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Decarbonizing the electricity sector through energy storage: A life cycle assessment approach

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Abstract: This paper examines the potential role of energy storage in the Greek electricity sector under strict decarbonization targets. The sector is characterized by a large share of Renewable Energy Sources (RES). In 2025, the interconnected High Voltage (150 kV) and Extra High Voltage (400 kV) transmission system had approximately 12.2 GW of conventional power capacity and 9.3 GW of RES capacity, corresponding to electricity production of 28.2 TWh and 15.7 TWh, respectively. Based on the energy storage technologies and deployment pathways outlined in the National Energy and Climate Plan, the present study developed and evaluated realistic Life Cycle Assessment scenarios using the SimaPro software tool. The scenarios include the deployment of: i) Pumped Hydro Storage (PHS); ii) Battery Energy Storage Systems (BESS); and iii) the production and utilization of green hydrogen as a Long-Duration Energy Storage option. In absolute terms, the environmental impact (Global Warming Potential) of PHS, BESS, and green hydrogen, in the years 2030 and 2050 reaches 61.5 gCO_2eq/kWh, 95.6 gCO_2eq/kWh, 1,880 gCO_2eq/kgH_2, and 55.5 gCO_2eq/kWh, 90.3 gCO_2eq/kWh, and 1,660 gCO_2eq/kgH_2, respectively. For the year 2030, BESS exhibits the highest impact, whereas PHS demonstrates the lowest impact across all impact categories. Similar trends are observed for the year 2050, during which the environmental impacts associated with BESS remain comparatively elevated. The production and combustion of green hydrogen result in lower environmental impacts on human health, ecosystems, and resource availability than BESS under the 2050 scenario. Pumped Hydro Storage demonstrates the lowest overall environmental impact, while BESS can play a significant role in facilitating the dispatch of RES. All three examined technologies exhibit complementary operational characteristics capable of maintaining power system reliability under future energy scenarios. Future research should incorporate hydrogen transport and distribution, real operational and technical data, and additional emerging storage technologies.

Keywords: electricity; greenhouse gas emissions; life cycle; green hydrogen; battery energy storage systems; pumped hydro storage

1. Introduction

The energy transition trajectory of Greece presents distinct characteristics compared to those of other international economies due to the country's fragmented geographical configuration, the need to optimize interregional and transboundary electricity flows, and its historical reliance on lignite-based energy production.

The Greek power generation system consists of the interconnected mainland electricity network and the non-interconnected island systems. Within the interconnected system, electricity demand is primarily met through fossil-fuel-based generation units, including lignite- and natural-gas-fired power plants, as well as hydroelectric, wind, and

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photovoltaic generation units. The contribution of these technologies to the country's installed electricity generation capacity is outlined in the draft Ten-Year Network Development Plan (TYNDP) 2025–2034, published in January 2024, and in the National Energy and Climate Plan (NECP, 2024). Among its principal priorities, the TYNDP (IPTO, 2026) emphasizes the further electrical interconnection between the mainland system and the Aegean islands, aiming to enhance system reliability, energy security, and the integration of Renewable Energy Sources (RES).

The high electricity generation prospects for 2030 rely mainly on the planned increase in installed solar power capacity by a factor of three between 2023 and 2030. The system is further supported through electricity imports, reflecting the strong interdependency between its electricity and natural gas sectors. Within the interconnected mainland system, electricity generation from oil units has been phased out, whereas in the non-interconnected islands, electricity demand continues to be met by oil-fired generation and RES.

The Greek transmission system comprises the interconnected mainland system, as well as the islands connected to it through high-voltage (150 kV and 66 kV) and extra-high-voltage (400 kV) transmission infrastructure. The Greek Independent Power Transmission Operator (IPTO) is responsible for the development of the Hellenic Electricity Transmission System. In this capacity, the TYNDP plan outlines the infrastructure required for the further integration of RES, along with the associated implementation timelines and estimated investment costs necessary for achieving the relevant national targets. Interconnections with neighboring countries include Italy, Albania, FYROM, Bulgaria, and Turkey. Further expansion plans are currently under discussion, driven by the increasing need to enhance cross-border electricity transmission capacity and facilitate regional electricity trading.

The target for RES as a share of gross final energy consumption by 2030 is set at 43.0%. Individual binding targets have been established for each sector. Nevertheless, the integration of RES into electricity consumption constitutes the primary policy priority for the attainment of this objective, thereby necessitating the timely and efficient implementation of the planned measures. The NECP sets a target for the share of electricity generation from RES in gross electricity consumption of 75.7% by 2030, compared to an existing share of 58.6% in 2025. In parallel, national Greenhouse Gas Emissions (GHG) need to be reduced by at least 55% by 2030. Long-term objectives for 2050 envisage electricity consumption being supplied entirely by RES while GHG emissions are expected to reach net-zero levels. Within this context, a comprehensive assessment of the role of energy storage technologies in the national energy system is required. The integration of RES with energy storage systems constitutes an effective approach for achieving deep decarbonization in electricity generation (Paračková et al., 2026). In particular, the declining costs of BESS have enhanced their potential to facilitate the reduction of RES curtailment. In addition, the high energy density of hydrogen (120 MJ/kg), approximately three times greater than that of gasoline, renders it a particularly attractive and efficient energy carrier for electricity generation applications and for Long-Duration Energy Storage (LDES) (Hamedi et al., 2026).

The present study examines the environmental performance of three energy storage types, namely PHS, BESS, and green hydrogen storage. PHS and BESS are considered capable of mitigating the curtailment of RES in over intraday and intra-hour time horizons, whereas green hydrogen can address seasonal load variation.

The Life Cycle Assessment (LCA) methodology was implemented, and the SimaPro software tool was utilized to model and analyze ten scenarios. These include one scenario for each of the years 2030 and 2050 for PHS, Li-ion - Lithium Ferro Phosphate (LFP) batteries, and Li-ion-Nickel Manganese Cobalt (NMC) batteries; two scenarios for hydrogen production (2030 and 2050); and two scenarios for hydrogen combustion (2035 and 2050).

The novelty of the present study, in comparison with previous LCA studies on energy storage systems, is reflected in the following key aspects.

First, the analysis is conducted at the national level, focusing on Greece, whose geographically fragmented electricity system is characterized by extensive island networks, increasing electrification demand, and elevated geopolitical risks associated with energy security and fuel supply diversification. Consequently, Greece constitutes a particularly relevant case study for electricity systems facing complex decarbonization and flexibility challenges under conditions of high renewable energy penetration. Furthermore, the analysis is grounded in the most recent developments and contemporary energy-transition conditions in Greece, during a period in which utility-scale Battery Energy Storage System (BESS) deployment is rapidly accelerating. To the best of the authors' knowledge, limited recent literature published from 2024 onward integrates these elements within a realistic and policy-oriented framework for the Greek electricity sector. Moreover, the available studies are primarily focused on individual Greek islands rather than on the mainland interconnected electricity system and mainly address island-specific applications, including desalination, energy autonomy, and the water–energy nexus.

Second, existing studies on hydrogen-based energy storage systems are predominantly limited to the assessment of Global Warming Potential (GWP), without considering the broader spectrum of environmental impacts (Alves et al., 2025). In contrast, the present study evaluates all 18 midpoint impact categories and all three endpoint impact categories, as illustrated in Fig. 5, Fig. 6, and Fig. 7.

1.1 Energy storage technologies

Energy storage technologies can be classified (Jing et al., 2026; Mahadevan et al., 2025) into the following categories according to the form in which energy is stored:

1) Mechanical storage: pumped hydroelectric energy storage (PHS), compressed air energy storage (CAES), liquefied air energy storage (LAES), flywheel energy storage (FES), and gravity energy storage (GES).
2) Electrochemical storage: conventional rechargeable batteries, flow batteries (FB), and hybrid supercapacitors (HSCs).

3) Chemical storage: energy storage in the form of hydrogen (H_2ESS), ammonia, methanol, synthetic natural gas (SNG), drop-in fuels or electrofuels (e-fuels)
4) Thermal storage: sensible heat storage (SHS), latent heat storage (LHS), and thermochemical energy storage (TES).
5) Electrical storage: capacitors, supercapacitors, and superconducting magnetic energy storage (SMES).

Energy storage technologies are characterized according to their: i) response time; ii) storage capacity; iii) energy and power density; iv) discharge time, and v) lifetime. Table 1 presents the characteristics of prominent energy storage technologies.

The integration of storage technologies at the national level must ensure system reliability. To achieve this objective, the relevant systems should combine complementary operational characteristics capable of providing: i) uninterrupted and high-quality power supply through units with discharge durations ranging from a few seconds to several minutes; ii) load shifting capabilities through units with discharge durations extending from several minutes to a few hours; and iii) high-power backup support through units capable of retaining stored energy over extended periods and delivering electricity for several hours.

Table 1. Prominent energy storage technologies.

Energy Storage Type	Power Density W/kg (kW/m^3)	Energy Density Wh/kg (kW/m^3)	Discharge time s,min,h,d	Lifetime years	Efficiency %	Response time ms,s,min
			MECHANICAL			
PHS	1-1.5	0.2-2.0	1-24h+	30-85	65-90	min
CAES	(0.5-2.0)	(3-6)	1-24h+	20-40	38-70	min
FES	(1000-2000)	(20-80)	msec to 1h	15-20	85-95	s
			ELECTROCHEMICAL			
Lead acid	75-305	25-55	sec to h	5-20	60-90	<5ms
Nickel-Cadmium	100-300	40-75	sec to h	10-20	60-90	<10ms
Sodium –Sulfur (NaS)	90-235	150-245	sec to h	10-20	70-95	<5ms
Lithium-ion	500-2005	75-205	min to h	5-15	85-97	<1ms
Flow Battery (Vanadium FB)	(0.5-2)	(20-70)	sec-10h	5-10	60-90	<5ms
			CHEMICAL			
H_2ESS	(>500)	(500-3000)	s-h	5-20	20-50	<5ms
Fuel cells	>500	800-10000	s-24h+	5-20	25-58	<5ms
			THERMAL			
SHS	Hundreds -	(50-150)	1h	15-20	60-90	s-m
LHS	Hundreds	70	1h	15-20	60-90	m-h
TES	15-35	155–255	hours	25-45	85-95	s-m
			ELECTRICAL			
Supercapacitors	500-5000	0,1-50	ms-hour	10-20	85-98	<5ms
SMES	1000-5000	0,5-10	s -30 min	25-45	>90	5ms

Note: Compiled by the authors based on Conde et al. (2025); Jing et al. (2026); Liu et al. (2026); Mahadevan et al. (2025); and She et al. (2025).

Among the commercially available and technologically viable energy storage technologies, PHS, Li-ion batteries and SHS represent mature solutions, all classified at Technology Readiness Level (TRL) 9. These are followed by technologies at the pre-commercial or demonstration stage, including LHS and lead-acid batteries (TRL 8), as well as sodium–sulfur (NaS) batteries, flow batteries, FES, and TES, all of which are categorized at TRL 7. Notably, supercapacitors have also achieved TRL 7 in power quality applications; however, their large-scale deployment for energy storage remains constrained by their relatively low energy density (Jing et al., 2026). Additional technologies remain at the development or validation stage, corresponding to TRL 6 or lower.

The suitability of energy storage technologies is strongly influenced by the required storage duration. Consequently, Li-ion batteries, which are typically suitable for short-duration storage applications of approximately 1–2 hours, are generally preferred for fast-response operational requirements, whereas NaS batteries, offering storage durations in the range of 6–10 hours, are more appropriate for medium- to long-duration energy storage applications (Salmon and Grubb, 2025). Solid-state batteries, characterized by higher energy density, rapid charging capability, and improved operational safety, may contribute in the future to the development of more compact and efficient Battery Energy Storage Systems (BESS). In parallel, hybrid energy storage configurations combining high-energy-density batteries with supercapacitors could provide enhanced flexibility, resilience, and dynamic response capabilities for the integration of RES into modern electricity grids.

Furthermore, emerging gravity-based energy storage technologies constitute an additional storage option. These systems operate by elevating heavy masses during periods of excess electricity generation and releasing them to generate electricity during periods of increased demand. Such technologies may offer a cost-effective and LDES solution for wind and solar energy systems, particularly in applications where conventional battery storage technologies are subject to technical or economic constraints.

1.1.1 Current status of energy storage technologies

The Global energy storage capacity is expected to reach 1,200 GW by 2030 (Liu et al., 2026). In Europe, installed energy storage capacity reached 100 GW in 2025. Of this total, 54 GW corresponded to PHS and 45 GW to battery storage systems. (Energy Storage Europe, 2026). European Union storage capacity is projected to reach 200 GW and 600 GW by 2030 and 2050, respectively, while the corresponding targets for Greece are 6.3 GW and 17.5 GW, respectively (Energy Storage Europe, 2022; NECP, 2024).

A cost-reduction trajectory for investment costs under scenarios in which cumulative installed storage capacity approaches 1 TWh was examined, resulting in estimated cost ranges for established storage technologies between USD 100 and USD 500 per kWh. (Schmidt and Staffell, 2023). The storage duration of BESS is typically limited to a few hours, whereas PHS systems can provide storage over periods ranging from several hours to more than twenty-four hours. Consequently, the energy capacity of PHS remains higher than that of battery storage installations. However, the costs of BESS projects have declined significantly in the recent years by approximately 40% in 2024 to a price of around USD 150/kWh. Hence, utility-scale battery systems are playing an increasingly significant role in meeting peak electricity demand across many power systems. (International Energy Agency, 2024; 2026). The reduction in BESS costs, combined with high and widening intraday electricity market price spreads, have rendered investment in BESS an increasingly attractive and economically viable solution. (EMBER, 2026)

1.1.1.1 The role of long-duration energy storage (LDES)

Long-Duration Energy Storage (LDES) technologies mitigate the impacts associated with the stochastic nature of RES and the seasonal variation in energy supply and demand. In particular, storage solutions such as hydrogen storage are considered essential for transferring energy from periods of surplus generation during the summer months to winter periods characterized by limited RES availability. Consequently, LDES is increasingly recognized as a prerequisite for energy security, cost containment, and the development of clean industrial systems within the European Union. The strategic importance of LDES for the global energy transition, was reaffirmed during the 30th Conference of the Parties (COP30) to the United Nations Framework Convention on Climate Change, held in November 2025 in Belém, Brazil (Long-Duration Energy Storage Council, 2025). Furthermore, in January 2026, industrial stakeholders, through the Energy Storage Europe association, submitted a formal request to the EU, advocating for the systematic integration of LDES technologies into the design of the European energy system.

1.1.2 Hydrogen Valleys

In the context of achieving energy autonomy, the concept of “Hydrogen Valleys” (HVs) has emerged in the EU as a strategic initiative for the development of integrated hydrogen ecosystems. A HV refers to a geographically defined area in which multiple hydrogen applications are interconnected within an integrated energy ecosystem, promoting the local deployment of the hydrogen economy and encouraging stakeholder and citizen participation. Within these ecosystems, hydrogen is produced, distributed, stored, and consumed across various end-use sectors.

Hydrogen Valleys contribute significantly to increasing the production and availability of renewable, i.e. green hydrogen, thereby supporting the growing energy demand of the power generation, transport, and industrial sectors.

1.2 Energy storage in Greece

1.2.1 Energy storage targets

The role of energy storage in future decarbonization scenarios for the Greek economy is particularly significant, owing to the inherent variability and intermittency of RES and their expected extensive contribution to long-term decarbonization pathways. For example, in March 2026, the estimated RES curtailment in the interconnected system amounted to approximately 0.23 TWh (IPTO, 2026). This represents a considerable share, given that total electricity production and RES generation in the interconnected system were approximately 2.8 TWh and 1.6 TWh, respectively. The transition pathways designed to address climate change, have been incorporated into the NECP in December 2024. Within this framework, one of the key strategic priorities for ensuring the flexibility and reliability of the electricity system is the development of energy storage systems with adequate installed power and storage capacity.

Specifically, PHS is expected to provide a guaranteed storage capacity of 16.5 GWh in 2030, increasing to 66.8 GWh in 2050. Over the same period, BESS are projected to increase their guaranteed storage capacity from 11.0 GWh to 31.3 GWh. Consequently, the total guaranteed storage capacity is anticipated to rise from 27.5 GWh in 2030 to 98.1 GWh in 2050. Regarding absorption capacity, PHS installations are projected to increase from 1.93 GW in 2030 to 5.45 GW in 2050, while BESS capacity is expected to rise from 4.33 GW to 12.03 GW over the same period. Overall, total absorption capacity is forecast to expand from 6.26 GW in 2030 to 17.48 GW in 2050.

Regarding the domestic production and utilization of hydrogen and synthetic fuels, these technologies are expected to become technically and economically viable by 2040 (NECP, 2024).

The intraday and seasonal variation of load in the dispatched energy system is illustrated in Fig. 1 and 2, respectively, through diagrams depicting the characteristic "Duck Curve" profile, based on data obtained from the Regulatory Authority for Waste, Energy and Water (RAAEY, 2025; 2026). The Net Load Curve, defined as the residual system load remaining after the deduction of RES generation from total electricity demand, for a typical day in March 2026, is presented in Fig. 1.

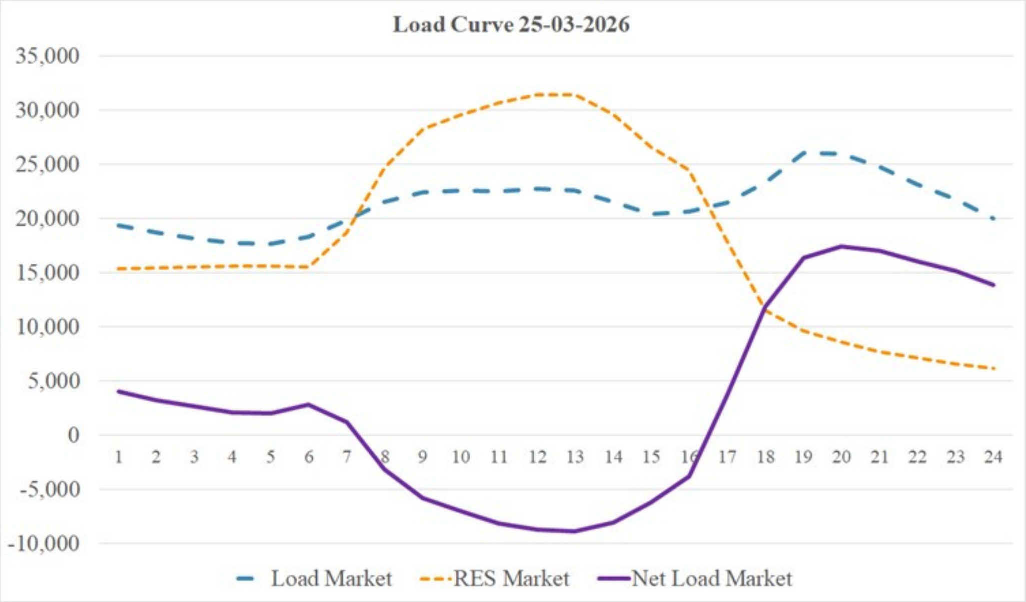


Fig. 1. Load profile on March 25th 2026 (RAAEY, 2026)

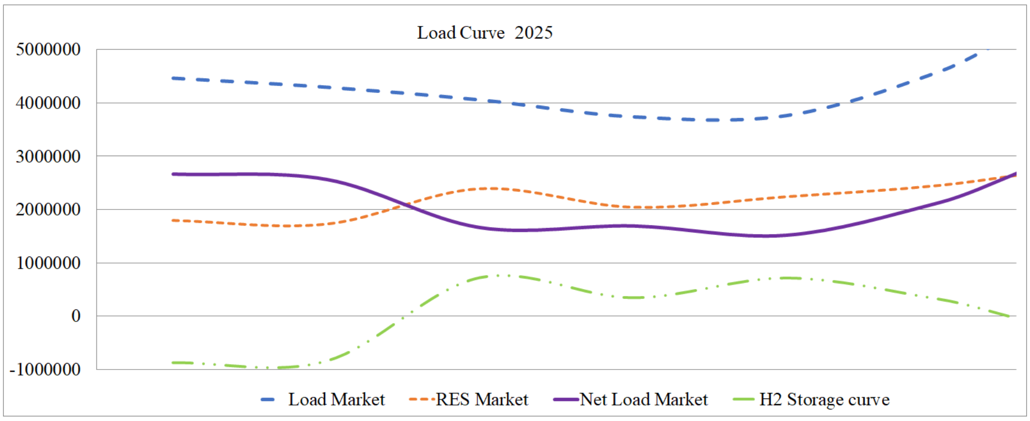


Fig. 2. Annual Load Curve & hypothetical hydrogen storage (RAAEY, 2025)

1.2.2 Implementation of energy storage infrastructure

By the first quarter of 2026, 97 PHS projects and 1,657 BESS projects had been licensed, corresponding to potential guaranteed usable capacities of 121 GWh and 144 GWh, respectively, as well as maximum absorption capacities of 14 GW and 58 GW. These licenses remain valid until the period 2044–2051.

Regarding PHS, major projects are under development, including the Amfilochia power station in Western Greece. The facility is expected to have an installed generation capacity of 680 MW, a pumping capacity of 730 MW, and an annual electricity generation potential of 816 GWh.

Moreover, three competitive tenders for the investment and operational support of BESS were completed during the period 2023–2025, promoting 32 BESS projects under the framework established by the Energy Branch of RAAEY. (RAAEY, 2026).

Regarding LDES, three HVs are currently planned in Greece: (i) TRIERES, located in the Peloponnese region, with an anticipated annual hydrogen production of 4,500 tH_2; (ii) North 1, situated in Western Macedonia, with an expected annual production of 6,500 tH_2; and (iii)

CRAVE-H_2CRETE, located in South Crete, with a projected annual production of 500 tH_2. All three projects are expected to support energy-sector end-use applications, whereas the North 1 project does not include transport and distribution activities within its scope.

1.2.2.1 Participation in the day-ahead market, intraday and the balancing market

BESS play a critical role in the Greek power system since they have been officially permitted to participate in the Greek electricity markets (Day-Ahead, Intraday, and Balancing Market). In April 2026, two BESS projects began operating under an Operational Support Contract, while the first battery-based electricity energy storage project commenced operation under market conditions without operational support (DAPEEP, 2026).

2. Methodological approach

According to the international standard ISO 14040:2006, the LCA methodology consists of four main phases: (i) goal and scope definition; (ii) inventory analysis; (iii) impact assessment; and (iv) interpretation (ISO 14040:2006, 2006). LCA is considered a systematic and analytical methodology that facilitates the identification, evaluation, and minimization of the environmental impacts associated with the entire life cycle of a product or system, such as the electricity sector. Furthermore, the methodology is replicable for future research activities.

As mentioned above, the principal aim of the present study was to assess the environmental performance of the energy storage technologies and scenarios included in the Greek NECP. Based on these scenarios, ten LCA scenarios were developed and evaluated in order to examine the realistic implementation of energy storage technologies in 2030, 2035, and 2050 using the SimaPro software tool. The year 2035 was selected as an intermediate assessment year for the evaluation of electricity generation through hydrogen combustion, since, according to the NECP, hydrogen-based energy scenarios are expected to reach technological maturity around 2040. The selected scenarios concern: i) PHS, which is expected to remain an established technology in future energy systems; ii) battery storage, specifically Li-ion batteries, as an evolving storage technology; iii) the production and utilization of green hydrogen, namely hydrogen produced through the electrolysis of water using electricity produced by RES, as a mitigation approach for addressing seasonal variability.

The energy output of the PHS and BESS projects was assumed to correspond to 30% of their total storage capacity, while charging was considered to be supplied exclusively by the renewable share of the electricity mix, in line with NECP projections. The selected functional unit (i.e., the reference unit for the calculation of results) was defined as "1 kWh of electricity delivered by the aforementioned energy storage systems". A cradle-to-grave approach was applied, encompassing all stages from raw material extraction and manufacturing to the use phase and end-of-life management. Regarding the end-of-life phase, complete recycling of raw materials was assumed. In the case of PHS, the end-of-life phase of major structural components, such as the dam and the water conveyance pipeline were not included in the study. This assumption is commonly adopted in the literature (Simon et al., 2023; Zhang et al., 2023). Furthermore, operational lifetimes of up to 100 or 150 years have been reported for PHS facilities (Immendoerfer et al., 2017; International Hydropower Association, 2020), whereas the present study adopted a comparatively conservative operational lifetime of 50 years for the PHS facility (PPC, 2026). In addition, PHS infrastructure components may be repurposed for secondary or alternative applications following decommissioning (de Almeida et al., 2017). Accordingly, the present study adopted an optimistic assumption regarding the potential reuse and recycling of PHS infrastructure components.

In the present study, the authors also adopted an optimistic assumption regarding the full recycling of materials associated with BESS systems and hydrogen infrastructure. This assumption was intended to reflect the anticipated recycling efficiencies at the end of the technologies' useful lifetimes (2030–2050), while also aligning with current European circular economy regulatory frameworks. In particular, European Regulation 2023/1542 stipulates that, by no later than 2030, recycling processes for lithium-based batteries should achieve a minimum recycling efficiency of 70% by average weight. For BESS, relatively short replacement cycles were assumed in order to reflect the possibility that battery systems operating under Mediterranean climatic conditions may experience accelerated degradation (Apribowo et al., 2022; Collath et al., 2022). Furthermore, a mean electricity output corresponding to 30% of the installed storage capacity was assumed, implying comparatively moderate utilization rates throughout the operational lifetime.

According to the NECP, total net electricity generation in 2030 is projected to reach approximately 60,400 GWh, of which less than 19% is expected to be derived from fossil fuels. In parallel, the combined storage capacity of Pumped Hydro Storage (PHS) and Battery Energy Storage Systems (BESS) is projected to reach 27.5 GWh. In the present study, the annual energy output of both the PHS and BESS installations was conservatively assumed to correspond to a maximum of 30% of their combined storage capacity, equivalent to 8.25 GWh, or approximately 3,000 GWh annually in 2030. Considering that RES curtailment within the interconnected Greek power system had already reached approximately 2,170 GWh during the 12-month period between May 2025 and April 2026 (IPTO, 2026), it is assumed that RES curtailment levels in 2030 will likely exceed the threshold of 3,000 GWh.

The modeling of the technologies and systems, including raw materials, processes, and energy flows, was carried out using the ecoinvent v3.9.1 Life Cycle Inventory database (Wernet et al., 2016), under the "cut-off" approach. This system model is widely applied in LCA studies and facilitates comparability with previous research, in which it often constitutes the only available modelling approach (Saade et al., 2019). Under this approach, burdens associated with waste are fully allocated to the producer, while no environmental credit is assigned for the recycling of materials. As a result, recyclable materials are considered "burden-free" whereas recycled materials bear only the environmental impacts associated with the recycling process itself. The ecoinvent datasets were appropriately modified where necessary, particularly with respect to the projected electricity generation mix for 2030 and 2050. In cases where data were unavailable, information from the international literature was adopted, together with assumptions and methodological approximations, which are described separately for each case below.

The environmental impacts were evaluated according to the ReCiPe 2016 v1.08 Midpoint and Endpoint methodology (Huijbregts et al., 2017), which includes 18 Midpoint impact categories and 3 Endpoint areas of protection (Schumacher et al., 2016).

The ReCiPe methodology can generally be applied under three alternative perspectives. Specifically, it incorporates three categories of "cultural perspectives," which reflect subjective approaches regarding the duration and severity of environmental impacts. These are: i) the Individualist (I) perspective; ii) the Hierarchist (H) perspective; and iii) the Egalitarian I perspective. Among these, the Hierarchist (H) perspective is the most commonly applied. It is based on: i) maintaining a balance between short-term and long-term time horizons; ii) the assumption that the implementation of appropriate policies can lead to positive outcomes; and iii) the inclusion of parameters and assumptions grounded in scientific consensus.

All calculations in the present study were conducted using the Hierarchist cultural perspective, as it constitutes the default approach applied in LCA studies. Unlike the Individualist and Egalitarian perspectives, which are characterized by optimistic and highly precautionary assumptions respectively, the Hierarchist perspective provides a balanced and policy-oriented framework. Furthermore, the medium-term orientation of the Hierarchist perspective is aligned with the temporal framework of the NECP, upon which the scenarios examined in the present work are based.

The contribution of each resource use or pollutant emission (e.g., particulate matter, water consumption, etc.) to the overall environmental impact was calculated through characterization factors for each impact category, followed by their aggregation and weighting into three final Endpoint impact categories: human health, ecosystems, and resource availability). The outcomes presented are based, on assumptions and methodological approaches derived from the literature as well as the ecoinvent Life Cycle Inventory database (Wernet et al., 2016), whose datasets constitute a widely recognized and validated database for LCA studies.

2.1 Scenarios for PHS

For the evaluation of the PHS scenarios, the operation of a representative PHS facility was modeled based on data derived from international literature (Singal et al., 2023; Trani et al., 2015; Quaranta et al., 2023; Kapila et al., 2019), in combination with project-specific parameters concerning raw materials, construction processes, and infrastructure, obtained from the Environmental Impact Assessment (EIA) of the PHS project located at the Megalopolis mine in the region of Arcadia in Peloponnese (PPC, 2026). The project lifetime was assumed to be 50 years, the energy output of the project was assumed to correspond to 30% of the storage capacity and the overall round-trip efficiency was assumed to be 72%. (RAAEY, 2026).

2.2 Scenarios for Li-ion batteries

The scenarios were developed for two types of batteries based on relevant literature (Komesse et al., 2024; Desideri et al., 2012; Hegedić et al., 2016) along with data provided in the technical datasheet of the commercial solution "evesco ES-10002000S" (EVESCO, 2021). The operation of a representative BESS was modeled according to the technical specifications included in the Environmental Terms Approval Decision for the project entitled "Three battery storage stations with a nominal power of 250 MW, storage capacity of 750 MWh, and a 33/400 kV Medium Voltage–Extra High Voltage Substation at the location Alepotrypes, Municipality of Amfikleia-Elateia, Region of Central Greece." (YPEN, 2026). The overall round-trip efficiency of the system was assumed to be 82% (RAAEY, 2026), while the energy output of the project was considered to correspond to 30% of the total storage capacity.

The project lifetime for each implemented BESS was assumed to be 20 years for both battery technologies. The operational lifetime of Li-ion LFP batteries was assumed to be 10 years, corresponding to one replacement over the project lifetime, whereas the operational lifetime of Li-ion NMC batteries was assumed to be 5 years, corresponding to three replacements over the project lifetime. The replacement of infrastructure components over the project lifetime was taken into consideration in the environmental assessment and evaluation of each project.

The relatively short replacement cycles considered reflect the possibility that battery systems operating under Mediterranean climatic conditions may experience accelerated degradation. Such conditions are characterized by elevated ambient temperatures, increased humidity, dust accumulation, and salt exposure, all of which may adversely affect battery performance and operational lifespan. In addition, extreme operating conditions, including the severe heatwaves frequently observed in Greece, may increase the risk of catastrophic failures and thermal runaway incidents (Apribowo et al., 2022; Collath et al., 2022). The replacement cycle adopted in the present study is therefore considered by the authors to be realistic, whereas also NMC batteries typically withstand approximately half the charge–discharge cycles of LFP batteries.

2.3 Scenarios for hydrogen production and combustion scenarios

The modeling of the hydrogen production unit and the calculation of the corresponding scenarios were based on the international literature (Hoppe and Minke, 2025; Sabu et al., 2024; Ajeeb et al., 2024). The operation of a representative hydrogen production facility was modeled according to the Environmental Terms Approval Decision concerning the installation and operation of an electrolytic hydrogen production unit with an annual production capacity of 15,500 tonnes and electricity consumption capacity of 100 MW. The facility is planned to be installed within the former Amyntaio–Filotas Lignite Power Plant, within the boundaries of the Municipal Unit of Filotas, Municipality of Amyntaio, Regional Unit of Florina, and the Municipal Unit of Vermio, Municipality of Eordaia, Regional Unit of Kozani, in the Region of Western Macedonia. More specifically, the operation of a "green" hydrogen production unit based on alkaline water electrolysis was presumed, with a capacity of 100 MW (Power-to-Gas), a maximum annual electrolytic hydrogen production of 15,500 tonnes, and an annual operating duration of 5,000 hours (YPEN, 2026).

The following assumptions and methodological approaches were applied: i) the project lifetime was assumed to be 20 years, whereas the lifetime of the individual system components was adopted from the aforementioned literature; ii) for hydrogen combustion, a fuel mixture scenario consisting of 50% hydrogen and 50% natural gas was considered; iii) the thermoelectric power plant was modeled using a predefined dataset from the ecoinvent Life Cycle Inventory database (Wernet et al., 2016), whereas the final environmental impact associated with electricity generation from hydrogen combustion was determined through an appropriate allocation of the total environmental burden between hydrogen and natural gas.

3. Results and discussion

The LCA of energy storage technologies was implemented through ten scenarios for the years 2030, 2035 and 2050 using the SimaPro software tool. The technologies examined included PHS, BESS and green hydrogen production, and electricity generation from hydrogen combustion. The investigation of energy storage within future decarbonization scenarios for the Greek economy led to the following findings.

In the case of PHS, the electricity supplied to the pumped-storage plant constitutes the largest contributor to environmental impacts across all impact categories. In contrast, for BESS, the infrastructure itself represents the primary contributor to the overall environmental impact in the majority of impact categories. A comparison between the principal PHS and BESS scenarios at the Midpoint impact level (Fig. 3), indicates that PHS results in lower environmental impacts across all impact categories for both 2030 and 2050. With respect to the global warming impact category, PHS exhibits a 17%~20% lower environmental impact compared to battery storage systems. In 2030, BESS consistently exhibit higher impacts in specific Midpoint categories, such as mineral resource depletion, ecotoxicity, and eutrophication, compared with the electricity generation mix, mainly due to the proportionally higher consumption of raw materials. In 2050, as the share of RES in the electricity generation mix increases, energy storage systems are associated with comparatively higher CO_2eq emissions. Similarly, storage technologies exhibit elevated impacts across the majority of Midpoint impact categories, including eutrophication, ecotoxicity, mineral resource scarcity, and water consumption.

In the hydrogen production scenarios for 2030 and 2050 (Fig. 5), electricity consumption was identified as the dominant contributor to the overall environmental impact of hydrogen production across all impact categories. In contrast, during electricity generation through hydrogen combustion, the environmental impact was primarily attributed to hydrogen itself, with the exception of one of the 18 Midpoint impact categories, namely water consumption (Fig. 6).

At the Endpoint level, namely human health, ecosystems and resource availability, the comparison of storage technologies for the year 2030 indicates that BESS consistently exhibit the highest environmental impacts across all categories, in agreement with the Midpoint-level results. Conversely, PHS demonstrates the lowest environmental impact. Similar results are observed for 2050, during which the environmental impact of BESS remains higher, even compared with that of the electricity generation mix itself. Those results are derived from Fig. 4 and 7.

The production and utilization of hydrogen and synthetic fuels are projected to become technically and economically viable by 2040, according to the NECP Consequently, a scenario for hydrogen production in 2030, was followed by a separate scenario for hydrogen combustion in 2035. No direct comparison between hydrogen storage and either BESS or PHS technologies was performed for 2030, as hydrogen storage is not expected to reach commercial viability by that time. In contrast, for 2050, all three technologies were comparatively assessed exclusively at the endpoint level in terms of the three-endpoint level environmental impacts (human health, ecosystems, and resource availability) as presented in Fig. 7, complementing the 2050 results illustrated in Fig. 4.

Among the examined technologies, PHS, exhibits the lowest environmental impact across all scenarios. In addition, the production and combustion of green hydrogen result in lower environmental impacts than BESS at the Endpoint level across all impact categories in the 2050 scenario. Although the observed reduction is generally limited to an average of approximately 16%, hydrogen production and combustion under on-site capture and utilization configurations can achieve environmental impact reductions of up to 28% (Fig. 7).

Regarding the results expressed in absolute values, a general agreement with the international literature is observed. Nevertheless, the results reported in each individual study depend on parameters such as technology components and raw materials, the electricity generation mix, geographical location, as well as case-specific assumptions and methodological approaches, all of which may vary significantly among studies. More specifically, with regard to the midpoint Global Warming Potential (GWP) impact category:

1) Concerning PHS, the international literature reports values ranging from 58 to 530 gCO_2eq/kWh of delivered electricity, with this variation being mainly attributed to the electricity generation mix assumed for charging the storage systems (Simon et al., 2023; Kapila et al., 2019; Zhang et al., 2023). In the present analysis, the corresponding values were estimated at 61.5 and 55.5 gCO_2eq/kWh for 2030 and 2050, respectively.
2) Regarding Li-ion BESS, values reported in the literature range indicatively from 49 to 810 gCO_2eq/kWh (Jasper et al., 2026; Li et al., 2024; Hiremath et al., 2015). In this case as well, the electricity generation mix and the operational profile of the storage systems play a decisive role. In the present study, the resulting values

ranged from 90.3 to 95.6 gCO$_2$eq/kWh in 2030 and from 85.0 to 90.3 gCO$_2$eq/kWh in 2050, depending on the battery type (LFP or NMC).

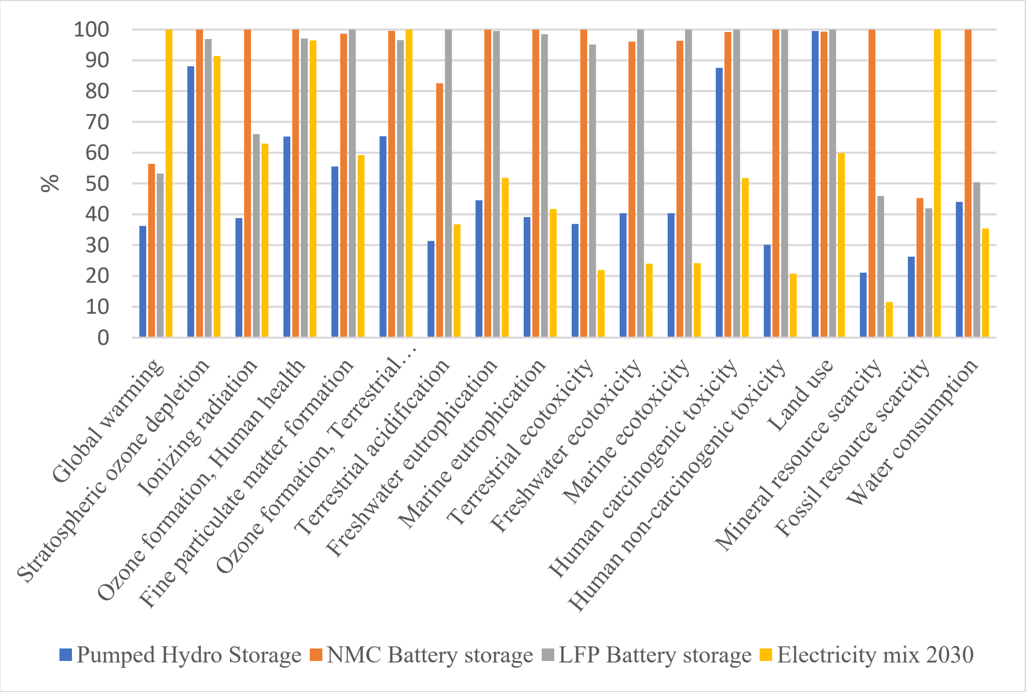
3) Regarding energy production through the combustion of green hydrogen in combination with natural gas, the environmental impact associated with the global warming category corresponds to 85.5 gCO$_2$eq/kWh for 2050, which is close to the resulting values for Li-ion BESS systems.

4) With respect to green hydrogen, the literature reports values ranging from 33 to 2,890 gCO$_2$eq/kgH$_2$ (Ajeeb et al., 2024; Sabu et al., 2024). The results of the present study indicate environmental impacts equal to 1,880 gCO$_2$eq/kgH$_2$ for 2030 and 1,660 gCO$_2$eq/kgH$_2$ for 2050.

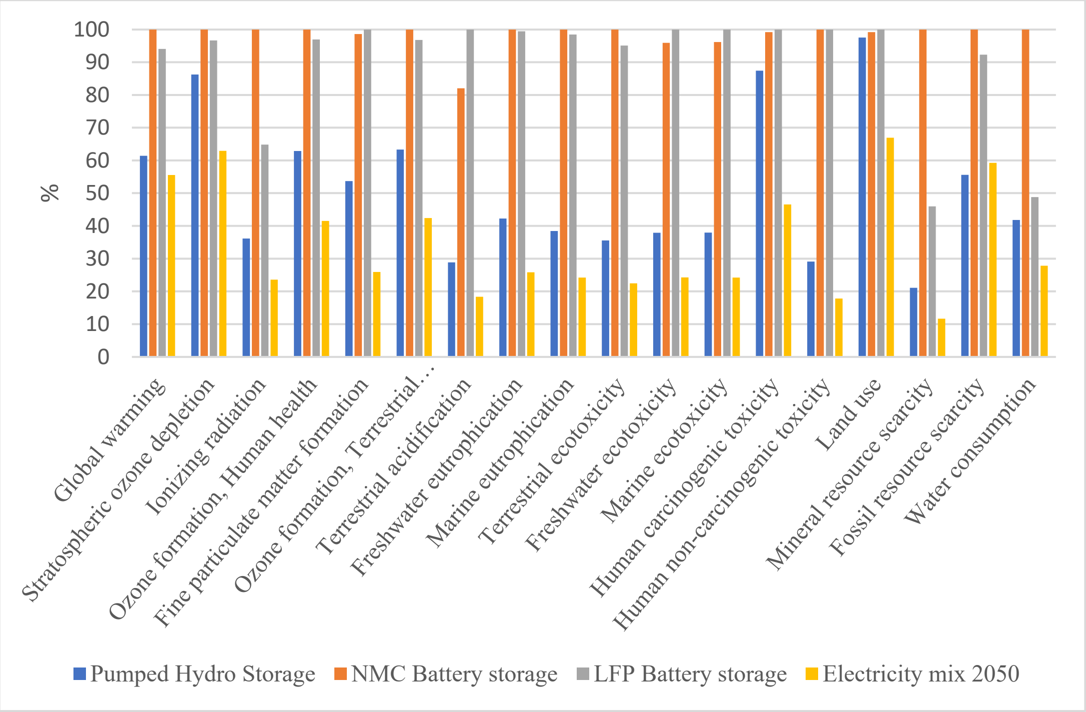
The pathways for achieving the targets related to climate change mitigation have been established through the NECP. These targets include the deployment of energy storage through PHS and BESS, with projected installed capacities of 5.4 GW and 12 GW by 2050, respectively. Due to the stochastic nature of RES, particularly wind and solar energy, electricity systems based exclusively on RES cannot ensure reliability.

In addition to the variability in resource availability, the management of energy flows and the protection of the supply–demand balance render the integration of RES into the electricity grid highly demanding. Energy storage is therefore considered essential for establishment flexibility, stability, and reliability within the energy system. Furthermore, it is decisive for ensuring security of supply, facilitating energy system integration, and supporting sustainable electrification. In particular, the role of LDES has been recognized as critical for achieving regional energy autonomy.

The prospects for the examined energy storage technologies appear promising due to the recent developments related to the deployment of BESS facilities supported through operational and investment subsidizing schemes. In addition, although the global development of green hydrogen continues to rely predominantly on public–private financing mechanisms and policy support measures (Risse et al., 2026), the planned development of relevant infrastructure through national HVs, together with the findings of the present work, enhance the prospects for the introduction of green hydrogen in future decarbonization scenarios. Within this context, the proven technological option of PHS constitutes a supportive solution for future energy transition pathways.

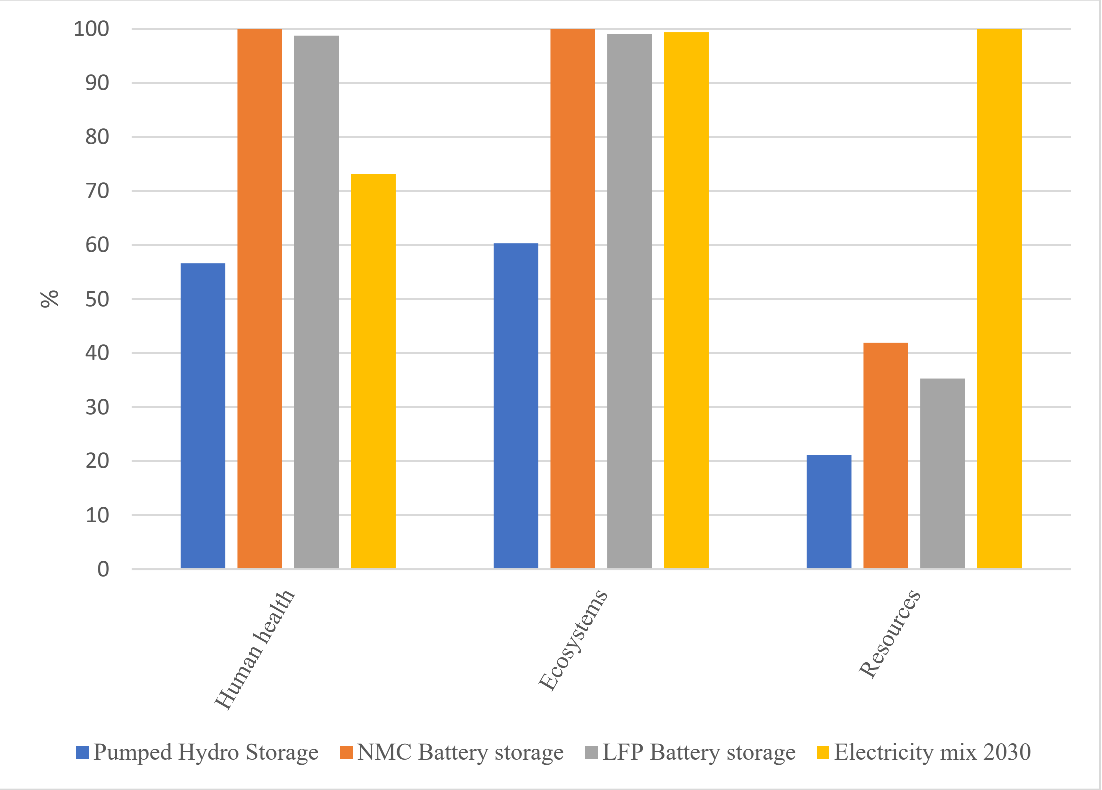


(a) 1 kWh 2030 – Midpoint level

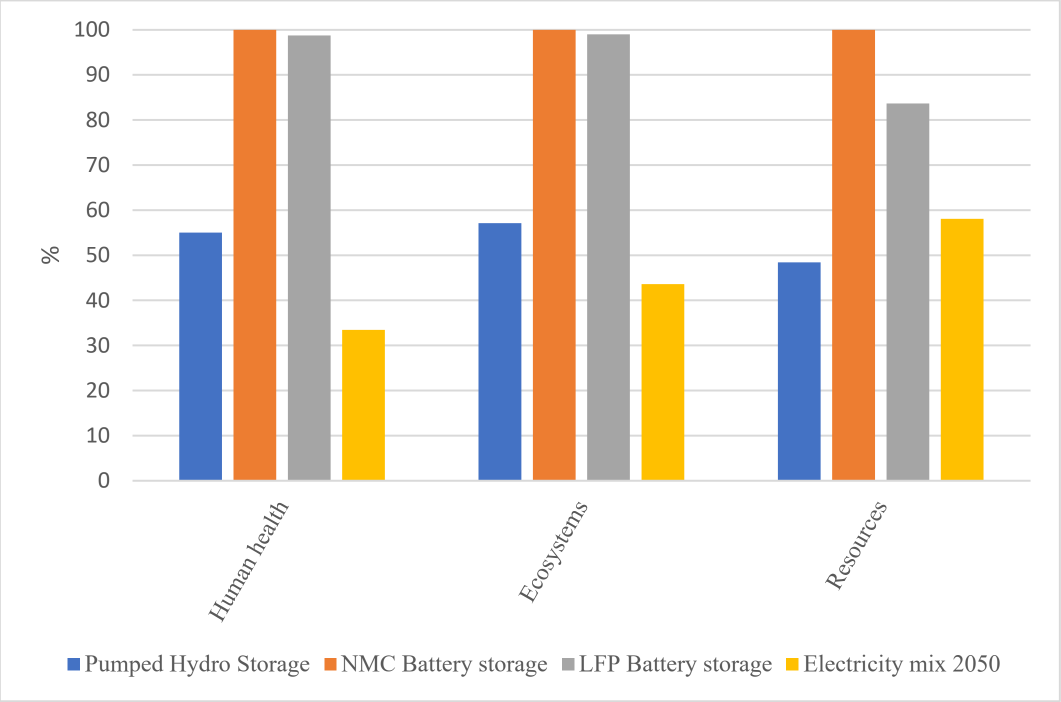


(b) 1 kWh 2050 – Midpoint level

Fig. 3. Comparison of main scenarios at Midpoint level

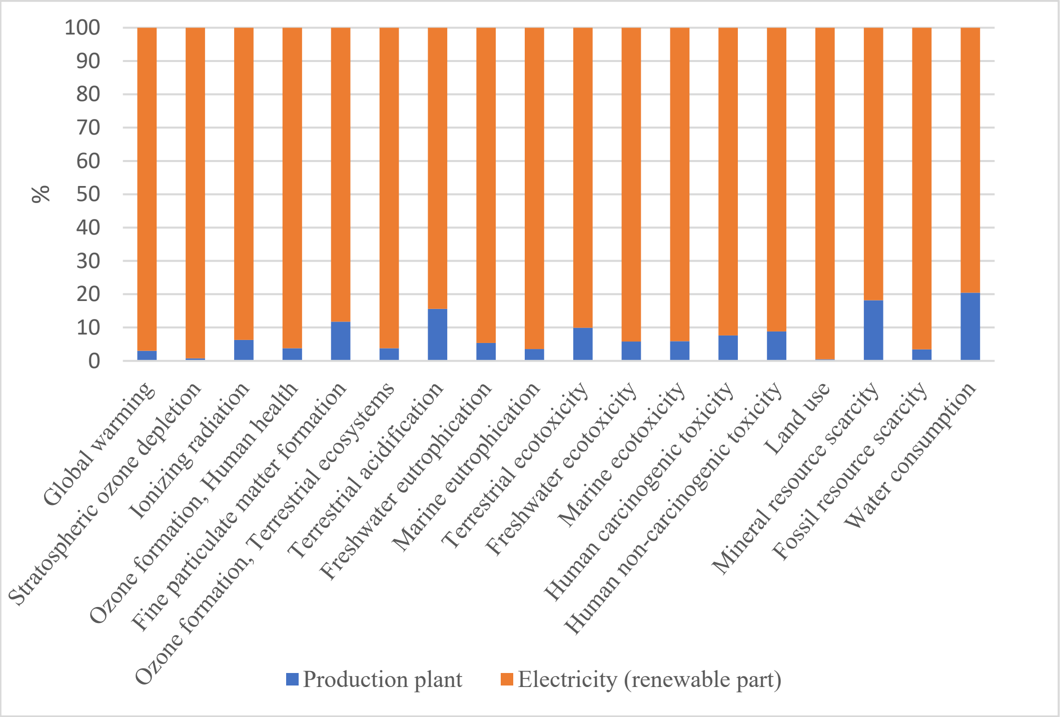


(a) 1 kWh 2030 – Endpoint level

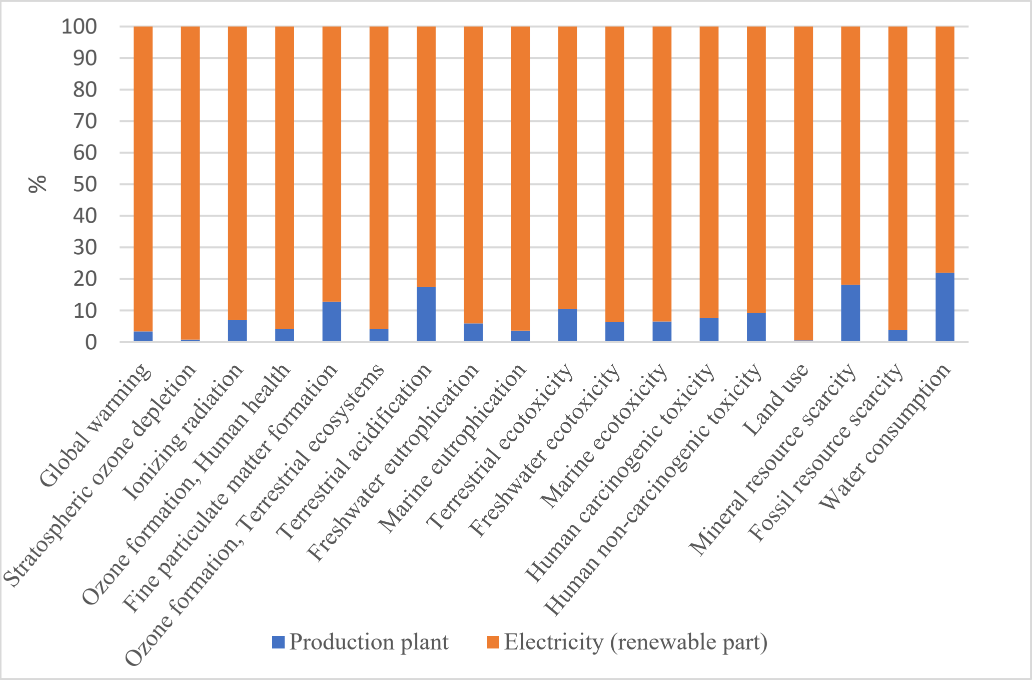


(b) 1 kWh 2050 – Endpoint level

Fig. 4. Comparison of main scenarios at Endpoint level

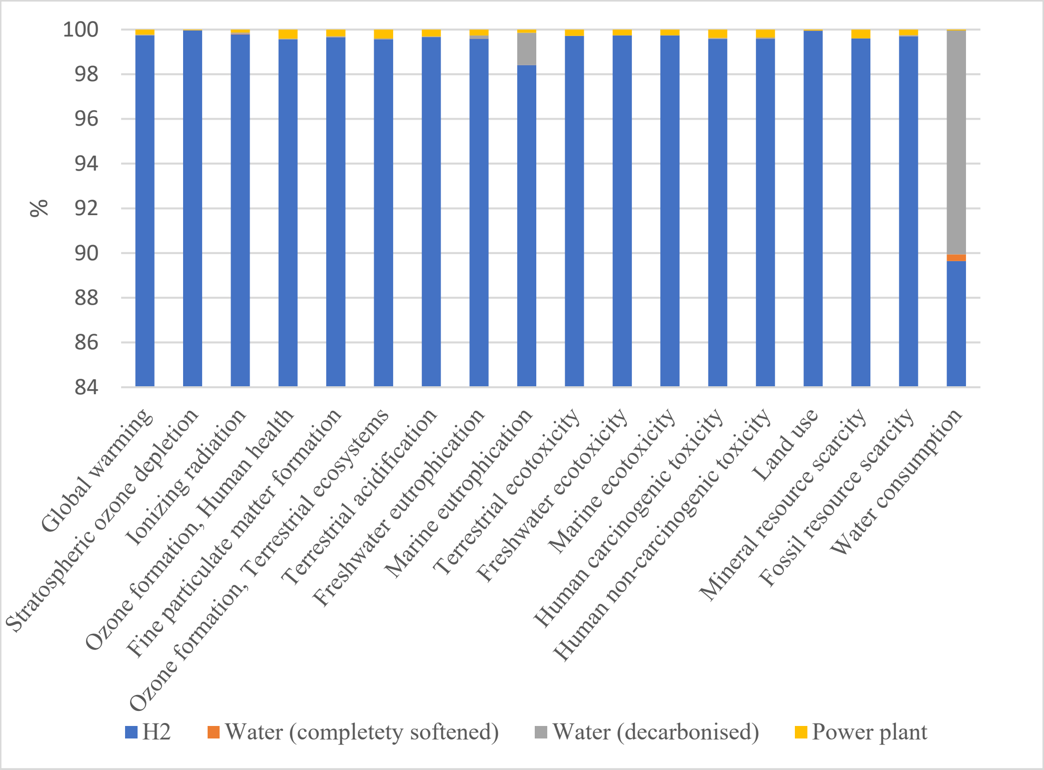


(a) Hydrogen production in 2030

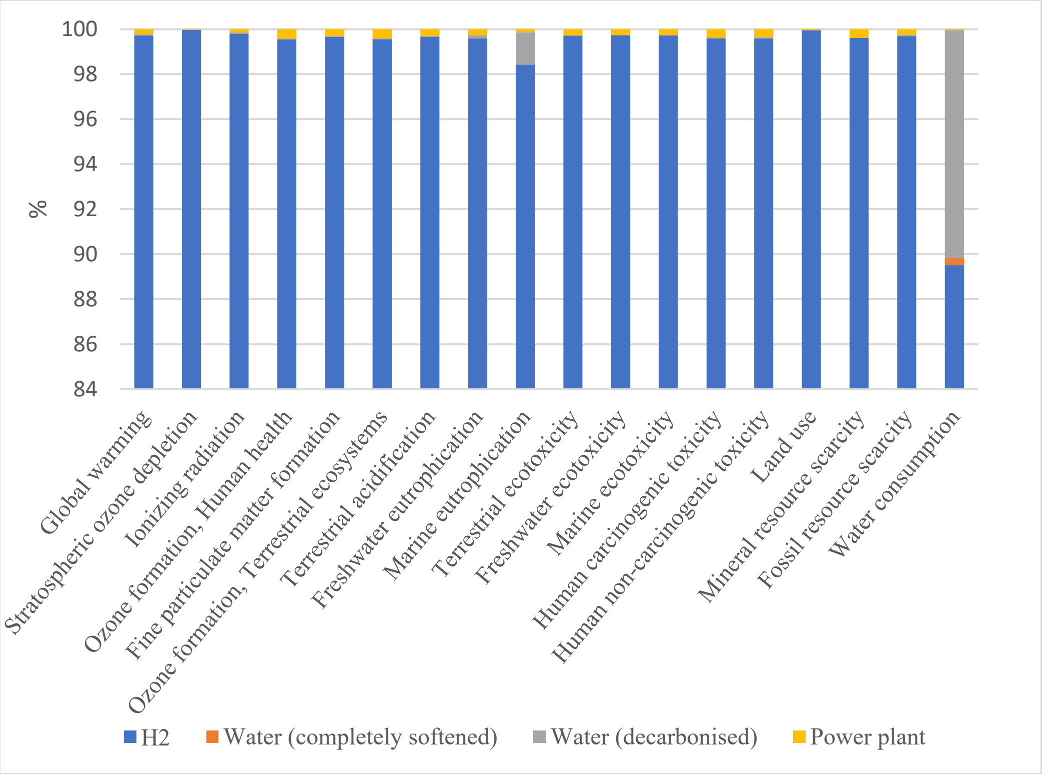


(b) Hydrogen production in 2050

Fig. 5. Modelling hydrogen production

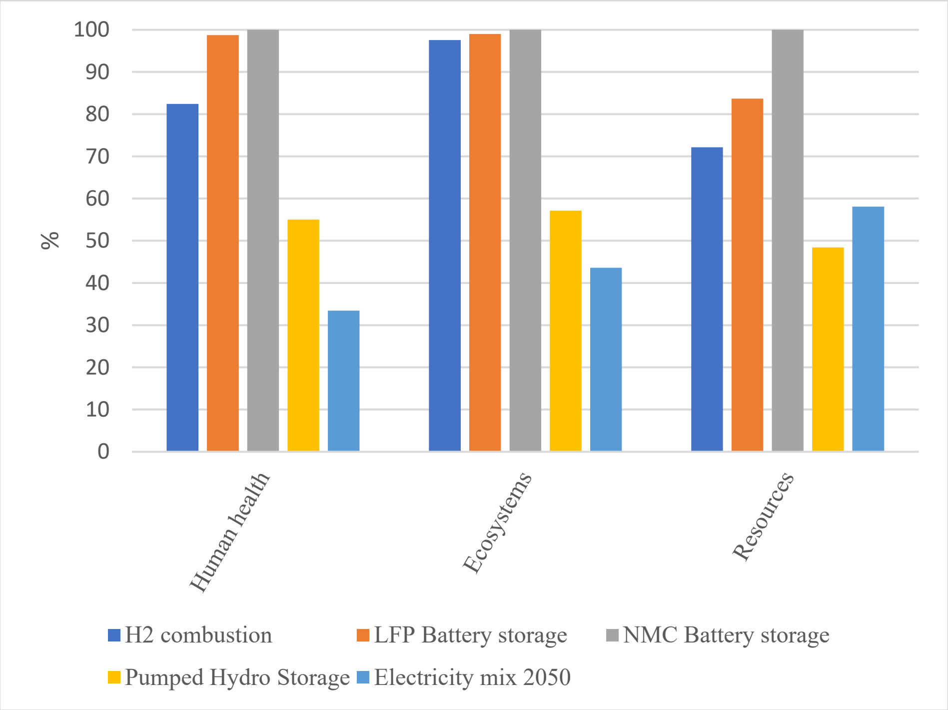


(a) Energy generation from hydrogen combustion 2035



(b) Energy generation through hydrogen combustion 2050

Fig. 6. Modelling energy production from hydrogen combustion



1 kWh 2050 –Endpoint level

Fig. 7. Comparison of Storage Technologies at Endpoint level

4. Conclusions

Numerous countries currently face more severe decarbonization challenges than others. In a country such as Greece, which is geographically fragmented and has historically relied on domestic lignite resources, the transition toward energy security can be strengthened through the decarbonization of the electricity sector by means of an optimized combination of energy storage systems.

The Life Cycle Assessment (LCA) conducted in the present study for Pumped Hydro Storage (PHS), Battery Energy Storage Systems (BESS) and green hydrogen, for the years 2030 and 2050 concludes that the combined deployment of all three examined technologies can provide complementary operational characteristics capable of maintaining the reliability of the national power system under future energy scenarios. PHS continues to demonstrate the lowest environmental impact among the examined technologies and can therefore remain a key pathway toward the deep decarbonization of the electricity sector. BESS can also play a significant role in facilitating the dispatch of variable RES. Particularly nowadays, as their costs continue to decline, BESS technologies are becoming increasingly important for the decarbonization of the electricity sector. On the other hand, Long-Duration Energy Storage (LDES) is strategically important for the global energy transition. Green hydrogen is considered a reliable energy carrier and energy storage medium for achieving this objective. The present study demonstrates that green hydrogen can constitute a viable solution, particularly in light of the planned development of hydrogen Valleys (HVs) within the country. Its implementation may result in lower environmental impacts on human health, ecosystems, and resource availability compared with BESS.

The present work may serve as a replicable framework for regions worldwide facing similar challenges. Future research could include the development of detailed LDES scenarios encompassing hydrogen transport and distribution pathways, building upon the scenarios developed in the present study. Moreover, the incorporation of additional real operational and technical data from existing installations could enhance the realism and accuracy of the obtained results. Furthermore, the inclusion of additional storage technologies in future scenarios related to a country's decarbonization policy, even if such technologies are not integrated into the national planning framework, could contribute to the development of a more proactive and resilient decarbonization pathway.

Author Contributions

C-S.H.: conceptualization, methodology, writing, software validation; G.K.: methodology, writing, software; D.G: writing, reviewing; S.K.: conceptualization and editing; E.K.: supervision. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Not applicable

Conflict of interest

The authors declare no conflict of interest.

Use of AI and AI-assisted Technologies

During the preparation of this work, the authors used ChatGPT to proofread and edit the grammar and syntax of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery Energy Storage Systems
CAES	Compressed Air Energy Storage
CO_2eq	Carbon dioxide equivalent
COP30	30th Conference of the Parties
DAM	Day-Ahead Market
e-fuels	Electro fuels
FB	Flow Batteries
FES	Flywheel Energy Storage
GES	Gravity Energy Storage
GHG	Greenhouse Gas Emissions
GWP	Global Warming Potential
H_2ESS	Hydrogen Energy Storage Systems
HSCs	Hybrid Supercapacitors
HVs	Hydrogen Valleys
IPTO	Independent Power Transmission Operator
LAES	Liquefied Air Energy Storage
LCA	Life Cycle Assessment
LDES	Long-Duration Energy Storage
LFP	Lithium Ferro Phosphate
LHS	Latent Heat Storage
NECP	National Energy and Climate Plan
NMC	Nickel Manganese Cobalt
RES	Renewable Energy Sources
PHS	Pumped Hydro Storage
SHS	Sensible Heat Storage
SMES	Superconducting Magnetic Energy Storage
SNG	Synthetic Natural Gas
TES	Thermochemical Energy Storage
TRL	Technology Readiness Level
TYNDP	Ten-Year Network Development Plan

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