuels are shown. For some of the synthetic fuels, emissions are negative due to the CO_2 credit obtained from the utilization of captured CO_2.

Table 1. GHG emissions of different ESS found in the literature.

	GHG emissions (manufacturing)	**Unit**	**References**
Chemical storage			
Hydrogen	0.003-0.3	kg CO_2eq/MJ fuel	[25–29,32–36]
CO_2 supply	-0.95 - (-0.34)	kg CO_2eq/kg CO_2	[30,31]
Methane	-0.12 - 0.299	kg CO_2eq/MJ fuel	[29,30,32,37–39]
Syngas	-0.05 - 0.35*	kg CO_2eq/MJ fuel	[38,40]
Ammonia	0.008 - 0.36	kg CO_2eq/MJ fuel	[41]
Methanol	-0.05 - 0.002	kg CO_2eq/MJ fuel	[39,42,43]
Syndiesel	-0.063 - 0.12	kg CO_2eq/MJ fuel	[44–48]
DME	-0.05 - 0.0017	kg CO_2eq/MJ fuel	[42,48]
OME	-0.08 - 0.0019	kg CO_2eq/MJ fuel	[48,49]
Electrochemical storage			
Lead acid batteries	77-110	kg CO_2eq/MWh electricity	[50,51]

Alkaline batteries	27	kg CO_2eq/MWh electricity	[51,52]
Molten salts batteries	49 - 58	kg CO_2eq/MWh electricity	[50,51,53]
Lithium ion batteries	20 - 82	kg CO_2eq/MWh electricity	[50,51,54,55]
Flow batteries	15-93	kg CO_2eq/MWh electricity	[50,56,57][51]
Electrical storage			
Superconducting magnets (SMES)	416	kg CO_2eq/MWh electricity	[58]
Mechanical storage			
Pump storage	1 - 6	kg CO_2eq/MWh electricity	[13,20,65–67,56,58–64]
Diabatic CAES	4 - 107	kg CO_2eq/MWh electricity	[13,14,71,20,56,58,64,65,68–70]
Adiabatic CAES	2 - 30	kg CO_2eq/MWh electricity	[64,65,68,69,72]
LAES	14 - 21	kg CO_2eq/MWh electricity	[73]
Fly wheels	3.5 – 159	kg CO_2eq/MWh electricity	[74,75]
Thermal storage			
Thermal storage in CSP plants (sensible heat)	0.91 - 30	kg CO_2eq/MWh electricity	[76–80]
Thermal storage in CSP plants (thermochemical)	19	kg CO_2eq/MWh electricity	[79]
Thermal storage in CSP plants (latent heat)	20	kg CO_2eq/MWh electricity	[79]
Electrothermal energy storage (ETES)	89	kg CO_2eq/MWh electricity	Calculated value from [81–83]
Thermal storage in residential sector (sensible heat) (SH-TES)	0.0025 - 0.009	kg CO_2eq/MJ heat	[84–86]
Thermal storage in residential sector (latent heat) (LH-TES)	0.0087	kg CO_2eq/MJ heat	[85]

*No credits for CO_2 captured considered. Electricity from the German grid

2.1.2.Electrochemical storage

Electrochemical storage supports its principle of operation in reversible electrochemical reduction and oxidation conversions, commonly known as redox reactions that occur between electrochemically active species. Batteries can be classified into four large families: lead-acid, alkaline, molten salt and lithium ion batteries. Lead acid batteries are the most mature technology and the applicability of these batteries extends to both mobile applications and stationary systems. Among the alkaline batteries, those of the nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) types stand out, and their main application is found in various stationary environments. In molten salt batteries, the electrodes are in a liquid state, and the main types are sodium sulphur (NaS) and sodium-metal halide ($Na/NiCl_2$) batteries. They are considered applicable to various fields, mainly in stationary systems. Lithium-based batteries are used to boost electro-mobility, as well as for the storage of electricity produced with renewable energies on an intermittent basis. There are various chemistries for these lithium ion batteries: $LixCoO_2$, $LiNiCoMnO_2$, $LiMn_2O_4$ and $LixFePO_4$. Finally, in flow batteries, unlike in the previous batteries, the electrolyte is pumped from two external tanks into the cell. The two most developed chemistries for flow batteries are those based on vanadium and the zinc-bromine.

Large-scale energy storage using battery technology requires specific configurations and chemistries that enable a low-cost, long-life, large-scale energy storage. In this direction, a new liquid metal battery has been proposed by the AMBRI project developed at MIT. It is a high-temperature (700 °C) magnesium–antimony (Mg||Sb) liquid metal battery comprising a negative electrode of Mg, a molten salt electrolyte, and a positive electrode of Sb [87]. The battery operates at a high temperature, but does not overheat, but rather cools down. Such a battery is much better suited for electricity grids.

There is LCA literature that analyses the production and use of these types of batteries. Table 1~~Table 1~~ shows the GHG emissions from the manufacturing of the different types of batteries found in literature, which ranges from 20 kg CO_2eq/MWh electricity for the Li-ion batteries to 110 kg CO_2eq/MWh electricity for the lead acid batteries.

2.1.3.Electrical storage

The electrical storage technology considered in this review is the Superconducting Magnetic Energy Storage (SMES). According to the literature, SMES technologies have significant GHG emissions associated with them, mainly due to the high cooling requirements [58].

2.1.4.Mechanical storage

The mechanical storage methods considered are pump hydro storage (PHS), compressed air energy storage (CAES), liquid air energy storage (LAES) and flywheels. The GHG emissions from producing these energy storage devices are shown in Table 1~~Table 1~~.

PHS stores energy in the form of the gravitational potential energy of water. Surplus electric power is used to pump water from a reservoir located at a lower elevation to a higher one. Then, in periods of high electrical demand, the stored water is passed through turbines to produce electric power. Pump storage installations have very reduced GHG emissions associated with their construction and are quantified in 1-6 kg CO_2eq/MWh of electricity produced, in the literature consulted.

The lack of water associated with climate change could potentially reduce the usability of hydro storage systems and, therefore, reduce the electricity production by reservoirs. The study by Opperman et al, 2021, [88] considering 2488 existing dams and 3700 projected dams confirmed that 32% and 20% of the existing and projected dams, respectively, will have increased water scarcity risk by 2050 due to climate change. Research on the current long drought (19 years) of the SE USA [89] warns of the danger of depletion, both of groundwater in aquifers and of water storage in reservoirs in times of severe and prolonged drought with consequences for life and the production of electricity in the reservoirs. Therefore, PHS planning and management should fully account for these potential shifts in hydrological risks.

CAES consists of using the surplus energy production to compress air stored underground, either in natural or artificial deposits (caverns, aquifers or mines), or in facilities above ground. When its maximum capacity is reached or the demand increases, the direction of the flow is modified using compressed air to drive turbines and produce electricity. This storage system is divided into two main types: conventional compressed air energy storage (CCAES), and adiabatic compressed air (ACAES), which uses the heat recovered from the air compression process to heat it during the expansion process, reducing environmental impacts. GHG emissions associated with the construction of these installations are quantified from 4 to 107 kg CO_2eq/MWh for CAES and from 2 to 30 kg CO_2eq/MWh for ACAES. It seems that the design and processing of underground air storage could have a large influence on the final GHG emissions [68], which could lead to the large differences found in the results of some studies. Additionally, CAES have a heat input in the process that is quantified as 1.2 $kWh_{heat}/kWh_{electricity}$ [90] and would lead to additional GHG emissions during the operation of these installations.

LAES uses surplus electricity to cool air until it liquefies and stores the liquid air in a tank. When needed, it brings the liquid air back to a gaseous state, and that gas runs a turbine to generate electricity. We are aware of just one LCA for this technology [73], quantifying the GHG emissions associated to its construction as14-21 kg CO_2eq/MWh.

Finally, flywheels work by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. GHG emissions of the manufacturing of these systems have been scarcely investigated in the literature, with reported values of 3.5 kg CO_2eq/MWh [75].

2.1.5. Thermal storage

Thermal storage systems (TES) can be classified into sensible heat, latent heat and thermochemical storage. The most frequent LCAs of these technologies found in literature are for concentrated solar power (CSP) and for heating and / or cooling systems in buildings.

The GHG emissions from thermal storage systems used in CSP plants found in the literature varies from 0.9-30 kg CO_2eq/MWh [76–79]. The use of systems using latent heat and thermochemical storage has been investigated by [79] resulting in values of 19 (for latent heat) and 20 (for thermochemical) kg CO_2eq/MWh.

The surplus electricity produced by renewable sources can be used directly for residential or industrial thermal uses through the use of electric heaters with storage systems. The GHG emissions associated with the use of thermal (sensible heat and latent heat) energy storage have been investigated in the LCA literature, resulting in values ranging from 0.0025 to 0.009 kg CO_2 eq/MJ for sensible heat TES [84–86] and 0.0087 kg CO_2 eq/MJ for latent heat TES using phase change materials (PCM) [85].

Electro-thermal energy storage (ETES) systems convert electrical energy into thermal energy. This can then be used for heating or cooling, or reconverted into electricity. There is no LCA for this technology in the literature but coupling a TES system with electric heaters at the reported efficiencies [82,83] gives an estimated value of 89 kg CO_2eq/MWh.

2.2. Comparative analysis

Different storage systems provide different services to the energy system and, thus, direct comparisons of GHG emissions are meaningless. To overcome this limitation, we have performed a comparative analysis, considering the services that each of the considered storage systems can provide in the different end use applications.

We have considered the storage of 1 MWh of overproduced electricity in Spain. As a base case, we have considered that 50% of this surplus electricity would come from wind farms and 50% from PV installations. In the case of self-consumed electricity, the technology considered is PV. Global warming emissions from the electricity production from wind and PV are obtained from the Ecoinvent database and are quantified as 14 kgCO_2eq/MWh for wind electricity, 66 kgCO2eq/MWh for PV grid electricity and 67 kgCO_2eq/MWh for self-consumed PV electricity (see the details in Table S1 of the supplementary information).

We have analysed four end use applications of the stored overproduced electricity:

- P2Power: where the stored energy is used to produce electricity again at peak times or provide electricity grid regulation services
- P2Mob: where electricity is used to power hybrid vehicles or to produce synthetic fuels
- P2Heat: where electricity is stored in the form of heat and can be used in thermal end use applications
- P2Chem: where electricity can be used to produce H_2 and thus a number of synthetic chemicals that can be an alternative to the production of chemical products

As noted above, not all the storage systems are appropriate for all the end use applications, as shown in Figure 2Figure 2, where the framework proposed for the analysis is shown.

In the P2Power end use, different services are needed. Seasonal storage involves large amounts of energy that must be stored over longer periods. This service can be provided by mechanical storage systems or chemical storage. Shorter term storage in the form of days or few hours can be provided also by thermal storage systems, electrochemical and electrical storage. Other grid services for voltage and frequency control can be provided by electrochemical and electrical storage, as well as mechanical storage. The reference technology, used in the absence of any storage system, would be a natural gas combine cycle power plant (NGCC). Behind the meter, users can store their self-produced electricity (exemplified here by PV electricity) to use it during the night or can alternatively connect their installation to the grid (reference technology in this case) to export and import the electricity produced or required at each moment of the day.

In the P2Mob end use, we consider the mobility services provided by the stored electricity to directly power electric and hybrid vehicles using batteries (electrochemical storage), or to produce alterative e-fuels to propel passenger and HD vehicles (chemical storage). E-fuels are synthetic fuels, also called electrofuels, that result from the combination of 'green or e-hydrogen' produced by electrolysis of water using renewable electricity and CO_2 captured either from a concentrated source (e.g. flue gases from an industrial site) or from the air (via direct air capture, DAC) [91]. The reference system in this case would be the emissions of the average fleet of passenger and HD vehicles for the year 2019, taken from [44,92].

In the P2Heat end use, the use of electricity in thermal applications is considered either in the form of electricity transformed to heat (thermal storage) or electricity converted into e-fuels to produce heat (chemical storage) in residential or industrial applications. The reference technology to produce heat would be heat produced from natural gas combustion in a condensing boiler.

Finally, in the P2Chem end use, we consider the synthesis of H_2 from hydrolysis using the surplus electricity from VRES and the subsequent synthesis of chemical products using this H_2 and captured CO_2 from carbon capture installations (chemical storage). The reference system in this case is the current chemical production processes.

In each of the end uses, we have computed the benefits from storing 1 MWh of overproduced PV and wind (50%/50%) electricity in Spain and using this stored energy in different applications in comparison with the reference system, according to the following expression (Eq. 1):

$$GHG\ emissions\ benefit = GHG\ emissions_{P2X} - GHG\ emissions_{reference\ system} \quad \text{(Eq. 1)}$$

All the data used to perform the computation of the benefits of each type of storage has been obtained from the reviewed literature on LCA and is provided in the tables in the Supplementary Information.

For the 2030 scenario, we have used the information provided by the Spanish National Energy and Climate Plan (NECP)[93] to update the GHG intensity of the Spanish electricity mix in 2030. The well to wheel analysis performed by the JEC-CONCAWE consortium provides some estimations for the fuel consumption and fuel efficiency of different vehicles in the future (2025) fleets [94]; a 36% penetration of clean passenger vehicles and a 14% penetration of clean HD vehicles in 2030 have been considered [93]. A combination of heat pumps and natural gas boilers has been considered as the reference technology for heat production in residential and industrial applications in 2030, in line with the objectives set in the Spanish NECP. As for the reference technology for chemical production, it has been considered that the implementation of CCS technologies could lead to significant GHG emission reductions in the conventional production of H_2 -94% according to [95], methanol -89% according to [96], and ammonia -25% according to [97]. As a conservative scenario, it has been considered that CCS technologies could be deployed in around 20% of the chemical sector in Spain in 2030.

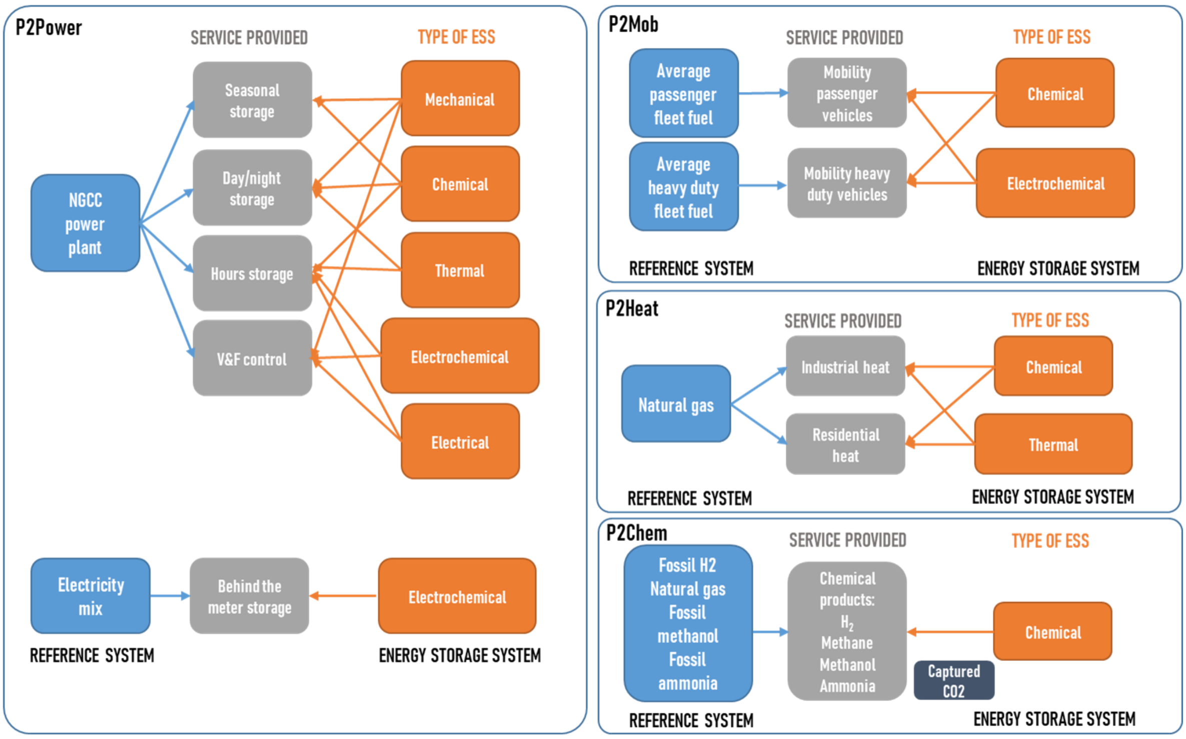

Figure 2. Proposed framework for the comparative analysis

3. Results and discussion

3.1. GHG emissions from storing and using surplus electricity

In this section we present the results of the GHG emissions of different storage systems in each of the end use applications studied, namely P2Power, P2Mob, P2Chem and P2Heat.

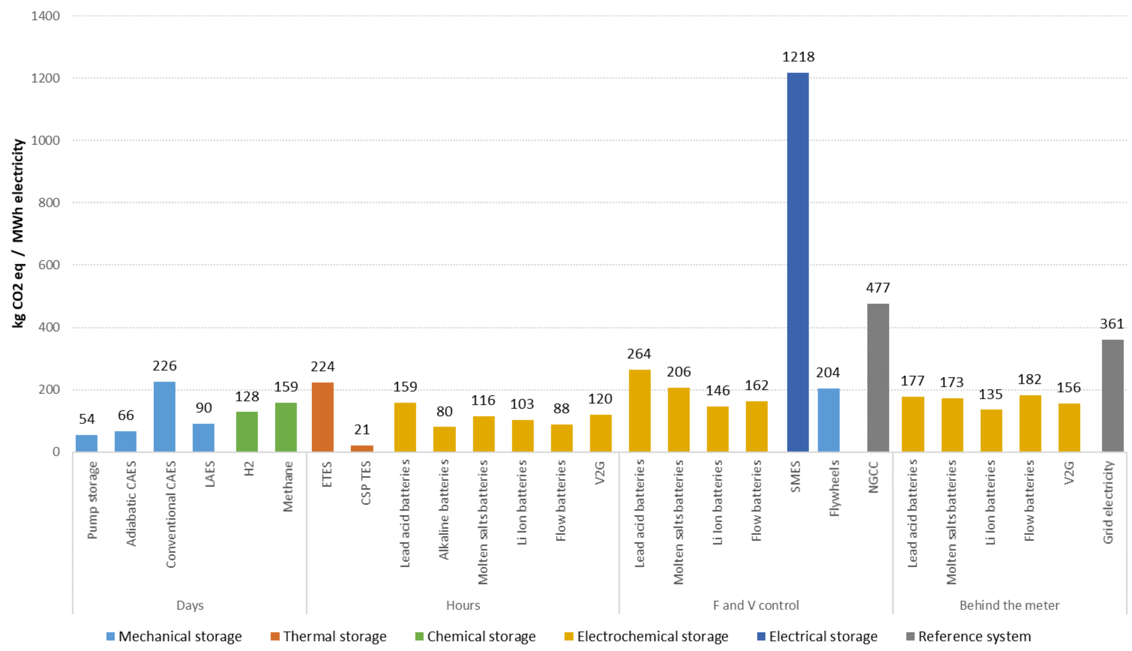

Figure 3. GHG emissions in the P2Power energy storage end use. "F and V" stands for Frequency and Voltage control. The same technology (e.g.. Li Ion battery) can provide different services (e.g. centralized short term storage, F and V control and short term storage behind the meter) and can have different associated GHG emissions

Figure 3~~Figure 3~~ shows the GHG emissions of the different storage technologies. Seasonal storage can be provided by mechanical and chemical storage technologies. Mechanical storage, especially pump storage and adiabatic CAES, are the technologies with lowest associated GHG emissions. CSP with TES systems appear is the option with the lowest GHG emissions among the available options to store energy during some hours, followed by the use of batteries, with GHG emissions ranging from 80 to 159 kgCO_2eq/MWh. In this category, the use of ETES would lead to the highest GHG emissions. When it comes to the use of storage systems for frequency and voltage control, batteries in general, and Li ion batteries in particular, would be the options with the lowest GHG emissions. The use of SMES would lead to much higher GHG emissions than the use of the reference technology (NGCC). As for the storage behind the meter, it becomes evident that storing the surplus electricity using batteries is preferable than connecting it to the grid in terms of GHG emissions. This later statement is dependent on the GHG intensity of the current electricity mix (quantified as 361 kgCO_2eq/MWh). As the electricity mix becomes more decarbonized, the benefit of storing electricity in batteries is less evident.

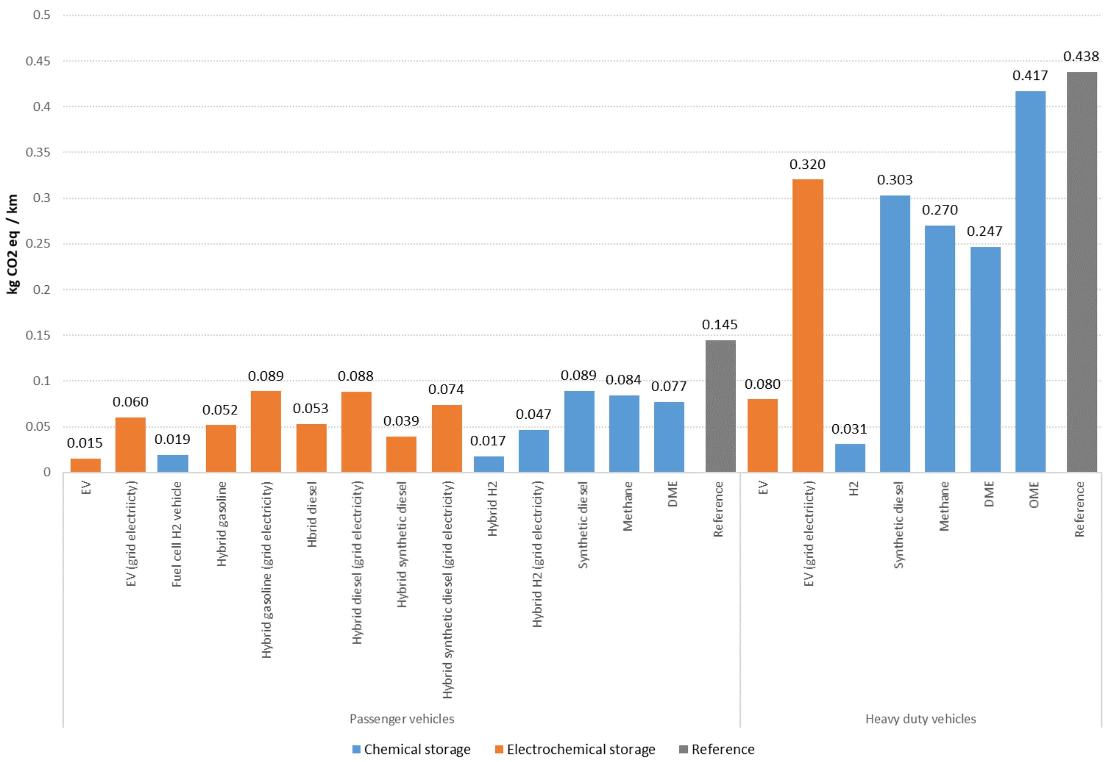

Figure 4. GHG emissions in the P2Mob energy storage end use.

Surplus electricity stored in batteries or in synthetic fuels can be used to propel passenger and HD vehicles. The GHG emissions associated with each P2Mob technology is shown in Figure 4~~Figure 4~~. According to our results, in the case of passenger vehicles, the lowest emissions are obtained for electric vehicles, followed by hybrid electric fuel cell vehicles using H_2. Electric vehicles that use grid electricity (instead of pure renewable electricity) to charge their batteries would produce much higher emissions, but still less than the reference vehicle. The use of synthetic fuels, synthetic diesel, methane and DME have considerably higher emissions than electric or fuel cell vehicles and close to those of hybrid vehicles charged with grid electricity, which is the worst option. In the case of HD vehicles, H_2 would be the best option, even better than pure electric vehicles. These results back up the analysis performed by the IEA [98] and IRENA [99] on the very important niche market that fuel cell vehicles could have on the HD transport segment. According to our results, this option would be a good alternative also in environmental terms. The use of synthetic fuels, however, especially in the case of OME, gives rise to very high emissions, quite close to those of the reference vehicle, and would not be a priority option for transport sector decarbonisation.

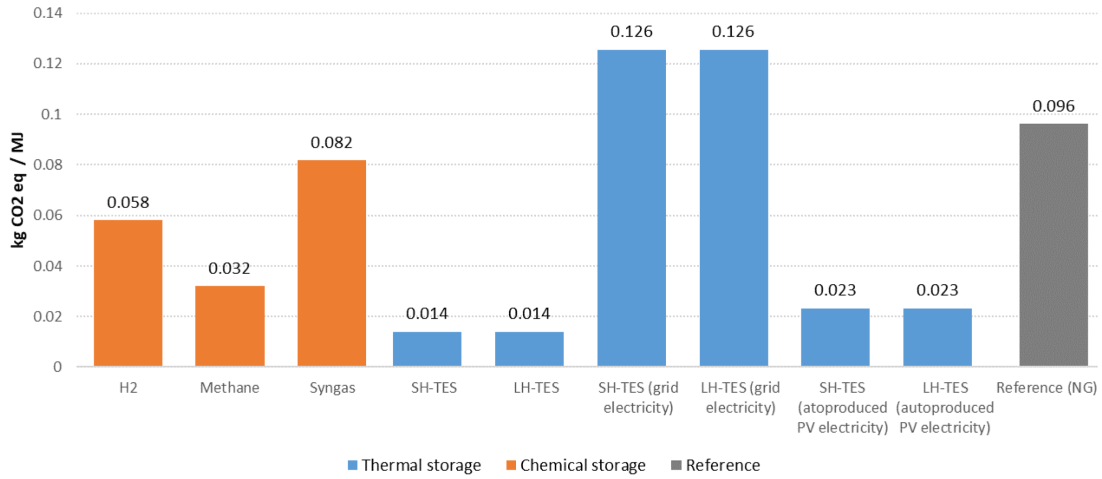

Figure 5. GHG emissions in the P2Heat energy storage end use

The GHG emissions associated to P2Heat alternatives is shown in Figure 5~~Figure 5~~. Thermal uses for the surplus electricity stored are provided by chemical storage technologies by combusting H_2, methane or syngas and by thermal storage systems (TES) using sensible (SH-TES) or latent heat (LH-TES). The results obtained for the GHG emissions show that TES can be very effective in providing heat with low GHG emissions when they use pure renewable electricity (surplus electricity from PV and wind or PV electricity from self-consumption). In the case that grid electricity is used, the associated emissions are higher than those of the reference technology (natural gas).

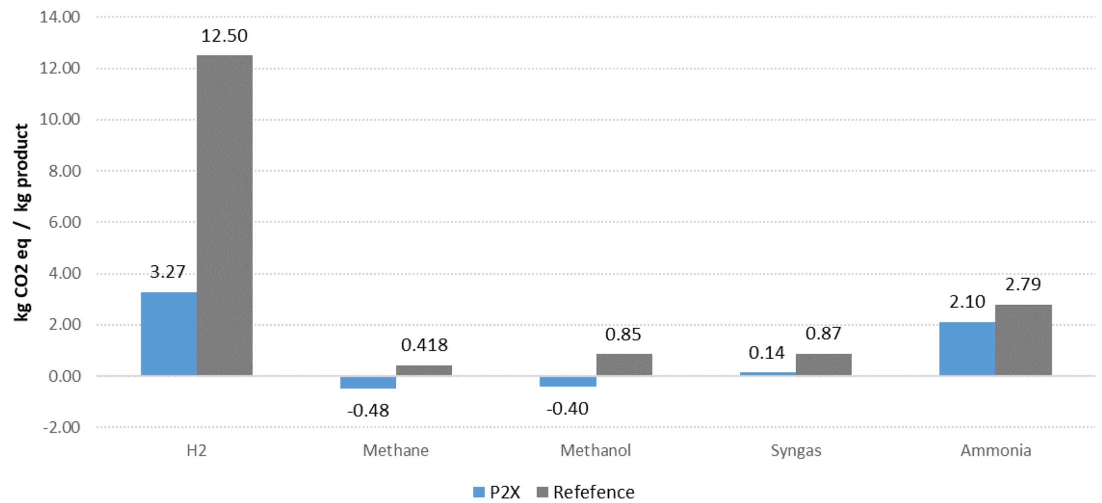

Figure 6. GHG emissions in the P2Chem energy storage end use. Negative emissions are due to the incorporation of captured CO_2 in e-fuels

When using surplus electricity to produce chemicals, GHG emissions are lower than those of the conventional production route and, in some cases, such as the production of methane and methanol, negative emissions can be obtained (Figure 6~~Figure 6~~). These negative emissions are the consequence of using captured CO_2 in the production process. These results are in line with the GHG emissions intensity found in the review of the LCA literature performed (see Table 1~~Table 1~~) and are adapted to the particular case of using surplus PV and wind electricity from the

Spanish market. However, they can be extrapolated to a general situation of using pure renewable electricity and CO_2 from carbon capture.

3.2. GHG emissions benefits

Once GHG emissions intensity of the different end uses are calculated, we compute the benefits that could be obtained by storing 1 MWh of surplus electricity in each case. This is useful to evaluate which end use will provide the highest benefits in term of CO_2 mitigation and, therefore, which application policy initiatives should be prioritized.

As pointed out in the introductory section, as energy systems becomes more decarbonized, the relative benefits of using stored electricity will change. However, the size and sign of the relative changes are not easy to anticipate. In order to shed some light on this issue, a theoretical prognosis exercise has been performed. The results are shown in Figure 7~~Figure 7~~.

The use of the surplus electricity to power electric vehicles leads to the highest GHG emissions reductions per MWh stored, especially in the passenger segment in the current scenario. In the HD mobility segment, electric trucks are also the ones that provide the largest benefit, even more than fuel cell vehicles, due to the higher efficiency of the complete chain. Still, H_2 seem to be a very good alternative. In the future, the benefits for passenger cars becomes lower due to the expected improvements in the efficiency of vehicles and the penetration of clean fuels. It becomes evident from the results that the use of synthetic fuels leads to very low GHG emissions avoidance benefits.

The expected benefits from the P2Power end use are the next highest GHG mitigation option, with values ranging from 200 to 450 kg CO_2eq avoided per MWh stored, and it remains constant, as the reference technology (NGCC) has been kept unchanged. Due to the very high emissions of SMES technologies, their use would lead to additional GHG emissions to the system. Behind the meter storage seems to be beneficial nowadays, but will become a net GHG emission source when the electricity mix is fully decarbonized in 2030. By then, it will be better to simply connect to the grid and avoid the installation of batteries. The use of H_2 or methane to produce electricity would lead to higher benefits in the future, due to the lower GHG emissions associated with the compression and storage of H_2 (electricity powered). The storage of electricity in the form of heat in thermal storage systems (TES) is next in the rank of decarbonisation options, but its benefits will reduce in time, as heat provision will increasingly make a bigger use of heat pumps.

The production and use of H_2 from the surplus electricity in the chemical sector leads to lower GHG emissions avoidance in comparison with the other possible end uses of H_2, as these benefits will reduce with time. However, the use of this H_2 and captured CO_2 from CCS installations to produce synthetic chemicals in the industrial sector would generate increasing benefits in the future.

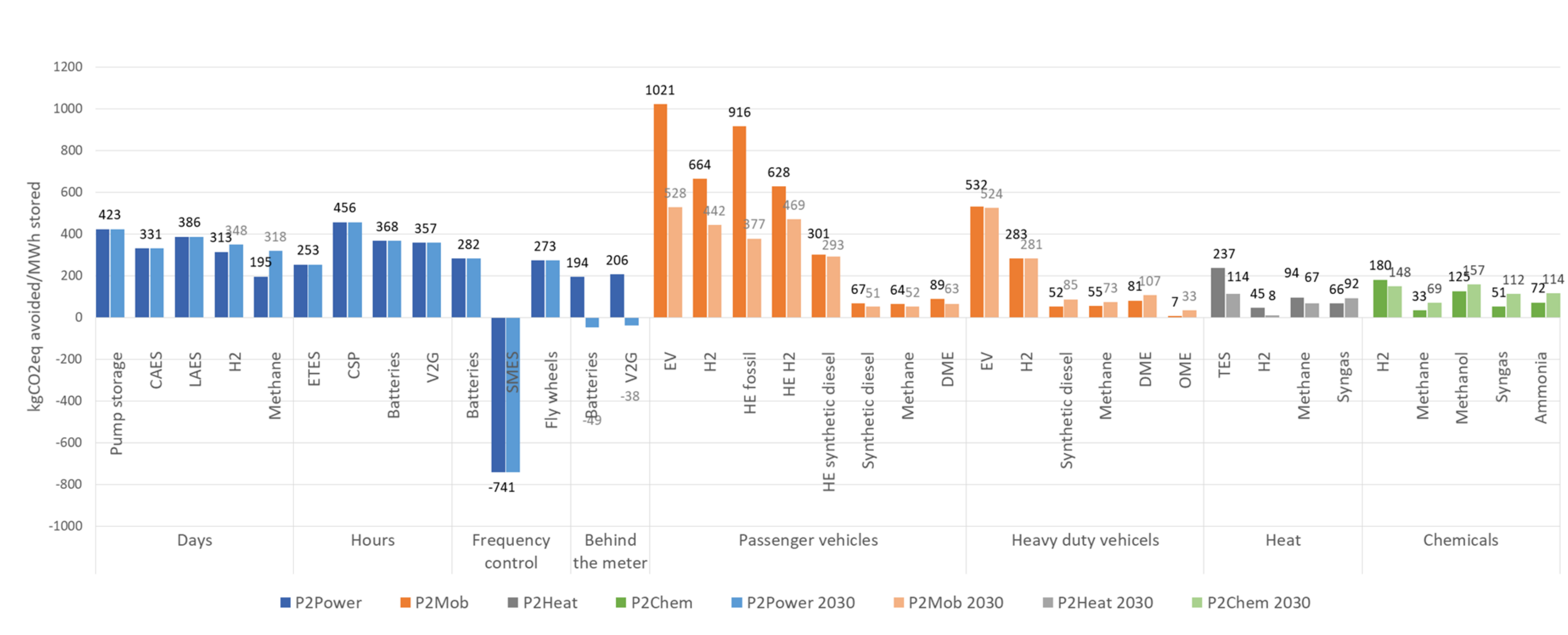

Figure 7. GHG emissions benefits of different storage options in the 2020 and 2030 scenarios expressed in kg of CO2eq avoided for each MWh stored. Dark colour: the results for 2020; Light colour: the results for 2030.

3.3. Limitations of the analysis and potential sources of errors

Results obtained in this study cannot be directly extrapolated, especially in P2Power applications, as there are many site-specific circumstances that can influence the outcomes. Benefits of ESS strongly depends on site-specific conditions and power system characteristics. For instance, within P2Power applications, recent literature in the UK shows big differences in the decarbonizing benefits depending on the application[100]. When analysing the benefits of storing surplus wind energy in the UK, the highest benefits (reduction of 608 g CO_2eq/kWh) were obtained in wind curtailment scenarios (surplus is stored and discharged when the demand is high) in regions with fossil-intensive electricity mix. However, for wind balancing (surplus is stored and discharged when the output is low) the GHG emissions increased by 133 g CO_2eq/kWh.

In the USA, [101] analysed two regions (Texas and California) with different renewables penetration and curtailment rates. Results show that in California, with 60 GW of installed renewable energy capacity installed and without energy storage, a 72% of CO_2eq reduction is achieved with a 33% of renewable curtailment. With energy storage, for the same renewable penetration, emissions abatement of 90% of CO_2eq can be achieved with only 9% curtailment. The same penetration of renewable power in Texas leads to a 3% of renewable curtailment and provide a decrease of CO_2eq emissions of 54% if no energy storage is used and 0.3% curtailment and 87% CO_2eq reduction if energy storage is in place.

In our case, the rate of penetration of VRES in the Spanish electricity mix is 27% in 2020 and 55% in 2030, with a clear predominance of wind power in 2020 but with an increasing role of solar photovoltaic in 2030. The projected total renewable penetration in the country in 2030 is 74%. The average penetration of renewable energies in Europe, according to the National Energy and Climate Plans is around 60% in 2030 with wind and solar contributing 40% [102]. This composition of the renewable electricity mix is, therefore, not so different from the projected portfolio in other countries and the conclusions reached in the article could be valid. However, caution should be exercised in situations where the VRES penetration and mix of technologies are radically different.

In other end use applications (P2Mob, P2heat, P2Chem), the reference technologies are more standard (e.g. carbon footprints of fossil vehicles emissions and other chemical products are less context dependent) and, therefore, the ESS benefits anticipated in this paper for the Spanish scenario can be extrapolated to other contexts with less uncertainty.

Results are based on a review of GHG emissions from the different ESS technologies found in LCA literature. While comprehensive and detailed, LCA studies are also static. Therefore, emissions reported in these studies can change in the future due to advancements in technology and the transition of energy systems towards low carbon energy mixes that can affect the results of ESS technologies GHG inventories. As pointed out by [103], even prospective LCA studies include changes to the energy system when modelling foreground processes, but usually the background processes are not modified leading to uncertainty in GHG emission estimates.

This study has based its conclusions on the evaluation of carbon reduction benefits only. But beyond them, other environmental impacts are associated with energy storage technologies and could pose some potential trade-offs. Three impact categories are clearly improved when storing renewable energies for later use: human toxicity, particulate matter formation and depletion of fossil resources [13,20]. Impacts connected to chemical storage are very reliant on the origin of the electricity used to produce H_2 and the origin of the carbon source needed for the synthesis of fuels, where impacts such as eco-toxicity and abiotic resources use may increase [30]. In the case of batteries, the impacts that could be of concern are related to the toxicity, eco-toxicity and depletion of the abiotic resources, some of which are critical raw materials [54]. These concerns could be solved increasing recyclability, life time and efficiency of batteries. PHS impacts are highly dependent on site-specific factors, such as the location and dam scale. Some of the criticisms towards environmental studies of this technology are associated with not adequately accounting for emissions related to the decomposition of biomass in dams, especially those located in tropical areas, and the impacts on aquatic biota [60,66]. Acidification and eutrophication are also relevant impacts in this technology. CAES (diabatic and adiabatic) storage systems present different impacts depending on the energy used to compress the air. Diabatic D-CAES using natural gas has higher impacts on acidification, particulate matter and photochemical oxidant formation, while adiabatic A-CAES using wind energy for air compression increases the impacts on land use, eutrophication and mineral resource depletion [68,69]. The extraction of some raw materials for thermal storage systems affects human health and resource use, impacts that can be reduced through research on new synthetic materials [104].

Finally, the economic impacts associated with the use of ESS for storing surplus electricity from VRES are also out of the scope of this study, which is only focused on carbon benefits. However, potential economic advantages are found in the literature. For instance, the ESS deployment at a large scale would influence electricity prices by stabilizing the supply of electricity by preventing high prices at times of peak demand. However, other aspects also have an influence on the electricity pricing, such as the location of ESS (high voltage transmission network versus lower voltage distribution network), size of the systems (centralised versus distributed), and the competition between VRES and a carbon-neutral baseload technology [105].

4. Conclusions

The highest benefits in terms of GHG emissions avoidance from storing surplus electricity from VRES would be obtained by directly storing this electricity in the batteries of electric or hybrid vehicles or by using it to produce H_2 to be used in fuel cell vehicles.

Storing electricity in the power sector to produce electricity again at other times also seems to be an option that leads to important GHG emissions avoidance benefits both behind and ahead of the meter. However, as the electricity mix becomes decarbonized, the use of batteries behind the meter would make much less sense in terms of reducing emissions, leading to a net increase in emissions in 2030. This drawback should be considered in policies encouraging battery installations in end use sectors.

Using electricity to produce heat either directly in thermal energy storage systems or via the production of synthetic fuels leads to low GHG emission avoidance benefits that will be reduced in time, as heat pumps become a widespread technology for heat production.

The use of synthetic chemicals and fuels leads to very low benefits in all the studied end use applications in comparison with other possible uses of the stored electricity. However, these benefits will improve over time in the chemical sector, as there are few alternatives to decarbonize this sector.

Energy storage will be a critical factor on the path towards the decarbonisation of energy systems based on a high penetration of VRES (PV and wind), providing flexibility and availability of energy to several demanding sectors and end use applications (power, heat, chemical and mobility).

The assessment of the whole life cycle of ESS, including the end-use phase of the range of applications covered in this study, reveals that a specific storage strategy must be formulated in each particular case, in line with the energy production portfolio, the specific site characteristics and the end-use sectors. Apart from the technical principles, environmental criteria should support the decision-making process to determine the design of the ESS strategy. Future research should undertake the assessment of environmental impacts, other than carbon emissions, and the costs and socioeconomic advantages and disadvantages of the application of different ESS strategies.

Acknowledgements

This work has been funded by the Institute for Energy Diversification and Saving by the contract MENOR/2020/0655. Authors want to thank Mark Theobald and Pablo Lechón-Alonso for their valuable input to the text.

Author statement

Yolanda Lechón: Conceptualization, Methodology, Validation, Formal analysis, Writing- Original draft preparation, Writing - Review & Editing, Project administration, Funding acquisition

Carmen Lago: Conceptualization, Methodology, Validation, Formal analysis, Writing - Review & Editing,

Israel Herrera: Conceptualization, Methodology, Validation, Formal analysis, Writing - Review & Editing,

Ana Rosa Gamarra: Conceptualization, Methodology, Validation, Formal analysis, Writing - Review & Editing,

Alberto Pérula: Formal analysis, Writing - Review & Editing,

References

[1] EC. 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 European Green Deal COM/2019/640 final. Brussels: European Commission (EC); 2019.

[2] European Commission. REGULATION (EU) 2021/1119 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law') 2021:L243/1-L243/51.

[3] European Consillium. Fit for 55 - The EU's plan for a green transition 2021.

[4] Engeland K, Borga M, Creutin JD, François B, Ramos MH, Vidal JP. Space-time variability of climate variables and intermittent renewable electricity production – A review. Renew Sustain Energy Rev 2017;79:600–17. https://doi.org/10.1016/J.RSER.2017.05.046.

[5] O'Shaughnessy E, Cruce JR, Xu K. Too much of a good thing? Global trends in the curtailment of solar PV. Sol Energy (Phoenix, Ariz) 2020;208:1068.

https://doi.org/10.1016/J.SOLENER.2020.08.075.

[6] California ISO. What the duck curve tells us about managing a green grid. Folsom CA: 2016.

[7] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. https://doi.org/10.1016/J.RSER.2015.01.057.

[8] MITECO. Estrategia a Largo Plazo Para Una Economía Española Moderna, Competitiva Y Climáticamente Neutra En 2050. Madrid, Spain: 2020. https://doi.org/.

[9] MITECO. Plan Nacional Integrado de Energía y Clima 2021-2030- Ministerio para la Transición Ecológica. 2019.

[10] IRENA. Costs and Markets to 2030. Eur Technol Inov Platf 2018;ENER-2018-:24.

[11] Behabtu HA, Messagie M, Coosemans T, Berecibar M, Fante KA, Kebede AA, et al. A Review of Energy Storage Technologies' Application Potentials in Renewable Energy Sources Grid Integration. Sustain 2020, Vol 12, Page 10511 2020;12:10511. https://doi.org/10.3390/SU122410511.

[12] Zakeri B, Syri S. Electrical energy storage systems: A comparative life cycle cost analysis. Renew Sustain Energy Rev 2015;42:569–96. https://doi.org/10.1016/j.rser.2014.10.011.

[13] Oliveira L, Messagie M, Mertens J, Laget H, Coosemans T, Van Mierlo J. Environmental performance of electricity storage systems for grid applications, a life cycle approach. Energy Convers Manag 2015;101:326–35. https://doi.org/10.1016/j.enconman.2015.05.063.

[14] Mostert C, Ostrander B, Bringezu S, Kneiske TM. Comparing electrical energy storage technologies regarding their material and carbon footprint. Energies 2018;11. https://doi.org/10.3390/en11123386.

[15] Brandeis L, Sprake D, Vagapov Y, Tun H. Analysis of electrical energy storage technologies for future electric grids. Proc 2016 IEEE North West Russ Sect Young Res Electr Electron Eng Conf EIConRusNW 2016 2016:513–8. https://doi.org/10.1109/EIConRusNW.2016.7448235.

[16] Sarbu I, Sebarchievici C. A comprehensive review of thermal energy storage. Sustain 2018;10. https://doi.org/10.3390/su10010191.

[17] Dowling JA, Rinaldi KZ, Ruggles TH, Davis SJ, Yuan M, Tong F, et al. Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. Joule 2020;4:1907–28. https://doi.org/10.1016/j.joule.2020.07.007.

[18] Kebede AA, Kalogiannis T, Van Mierlo J, Berecibar M. A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. Renew Sustain Energy Rev 2022;159:112213. https://doi.org/10.1016/J.RSER.2022.112213.

[19] Schmidt O, Hawkes A, Gambhir A, Staffell I. The future cost of electrical energy storage based on experience rates. Nat Energy 2017 28 2017;2:1–8. https://doi.org/10.1038/nenergy.2017.110.

[20] Sternberg A, Bardow A. Power-to-What?-Environmental assessment of energy storage systems. Energy Environ Sci 2015;8:389–400. https://doi.org/10.1039/c4ee03051f.

[21] ISO. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. ISO 2006. https://www.iso.org/standard/37456.html.

[22] ISO. ISO - ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines. 2006.

[23] Huang J, Mendoza B, Daniel JS, Nielsen CJ, Rotstayn L, Wild O. Anthropogenic and natural radiative forcing. Clim Chang 2013 Phys Sci Basis Work Gr I Contrib to Fifth Assess Rep Intergov Panel Clim Chang 2013;9781107057:659–740. https://doi.org/10.1017/CBO9781107415324.018.

[24] Guney MS, Tepe Y. Classification and assessment of energy storage systems. Renew Sustain Energy Rev 2017;75:1187–97. https://doi.org/10.1016/J.RSER.2016.11.102.

[25] Timmerberg S, Kaltschmitt M, Finkbeiner M. Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas – GHG emissions and costs. Energy Convers Manag X 2020;7. https://doi.org/10.1016/j.ecmx.2020.100043.

[26] Dufour J, Serrano DP, Gálvez JL, González A, Soria E, Fierro JLG. Life cycle assessment of alternatives for hydrogen production from renewable and fossil sources. Int J Hydrogen Energy 2012;37:1173–83. https://doi.org/10.1016/j.ijhydene.2011.09.135.

[27] Valente A. Advances in Life Cycle Sustainability Assessment of Hydrogen Energy Systems. 2020.

[28] Bareiß K, de la Rua C, Möckl M, Hamacher T. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. Appl Energy 2019;237:862–72. https://doi.org/10.1016/j.apenergy.2019.01.001.

[29] Reiter G, Lindorfer J. Global warming potential of hydrogen and methane production from renewable electricity via power-to-gas technology. Int J Life Cycle Assess 2015;20:477–89. https://doi.org/10.1007/s11367-015-0848-0.

[30] Thonemann N, Pizzol M. Consequential life cycle assessment of carbon capture and utilization technologies within the chemical industry. Energy Environ Sci 2019;12:2253–63. https://doi.org/10.1039/c9ee00914k.

[31] Müller LJ, Kätelhön A, Bringezu S, McCoy S, Suh S, Edwards R, et al. The carbon footprint of the carbon feedstock CO 2 . Energy Environ Sci 2020;13:2979–92. https://doi.org/10.1039/d0ee01530j.

[32] Parra D, Zhang X, Bauer C, Patel MK. An integrated techno-economic and life cycle environmental assessment of power-to-gas systems. Appl Energy 2017;193:440–54. https://doi.org/https://doi.org/10.1016/j.apenergy.2017.02.063.

[33] Cetinkaya E, Dincer I, Naterer GF. Life cycle assessment of various hydrogen production methods. Int J Hydrogen Energy 2012;37:2071–80. https://doi.org/10.1016/j.ijhydene.2011.10.064.

[34] Bhandari R, Trudewind CA, Zapp P. Life cycle assessment of hydrogen production via electrolysis - A review. J Clean Prod 2014;85:151–63. https://doi.org/10.1016/j.jclepro.2013.07.048.

[35] Spath PL, Mann MK. Life Cycle Assessment of Renewable Hydrogen Production via Wind/Electrolysis: Milestone Completion Report 2004.

[36] Wulf C, Kaltschmitt M. Hydrogen Supply Chains for Mobility—Environmental and Economic Assessment. Sustainability 2018;10:1699. https://doi.org/10.3390/su10061699.

[37] Zhang X, Bauer C, Mutel CL, Volkart K. Life Cycle Assessment of Power-to-Gas: Approaches, system variations and their environmental implications. Appl Energy 2017;190:326–38. https://doi.org/10.1016/j.apenergy.2016.12.098.

[38] Sternberg A, Bardow A. Life Cycle Assessment of Power-to-Gas: Syngas vs Methane. ACS Sustain Chem Eng 2016;4:4156–65. https://doi.org/10.1021/acssuschemeng.6b00644.

[39] Uusitalo V, Väisänen S, Inkeri E, Soukka R. Potential for greenhouse gas emission reductions using surplus electricity in hydrogen, methane and methanol production via electrolysis. Energy Convers Manag 2017;134:125–34. https://doi.org/10.1016/j.enconman.2016.12.031.

[40] Schreiber A, Peschel A, Hentschel B, Zapp P. Life Cycle Assessment of Power-to-Syngas: Comparing High Temperature Co-Electrolysis and Steam Methane Reforming. Front Energy Res 2020;8. https://doi.org/10.3389/fenrg.2020.533850.

[41] Chisalita DA, Petrescu L, Cormos CC. Environmental evaluation of european ammonia production considering various hydrogen supply chains. Renew Sustain Energy Rev 2020;130. https://doi.org/10.1016/j.rser.2020.109964.

[42] Matzen M, Demirel Y. Methanol and dimethyl ether from renewable hydrogen and carbon dioxide: Alternative fuels production and life-cycle assessment. J Clean Prod 2016;139:1068–77. https://doi.org/10.1016/j.jclepro.2016.08.163.

[43] Prussi M, Yugo M, De Prada L, Padella M, Edwards M, Lonza L. JEC Well-to-Tank report v5. 2020. https://doi.org/10.2760/959137.

[44] Edwards R, Hass H, Larivé J-F, Lonza L, Mass H, Rickeard D, et al. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context WELL-TO-TANK (WTT) Report. Version 4. 2013. https://doi.org/10.2790/95629.

[45] Van Der Giesen C, Kleijn R, Kramer GJ. Energy and climate impacts of producing synthetic hydrocarbon fuels from CO2. Environ Sci Technol 2014;48:7111–21. https://doi.org/10.1021/es500191g.

[46] Liu CM, Sandhu NK, McCoy ST, Bergerson JA. A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production. Sustain Energy Fuels 2020;4:3129–42. https://doi.org/10.1039/c9se00479c.

[47] Guo H, Liu Y, Chang W-S, Shao Y, Sun C. Energy Saving and Carbon Reduction in the Operation Stage of Cross Laminated Timber Residential Buildings in China. Sustainability 2017;9:292. https://doi.org/10.3390/su9020292.

[48] Prussi M, Yug M, Padella M, Edwards R, Lonza L, De Prada L. JEC Well-to-Tank report v5: Annexes Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. 2020. https://doi.org/10.2760/06704.

[49] Deutz S, Bongartz D, Heuser B, Kätelhön A, Schulze Langenhorst L, Omari A, et al. Cleaner production of cleaner fuels: Wind-to-wheel-environmental assessment of CO2-based oxymethylene ether as a drop-in fuel. Energy Environ Sci 2018;11:331–43. https://doi.org/10.1039/c7ee01657c.

[50] Hiremath M, Derendorf K, Vogt T. Comparative Life Cycle Assessment of Battery Storage Systems for Stationary Applications 2015. https://doi.org/10.1021/es504572q.

[51] Baumann M, Peters JF, Weil M, Grunwald A. CO2 Footprint and Life-Cycle Costs of Electrochemical Energy Storage for Stationary Grid Applications. Energy Technol 2017;5:1071–83. https://doi.org/10.1002/ente.201600622.

[52] Rydh CJ, Sandén BA. Energy analysis of batteries in photovoltaic systems. Part I: Performance and energy requirements. Energy Convers Manag 2005;46:1957–79. https://doi.org/10.1016/j.enconman.2004.10.003.

[53] Longo S, Antonucci V, Cellura M, Ferraro M. Life cycle assessment of storage systems: The case study of a sodium/nickel chloride battery. J Clean Prod 2014;85:337–46. https://doi.org/10.1016/j.jclepro.2013.10.004.

[54] Majeau-Bettez G, Hawkins TR, StrØmman AH. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. Environ Sci Technol 2011;45:4548–54. https://doi.org/10.1021/es103607c.

[55] Peters JF, Baumann M, Zimmermann B, Braun J, Weil M. The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renew Sustain Energy Rev 2017;67:491–506. https://doi.org/10.1016/j.rser.2016.08.039.

[56] Denholm P, Kulcinski GL. Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. Energy Convers Manag 2004;45:2153–72. https://doi.org/10.1016/j.enconman.2003.10.014.

[57] Weber S, Peters JF, Baumann M, Weil M. Life Cycle Assessment of a Vanadium Redox Flow Battery. Environ Sci Technol 2018;52:10864–73. https://doi.org/10.1021/acs.est.8b02073.

[58] Hartikainen T, Mikkonen R, Lehtonen J. Environmental advantages of superconducting devices in distributed electricity-generation. Appl Energy 2007;84:29–38. https://doi.org/10.1016/j.apenergy.2006.04.011.

[59] Mahmud MAP, Huda N, Farjana SH, Lang C. Life-cycle impact assessment of renewable electricity generation systems in the United States. Renew Energy 2020;151:1028–45. https://doi.org/10.1016/j.renene.2019.11.090.

[60] Torres O. Life Cycle Assessment of a pumped storage power plant. Dep Energy Process Eng 2011:134.

[61] Flury K, Frischknecht R. Life Cycle Inventories of Hydroelectric Power Generation 2012:51.

[62] Jiang T, Shen Z, Liu Y, Hou Y. Carbon footprint assessment of four normal size hydropower stations in China. Sustain 2018;10:1–14. https://doi.org/10.3390/su10062018.

[63] Kadiyala A, Kommalapati R, Huque Z. Evaluation of the life cycle greenhouse gas emissions from hydroelectricity generation systems. Sustain 2016;8:1–14. https://doi.org/10.3390/su8060539.

[64] Kapila S, Management E. Techno-economic and life cycle assessment of large energy storage systems 2018.

[65] Kapila S, Oni AO, Gemechu ED, Kumar A. Development of net energy ratios and life cycle greenhouse gas emissions of large-scale mechanical energy storage systems. Energy 2019;170:592–603. https://doi.org/10.1016/j.energy.2018.12.183.

[66] Song C, Gardner KH, Klein SJW, Souza SP, Mo W. Cradle-to-grave greenhouse gas emissions from dams in the United States of America. Renew Sustain Energy Rev 2018;90:945–56. https://doi.org/10.1016/j.rser.2018.04.014.

[67] Kumar A, Schei T, Ahenkorah A, Rodriguez RC, Devernay J-M, Freitas M, et al. Hydropower. Renew. Energy Sources Clim. Chang. Mitig., Cambridge University Press; 2011, p. 437–96. https://doi.org/10.1017/cbo9781139151153.009.

[68] Bouman EA, Øberg MM, Hertwich EG. Life Cycle Assessment of Compressed Air Energy Storage (Caes). 6th Int Conf Life Cycle Manag 2013.

[69] Bouman EA, Øberg MM, Hertwich EG. Environmental impacts of balancing offshore wind power with compressed air energy storage (CAES). Energy 2016;95:91–8. https://doi.org/10.1016/j.energy.2015.11.041.

[70] Liu W, Ramirez A. State of the art review of the environmental assessment and risks of underground geo-energy resources exploitation. Renew Sustain Energy Rev 2017;76:628–44. https://doi.org/10.1016/j.rser.2017.03.087.

[71] Stougie L, Del Santo G, Innocenti G, Goosen E, Vermaas D, van der Kooi H, et al. Multi-dimensional life cycle assessment of decentralised energy storage systems. Energy 2019;182:535–43. https://doi.org/10.1016/j.energy.2019.05.110.

[72] Claret AFG. Environmental and Society Related Issues 2018.

[73] Jones C, Gilbert P, Stamford L. Assessing the Climate Change Mitigation Potential of Stationary Energy Storage for Electricity Grid Services. Environ Sci Technol 2019. https://doi.org/10.1021/acs.est.9b06231.

[74] Hartikainen T. Environmental Impacts of Superconducting Power Applications. 2005.

[75] Torell W. Lifecycle Carbon Footprint Analysis of Batteries vs. Flywheels Revision 0. 2015.

[76] Lalau Y, Py X, Meffre A, Olives R. Comparative LCA Between Current and Alternative Waste-Based TES for CSP. Waste and Biomass Valorization 2016;7:1509–19. https://doi.org/10.1007/s12649-016-9549-6.

[77] Baeuerle Y. Life Cycle Assessment Thermal Energy Storage Systems Using Recycled Steel Industry Waste for Concentrated Solar Power Plants. University Koblenz - Landau, 2017. https://doi.org/10.13140/RG.2.2.26903.27043.

[78] Corona Bellostas B. Análisis de sostenibilidad del ciclo de vida de una configuración innovadora de tecnología termosolar 2016:1.

[79] Thaker S, Oni AO, Gemechu E, Kumar A. Evaluating energy and greenhouse gas emission footprints of thermal energy storage systems for concentrated solar power applications. J Energy Storage 2019;26. https://doi.org/10.1016/j.est.2019.100992.

[80] Klein SJW, Rubin ES. Life cycle assessment of greenhouse gas emissions, water and land use for concentrated solar power plants with different energy backup systems. Energy Policy 2013;63:935–50. https://doi.org/10.1016/j.enpol.2013.08.057.

[81] Meroueh L, Chen G. Thermal energy storage radiatively coupled to a supercritical Rankine cycle for electric grid support. Renew Energy 2020;145:604–21. https://doi.org/10.1016/j.renene.2019.06.036.

[82] Praveen RP, Baseer MA, Awan AB, Zubair M. Performance Analysis and Optimization of a Parabolic Trough Solar Power Plant in the Middle East Region. Energies 2018;11:741. https://doi.org/10.3390/en11040741.

[83] Siemens-Gamesa. Introducing Electric Thermal Energy Storage (ETES)-putting gigawatt hours of energy at your command. Hamburg: 2019.

[84] Piroozfar P, Pomponi F, Farr ERP. Life cycle assessment of domestic hot water systems: a comparative analysis. Int J Constr Manag 2016;16:109–25. https://doi.org/10.1080/15623599.2016.1146111.

[85] Bonamente E, Aquino A. Environmental Performance of Innovative Ground-Source Heat Pumps with PCM Energy Storage. Energies 2019;13:117. https://doi.org/10.3390/en13010117.

[86] Moore AD, Urmee T, Bahri PA, Rezvani S, Baverstock GF. Life cycle assessment of domestic hot water systems in Australia. Renew Energy 2017;103:187–96. https://doi.org/10.1016/j.renene.2016.09.062.

[87] Bradwell DJ, Kim H, Sirk AHC, Sadoway DR. Magnesium-antimony liquid metal battery for stationary energy storage. J Am Chem Soc 2012;134:1895–7. https://doi.org/10.1021/JA209759S/SUPPL_FILE/JA209759S_SI_001.PDF.

[88] Opperman JJ, Camargo RR, Laporte-Bisquit A, Zarfl C, Morgan AJ. Using the WWF Water Risk Filter to Screen Existing and Projected Hydropower Projects for Climate and Biodiversity Risks. Water 2022, Vol 14, Page 721 2022;14:721. https://doi.org/10.3390/W14050721.

[89] Williams AP, Cook ER, Smerdon JE, Cook BI, Abatzoglou JT, Bolles K, et al. Large contribution from anthropogenic warming to an emerging North American megadrought. Science (80-) 2020;368:314–8. https://doi.org/10.1126/SCIENCE.AAZ9600/SUPPL_FILE/AAZ9600_WILLIAMS_SM.PDF.

[90] Kim Y-M, Lee J-H, Kim S-J, Favrat D. Potential and Evolution of Compressed Air Energy Storage: Energy and Exergy Analyses. Entropy 2012, Vol 14, Pages 1501-1521 2012;14:1501–21. https://doi.org/10.3390/E14081501.

[91] Yugo M, Soler A. Concawe Review. A look into the role of e-fuels in the transport system in Europe (2030-2050). 2019.

[92] DGT. Tablas estadísticas 2019.

[93] PNIEC. Borrador del Plan Nacional Integrado de Energía y Clima 2021-2030 2019.

[94] EUCAR C. JEC Well-To-Wheels report v5 2020.

[95] Consonni S, Mastropasqua L, Spinelli M, Barckholtz TA, Campanari S. Low-carbon hydrogen via integration of steam methane reforming with molten carbonate fuel cells at low fuel utilization. Adv Appl Energy 2021;2:100010. https://doi.org/10.1016/J.ADAPEN.2021.100010.

[96] Collodi G, Azzaro G, Ferrari N, Santos S. Demonstrating Large Scale Industrial CCS through CCU – A Case Study for Methanol Production. Energy Procedia 2017:122–38.

[97] Young B, Krynock M, Carlson D, Hawkins TR, Marriott J, Morelli B, et al. Comparative environmental life cycle assessment of carbon capture for petroleum refining, ammonia production, and thermoelectric power generation in the United States. Int J Greenh Gas Control 2019;91:102821. https://doi.org/10.1016/J.IJGGC.2019.102821.

[98] IEA. Hydrogen – Analysis - IEA 2020.

[99] Taibi E, Miranda R, Vanhoudt W, Winkel T, Lanoix J-C, Barth F. Hydrogen from renewable power: Technology outlook for the energy transition 2018.

[100] Pimm AJ, Barbour ER, Cockerill TT, Palczewski J. Evaluating the regional potential for emissions reduction using energy storage. 2019 Offshore Energy Storage Summit, OSES 2019 2019. https://doi.org/10.1109/OSES.2019.8867357.

[101] Arbabzadeh M, Sioshansi R, Johnson JX, Keoleian GA. The role of energy storage in deep decarbonization of electricity production. Nat Commun 2019 101 2019;10:1–11. https://doi.org/10.1038/s41467-019-11161-5.

[102] Moore C, Tunbridge P, Kasprzak M, Graham E. Vision or division? What do National Energy and Climate Plans tell us about the EU power sector in 2030? 2020.

[103] Treyer K, Turconi R, Boyano A. Life Cycle Management of Energy and Energy Transitions—Managing the Complexity of Todays and Future Energy Systems with a Life Cycle Focus: Challenges and Methodological Solutions. Des. Sustain. Technol. Prod. Policies, Cham: Springer International Publishing; 2018, p. 243–7. https://doi.org/10.1007/978-3-319-66981-6_27.

[104] Oró E, Gil A, de Gracia A, Boer D, Cabeza LF. Comparative life cycle assessment of thermal energy storage systems for solar power plants. Renew Energy 2012;44:166–73. https://doi.org/10.1016/j.renene.2012.01.008.

[105] Jonson E, Azar C, Lindgren K, Lundberg L. Exploring the competition between variable renewable electricity and a carbon-neutral baseload technology. Energy Syst 2020;11:21–44. https://doi.org/10.1007/S12667-018-0308-6/FIGURES/15.