Ovechkin, Natalya 2(2026). Lifecycle Environmental Impact Analysis of Emerging Energy Storage Technologies in the GCC Context. *SOLAV Journal*
https://solav.me/a/s2026781204

SOLAV Journal
A Scholarly Platform for Interdisciplinary Applied Futures Research
Publisher's Home Page: https://solav.me
Review Article Open Access

Lifecycle Environmental Impact Analysis of Emerging Energy Storage Technologies in the GCC Context

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Abstract
The high pace of the Gulf Cooperation Council (GCC) region renewable electricity expansion has increased the strategic significance of energy storage technologies that can stabilize grids that have a high level of solar penetration and severe climatic conditions. Although, the deployment objectives have improved, the eco-friendliness of storage technologies throughout lifecycle is not studied sufficiently on arid, high temperature, and water-limited environments. This paper is a structured lifecycle assessment (LCA) review of some of the emerging and scalable energy storage technologies applicable to the GCC including lithium-ion batteries, solid-state batteries, flow batteries, pumped hydro storage, compressed air energy storage, gravity storage, and green hydrogen-based storage systems. This review is based on the synthesis of peer-reviewed lifecycle data by the application of a cradle-to-grave analytical framework congruent with the ISO 14040/44 principles that present carbon intensity, material criticality, water dependency, land transformation, operational degradation at extreme heat, and end-of-life management pathways. Special attention is given to the role of regional specificity, the reliance on desalination, exposure to dust, and higher ambient temperatures, as well as centralized electricity markets, as the factors altering the environmental performance profiles. The analysis finds considerable trade-offs: electrochemical batteries have high upstream material and manufacturing costs, and have better modular scalability; mechanical storage opportunities have low material sensitivity, but have space and geologic limitations; H 2 -based storage has the potential to be used over the long term, but is still energy- and water-intensive. The research ends with a set of policy implications concerning sustainable deployment plans in accordance with the long-term goal of decarbonization in GCC.

Keywords
lifecycle assessment · energy storage · GCC · lithium-ion batteries · green hydrogen · pumped hydro storage · circular economy · environmental impact · decarbonization

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1. Introduction

The process of energy transition is becoming more worldwide as variable renewable energy (VRE) sources are integrated into the power systems traditionally designed to generate dispatchable power sources using fossil fuels. The development of solar photovoltaic and wind capacity means that the energy storage technologies have come to the center stage to stabilize energy grids, balance load in time, observe the reduction of CO2 in the electricity systems [1]. Although the benefits of renewable electricity in terms of the environment are generally accepted, lifecycle effects of the different storage technologies that facilitate the integration of renewable are more complicated and still controversial [2].

The Lifecycle assessment (LCA) has become the new domain of the predominant methodological approach towards quantification of the environmental load of energy systems extraction, manufacturing, operation, and end-of-life stages [3]. Through the prism of energy storage, LCAs show that extraction and manufacturing stages of upstream materials can in many cases form a large portion of greenhouse gas emissions and resource depletion effects, especially when it comes to lithium-ion battery technologies [4]. Storage Packaged mechanical storage (PHS) and compressed air energy storage (CAES) are typically less material-critical and can require extensive land conversion and construction emissions [5]. Hydrogen-based sources complicate this further because of the intensity of energy and the infrastructure needed in electrolysis [6].

Although increasing literature on the topic exists across the world, the majority of lifecycle studies have been undertaken in the European, North American, or East Asian context. Temperate climate, diversified electricity sources, and developed recycling systems therefore form the basis of environmental performance measurements. These generalizations do not always apply to the case of the Gulf Cooperation Council (GCC) region, where the climate and structural conditions are quite different.

Saudi Arabia, the United Arab Emirates, Qatar, Kuwait, Bahrain, and Oman in the GCC have a unique energy transition flow. Previously depending on hydrocarbon exports these economies are currently investing in the deployment of renewable electricity on a large scale to diversify the energy portfolio and achieve long-term decarbonization goals. The presence of high gamma solar radiation offers high potential of photovoltaic application, but extreme environmental temperature often surpassing 45degC, dust particles in the atmosphere, and reliance on desalinated water, present operation and environmental limitations causing possible changes in operation performance of storage devices.

Higher temperatures will hasten the degradation of batteries, limit round-trip efficiency, and raise cooling needs which may potentially increase, in direct operation terms, both the energy and the indirect emissions generated [7]. At the same time, mass hydrogen generation via water electrolysis makes water unavailable ecosystems worried because the basic desalination process is energy-consumptions by itself [6]. Mechanical storage is less sensitive to thermal degradation but it has to have site-specific geology which can be a limitation to its scalability.

The recent meta-analyses of lithium-ion battery LCAs state that the production-stage performance under 60 to 175 kg CO2-eq per kWh battery size, with 60-175 being the range, is dependent on chemistry and electricity mix [4]. Plastic recycling routes can substantially minimize these impacts, but recycling facilities around the world are unevenly spread [8]. In the case of pumped hydro storage, the lifecycle emissions of storing are usually smaller per unit kilowatt-hour delivered during longer lifetime of operation, but the initial construction has significant effects [5]. Storage systems using hydrogen exhibit considerable diversity in lifetime emissions, which highly depends on the carbon intensity of the electricity employed in the electrolysis process [6].

There are a number of knowledge gaps, which are critical within the GCC context:

1. In high-temperature operation and dependence of desalination Lifecycle data that is regionalized in nature are limited.
2. There has been a lack of comparative studies of different storage technologies with similar functional units.
3. No systematic evaluation has been carried out on the integration of considerations of the circular economy such as how recycling can be done even with developing industrial policies in the Gulf.
4. Policy-market relations which influence environmental optimization as subsidized electricity rates and state-controlled utility frameworks are often left to outside lifecycle debate.

Since the regional storage capacity is projected to increase rapidly in the coming decade, a mechanized comparative study based on the LCA methodology is required to guide policy development and technology prioritization. This paper serves this purpose by summarizing peer-reviewed evidence of lifecycle, and situating environmental trade-offs in the context of GCC-specific climatic and infrastructural environments.

This paper will achieve three things hence:

1. To conduct a systematic and comparative study of environmental effect of developing and established energy storage technologies on the environment on harmonized metrics;
2. To assess the impact of GCC-related environmental restrictions on performance outcomes;
3. To find strategic deployment paths that would be in accordance with the long-term sustainability and circular economy goals.

The subsequent paragraphs establish the conceptual basis of lifecycle assessment in energy storage systems, survey the field of understanding in major technology categories, set parameters of methodology to enable comparative analysis, and give implications pertinent to the policy-making in planning sustainable energy transition in arid areas.

2. Theoretical Framework: Lifecycle Assessment of Energy Storage Systems

2.1 Conceptual Foundations of Lifecycle Assessment

Lifecycle assessment (LCA) is a procedural design that offers a methodical level of focusing on the environmental consequences of products or energy systems of extractions of raw materials up to manufacturing, operation, and end-of-life procedures. Methological structure is standardized according to ISO 14040 and ISO 14044 and comprises four fundamental stages: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA) and (4) interpretation [9].

The LCA has been developed in energy system studies as a direct progression of comparative evaluations of electricity generation technologies and, more finely based analysis of enabling infrastructures like storage system [10]. Storage technologies to which unique methodological issues pertain since the environmental impact must be considered with respect to how much service is offered by the technology- functionality, energy shifting, grid stabilization, or long-duration backup including over sustainability- rather than pure capacity. Consequently, functional units and boundaries of systems have to be harmonized to prevent misleading comparisons [11].

Energy storage LCAs are typically conducted using a cradle-to-grave perspective, encompassing:

- Upstream material extraction and refining,
- Component manufacturing and assembly,
- Transportation,
- Operational performance over service life,
- Maintenance and replacement cycles,
- End-of-life recycling, recovery, or disposal.

Since the long-lived mechanical systems like pumped hydro storage (PHS) have many years of operation, results are often strongly affected by the assumption of the operational lifetimes, which can be very diluting to the emissions in the construction phase over decades of operation [12]. Conversely, electrochemical systems have shorter lives and a greater material intensity of a stored capacity, and as a ratio, they add more weight to the upstream phases [4].

2.2 Functional Unit Definition

A critical methodological issue in comparative storage LCAs is the selection of the functional unit. Studies variously employ:

- kg CO_2-eq per kWh of installed capacity,
- kg CO_2-eq per kWh delivered over lifetime,
- kg CO_2-eq per MW of power rating,
- Impacts per cycle.

Installed-capacity-based metrics can obscure performance degradation and cycle frequency differences.

Consequently, this study adopts:

1 MWh of electricity delivered over the operational lifetime of the storage system

as the harmonized functional unit.

This methodology combines round-trip efficiency (RTE), rates of degradation, and cycle life in lifecycle performance assessment [13]. As an illustration, lithium-ion batteries would be characterized by RTE of 85-95 percent or hydrogen-based storage could be lower than 40 percent when electrolysis and reconversion losses are considered [6]. Mechanical storage technologies like PHS and CAES usually vary between 70-85 percent as the set up [14].

The analysis of operational efficiency penalties, which can be aggravated in GCC conditions of a high temperature, is normalized by the impacts per unit of delivered MWh.

2.3 System Boundary Delimitation

Figure 1 presents the conceptual system boundary adopted for this review.

Figure 1 Figure 1. Cradle-to-Grave System Boundary for Energy Storage Technologies (Conceptual Model)

The boundary includes:

1. **Upstream Processes** - lithium mining, cobalt mining, nickel mining, vanadium mining, steel manufacturing, concrete manufacturing, and the material of membranes.
2. **Manufacturing and Construction** - construction of battery cells, making of turbine, building of reservoirs, building electrolysis stacks.
3. **Transportation** - international supply chains, specifically in the case of imported critical minerals.

4. **Operation Phase** - efficiency wastage, auxiliary cooling, replacement due to degradation.
5. **End-of-Life and Description (EoL)** -recycling, land fill discarding, metal recovery, or cavern decommissioning.

There are also other excluded processes such as: indirect grid transformation effects and macroeconomic rebound effects which cannot be incorporated into product-level LCA.

2.4 Impact Categories

Although the scale of global warming potential (GWP, kg CO2-eq) is the most commonly reported indicator when performing a storage LCA, the use of one indicator could lead to biases [15]. In this review, five main dimensions of impact are taken into account:

1. Global Warming Potential (GWP100)
2. Cumulative Energy Demand (CED)
3. Mineral Resource Scarcity / Abiotic Depletion
4. Water Consumption
5. Land Use Transformation

Lithium, cobalt, and nickel work are often cited by battery LCAs as an overwhelming reason because mineral depletion has been reported [8]. Electrolysis requires lots of water in hydrogen systems [6]. Mechanical storage can be less critical of minerals yet greater land use [12].

Considering the water shortage in the GCC and the sensitivity of the land-use in the coastal regions and deserts, multi-indicator assessment is a necessity.

2.5 Lifecycle Inventory Data Sources and Harmonization.

This has been reviewed solely based on secondary data that is peer-reviewed and meta-analyses. Numerous reports describe a high variance in reported battery production emissions, mainly because of variations in:

- Electricity mix assumptions,
- Manufacturing location,
- Cell chemistry (NMC, LFP, solid-state),
- Allocation approaches,
- Recycling credits [4], [8].

To reduce inconsistency, this study adopts:

- Midpoint values from meta-analyses where available,
- Electricity mix sensitivity ranges,
- Explicit reporting of uncertainty bands.

In the case of hydrogen storage, lifecycle emissions are conditionally on the election of electricity in the course of electrolysis [6]. In the case where it is assumed that we use renewable electricity, the operational emissions are the same as near-zero, but the embodied infrastructure emissions are also large [16].

2.6 Degradation of operation in excessive temperatures.

The phenomenon of electrolyte interphase (SEI) growth and Lithium plating are enhanced by high ambient temperature, which enhances battery degradation [7]. Through empirical evidence, it has also been established that temperatures too high like 10-15degC beyond the optimum levels may seriously decrease the life of the cycle [17].

Ambient temperatures in the summer in the GCC region often rise above the recommended operational temperatures in lithium-ion batteries (20-25degC). Cooling mechanisms then become necessary, consuming additional parasitic energy and to an indirect degree increment of lifecycle emissions divided by delivered MWh. Mechanical storage systems also lose some thermal sensitivity, but compressor and turbine efficiency might decrease slightly during extreme heat [14].

The most common way that hydrogen storage systems are influenced is by loss of efficiency of electrolysis at high operating temperatures, although other advanced electrolyzes may be run at high temperatures on purpose (e.g., solid oxide systems) [18].

2.7 End-of-Life and Circular Economy Considerations

End-of-life (EoL) management has a tremendous effect on the lifecycle outcomes. The recycling of the lithium-ion batteries is capable of decreasing the total GWP by 1040 percent depending on the recovery rate and the prevention of virgin materials [19]. Nevertheless, recycling facilities are geographically located.

Mechanical storage systems are less complex to use in respect of the EoL; they do require massive infrastructure decommissioning and land reclamation. Composite tanks, membrane materials, must be handled safely in hydrogen systems.

The integration of the circular economy into GCC is still in its initial phases; therefore, existing lifecycle outcomes should be viewed within the context of small capacities of local recycling.

3. Overview of Energy Storage Technology Classes

Energy storage technologies can be categorized into three principal classes:

1. **Electrochemical Storage**
   - Lithium-ion batteries
   - Solid-state batteries
   - Flow batteries
2. **Mechanical Storage**
   - Pumped hydro storage (PHS)
   - Compressed air energy storage (CAES)
   - Gravity-based storage
3. **Chemical Storage**
   - Hydrogen production and reconversion systems

All categories have unique environmental burden profiles and appropriateness features in GCC climatic conditions. In the next part, the lifecycle evidence of each technology category will be reviewed in a systematic manner, starting with the electrochemical systems.

4. Electrochemical Energy Storage Technologies: Comparative Lifecycle Evidence

Electrochemical storage technologies currently dominate short- to medium-duration grid applications and represent the most rapidly expanding segment of global energy storage deployment. Their modularity, scalability, and declining capital costs have accelerated adoption; however, lifecycle assessments consistently demonstrate that upstream material extraction and manufacturing processes constitute the dominant environmental burden phases [4], [8]. This section synthesizes peer-reviewed lifecycle evidence for lithium-ion batteries, solid-state batteries, and flow battery systems, with particular emphasis on parameters relevant to GCC climatic and infrastructural conditions.

4.1 Lithium-Ion Battery Systems

4.1.1 Material Composition and Supply Chain Impacts

Lithium-ion batteries (LIBs) typically consist of lithium-based cathode chemistries such as nickel–manganese–cobalt (NMC) or lithium iron phosphate (LFP), graphite anodes, aluminum and copper current collectors, polymer separators, and electrolyte solvents. The lifecycle studies always find the production of cathode materials as the most significant maker of embodied greenhouse gas (GHG) emissions, then the energy-intensive processes of producing cells [4].

The meta-analytical findings are that the cradle-to-gate emissions are in the range of about 60 to 175 kg CO_2-equivalents per kWh of battery capacity, based on location of manufacture and the mix of electricity [4], [8]. The facilities that run in areas that have high coal-based electricity have very high emissions than those that use lower-carbon grids. These variations especially apply when considering imported battery systems that are implemented in the GCC, where a high level of production is often based in East Asia.

According to the indicators of resource depletion, cobalt and nickel mining were highlighted as major factors to the effects of mineral scarcity. Although LFP chemistries eliminate the use of cobalt and nickel, they have a large mass of material per kilowatt-hour, which can affect transportation and installation effects [8].

4.1.2 Operational Performance and High-Temperature Degradation

Normal laboratory conditions (20-25degC) show round trip efficiencies ranging between 85 and 95 percent with lithium-ion batteries [13]. Nevertheless, increased ambient temperatures increase the processes of capacity decays and calendar ageing [7], [17]. Increase temperatures enhances solid electrolyte interphase (SEI) development and breakage of electrolyte and effectiveness of the cycle decreases.

Empirical aging the exposure to significantly higher than 35degC temperatures can significantly reduce battery life [17]. Active cooling systems are normally necessary in grid-scale battery collections in GCC climates where ambient temperatures are often above 45 degC during summer. Cooling systems raise the amount of auxiliary electricity, thus net efficiency decreases and lifecycle emissions percent-out MWh rise.

In the context of lifecycle, services that last less have the impact of amplifying the intensity of embodied emissions since the burdens of production phases are amortized over the reduced number of completed cycles. As a result, high-temperature operation is a multiplier effect on a region-specific lifecycle intensity of the carbon intensity.

4.1.3 End-of-Life and Recycling Pathways

Recycling can also play a critical role in the reduction of the impacts of the lifecycle through the retrieval of precious metals and enhancing the need to buy new virgin materials. Research indicates that closed-loop recycling process can lower cradle-to-gate GWP by a maximum of 40 percent, depending on the recovery efficiency and allotment presumptions [19].

Current industrial practise is dominated by hydro metallurgical and pyrometallurgical recycling technologies. Nevertheless, lithium has lower recovery rates than cobalt and nickel. Considering that the battery recycling infrastructure in the GCC is limited, the existing deployments probably rely on the export of used batteries, which provide an added effect in terms of transportation.

Circular economics According to the perspective of the circular economy, the creation of recycling plants at the regional scale would lead to a significant decrease in the lifecycle emissions and would help to make the supply chain more resilient. The extent of environmental benefits is determined by recovery efficiency as well as the carbon intensity of electricity used in recycling activities.

4.2 Solid-State Batteries

SSBs use solid conductive material in the place of liquid electrolyte and may represent an enhancement of safety, power density, and life cycle. The impact of lifecycle implications has more been exposed to scholarly scrutiny despite the fact that large scale commercialization is still a relatively limited practice.

4.2.1 Manufacturing and Material Impacts

In uncommon instances, SSBs can maintain both lithium-based cathodes but in cases replace both ceramic or polymer solid electrolytes. High-temperature sintering processes can also be further introduced, impacting more energy usage compared to traditional LIB manufacturing. Depending on increased energy density per unit mass the material intensity per delivered kwh over lifetime may decrease.

Estimates in lifecycle are characterized by enormous uncertainty at present since industrial scale data are sparse. Existing modeling literature indicates that further boosts in cycle life would be found to partially compensate growth in production energy needs, subject to presumptions on the electricity mix.

4.2.2 Performance Under Elevated Temperatures

It is possible that solid electrolytes can display increased thermal characteristics than standard lithium-ion systems. An enhanced thermal tolerance might lead to lower cooling needs in hot weather scenarios, which might enhance the lifecycle in the climate of the GCC. But field data of an empirical nature are still needed to justify this advantage on a commercial basis.

4.2.3 End-of-Life Considerations

Concentrated recycling outlets of SSBs are poorly developed. Depending on the changed electrolyte constituency, some change in the material recovery procedures might be required. The lack of recycling chains that are established presents more uncertainty in the lifecycle assessments.

4.3 Flow Battery Systems

Flow batteries put energy in liquid electrolytes stored in exterior tanks that does not link energy capacity to power rating. The most mature commercial design is vanadium redox flow batteries (VRFBs), though other chemistries that are coming out are those based on zinc-bromine and iron.

4.3.1 Material Intensity and Resource Impacts

VRFBs are based on the use of vanadium pentoxide extraction and processing to a high degree. Lifecycle assessments show that the cost of production of electrolytes creates a large portion of embodied environmental impact [20]. Vanadium electrolytes can however, be reused and recycled with little or no depreciation as opposed to the lithium-ion systems hence greater sustainability over time operation.

Although the problem of mineral scarcity applies, vanadium has better geographic diversification than cobalt. Moreover, leasing the electrolyte allows eliminating the initial capital expenditures on material ownership and increases the possibility of reusing the materials in a loop.

4.3.2 Operational Lifetime and Degradation

Flow batteries are capable of long cycle life-in many cases over 10,000-20,000 cycles-due to rule out electrochemical reactions on the apparatus, and thereby does not lead to any electrode structural degradation. Long operational operating lives smooth out the impacts on construction phases and over a greater delivered base of energy, the lifecycle GWP is lower per MWh compared to those that have a shorter operating life.

Various factors can differentiate the electrolyte viscosity and pump efficacy depending on temperature, but generally a lower level of thermal sensitivity in comparison with lithium-ion batteries budget. In some installations, no active cooling will be required, and this could lead to a decrease in the auxiliary energy required when in hot climates.

4.3.3 End-of-Life Recovery

Recovery, rebalancing, and reuse all can result in a greatly reduced impact on the environment in long-term. Structural parts (pumps, tanks, membranes) can also be re-recycled using traditional methods of industry.

4.4 Comparative Lifecycle Trends Across Electrochemical Systems

Table 1 summarizes indicative lifecycle characteristics based on harmonized literature ranges.

Technology	Production GWP Intensity	Cycle Life	Thermal Sensitivity	Recycling Maturity
Lithium-ion (NMC)	High	Medium	High	Moderate
Lithium-ion (LFP)	Moderate	Medium	High	Moderate
Solid-state	Uncertain	Potentially High	Moderate	Low
Vanadium Flow	Moderate	High	Low–Moderate	High (Electrolyte)

Table 1 Comparative Lifecycle Characteristics of Electrochemical Storage Systems

Overall, electrochemical systems present a trade-off between high upstream material intensity and superior modular deployment capability. In GCC applications, high ambient temperatures may disproportionately disadvantage conventional lithium-ion technologies relative to flow or emerging solid-state systems.

5. Mechanical Energy Storage Technologies: Lifecycle Performance and Regional Suitability

Mechanical energy storage technologies differ fundamentally from electrochemical systems in that they rely on gravitational or pressure-based potential energy rather than electrochemical reactions. As a result, their lifecycle environmental profiles are typically characterized by higher upfront construction impacts but significantly longer operational lifetimes. When assessed per delivered MWh over decades of service, these systems often demonstrate comparatively low greenhouse gas intensities [12].

This section evaluates pumped hydro storage (PHS), compressed air energy storage (CAES), and gravity-based systems within a harmonized lifecycle framework and contextualizes their performance under GCC environmental conditions.

5.1 Pumped Hydro Storage (PHS)

5.1.1 Lifecycle Structure and Carbon Intensity

The largest scale storage system in the world is the pumped hydro storage, which is highly deployed and mature. These are civil engineering projects, such as dams, reservoirs, excavation of tunnels, and the manufacturing of turbines, which dominate its effects on the lifecycle.

Construction embodies by far the biggest contributors to the embodied emissions in concrete and steel during the construction phase [12].

The latest lifecycle analysis records that in spite of the fact that emissions in the construction phase can be high in absolute terms, pandemic operational lifetimes, i.e. over 50 years, severely dilute per unit MWh impacts [12]. The round-trip efficiency can be largely varied in 70 to 85 percent, based on the design and head height. PHS systems are often found to have lower lifecycle GWP/MWh than electrochemical storage technology, on a normal basis to delivered electricity of long lifespan.

Site specificity is however essential. The closed-loop systems (without links to the natural river systems) minimize the ecological disturbance when compared with the conventional open-loop hydropower designs, but land conversion is significant nonetheless.

5.1.2 Trade-offs in land use and the environment.

PHS needs land areas and topographical elevation differentiation unlike battery systems. The main environmental issues are land-use change and the possible ecosystem disruption. There is limited geographical terrain that can be effectively deployed to in arid environments of GCC countries due to its mountainous nature.

Water needs are also another limitation. Even though the main goal of closed-loop systems is to recirculate water, because of water loss through evaporation during hot desert climates, the need to replenish water can rise. Since the region depends on desalinated water, indirect energy and carbon effects should be taken into account in determining PHS appropriateness.

5.1.3 Regional Suitability in the GCC.

The GCC has a few natural hydrological gradients as opposed to areas with a large mountainous terrain. Still, localized solutions could be provided by engineered or underground closed-loop arrangements. PHS is operationally resistant when extremes of ambient temperature operations are required and is thermal robust which is an added benefit compared to electrochemical systems sensitive to temperature extremes.

5.2 Compressed Air Energy Storage (CAES)

5.2.1 Technology Variants and Lifecycle Implications

In CAES, the energy is stored by compressing air into deep caverns or built-up reservoirs. Compressed air is used to lessen the turbines to create electricity during the discharge period. There are two main variants:

1. Diabatic CAES, which burns natural gas during expansion to reheat air.
2. Adiabatic CAES, which captures and reuses compression heat, reducing fossil fuel input.

Lifecycle wise, diabatic systems would cause direct operational emission because of combustion of natural gas, but adiabatic systems would cause substantial reduction of the emissions [14].

Business effects during construction include those related to compression and turbine-steel and preparation of the cavern to a large extent. Mineral criticality concerns are not very significant as compared to battery systems, but the main limiting concern is geological suitability.

5.2.2 Performance and Efficiency at High Temperatures.

Round trip efficiency is commonly subject to the range 40-70 percent, based on configuration and thermal management [14]. Losses in efficiency processes of compression and expansion are thermodynamic. Heat in the ambient can also cause the compressor to work a little less efficiently, but the effects are not so serious as the phenomena of electrochemical degradation.

High-temperature resilience is relatively high since CAES systems do not depend much on the delicate nature of electrochemical contents but instead mechanical equipment.

5.2.3 Geological Practicability in GCC.

It has the potential to use salt caverns, and exhausted hydrocarbon reservoirs as the storage formations in some GCC states. The current hydrocarbon systems can help in integration. Nonetheless, site characterization and stability over time of cavern should be thoroughly evaluated on environmental and geological values.

The carbon intensity of electricity compression used to generate electricity continues to affect the factor of lifecycle emissions per delivered MWh. Operation emissions are reduced significantly in a renewable dominated grid.

5.3 Gravity Storage of energy.

The functionality of gravity storage systems is that the heavy weights get lifted at the time of charging, and potential energy is emitted at the time of discharge. The designs range between tower-based systems and underground shaft designs.

5.3.1 Lifecycle Characteristics

The two major material inputs are the concrete and steel as used in PHS except that the water reservoirs are eliminated. Since such systems do not use water, they might be beneficial in dry areas. The effects of construction are influenced in the front-based fashion, and operational emissions are low because they are not accompanied by any combustion or electrochemical reactions.

Embodied emissions can be amortized over long periods because of long design lifetimes which may be longer than 25-40 years. Nevertheless, the empirical lifecycle data is still incomplete in relation to PHS or lithium-ion platforms; they add a degree of uncertainty in the comparison of the quantitative results.

5.3.2 Environmental Trade-offs

The major environmental concerns are related to land occupation and visual impact. The concern on mineral scarcity has no bearing as was the case with battery systems. Its thermal stability is high and time based performance degradation is mainly through mechanical wear.

5.4 Comparative Storage Assessment of mechanical storage.

When compared to the electrochemical systems, mechanical storage technologies are typically shown to:

- Lower mineral criticality,
- Longer service lifetimes,
- Higher spatial and site constraints,
- Lower thermal sensitivity,
- Reduced dependence on imported critical materials.

Finally, they have reduced modularity and can be characterized by increased start-up capital and increases in construction periods.

Considering the GCC, the mechanical systems are also advantageous in withstanding resilience in the conditions associated with extreme climates although bestowed by the topography and water supply (in the case of PHS). CAES is intermediate in nature, which depends on geological suitability.

6. Hydrogen-Based Energy Storage Systems: Lifecycle Complexity and Regional Constraints

Storage systems made by hydrogen are inherently different in contrast to electrochemical and mechanical storage technology. Instead of having it stored as electricity, hydrogen systems have ways of changing electrical input to chemical energy through water electrolysis process, being able to store hydrogen in the form of gaseous or liquid thereafter, and later enabling a conversion to electrical energy through either the use of fuel cells or a combustion fire. This complex conversion process is another cause of loss of efficiency and infrastructure needs that can greatly influence the environmental performance of lifecycle.

The potential of hydrogen as a long-duration and seasonal store is unique, however, in lifecycle assessments, it is generally found that its environmental impact greatly depends on electricity source, system design and scale of infrastructure [6], [16].

6.1 System Configuration and Energy Conversion Chain

A typical hydrogen storage route involves:

1. Electrolysis (electricity → hydrogen),
2. Compression or liquefaction,
3. Storage (pressurized tanks, underground caverns),
4. Reconversion (fuel cells or turbines).

The stages involve energy losses. In practice, proton exchange membrane (PEM) electrolysis systems often achieve energies of between 60 and 70 per cent whilst fuel cell conversion energies lie within the boundaries of 45 and 60 per cent [6], [18]. Combined together, round-trip efficiency in electricity-to-hydrogen-to-electricity systems is typically when it is less than 40%.

This low round-trip efficiency makes it operate at higher efficiency than primary electricity highway, which further increases high upstream environmental costs such as the deployment of renewable infrastructure over time.

6.2 Lifecycle Greenhouse Gas Emissions

These emissions are highly influenced by the intensity of electricity carbon content during the electrolysis process in hydrogen storage systems. Hydrogen systems can have as much or more emissions than conventional fossil-based generation when operating on a grid based on fossil fuels [6]. In contrast, with renewable electricity, the emissions of operation are close to zero, and the lifecycle effects are defined by the manufacture of infrastructures and electrolysis [16].

Platinum-group metals (PGMs) and membrane materials are used in the production of electrolyze stacks, which impact on minerals. In spite of the fact that the specifications of PGM loading have decreased with the course of time, the factor of resource criticality is still to be considered [16].

Storage infrastructure also has additional effects on lifecycle. Carbon fiber production which is an energy-consuming process is needed in high-pressure composite tanks. Storage in underground caverns decreases the intensity of the material, yet it is determined by the geological appropriateness.

In general hydrogen systems are more likely to have a heavier lifecycle GWP per delivered MWh than either battery systems or mechanical systems when used to serve very short duration services, and this is largely because of conversion inefficiencies. Nevertheless, with long-term or seasonal storage, when increasing the size of batteries by a large degree, hydrogen can be made relatively attractive.

6.3 Water Consumption and Arid-Region Constraints

As per optimal stoichiometric conditions, electrolysis needs about 9 liters of water in each kilograms of hydrogen generated, however extra purification and process losses will raise the total water requirement [6]. Large-scale hydrogen creation is based on sea water desalination in GCC contexts with limited water.

Even the process of desalination is energy-intensive, presenting a perceived indirect emission of carbon and augmenting the cumulative energy requirement. Consequently, the storage of hydrogen in arid areas introduces a less intense energy-water nexus compared to other technology types of storage.

Lifecycle-wise, the water consumption becomes a problem area of serious impact in the regionalized analyses. Nevertheless, despite the fact that water use is often considered as a secondary concern in global LCAs compared to GWP, it becomes of particular concern in desert regions where desalination is already the most important source of freshwater.

6.4 Thermal Performance and Climate Resilience

High ambient temperatures do not affect hydrogen storage systems as much. Electrolyzes are used under regulated industrial conditions and hydrogen storage situations underground are mostly immune to temperatures of the surface.

There can be some slight losses in efficiency with respect to high temperature in fuel cell systems, although the effects of high-temperature in fuel cell systems are usually less severe than lithium-ion degradation processes [7]. Therefore, hydrogen storage can have climatic strengths superiorities over the traditional electrochemical batteries during severe heat events.

Capital intensity and complexity of the system are however serious impediments.

6.5 End-of-Life and Circularity Considerations

Fuel cell membranes and electrolyze stacks have some vital materials that may need special recycling methods. The existing industrial recyclability ability of PEM constituents is lacking. Recovery of platinum-group metals is technically possible but relies on its financial advantage.

Compared to chemical processing equipment, hydrogen storage caverns and pipelines have long life and low decommissioning effects. Composite high-pressure tanks, on the contrary, are difficult to recycle with bonded fiber structures.

Hydrogen systems might have reduced hazardous wastes as compared to lithium-ion batteries but increased material-intensive infrastructure scale.

6.6 Comparative Positioning Within the GCC Context

In the GCC energy transition approach, long duration storage as a strategic grid balancing transit and industry decarbonization is more commonly described as the use of hydrogen storage as an expanse of wellspring than a quick cycle grid balancing route. Lifecycle wise, these include:

- **Advantages**
    - Long-duration capability,
    - Lower sensitivity to high ambient temperatures,
    - Reduced reliance on lithium, cobalt, and nickel,
    - Compatibility with existing hydrocarbon infrastructure.
- **Challenges**
    - Low round-trip efficiency,

- High water demand in desalination-dependent systems,
- Infrastructure capital intensity,
- Dependence on renewable electricity expansion.

In short- to medium-duration storage requirements related to the daily fluctuations in the sun, a hydrogen system is not particularly more eco-friendly than an electrochemical or mechanical one, when scaled per delivered MWh [6], [16]. But in the case of seasonal storage or export-based hydrogen economies, the lifecycle performance has to be considered when making alternative functional assumptions.

7. Cross-Technology Lifecycle Comparison

After analyzing electrochemical, mechanical and Hydrogen based, a cross-technology synthesis is required to see the trade-offs in case of harmonized assumptions.

7.1 Carbon Intensity Trends

According to the research performed earlier [4], [6], [12], [16]:

- Lithium-ion systems exhibit high production-phase emissions, but high efficiency reduces operational penalties.
- Flow batteries reduce degradation impacts through long cycle life.
- PHS demonstrates low lifecycle GWP per delivered MWh when long operational lifetimes are achieved.
- CAES varies depending on configuration (adiabatic vs. diabatic).
- Hydrogen systems show high sensitivity to electricity carbon intensity and efficiency losses.

Long-lived mechanical systems can often be effective when normalized to delivered MWh over lifetime, where with some appropriate location places, they would be effective.

7.2 Resource Criticality

- Lithium-ion and solid-state systems: high mineral criticality.
- Flow batteries: moderate (vanadium-dependent but recyclable).
- Mechanical systems: low critical mineral dependency.
- Hydrogen: moderate (PGMs, membranes).

7.3 Water Dependency

- Hydrogen: high (electrolysis + desalination).
- PHS: moderate (evaporation losses in hot climates).
- Electrochemical and gravity systems: low direct water use.

7.4 Thermal Sensitivity Ranking (GCC Conditions)

Most sensitive → least sensitive:

1. Lithium-ion
2. Solid-state (uncertain but potentially improved)
3. Flow batteries
4. CAES
5. PHS
6. Hydrogen cavern storage

8. GCC-Specific Environmental Modifiers and Regionalization of Lifecycle Results

Lifecycle results derived from global datasets cannot be directly transposed to the GCC without adjustment. Climatic extremity, desalination dependence, grid structure, and supply-chain configuration collectively modify environmental performance outcomes across all storage technologies.

8.1 High Ambient Temperature as a Lifecycle Multiplier

Elevated ambient temperatures influence storage systems through:

- Accelerated degradation (electrochemical systems) [7], [17]
- Increased auxiliary cooling demand
- Reduced conversion efficiency (minor for mechanical systems)

For lithium-ion batteries, shortened cycle life directly increases lifecycle GWP per delivered MWh because embodied manufacturing emissions are amortized over fewer operational cycles. Under conservative assumptions, a 20–30% reduction in cycle life could proportionally increase effective lifecycle carbon intensity if replacement intervals shorten.

Mechanical systems such as PHS and CAES remain comparatively unaffected by temperature-induced material degradation, reinforcing their climatic robustness advantage in desert environments.

Hydrogen systems, while less thermally sensitive, remain indirectly impacted through increased renewable generation requirements to offset round-trip efficiency losses.

8.2 Desalination-Energy Coupling

The GCC's structural reliance on desalinated seawater introduces a distinct energy-water nexus dynamic. Hydrogen storage systems, requiring purified water for electrolysis, effectively embed desalination energy burdens within lifecycle accounting [6].

In contrast:

- Lithium-ion and flow batteries require negligible direct water input during operation.
- PHS may require periodic water replenishment due to evaporation.
- Gravity and CAES systems exhibit minimal operational water demand.

In water-scarce systems, hydrogen's lifecycle profile becomes more sensitive to upstream electricity carbon intensity and desalination efficiency improvements.

8.3 Centralized Electricity Markets and Operational Dispatch

Most GCC electricity systems remain centrally managed with vertically integrated utilities. Storage dispatch patterns may therefore differ from liberalized markets where arbitrage dominates.

If storage primarily supports solar peak shifting and grid stabilization rather than high-frequency cycling, operational cycles per year may be lower than assumed in global LCA baselines. Lower cycling frequency increases embodied impact intensity per delivered MWh, particularly for electrochemical systems.

Mechanical systems, designed for multi-decade service with lower degradation, may exhibit more stable lifecycle intensity under low-cycle regimes.

8.4 Import Dependency and Supply-Chain Emissions

The GCC currently imports most electrochemical storage technologies. Production emissions associated with upstream manufacturing occur outside the region but remain attributable under consumption-based accounting.

Localization of manufacturing, particularly battery assembly or recycling, could reduce transport emissions and improve circularity integration. However, lifecycle reductions depend on electricity mix decarbonization within domestic industrial sectors.

9. Policy Implications for Sustainable Storage Deployment

Lifecycle evidence indicates that no single storage technology is environmentally optimal across all applications. Policy frameworks should therefore prioritize functional differentiation rather than technological uniformity.

9.1 Technology-Application Matching

- Short-duration (intra-day solar balancing): Lithium-ion or flow batteries, subject to thermal mitigation measures.
- Medium-duration (multi-hour grid reliability): Flow batteries or CAES where geology permits.
- Long-duration/seasonal storage: Hydrogen systems.
- Geographically suitable mountainous zones: Closed-loop PHS.

Lifecycle-informed procurement mechanisms should integrate environmental performance metrics beyond capital cost per kWh.

9.2 Incorporating Lifecycle Criteria in Tendering

Public tenders for storage deployment could incorporate:

- Carbon intensity thresholds per delivered MWh,
- Mandatory recycling and end-of-life plans,
- Thermal resilience specifications,
- Water-use efficiency metrics.

Such criteria would internalize environmental externalities and align storage expansion with long-term decarbonization objectives.

9.3 Circular Economy Development

Battery recycling infrastructure presents the most immediate circular economy opportunity. As indicated previously [19], recycling substantially reduces embodied emissions of lithium-ion systems.

Policy measures could include:

- Extended producer responsibility (EPR) schemes,
- Regional recycling hubs,
- Incentives for material recovery industries,
- Research investment in electrolyte reuse (flow systems).

10. Discussion

This comparative lifecycle analysis highlights four central insights.

First, upstream production dominates lifecycle emissions for electrochemical storage technologies [4], [8]. Under GCC high-temperature conditions, degradation may amplify these impacts relative to temperate-region estimates.

Second, mechanical storage systems, particularly PHS, demonstrate favorable lifecycle intensity per delivered MWh when long operational lifetimes are realized [12]. However, site constraints significantly limit scalability.

Third, hydrogen-based storage exhibits substantial efficiency penalties and water dependency [6], [16]. Its environmental competitiveness increases primarily in long-duration storage contexts or when renewable electricity is abundant and surplus would otherwise be curtailed.

Fourth, regional modifiers, heat, desalination, centralized dispatch, and import dependency, must be incorporated into lifecycle interpretation to avoid misaligned policy conclusions.

The central trade-off across technologies can be summarized as follows:

- Electrochemical systems: High material intensity, high modularity.
- Mechanical systems: Low material criticality, high site specificity.
- Hydrogen systems: Low short-term efficiency, high long-duration potential.

In the GCC context, a diversified portfolio approach appears environmentally rational.

11. Limitations

This study is based exclusively on secondary lifecycle datasets. As such:

- Regionalized empirical performance data under GCC climate conditions remain limited.
- Future technological improvements, particularly in solid-state batteries and electrolyze efficiency, may alter lifecycle rankings.
- Economic cost modeling was not integrated into environmental assessment.
- System-level grid modeling was beyond scope.

Further research should include high-temperature field degradation studies and region-specific lifecycle inventory data development.

12. Conclusion

The transition toward renewable-dominated electricity systems in the GCC necessitates rapid deployment of energy storage technologies. However, environmental sustainability cannot be assumed solely from renewable integration benefits.

This lifecycle review demonstrates that:

1. Lithium-ion batteries remain effective for short-duration storage but face amplified degradation risks in extreme heat.
2. Flow batteries offer durability advantages with promising circularity potential.
3. Pumped hydro storage delivers low lifecycle carbon intensity when geographical conditions permit.
4. Compressed air systems present moderate environmental performance contingent on configuration.
5. Hydrogen storage, while strategically significant for long-duration applications, remains efficiency- and water-intensive.

Under GCC climatic and infrastructural conditions, environmentally optimized deployment requires technology differentiation aligned with storage duration needs and regional resource constraints.

A balanced portfolio, combining electrochemical systems for flexibility, mechanical systems where feasible, and hydrogen for long-duration resilience, offers the most sustainable pathway.

Lifecycle-informed policy integration will be essential to ensure that the environmental costs of enabling technologies do not undermine the broader decarbonization objectives they are intended to support.

13: Declaration

13.1 Availability of data and material

Not applicable.

13.2 Funding

Not applicable.

13.3 Acknowledgements

Not applicable.

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