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Moving Beyond Diesel Generators: Exploring Renewable Backup Alternatives for Data Centers

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Abstract. This study investigates sustainable alternatives to diesel generators for data centre backup power, focusing on renewable diesel (HVO), Hydrogen energy storage (HES), batteries (Lithium-ion and Sodium Sulfur) and Compressed Air Energy Storage (CAES). As environmental scrutiny of data centres grows, the need for cleaner energy sources intensifies. Our research assesses various storage technologies' energy performance metrics, environmental impacts, and economic feasibility. HVO is a seamless substitute for conventional diesel, compatible with existing infrastructure and less carbon-intensive. CAES offers lower life cycle emissions and operational costs but is geographically dependent. While currently more costly, batteries could achieve better economics with increased operational hours. However, extending the backup duration increases their capital and operating costs significantly, which is less advantageous than other technologies, where only fuel costs increase with longer backup times. For existing data centres transitioning to sustainable energy, HVO is optimal; for new facilities, CAES is ideal if geography allows, with HES as a robust alternative. This analysis offers a pathway for data centres to adopt sustainable, cost-effective energy storage solutions and reduce carbon footprints through on-site renewables or green energy procurement.

1 Introduction

Data centres have become the backbone of the modern digital landscape, pivotal in the rapid advancements of artificial intelligence(AI) and machine learning. As the world embraces the AI revolution, the importance of data centres becomes increasingly evident, serving as the foundational infrastructure that powers the data-driven innovations transforming various industries [1].

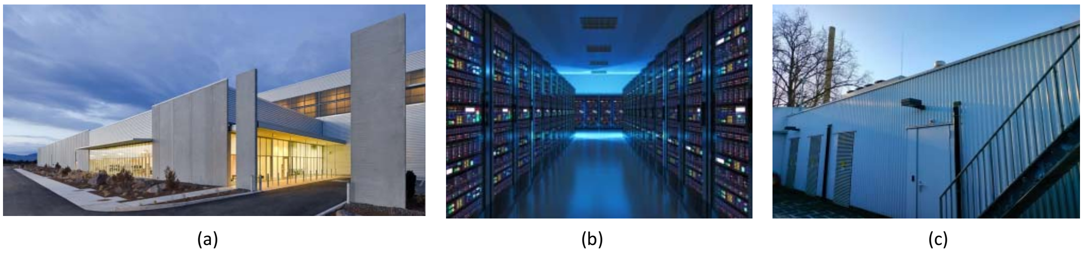

(a) (b) (c)

Figure 1: (a) Meta's datacentre [2] (b) Server room interior in data centre [3] (c) TU Delft datacentre

Data centres, categorized by power capacity, address various enterprise needs, as shown in Table 1. Operating 24/7 throughout the year, they are characterized by high energy intensity, with power densities typically ranging from $538\,\mathrm{W\,m^{-2}}$ to $2153\,\mathrm{W\,m^{-2}}$, and occasionally reaching up to $10\,\mathrm{kW\,m^{-2}}$ [4], [5]. In 2018, data centres worldwide consumed 205 TW h, exceeding the annual consumption of countries like Ireland and Denmark [6], [7]. By 2030, data centres are projected to consume approximately 3–13% of the world's electricity, a significant increase from the 1% consumed in 2010 [8], [9]. They are responsible for 2.5% to 3.7% of global greenhouse gas emissions, surpassing those from the aviation industry (2.4%) [10]. The global data centre market is estimated at $229 billion in 2023 and is projected to reach $641 billion by 2032 [11].

Data Centre Type	Power Usage	Description
Server room	<50kW	Supports business activities within or separate from buildings
Very small data centre	50-250kW	
Small data centre	250-1000kW	Critical for business functionality, can be in or outside buildings
Medium size data centre	1-2MW	Vital infrastructure for various businesses located in separate buildings
Large data centre	2-10MW	
Very large data centre	>10MW	

Table 1: Classification of data centres based on size [12]

Imagine a day without reliable access to essential online services like cloud storage and communication platforms. Such a disruption would significantly affect daily life. This scenario highlights the critical role of data centre reliability in maintaining uninterrupted access to the services we depend on for communication, entertainment, and productivity. Diesel generators are crucial for ensuring this reliability by providing backup power. Their use as backup systems is due to their established technology, widespread availability, high energy density, and rapid response times. However, relying on these generators increases greenhouse gas emissions due to the presence of sulfur and aromatic compounds.

Extensive research into data centre load variability and composition is crucial for designing effective backup power systems and improving energy efficiency. Studies have investigated power consumption distribution across data centre components, particularly regarding HVAC requirements based on geographic location. Shehabi et al. [13] found that server power consumption accounts for approximately 43% of total electricity use in U.S. data centres, with cooling and power provisioning systems consuming about 23% and 11%, respectively. The study also noted significant geographical variations, indicating that cooler climates require less energy for cooling. Similarly, Dayarathna et al. [14] reported that IT equipment (servers, storage, and network) typically comprises 55-60% of total power usage, while cooling systems consume 30-35%, and power distribution losses account for 10-15%. These findings underscore the importance of understanding load dynamics for developing effective backup power solutions. Another paper by Ghatikar et al. [15] examined the load flexibility of data centres and their potential for demand response, emphasizing the importance of rapid response times in backup power systems.

Regulatory bodies and the public are increasingly scrutinizing the environmental impact of data centres. As a result, technology firms are investing in renewable energy production to offset the energy consumption of data centres [16], [17], [18]. Amazon, Meta, and Google have collectively committed to generating 22 GW of renewable energy to meet their Net Zero targets. To achieve sustainability goals, traditional backup power sources like diesel generators must be replaced with reliable, widely available, and mature sustainable alternatives.

eBay's innovative data centre, operational since 2013 in South Jordan, Utah, has replaced diesel generators with Bloom Energy fuel cells powered by natural gas, thereby reducing emissions and enhancing reliability [19], [20]. NorthC is utilizing green Hydrogen for emergency power at its Groningen facility and plans to implement hybrid generators that can operate on both natural gas and Hydrogen at its upcoming site in Eindhoven, Netherlands [21]. Microsoft Sweden's data centres are leading the adoption of Preem Evolution Diesel Plus, a low-carbon fuel composed of over 50% renewables, significantly reducing net CO_2 emissions [22]. In New York, they have trialled a 3-MW hydrogen-powered system for zero-carbon data centre backup [23].

While numerous studies have explored alternatives to diesel generators for various applications, there is a noticeable gap in comprehensive comparative analyses that integrate energy performance, environmental impact assessment, and financial analysis. Existing research includes evaluations of medium-speed diesel generator sets and energy storage technologies to reduce fuel consumption and exhaust emissions in electric propulsion systems for platform supply vessels (PSVs) [24]. Other studies have focused on sustainable electricity generation using solar PV/diesel hybrid systems without storage for off-grid areas, as well as the optimization of off-grid photovoltaic-diesel-battery hybrid sustainable energy systems for remote residential applications ([25], [26], [27]). However, to the best of our knowledge, this report presents the first comparative study that systematically examines these factors, providing a holistic view of alternative energy solutions for data centres.

The following sections outline the research methodology and details of preselecting alternative storage technologies, thoroughly examining their energy performance, environmental impact, and financial assessments. This report aims to equip readers and stakeholders with the knowledge to make informed decisions about adopting alternative energy storage solutions for data centre applications.

2 Methodology

2.1 Methodology for Evaluating Sustainable Storage Technologies

The research followed a sequential exploratory strategy, beginning with a comprehensive literature review on existing studies working on green data centres, followed by a review of different sustainable alternative storage to data centre backups, their global warming potential, levelised costs and total costs of ownership.

Based on an initial literature review, several storage technologies were preselected for further investigation into sustainable data centre backups. This criterion included power rating, discharge time, technological maturity, and the area required for installation. Comparative studies were then conducted on the selected technologies, focusing on crucial energy performance metrics such as efficiency, lifespan, specific energy, and energy density. Additionally, each technology's cradle-to-grave lifecycle assessment was performed to evaluate its global warming potential, offering a comprehensive analysis of the environmental impacts associated with each option.

The Lifecycle Assessment (LCA) quantified the environmental impacts of each technology, focusing on global warming potential. This process involved aggregating and analyzing emissions data throughout the lifecycle of each option. For cost analysis, the Levelized Cost of Energy (LCOE) techniques evaluated the economic costs of different storage solutions, considering initial costs, operations, maintenance, and replacement. The Total Cost of Ownership (TCO) analysis was expanded to include carbon emission costs, providing a comprehensive view of financial impacts by integrating environmental externalities into traditional assessments.

The study rigorously adhered to ethical standards in data collection and analysis, ensuring the confidentiality of any proprietary data and maintaining the integrity of analytical processes. Despite offering significant insights into the sustainability of storage technologies for data centres, there are limitations due to the variability in technology maturity and regional differences in energy sources and costs, which could impact the generalizability of the findings. The methodology facilitated a comprehensive investigation into sustainable storage technologies, effectively balancing environmental, performance, and cost considerations. The results are poised to aid stakeholders in making informed decisions towards adopting greener data centre solutions. In conclusion, this research synthesizes the essential findings and underscores their implications for future research and practical applications in sustainable data centre management.

2.2 Evaluation Methods for Alternative Technologies

2.2.1 Energy Performance: The assessment of energy storage technology performance is critical, particularly when considering the replacement of diesel generators with more sustainable alternatives for backup power in data centres. This evaluation is essential to ensure that any proposed solutions maintain the high levels of reliability and accessibility that diesel generators currently provide. Key performance metrics such as capacity and energy, which reflect the system's ability to store and deliver sufficient power; efficiency and round-trip efficiency, which determine how effectively the storage system conserves energy; response time and ramp rate, which gauge how quickly the system can respond to power demands; and cycle life and degradation, which indicate the longevity and durability of the system, are all carefully analyzed. Additionally, specific energy and energy density are evaluated to ensure the storage solution fits the physical constraints often in data centre environments. Conducting a thorough energy performance assessment helps stakeholders make informed decisions that align with operational requirements and sustainability goals, ensuring that data centres can reliably function without interruption while transitioning away from diesel-based backup systems.

2.2.2 Environmental Impact Assessment: This paper presents a comparative life cycle assessment (LCA) of the global warming potential (GWP) of various storage technologies evaluated cradle-to-grave. Life cycle assessments are influenced by factors such as system description, functional unit selection, impact categories, inventory classification, normalization, and interpretation. We use different units—1 megawatt-hour (1 MWhd) for Diesel Generators and Flywheels and 1 kilowatt-hour (1 kWhd) for other technologies—due to a lack of consistent functional units in the literature for cradle-to-grave studies of GWP. To improve the relevance and comparability of our results against diesel, we scaled the functional units accordingly.

System Description: The ecological loop, shown in Figure 2, illustrates the product life cycle stages. Starting from the "Cradle," where raw materials are harvested and converted into products, the cycle progresses through transportation to the "Gate" (usage stage) and reaches the "Grave" (end-of-life or disposal). At this stage, materials may be recycled and re-enter the loop, promoting sustainability. In each stage, energy and materials enter, while waste and emissions exit, making recycling a crucial factor in reducing ecological impacts.

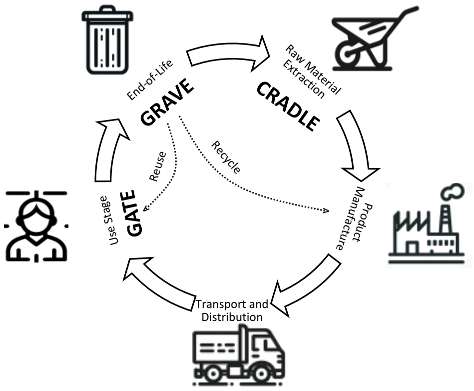


Figure 2: Ecological loop of product life cycle stages

2.2.3 Financial Assessment All the aforementioned technologies are expected to yield equivalent financial returns since they all serve the same purpose of providing backup power, thereby generating similar value. Therefore, the comparative factor among them lies in their respective average costs per kilowatt-hour of electricity produced throughout their operational lifetimes, which essentially reflects the levelised cost of electricity (LCOE). LCOE is widely used in the energy industry to compare the cost-effectiveness of different methods of electricity generation consistently.

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{n} \frac{C_t + M_t + R_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \tag{1}$$

In this formula:

- C_t represents the capital expenditures in the year t.
- M_t stands for operations and maintenance expenditures in the year t.
- R_t denotes costs associated with component replacements over the system's life.
- E_t is the electricity generation in the year t.
- r is the discount rate.
- n indicates the lifespan of the system.

Total Cost of Ownership
LCOE is a metric used to assess the cost efficiency of an energy-generating system over its operational life. Traditionally, LCOE is calculated without considering the external costs associated with carbon emissions. However, incorporating carbon credit costs provides a more comprehensive understanding of the economic impacts of energy production on the environment.

For a sustainable decision not solely informed by the traditional financial comparison of investments versus returns, TCO_2 stands for Total Cost of Ownership, which includes a carbon price. TU Delft coined the combination of a carbon price and Total cost of ownership (TCO is a financial assessment method that provides for all costs and benefits of the entire lifespan of a product or project.) TCO_2 in its Vision, Ambition and Action Plan for a Sustainable University [28]. The carbon price should cover the impact of (and adaptation and mitigation to) climate change. Current ETS value of a tonne of CO_2-equivalents: ± € 70. Based on various scientific sources, in its sustainable campus programme, TU Delft uses € 150 [29]. Based on a study by the German Ministry of the Environment, to cover all expenses related to carbon compensation, avoidance and recovery of damage done, the price should be close to € 1000/tCO_2eq.

2.3 Preselection of Technologies

Figure 3 classifies energy storage technologies based on power rating, the form of energy stored in, storage duration, and response time ([30], [31]). All technologies in the 50-kW to 10-MW power rating range and high discharge times are considered sustainable alternatives to diesel generators. Figure 4 showcases the technology readiness levels of various alternative storage methods. Only mature technologies are considered for this study. Finally, the area required for storage is considered to finalise the storage technologies. Renewable Diesel - Hydrotreated Vegetable Oil (HVO), Hydrogen energy storage (Electrolyser + Fuel Cell) (HES), Lithium Ion batteries (Li-ion), Sodium Sulphide batteries (NaS), Flywheel-based energy storage system (FBESS), and Compressed Air Energy Storage (CAES) are chosen as alternatives for this study.

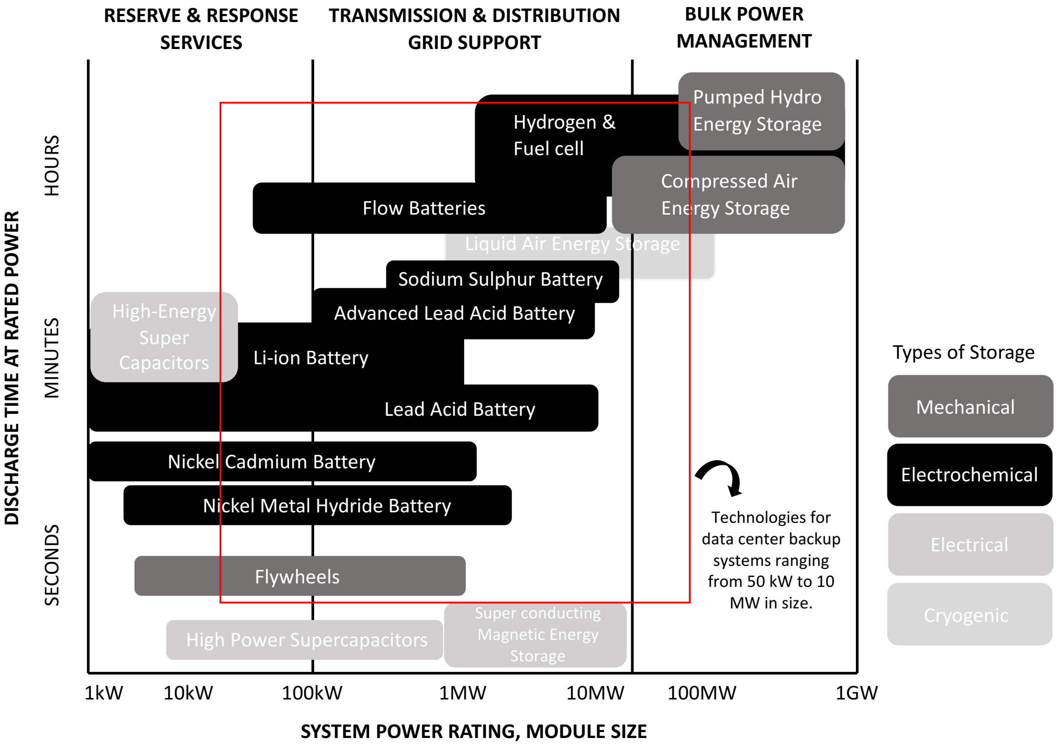


Figure 3: Characteristics of different energy storage technologies adapted from Taylor et al. and Akhil et al. The red square highlights the energy storage systems suitable for backup for data centres. Image adapted from [32]

HVO seamlessly integrates into existing systems but competes with food crops, causing a food-fuel conflict. HES presents a viable option for long-term storage, albeit at a high capital cost and with safety concerns. Both Li-ion and NaS batteries exhibit high energy densities, offering extended discharge times, making them well-suited for backup applications; however, battery manufacturing costs remain prohibitive. Batteries are constrained by charge-discharge cycles, necessitating significant oversizing to address discharge limitations. In contrast, fuel alternatives offer the advantage of refuelling to sustain continuous electricity generation, making them

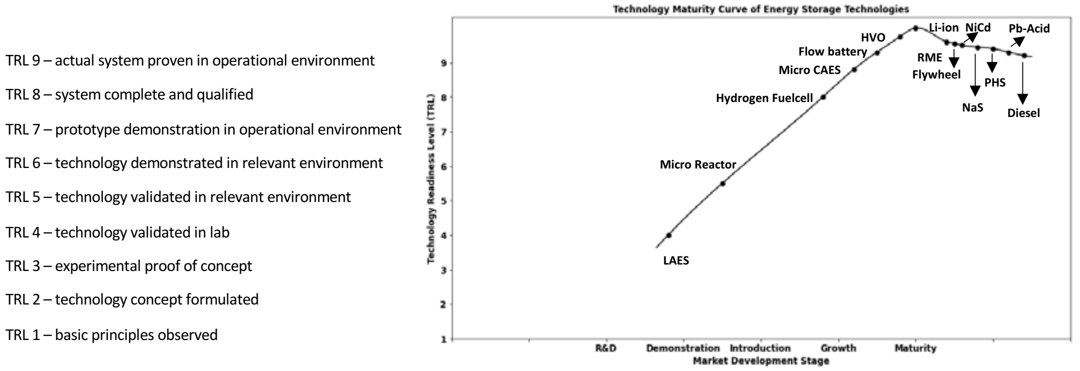


Figure 4: Technology Readiness Levels of energy storage technologies for small scale energy systems. Image adapted from [33]

a reliable power supply source. While CAES holds promise for long-duration storage, it faces geographical limitations in storing compressed air. While CAES systems offer longer-duration storage and potentially lower costs for large-scale applications, their slower ramp-up times compared to batteries could limit certain data centre operations [34]. FBESS, distinguished by its maturity, high efficiency, and energy density, has discharge times ranging from seconds to minutes, limiting its standalone application and favouring hybrid integration with other technologies with slower ramp-up times.

Comparative studies are essential for informed decision-making, resource optimisation, and achieving sustainability goals in data centre operations and other fields. This study offers crucial insights into various storage technologies' energy performance, environmental impact, and financial evaluation. The Energy Performance Analysis assesses storage options based on metrics such as round-trip efficiency, specific energy, discharge time, and lifespan to meet the energy needs of data centres. The Environmental Impact Assessment conducts a comparative Life Cycle Assessment (LCA) of these technologies. Financial analysis includes calculating the Levelized Cost of Energy (LCOE) and lifecycle costs while also considering carbon credit expenses. Despite significant research on sustainable energy solutions for data centres, there is a notable gap in comparative studies focused on alternative storage technologies for backup power. This research addresses this gap by providing a comprehensive comparative analysis of various storage technologies, evaluating their potential as sustainable alternatives to traditional diesel generators for backup power in data centres.

3 Energy Performance Assessment

3.1 Baseline: Diesel Generators

The efficiency values for diesel generators can vary based on the specific model, size, load level, and operating conditions. In general, diesel generators typically have peak efficiencies of 25% to 40% [35]. An industrial diesel generator can last from 20,000 to 40,000 hours of use, equating to approximately 20 to 25 years of operation [36]. Diesel generators boast a quick start-up time of typically 10 seconds or less, ensuring minimal downtime during power outages. In emergency scenarios, these generators can enter operation within a few seconds, providing prompt response to critical events. For routine testing, rapid loading should be avoided, with a recommended gradual loading over 5-15 minutes or more [37].

Attribute	**Diesel Generator**	**Hydrogen Fuel Cell**
Peak Efficiency	25% to 40%	45% to 60%
Lifetime (hours of use)	20,000 to 40,000	24000-30000
Lifetime (years of operation)	Approximately 20 to 25	20
Startup Time	Typically 10 seconds or less	10 minutes
Routine Testing Loading	Gradual loading over 5-15 minutes	10 minutes

Table 2: Comparison of Diesel Generator and Hydrogen Fuel Cell Attributes

3.2 *Diesel and its alternatives*

We compare different fuels, namely diesel and HVO (Hydrotreated Vegetable Oil), both of which can be operated in the same diesel generators. Diesel, a traditional fossil fuel derived from crude oil, which developed over 300 million years from organic remains, exhibits high energy density but emits high levels of pollutants. RME, produced from rapeseed oil, with a much shorter production cycle, offers a cleaner-burning alternative with reduced particulate matter and carbon monoxide emissions, albeit with slightly lower energy density. HVO, synthesized from hydrogenating vegetable oils, shares energy performance characteristics with diesel whilst being a waste product and burning much cleaner. Availability varies, with diesel being widely available but environmentally harmful and renewable diesel being eco-friendly yet dependent on agricultural production and policies. However, it is an emerging market with increasing availability but requires infrastructure development [38] [39].

Table 3: Selected important properties of fuels adopted from [39]

Properties	Lower heating value [MJ kg^{-1}]	Density at 15 °C [kg m^{-3}]	Volumetric lower heating value [MJ dm^{-3}]	Kinematic viscosity at 40 °C [mm^2 s^{-1}]	Cetane number	CFPP [°C]
Diesel	43.0	833.1	36.0	2.50	53	-22
HVO	44.0	781.0	34.0	2.89	95	-32.5
Hydrogen	119.9	0.0838	-	1.21	55	-

3.3 *Hydrogen Energy Storage*

Hydrogen is a versatile energy carrier with immense potential across various sectors. Its flexibility lies in its ability to be produced from multiple feedstocks through diverse methods, such as electrolysis, steam methane reforming, and biomass gasification. In this study, the focus is on hydrogen production through water electrolysis. There are different electrolysis techniques; Alkaline electrolysed water electrolyser (AEW) & Proton exchange membrane electrolyser (PEM) are the most mature technologies, whose energy performance is listed in table 4.

PEM (Proton Exchange Membrane) fuel cells are highly favoured for backup power applications due to their solid electrolyte, which not only minimizes issues related to corrosion and electrolyte management but also facilitates rapid start-up times. This makes PEM fuel cells exceptionally reliable and efficient for emergency power solutions, ensuring stability and quick response under critical conditions. Essential attributes of PEM fuel cells are mentioned in table 2.

Table 4: Detailed characteristics of AEW, PEM systems adopted from [40]

	AEW	**PEM**
Current density (A cm^{-2})	0.2–0.4	0.6–2.0
Cell voltage (V)	1.8–2.4	1.8–2.2
Cell area (m^2)	<4	<0.3
Operating Temp. ($°C$)	60–80	50–80
Operating Pressure (bar)	<30	<200
Production Rate^c (m^3 H_2 h^{-1})	<760	<40
Stack energy^c (kWh_{el} m^{-3} H_2)	4.2–5.9	4.2–5.5
System energy^c (kWh_{el} m^{-3} H_2)	4.5–6.6	4.2–6.6
Gas purity (%)	>99.5	99.99
System Response	Seconds	Milliseconds
Cold-start time (min.)	<60	<20
Stack Lifetime (h)	60,000–90,000	20,000–60,000
Lifetime of system (years)	20-30	10-20

Hydrogen offers high specific energy, but it is associated with high flammability, hence has safety concerns regarding storage. Fuel cells are used to convert Hydrogen to electricity, and Hydrogen showcases efficient conversion of chemical to electrical energy. Enhanced storage solutions and robust fuel cell technologies improve its longevity and reliability. Low self-discharge rates ensure prolonged availability, which is crucial for long-term storage applications. In addition, the rapid response times of fuel cells make Hydrogen suitable for quick start-up [41].

3.4 Batteries

3.4.1 Lithium Ion Lithium, renowned for its remarkable reactivity and energy storage capabilities, is pivotal in advancing Lithium-ion (Li-ion) battery technology. Its unique properties, including low atomic weight and small atomic radius, empower Li-ion batteries with high voltage and charge storage capacities per unit mass and volume, enabling rapid and efficient energy transfer and storage. Various electrode materials, such as lithium cobalt oxide, graphite, lithium manganese oxide, and lithium iron phosphate, cater to diverse applications, from portable electronics to electric vehicles [42, 43].

Li-ion batteries boast one of the highest energy densities among commercial battery technologies, making them versatile for various applications, especially power-intensive ones like transportation. With high efficiency and extended lifetimes of up to 15 years, Li-ion batteries offer reliability and longevity. They exhibit low self-discharge rates, minimal maintenance requirements, and no memory effects, ensuring sustained performance. However, challenges such as supply chain stress due to rare materials, high costs, and scalability issues in storage systems present notable hurdles for widespread adoption [42].

3.4.2 Sodium Sulphur NaS batteries are touted for their long-duration energy storage. Their superior performance stems from extensive research and commercial use over two decades. They boast high energy density, efficiency, and long life, and they are made from cost-effective and environmentally friendly materials. A notable feature of these batteries is zero daily self-discharge rates [44]. However, NaS batteries increase operational costs due to the requirement of higher operating temperatures (around 300-350°C to liquefy Na). They are prone to safety concerns due to the reactivity of sodium and sulfur. Therefore, they are best suited for stationary applications where safety precautions can be implemented effectively. Consequently, they function well as high-capacity grid solutions, offering reliable long-term energy storage, and can serve as alternatives to fossil fuel-based power generators [45]. The battery characteristics are given in Table 5.

Table 5: Battery Characteristics Comparison

Characteristics	Li-ion	NaS
Cell voltage	2.5 – 5 V	1.8 – 2.71 V
Specific energy	80 – 250 Wh/kg	150 – 240 Wh/kg
Energy density	95 – 500 kWh/m^3	150 – 350 kWh/m^3
Efficiency	75 – 97 %	75 – 90 %
Working temperature	20 – 65 °C	300 – 350 °C
Lifetime cycles	100 – 10000	2500 – 40000
Lifetime	5 – 15 years	10 – 15 years
Max. depth of discharge	100 %	100 %
Self-discharge rate	0.1 – 0.3 % per day	0 % per day
Power rating	0 – 0.1 MW	0.05 – 34 MW

3.5 Compressed Air Energy Storage

CAES systems exhibit notably low energy and power densities owing to factors such as closed-cycle operation, logarithmic pressure variations, energy losses during compression/expansion, pressure fluctuations, system configuration, and heat transfer inefficiencies necessitating extensive storage facilities for effective operation, such as underground salt caverns such as those in McIntosh and Huntorf. This makes CAES primarily suitable for large-scale, stationary energy storage applications. Additionally, CAES demonstrates impressive capabilities in storing and delivering substantial energy and power with minimal self-discharge over extended periods. Moreover, CAES facilities boast long lifespans and numerous charge-discharge cycles, offering cost-effective solutions despite high initial capital investments. However, CAES systems currently face challenges regarding roundtrip efficiency, typically ranging from 42% to 89%. While advancements like adiabatic and isothermal CAES hold promise for enhancing efficiency, further improvements are needed to rival Pumped Hydro Storage (PHS) plants in scale and efficiency while reducing environmental impact [46], [47], [48].

Characteristic	Unit	Value (range)
Energy density	Wh/L	2–6
Specific energy	Wh/kg	30–60
Power rating	MW	5–400
Rated energy capacity	MWh	580–2860
Daily self-discharge	N/A	Small
Lifetime	Years	20–60
Cycling times	Cycles	8000–30,000
Cycle efficiency	%	42–89
Storage duration	N/A	Hours — months
Discharge time	Hours	1–24+

Table 6: Energy Storage System Characteristics adopted from [48]

3.6 Flywheel-based energy storage systems

FBESS are known for their remarkable energy efficiency, which is attributed to advances in material science, minimal friction losses, and negligible wind resistance. Compared to batteries, FBESS demonstrate exceptional longevity and can endure numerous charge/discharge cycles without being affected by temperature or depth of discharge (DOD). Unlike batteries, FBESS are operationally reliable as their mechanical nature leads to fewer failure modes; disposal raises no environmental concerns as they do not contain any harmful chemicals. Monitoring the state of charge (SOC) for FBESS is straightforward, relying solely on measuring flywheel spinning speed. High-speed rotating masses require precision engineering and advanced materials, which escalate the complexity and cost of FBESS. The energy-to-weight ratio of FBESS tends to be less favourable than alternative storage options, limiting their application in mobile applications, and flywheels have high self-discharge rates, making them suboptimal for long-term energy storage [49], [50]. The FBESS characteristics are given in Table 7

Table 7: Flywheel Energy Storage Characteristics [50], [49]

Feature	Value
Efficiency (%)	85–95
Specific energy (Wh/kg)	5–150
Power rating (MW)	0.1–4200
Charging time	minutes
Discharge time	15 s–15 min
Discharge depth	deep
Response time	milliseconds
Service life (Year)	$\geq$ 20
Maintenance cycles	$\geq$ 10 years
Operating temperature (°C)	-40–50
Daily self-discharge	5%

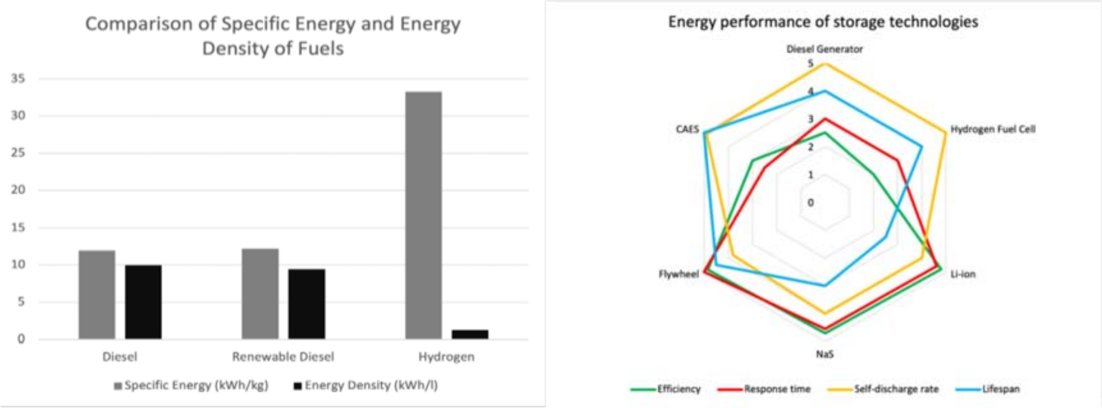
Figure 5 (a) provides a comparative bar chart detailing the specific energy and energy density of Diesel, Renewable Diesel, and Hydrogen. Figure 5 (b) visually represents the energy performance of various storage technologies, illustrating key attributes such as efficiency, response time, self-discharge rate, and lifespan across technologies like Diesel Generators, Hydrogen Fuel Cells, CAES, and others.

4 Environmental Impact Assessment

4.1 Diesel Generators

4.1.1 Diesel Eric A. Alsema [51] conducted a Life Cycle Assessment (LCA) on diesel generators, focussing on generating 1 MWh of electrical energy. The study aimed to evaluate diesel generators' environmental impacts for domestic electrification. The scope included analysing a 5 kVA diesel generator with a 25% fuel-to-electricity conversion efficiency, considering fuel transportation over 100 km and a 10-year life expectancy. Inventory analysis quantified material use, energy consumption, and emissions, while impact assessment utilized the Eco-indicator '95 method to assess Global Warming Potential [52].

The analysis highlighted in Table 8 shows that the primary environmental impact arises from emissions generated during fuel combustion, with a secondary influence attributed to the processes involved in fuel extraction and refining. Similar fuel combustion values are supported by a study by Volker Quaschning and Bernhard Siegel [53]. In contrast, the environmental ramifications associated with the manufacturing of the generator itself and the transportation of fuel over



(a) (b)

Figure 5: (a) Specific Energy and Energy Density of Fuels (b) Energy Performance of Storage Technologies (adopted from tables 3,4, 5, 6, 7)

Class	**Unit**	**Total**	**Diesel Genset**	**Fuel Production**	**Fuel Transport**	**Fuel Combustion**
GWP	kg CO_2	1.27E+03	4.4	205	4.62	1.05E+03

Table 8: LCA results of diesel generator adopted from [51]

a distance exceeding 100 kilometres were found to be relatively minimal. The emission factor applied to the diesel generator amounted to 1.27 x 10^3 kilograms of CO_2 per megawatt-hour (kg CO_2/MWh). A change in life expectancy and distance wouldn't impact the emissions. However, fuel combustion is inversely proportional to efficiency, and an efficiency of 40% could reduce the emissions to approximately 0.67 kg CO_2 and fuel production to 0.128 kg CO_2.

The above analysis offers a cradle-to-gate Life Cycle Assessment (LCA) of a diesel generator set. Thus, Benton et al.'s [54] investigation into the life cycle energy assessment of a standby diesel generator set has been consulted to address the disposal phase of a diesel generator. Scenario 2 (Landfill 34%, Recycle 34%, Remanufacture 32%) is chosen for analysis due to the uncertainty of the disposal route. As a midpoint between zero and complete recycling, Scenario 2 provides a balanced approach suitable for cradle-to-grave analysis, making it the most relevant scenario for our study's focus. **Scenario 2** results in a **-52.20%** change in materials energy, i.e. by remanufacturing, the product can lead to a 52% reduction in the initial energy consumption.

4.1.2 Renewable Diesel The studies conducted by Miguel Brandão et al., [55] [56], have been utilised to evaluate the environmental impacts associated with biofuel production. The first paper [56] discusses the modelling approach, while the second paper [55] quantifies the carbon footprint of biofuels using the openly accessible biograce tool. The study utilises four modelling approaches to evaluate biofuel carbon footprints, including the Renewable Energy Directive (RED), Attributional LCA (ALCA), and Consequential LCA (CLCA). These methods assess direct and indirect land-use changes, environmental impacts, and system-wide effects of biofuel production. The biofuel pathway involves multiple stages, including cultivation, processing, and combustion of biofuels as an alternative to fossil fuels.

Several vital stages are involved in the production process of renewable diesel from rapeseed, beginning with the cultivation activities, such as the growth and harvesting of rapeseed, followed by the drying of the harvested crop. Subsequently, during the processing phase, the oil undergoes essential procedures, including oil extraction from rapeseed and the subsequent hydrogenation of vegetable oil. Transportation plays a pivotal role in the logistical chain, encompassing the movement of rapeseed from cultivation sites to processing facilities, transportation of rapeseed oil, and the delivery of hydrogenated vegetable oil (HVO) to depots. Finally, transporting the final product to filling stations completes the chain. Each stage contributes to the overall environmental impact and sustainability of renewable diesel production from rapeseed. Our analysis assumes that any carbon dioxide captured during feedstock cultivation is offset by the emissions released during combustion. Consequently, we consider the carbon emissions during the usage phase negligible or zero.

4.2 Other technologies

Oliveira et al. [57] evaluated the environmental impacts of integrating storage systems into the electricity grid, comparing various energy storage technologies on a standardised functional unit: one kilowatt-hour of stored and delivered electricity utilising existing studies and databases for inventory data. It encompasses the entire lifecycle, cradle to grave (from raw material extraction worldwide to assembly and use in Belgium, including end-of-life disposal). Distribution network effects are excluded, focussing solely on system outputs. Energy mixes utilised include Belgium 2011 (Belgium electricity mix for 2011), UCTE 2004, 100% wind, and 100% photovoltaic. The energy mixes are shown in table 9. Impact assessment employs ReCiPe 2008 methodology, analysing relevant midpoint categories and providing a single-score evaluation via SimaPro 7.3.3, Commercial Analyst version.

Table 9: Energy Mixes

Production unit	**Nuclear**	**Natural gas**	**Coal**	**Municipal waste**	**Blast furnace gas**	**Wind**	**Hydro**	**Biomass**	**Oil**
BE2011	59.0	28.0	4.60	2.60	2.30	1.10	1.70	0.69	0.00
UCTE 2004	17.00	21.00	30.00	1.0	1.00	7.00	15.00	1.00	7.00

4.2.1 Hydrogen: The scope of hydrogen-based power generation encompasses various production methods, with electrochemical processes being prominent, employing electrolyzers to split water into Hydrogen and oxygen. In this study, the focus lies on proton exchange membrane fuel cells (PEMFC), a mature technology widely applied in commercial settings. These fuel cells utilize high-pressure Hydrogen derived from high-temperature electrolysis as a feedstock. The inventory for the fuel cell stack and electrolyzer is drawn from the NEEDS European Project database. Components crucial to hydrogen production include electrolyzers, diaphragm compressors, storage modules, and structural elements like walls and foundations, along with considerations for use and maintenance. For fuel cells, key components and maintenance aspects encompass the stack, balance of plant (BOP), potential reformers for methane feedstock, and requisite support structures. This integrated approach underscores the comprehensive evaluation and management of hydrogen-based power generation systems.

4.2.2 Li-ion & Sodium Sulphur batteries: The life cycle inventories used to model the battery systems are sourced from the SUBAT project on sustainable batteries [58] for Li-ion batteries and from [59] for the sodium-sulfur batteries. Li-ion batteries were found to have significant impacts during the manufacturing stage, attributed to mining activities for copper and lithium and energy requirements for production. The charge/discharge efficiency directly influenced the impact of the use stage. NaS batteries showed similar patterns, with manufacturing impacts from mining activities and energy needs. Renewable energy mixes generally performed better than average electricity mixes, except for scenarios where the manufacturing burdens of solar panels offset gains from energy storage. Li-ion and NaS batteries performed below the Belgian mix threshold when storing wind energy.

4.2.3 CAES: The emissions analysis for Compressed Air Energy Storage (CAES) systems reveals distinct contributors to greenhouse gas (GHG) emissions. In CAES, natural gas combustion in the turbine constitutes the primary source of GHG emissions, while construction-related activities contribute less than 2% of total emissions. Turbomachinery and air storage mediums contribute significantly to the total life cycle of GHG emissions for CAES infrastructure. Notably, the environmental impact of electricity consumption during the use phase is substantial, emphasising the importance of transitioning to cleaner energy sources. Efforts to optimise construction processes and reduce material requirements could further mitigate the environmental footprint of CAES technologies. Table 1 summarises the emissions range for CAES and systems.

Table 10: Total CO_2 Emissions for Li-ion and NaS Batteries Across Energy Mixes

Energy Mix	**UCTE 2004**	**Belgium 2011**	**PV**	**Wind**
HES (kg CO_2-eq./kWh)	1.62	0.58	0.29	0.05
Li-ion (kg CO_2-eq./kWh)	0.6	0.25	0.15	0.068
NaS (kg CO_2-eq./kWh)	0.65	0.24	0.13	0.034
CAES (kg CO_2-eq./kWh)	0.75	0.27	0.14	0.024

4.3 Flywheel

The study by Md Mustafizur Rahman [60] compares steel and composite rotor flywheel energy storage systems, assessing their environmental performance through net energy ratio (NER) and greenhouse gas emissions with a functional unit as 1 MWh of electricity delivered over a 20-year project lifetime. The assessment includes inventory analysis of energy/material inputs/outputs and impact assessment on environmental performance.

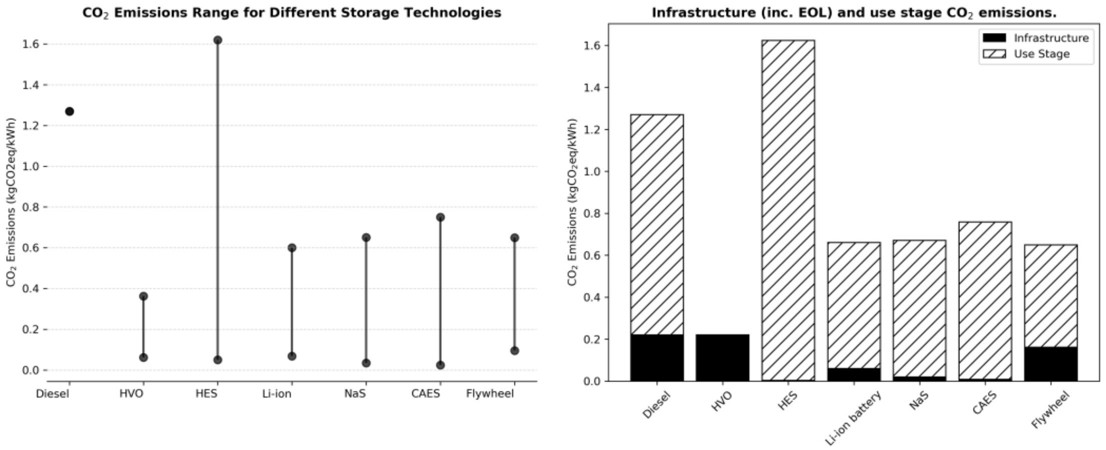
The life cycle assessment (LCA) of flywheel-based energy storage systems examines various phases contributing differently to greenhouse gas (GHG) emissions and energy consumption, including material production, manufacturing, operation, transportation, and end-of-life (EOL). Notably, the operation phase significantly contributes to GHG emissions, accounting for 60-75% for steel rotor FESS and 54-76% for composite rotor FBESS, with standby mode emissions contributing 34-70% and 17-48%, respectively. Material production emissions are 7.7 kg-CO_2eq/MWh for steel rotor FESS and 17.9 kg-CO_2eq/MWh for composite rotor FESS. In comparison, manufacturing emissions are 19.1 kg-CO_2eq/MWh and 1.7 kg-CO_2eq/MWh, respectively, with steel rotor manufacturing being more GHG-intensive. End-of-life emissions contribute 3-6% to the life cycle GHG emissions. Additionally, Table 11 compares flywheels' life cycle environmental impact with different electricity sources for charging, indicating that composite flywheels are a more environmentally friendly option for energy storage regarding carbon emissions. This assessment highlights the importance of considering various life cycle phases in evaluating the environmental performance of flywheel energy storage systems [61, 60].

The life cycle assessment values for global warming potential of various energy technologies, as shown in Figure 6(a), clearly demonstrate the environmental advantages of using wind energy,

Source of Electricity for charging	**Solar**	**Wind**	**Grid**	**Mixed**
Grid emission factor (kg-CO_2eq/MWh)	26 - 183	3 - 45	590	
Steel Flywheel (kg-CO_2eq/MWh)	121.4	95	649	288.5
Composite Flywheel (kg-CO_2eq/MWh)	75.2	48.9	623	249

Table 11: Life cycle carbon footprint of Flywheel [60, 61]

which results in the lowest CO_2 emissions. In stark contrast, energy systems dominated by fossil fuels contribute significantly higher emissions. This difference highlights the urgent need for a shift toward renewable energy sources. Further insights from Figure 6(b) show that the use phase—which is influenced by system efficiency and the energy mix—significantly impacts total emissions. This finding strengthens the case for adopting sustainable storage solutions, especially when paired with green energy generation. Such a move not only reduces environmental impact but also supports a broader shift towards sustainable energy practices.



(a) (b)

Figure 6: (a) GWP of various storage technologies (b) Infrastructure and Use phase CO_2 emissions

5 Financial assessment

5.1 Capital Costs:

The upfront capital expenditure denoted as $C_{\text{cap}}^{\text{initial}}$ (€), for an energy storage (ES) system encompasses all costs associated with its core components. These include storage containers, power converters, transformers, protective mechanisms, cooling systems, and other related hardware. This initial capital investment is categorically divided into three primary segments, as shown in equation 2:

- C_{SC} represents the cost of the storage container.
- C_{PC} covers the expenses for the power conversion systems.
- C_{BP}, or the balance of plant costs, pertains to the expenditures for protective devices, cooling systems, and other ancillary components.

The equation representing these contributions is:

$$C_{\text{cap}}^{\text{initial}} = C_{\text{SC}} + C_{\text{PC}} + C_{\text{BP}} \tag{2}$$

The annualized capital cost relative to the power capacity of the ES system (P), referred to as C_{t} (€/kW-year), provides a normalized metric to assess the capital efficiency per unit of power capacity, facilitating comparative analyses. The capital cost itself (C_t) can be detailed further:

$$C_t = \frac{C_{\text{cap}}^{\text{initial}}}{P} \times RF \tag{3}$$

Where RF is the recovery factor, calculated as:

$$RF = \frac{(1+r)^n - 1}{r \times (1+r)^n} \tag{4}$$

Here, r represents the discount rate and n the project's lifespan.

5.2 Operational and Maintenance Cost Estimations

Fixed and variable costs during the operational phase are crucial in overall cost calculations. The annual fixed costs do not depend on the operation phase and are typically lower, whereas variable costs can fluctuate based on the usage and maintenance requirements of the system. The total operational and maintenance cost, inclusive of fuel and other variable components when applicable, can thus be summarized:

$$M_t = C_{FOM} + C_{VOM} \tag{5}$$

Where C_{FOM} and C_{VOM} represent the fixed and variable operational and maintenance costs, respectively.

The annualized fixed cost per power capacity (€/kW-year) of an energy storage (ES) system can be computed by employing the annualizing factor (F_A), which incorporates the variation rate of fixed operation and maintenance costs (V_{FC}). The formula for the annualizing factor, which takes into account these operational costs, is provided below:

$$F_A = RF \sum_{m=1}^{n} \left(\frac{1 + V_{FC}^m}{1 + r^m} \right) \tag{6}$$

This equation reflects the compounded impact of the fixed operation and maintenance costs over the lifetime of the ES system, and m spans from 1 to n years of operation.
The fixed operational cost of an energy storage (ES) system, represented as C_{FOM}, integrates the annualized fixed costs and includes considerations for short-term operational scenarios. The primary calculation is outlined below:

$$C_{\text{FOM}} = C_{\text{fixed}} \times F_A + C_{\text{FOM}}^{\text{ST}} \tag{7}$$

where C_{fixed} is the fixed operation and maintenance cost coefficient.
For ES technologies intended for short-term applications, additional costs must be considered to cover the energy required to maintain readiness and compensate for self-discharge losses:

$$C_{\text{FOM}}^{\text{ST}} = B_{\text{elec}} \left(\frac{d}{24} \right) \left(\frac{S_{\text{dis}}}{100} \right) \times F_B \tag{8}$$

$$F_B = RF \sum_{m=1}^{n} \left(\frac{(1 + V_{\text{elec}})^m}{(1+r)^m} \right) \tag{9}$$

where B_{elec} is the market energy price, S_{dis} is the self-discharge rate, d is the number of working days, and V_{elec} is the rate of variation in energy prices.
Additionally, the variable operation and maintenance costs are formulated to reflect hourly operations:

$$C_{\text{VOM}} = B_{\text{elec}} \left(\frac{d}{24}\right) \left(\frac{h_d}{\mu}\right) \times F_B \tag{10}$$

For technologies that use natural gas, such as compressed air energy storage, the cost calculation is extended to include gas costs:

$$C_{\text{VOM}} = \left[B_{\text{elec}} \left(\frac{d}{24}\right) \left(\frac{h_d}{\mu}\right) \times F_B\right] + \left[B_{\text{gas}}\,(d)\,(h_d) \times G_r \times \frac{F_{\text{gas}}}{10^3}\right] \tag{11}$$

$$F_{\text{gas}} = RF \sum_{m=1}^{n} \left(\frac{(1+V_{\text{gas}})^m}{(1+r)^m}\right) \tag{12}$$

where h_d represents the operating hours per day, B_{gas} and G_r are the per unit gas cost and gas price factor, respectively, and V_{gas} represents the rate of variation in gas prices.

5.3 Replacement Costs

An energy storage project's service life typically exceeds its storage containers' operational lifespan due to ageing, technological wear and tear, and usage patterns. Consequently, the replacement costs for the storage containers are a critical component of the overall cost model for ES technologies. However, it is essential to note that replacement costs do not always extend to other system components, such as converters or balance of plant equipment, which may last for the entire duration of the project. The formula for calculating the annualized replacement costs is given as follows:

$$R_{\text{t}} = B_{\text{rep}} \times \frac{h \times N}{\mu} \times F_{\text{rep}} \tag{13}$$

where R_{t} represents the total replacement costs, B_{rep} is the unit replacement cost, h is the number of hours the component is operational per replacement cycle, N is the number of replacements during the project's life, and F_{rep} is the annual replacement cost factor.
The annual replacement cost factor, F_{rep}, is calculated as:

$$F_{\text{rep}} = RF \sum_{m=1}^{N} \left(\frac{1}{(1+r)^{m\times A}}\right) \tag{14}$$

where N is the number of replacements, and A is the period until the replacement of the ES is required.

5.4 Formulation of the cost model

In this work, the cost model for different types of energy storage (ES) technologies, which includes detailed economic metrics and operational factors, is developed in Python to ensure accurate calculations, effective data management, and rigorous testing, all of which guarantee the proper functioning of the model. Figure 7 shows a schematic diagram of the proposed cost model of the ES technologies.

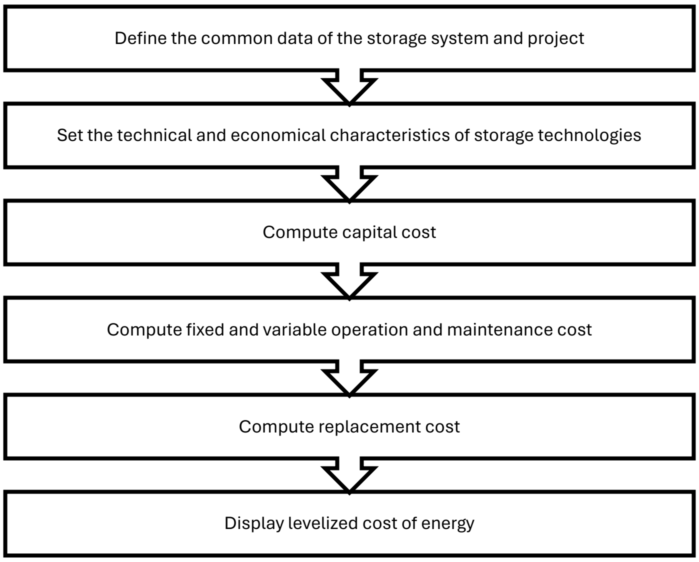


Figure 7: Schematic diagram of the proposed cost model of the ES technologies.

Table 12 provides the typical data and coefficients along a project lifetime, such as the discount rate, electricity price, rate of variation of the electricity cost, and rate of variation of the fixed operation and maintenance cost. The annual average electricity prices for the Netherlands for the year 2023 have been used for this study, which turns out to be 0.096 (€/kWh), which is rounded to 0.1 [62]. Similarly, the prices for diesel and renewable diesel have been taken for 2023 [63]. Commercially available values are considered for diesel-generator capital and maintenance costs. The storage systems have been sized to provide 24 hours of backup for a 1MW system.

Table 12: Common Data and Coefficients

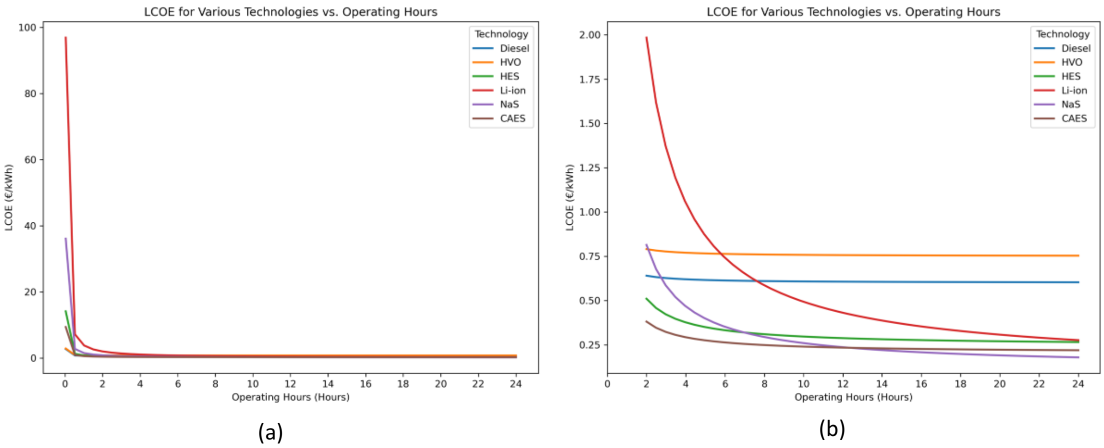
Parameter	Value
Lifespan of the project (years)	25
Market Price of Electricity (€/kWh)	0.1
Market Price of Diesel (€/kWh)	0.6
Market Price of HVO (€/kWh)	0.75
Discount rate	0.085
Rate of variation of Belec	0.03
Rate of variation of gas price	0.03
Rate of variation of FOM cost	0.01

Based on [64], [65], [66], [67], [68], [69], [70] the technical parameters required to perform the cost model are summarised in Table 13

Table 13: Energy Storage Configurations

Parameter	HES	Li-ion	NaS	CAES
P (Power Capacity MW)	1000	6000	4000	1000
E (Energy Capacity MWh)	25000	25000	25000	25000
c_s (Cost Storage €/kWh)	3.7	795	298	40
c_{pc} (Cost Power Conversion €/kW)	2465	463	366	843
c_{bp} (Cost Balance Plant €/kW)	25	80	80	15
μ (Efficiency %)	45	90	90	75
$DOD_{\max}$ (Max Depth of Discharge %)	100	80	80	60
c_{fixed} (Fixed Cost €/kW)	25	6.9	3.6	3.9
n (Cycle Life)	20000	4500	4500	250000
A (Age in Years)	15	10	12	40
N (Number of Replacements)	1	2	2	0
R_t (Replacement Cost)	413	795	298	0
d (Operating Days per Year)	365	365	365	365
S_{dis} (Self Discharge Rate)	0	0.002	0.2	0
G_r (Gas Rate Factor MJ/kWh)	-	-	-	4.43
B_{gas} (Gas Price €/GJ)	-	-	-	9.97

Diesel generators, traditionally employed for backup purposes, are characterized by their notably infrequent use, typically limited to approximately 14 hours annually (0.0384 hours daily average), primarily for testing and maintenance checks. Figure 8 delves into the LCOE across various technologies, examining the economic implications of different average daily operational hours.



(a) (b)

Figure 8: LCOE values of the ES technologies for operating hours in the range (a) 0 to 24 hours (b) 2 to 24 hours

From Figure 8(a), it is observed that the LCOE significantly decreases with even modest increases in the average daily operating hours. As shown in Table 13, the sizing requirements for batteries in terms of megawatts (MW) are higher than other technologies. This discrepancy arises because batteries possess inherently lower energy capacities due to their charge-discharge characteristics. In contrast, other technologies benefit from the ability to store fuel and utilize it as needed, offering a more flexible energy management approach. This leads to higher LCOE values for batteries. Figure 8(b) illustrates the LCOE across various technologies with daily average operating hours commencing from 2 hours. As previously noted, while batteries initially exhibit a higher LCOE, their costs decrease relative to diesel generators as operating hours increase (NaS has the least LCOE for a higher daily average operating hours). This cost efficiency is attributable to the higher efficiency of batteries and the economic advantage of electrical energy, which is significantly cheaper than diesel and HVO. A further decrease in the price of batteries will make a strong case for them. Notably, CAES is the most cost-effective technology across the observed range, followed by HES.

5.5 TCO_2

The social cost of carbon is incorporated, providing a more comprehensive understanding of the economic and environmental impacts of energy production. This adjusted calculation is called the $\mathrm{TCO_2}$, which sums up the traditional LCOE and the costs associated with purchasing carbon credits. The formula for the $\mathrm{TCO_2}$ is:

$$\mathrm{TCO_2} = \mathrm{LCOE} + C_{\mathrm{carbon}} \tag{15}$$

Table 14: LCOE and CO_2 Emissions for Various Energy Technologies

Technology	LCOE (€/kWh)	CO_2 Emissions Min (kg/kWh)	CO_2 Emissions Max (kg/kWh)
Diesel	0.64	1.27	1.27
Renewable Diesel (HVO)	0.79	0.061	0.363
Li-ion	1.98	0.068	0.6
NaS	0.81	0.038	0.65
HES	0.51	0.034	1.62
CAES	0.38	0.024	0.74

Table 14 presents the LCOE values for various storage technologies, assuming an average daily operation of two hours and the life cycle CO_2 emissions range. The minimum values indicate scenarios utilizing renewable energy sources, whereas the maximum values are derived from a predominantly fossil fuel-based energy mix.

The carbon credit costs required for various technologies to achieve the exact levelized cost of energy (LCOE) as diesel generators are specified as follows: For Renewable Diesel (HVO), the carbon price needs to range from €124.07/tonne to €165.38/tonne to match diesel's LCOE. Li-ion technology requires a significantly higher carbon price, ranging from €1,114.81/tonne to €2,000.00/tonne, to align with diesel's LCOE. For Sodium-sulfur (NaS) batteries, the carbon price varies between €137.99/tonne and €274.19/tonne to achieve equivalence. Hydrogen Energy Storage (HES) and Compressed Air Energy Storage (CAES) systems already exhibit lower LCOEs than diesel and have lower emissions, resulting in a consistently lower total cost of ownership than diesel generators.

Particularly for HES, if derived from green Hydrogen (produced using renewable energy sources), emissions are significantly lower than diesel generators. However, when the majority of energy used in hydrogen production comes from fossil fuels, emissions can be relatively high due to the low round-trip efficiency of the process. A carbon credit cost of €371.00/tonne is necessary for HES to equate its total carbon cost to diesel generators. Regarding HVO, current carbon prices already present a competitive alternative to diesel. As the production of HVO scales up and costs potentially decrease, it could become even more economically attractive, enhancing its market competitiveness.

Diesel generators, HES, and CAES systems typically require about 15 minutes for start-up. During this period, batteries have been traditionally employed to bridge the gap. However, FBESS emerge as a promising alternative due to their high efficiency and rapid response capabilities. For the initial start-up phase, the Levelized Cost of Energy (LCOE) for Sodium-sulfur (NaS) batteries, FBESS, and Lithium-ion (Li-ion) batteries increases in the mentioned order. It is important to note that the CO_2 emissions generated during this brief start-up phase are minimal and do not significantly affect the LCOE calculations.

6 Conclusion and Discussions

6.1 Key Findings

Renewable diesel has specific energy and energy density comparable to traditional diesel, allowing its use in existing diesel generators without modifications. This compatibility eases the transition to sustainable fuel options within established infrastructures. Hydrogen boasts a high specific energy but has a lower energy density. Its production versatility and adaptability across applications are significant advantages. However, hydrogen energy systems typically exhibit lower efficiency, requiring technological improvements for greater viability. Batteries are known for high efficiency and rapid response times, essential for applications needing quick energy dispatch. Their shorter lifespan compared to other storage technologies may limit long-term applications. Both batteries and flywheels provide immediate power during outages, but their energy storage capacity must be carefully sized to meet demand during critical backup periods. Their operation involves cyclic charging and discharging, which restricts available energy capacity at any moment. In contrast to fuel-based technologies, the operational capacity of batteries and flywheels is determined by their maximum stored energy and discharge rates. Flywheels, with low discharge times, can effectively replace batteries for the initial start-up of diesel generators, providing a quick energy-release solution. Compressed Air Energy Storage (CAES) has a long lifespan and is suitable for medium-term storage, but its feasibility is contingent on specific geographic conditions due to storage location requirements. $\mathrm{CO_2}$ emissions primarily occur during the use phase of these technologies. The efficiency of diesel generators directly affects emissions, with higher efficiency resulting in lower emissions. For other technologies, emissions depend significantly on the energy mix; systems powered by renewable sources emit far fewer emissions than those relying on fossil fuels. The Levelized Cost of Energy (LCOE) for storage systems varies with daily operational hours. CAES is cost-effective across different operating scenarios, while batteries and hydrogen energy systems (HES) face higher initial costs due to complex infrastructure needs. Nonetheless, HES has a lower LCOE than batteries, attributable to the higher sizing requirements of batteries. Fuel costs for renewable diesel significantly influence its LCOE. Overall, renewable diesel and CAES are scalable and cost-effective. The high upfront costs of batteries and HES underline the necessity for further research and development to reduce costs and enhance efficiency and lifespan.

6.2 Conclusions

In data centres that currently rely on diesel generator backups, transitioning to renewable diesel (HVO) presents a viable option due to its seamless integration with existing systems. While renewable diesel may be costlier initially, it is less carbon-intensive and could become more economical as production increases. Biodiesels are, therefore, crucial for the energy transition. Compressed Air Energy Storage (CAES) stands out for its lower lifecycle emissions and operational costs, making it an excellent choice when geographical conditions are favourable; if not, Hydrogen Energy Storage (HES) serves as a strong alternative with nearly comparable benefits.

Although batteries have a higher Levelized Cost of Energy (LCOE), their economic viability improves with extended daily operational hours, allowing them to potentially match or exceed the cost-effectiveness of diesel generators. However, extending backup times to three days significantly increases both capital and operational costs for batteries—tripling them compared to other technologies, which primarily face only rising fuel costs. Additionally, longer backup times necessitate more space to accommodate the larger battery systems. This emphasizes the importance of backup duration in technology selection for data centres. Both batteries and flywheels have unique characteristics and cost implications, yet their integration can substantially enhance operational resilience, ensuring reliable power during the start-up of conventional diesel generators.

6.3 Recommendations

Existing data centres using diesel generator backups should transition to renewable diesel to reduce environmental impacts. For new data centres, it is crucial to implement on-site renewable energy production or procure green energy to minimize CO_2 emissions. The choice of renewable energy should consider geographic and climatic conditions; for example, wind energy is effective in temperate and coastal regions, while solar energy performs best in hot, dry climates. Economically, designing storage systems to operate for an average of two hours daily may necessitate oversizing capacities. Emerging technologies like Liquid Air Energy Storage (LAES) and Small Modular Reactors (SMR) offer scalable and efficient backup solutions for hyper-scale data centres. These strategic implementations not only improve energy efficiency but also contribute to global efforts to reduce carbon footprints, guiding data centres towards more sustainable operations.

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