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COMPARATIVE LIFE CYCLE ASSESSMENT OF DIFFERENT ENERGY STORAGE TECHNOLOGIES

By

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A report submitted in partial fulfilment of the requirements for

the MSc and/or the DIC.

September 2017

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Comparative Life Cycle Assessment (LCA) of different energy storage technologies

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ABSTRACT

In a global effort for creating a sustainable future, the transition towards renewable energy sources seems inevitable for reducing the greenhouse gas emissions. However, the power networks face great challenges due to the unpredictable and seasonal energy production of renewables. Electrical energy storage technologies (EES) are encountering this problem by matching supply and demand through the storage of electricity surplus. The great variety of available technologies although, make it difficult for decision makers to select the most appropriate, while usually the environmental performance is not included in the selection criteria.

This study is trying to address this issue and provide transparent evidence for the environmental impacts of different energy storage technologies that could be used for further research. In this way, a comparison between the eight most promising and mature EES applications was conducting. More precisely, the Life Cycle Assessment principles were implemented in order to investigate the environmental burdens of several stationary energy storage applications. Specifically, PHS, CAES, Flywheel, and Hydrogen/Fuel cell systems as well as, Li-Ion, Lead-Acid, Sodium-Sulphur and VRF batteries were considered in this project. After a careful collection of input data, the different systems were modelled per kilowatt hour of storage capacity and then analysed based on three different characterization methods (Recipe, GWP and CED).

Results indicate that CAES technology presents the best performance in all three impact methods followed by the NaS battery which shows the lowest environmental impacts among the battery systems. In contrast, Hydrogen/PEM fuel cell installation displays the highest burdens in two out of three cases. Furthermore, PHS despite the expectations had quite extensive environmental impacts for all three categories but especially in regard to global warming contribution. Quite interesting is also the fact that all the results are by some hundreds higher than the literature review findings. Nevertheless, this divergence is probably caused by the different functional unit used in this report. This was also clarified by the comparison of the separate outcomes per kilogram of battery with the literature evidence. In conclusion, certain technologies such as CAES present great potential and should be further examined so as to justify and utilize the most environmentally EES techniques in the future.

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Abbreviations

SDG	Sustainable Development Goals
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
PHS	Pumped Hydroelectric Storage
CAES	Compressed Air Energy Storage
EES	Electrical Energy Storage
Li-Ion	Lithium-Ion Battery
PbAc	Lead-Acid Battery
NaS	Sodium-Sulphur Battery
VRFR	Vanadium Redox-Flow Battery
NMC	Lithium Nickel Manganese Cobalt Oxide Battery
LMO	Lithium Manganese Oxide Battery
LFP	Lithium Iron Phosphate Battery
NCA	Lithium Nickel Cobalt Aluminium Oxide Battery
LCO	Lithium Cobalt Oxide Battery
PEM	Proton Exchange Membrane
CO_2	Carbon Dioxide
GWP	Global Warming Potential
CED	Cumulative Energy Demand
PSB	Polysulfide Bromide Battery
SMES	Superconducting Magnetic Energy Storage
TES	Thermal Energy Storage

1. Introduction

In a world with finite resources, the conservation of the environment seems more necessary than ever in order to secure a sustainable future. The different nations around the world have realized their responsibilities and have already established specific sustainable development goals (SDGs) to be achieved by 2030. One of these SDGs is the affordable and clean energy for everyone. The clean - renewable energy is a major ally in the fight to maintain the global temperature rise below 2 degrees Celsius. Moreover, the last few decades major innovations have been achieved in the field of energy. The necessity for decarbonizing the energy in conjunction with the decrease in the price of renewable energy technologies such as wind farms and photovoltaic panels have created new opportunities for governments and public companies. In an environmental policy effort, governments are implementing new strategies for shifting the energy grid to more sustainable technologies. However, even if we could produce the entire world energy demand from renewables, we would still encounter one major problem called seasonal fluctuation and mismatch of demand. In detail, the energy production from renewable technologies is entirely depended on the weather condition. For instance, the PV panels can operate only between specific hours of the day. Although, the demand for energy during night hours can also be significant. Energy storage technologies are trying to address this problem and to identify viable solutions that will help societies to eliminate the CO_2 emissions from energy production which accounts for almost 35% of the total CO_2 emissions in the atmosphere. In this report, we are trying to compare eight different energy storage technologies from an environmental point of view through a Life Cycle Analysis. More precisely, a cradle-to-gate LCA was conducted based on the materials and energy requirements for the storage of 1 kWh of energy by Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), Lithium-Ion batteries, Lead-Acid batteries, Sodium-Sulphur batteries Vanadium Redox-Flow batteries, Flywheels and Hydrogen Electrolyser/Fuel Cell.

1.1. Energy Storage

Energy can be found in a number of different forms including thermal, electrical, chemical, kinetic, nuclear, radiant, sound, magnetic, elastic and gravitational. The storage of this energy for a potential use at a later time is called energy storage. Energy storage systems provide a wide range of technological approaches to managing the power supply in order to create a more resilient energy infrastructure and bring cost savings to utilities and consumers. There are quite a lot of emerging roles for electrical energy storage nowadays such as:

- Potential financial benefit for consumers by using EES systems during high demand periods.
- Secure of flexible supply by utilizing of EES in a period when conventional power supply fails to meet energy demand.
- Minimizing failures of the grid due to natural disasters between generation and consumption of electricity.
- Reinforcement of renewable technologies and mitigation of fossil fuels and CO_2.
- EES are expected to play a fundamental role in the future shift towards smart grids not only for remote areas but also for upgrade of the existing installed grid.
- The key feature for the promotion of the electric vehicles and the installation of charging stations.

Nevertheless, most of the technologies are not still mature, explaining the fact that over 99% of the global energy storage capacity is stored in Pumped Hydropower plants as we can observe from the findings of the integrated report conducted by the International Electrotechnical Commission in 2011 (Figure 1). It is important to point out that some changes on the percentages of the stored capacity may have been occurred during the last 6 years due to further installations. However, these changes are not significant. We can see that CAES is the technology with the second highest stored capacity. This can be explained by the fact that PHS and CAES are the two techniques with the highest rated power and therefore easier to achieve large storage capacities. The only drawback for PHS and CAES is their dependence on specific geographical formations (*Energy Storage Technologies* **|** *Energy Storage Association*, no date; IEC, 2011; European Commission, 2013).

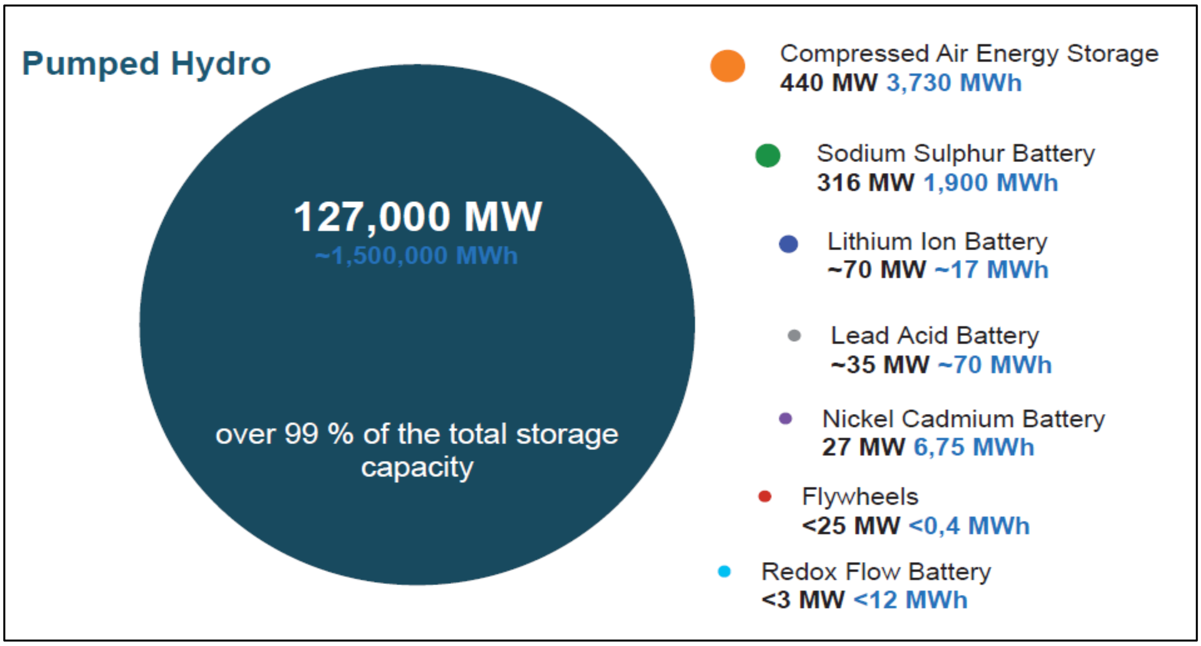

Figure 1: Worldwide installed energy storage capacity (IEC, 2011).

1.1.1. Energy Storage Technologies

There is a great number of different energy storage technologies, with some of them being more mature than others and a few of them being still in a laboratory level. Nevertheless, all of them are classified by the form of stored energy in six specific categories shown in Figure 2.

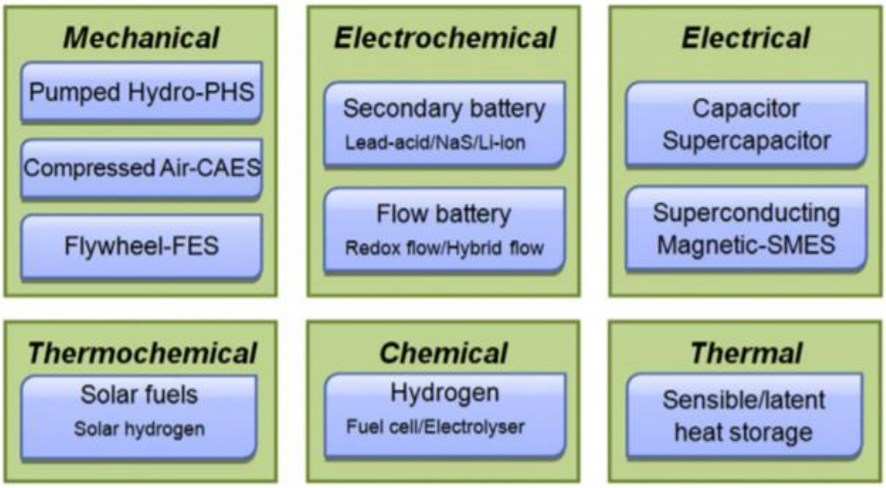

Figure 2: Classification of energy storage technologies by the form of stored energy (Munoz, Garcia and Gerlich, 2016).

Table 1: Technical and economical characteristics of electrical energy storage technologies (Luo *et al.*, 2015).

Technology	Specific energy (Wh/kg)	Rated energy capacity (MWh)	Lifetime (years)	Cycling times (cycles)	Cycle efficiency (%)	Energy capital cost ($/kWh)
PHS	0.5-1.5	500-8,000	40-60	10,000-30,000	70-85	5-100
Large-scale CAES	2-6	<1000,580, 2860	20-40	8,000–12,000	42, 54	2-120
Small-scale CAES	>2-6	0.01, 0.002-0.0083	>23	~30,000	-	200-250
Flywheels	20-80	0.0052, 0.75, - 5	~15-20	20,000+	90-95	1,000-14,000
Lead-Acid	50-90	0.001-40	5-15	200–1800	63-90	50-100, 200-400
Li-Ion	150-500	0.004-10	5-16	1,000–10,000	75-97	600-2,500, 2,770-3,800
NaS	150-300	0.4-244.8	10-20	2,500–4,500	75-90	300-500
NiCd	15-150	6.75	3-20	~2,000–2,500	60-83	400-2,400
VRB	16-35	<60	5-10, 20	12,000+	65-85	150-1,000
ZnBr	30-65	0.1-3, 4, 0.05	5-10	2000+	65-80	150-1,000
PSB	20-30	- 120	10-15	-	60-75	150-1,000
Capacitor	2-10	-	1-10	50,000+	60-70+	500-1,000
Super-capacitor	10-30	0.0005	10-30	100,000+	84-97	300-2,000
SMES	0.2-6	0.0008, 0.015	>20	100,000+	95-98	500-72,000
Solar Fuel	500-10,000	-	-	-	~20-30	-
Hydrogen/ Fuel Cell	500-3,000	0.312	5-20	1,000+, 20,000+	~20-60	2-15
TES	80-500	-	5-20, 30	-	~30-60	~3-60
Liquid Air Storage	4-6 times > than CAES	2.5	>25	-	55-80+	260-530

The selection among different EES relies on the assessment of their characteristics against the requirements of the power system applications. Table 1 includes some of the key characteristics of the most promising EES such as the specific energy, the cycle efficiency etc. Specific energy represents the total energy per unit of weight. It can be seen that most batteries, flywheels, and fuel cells have relatively moderate specific energies, while PHS and CAES have lower and therefore are mainly used for stationary EES applications.

Cycle efficiency or round-trip efficiency is the total electricity output to the total electricity input and is one of the key criteria for the deployment of those technologies. Most commercialized techniques like PHS, flywheels, and batteries have medium to high cycle efficiencies, while CAES and fuel cells have low cycle efficiency. However, there is a continuous effort for improvement of the cycle efficiency by the scientists in order for EES to become more attractive. All the characteristics in Table 1 were gathered from several different reports in the literature.

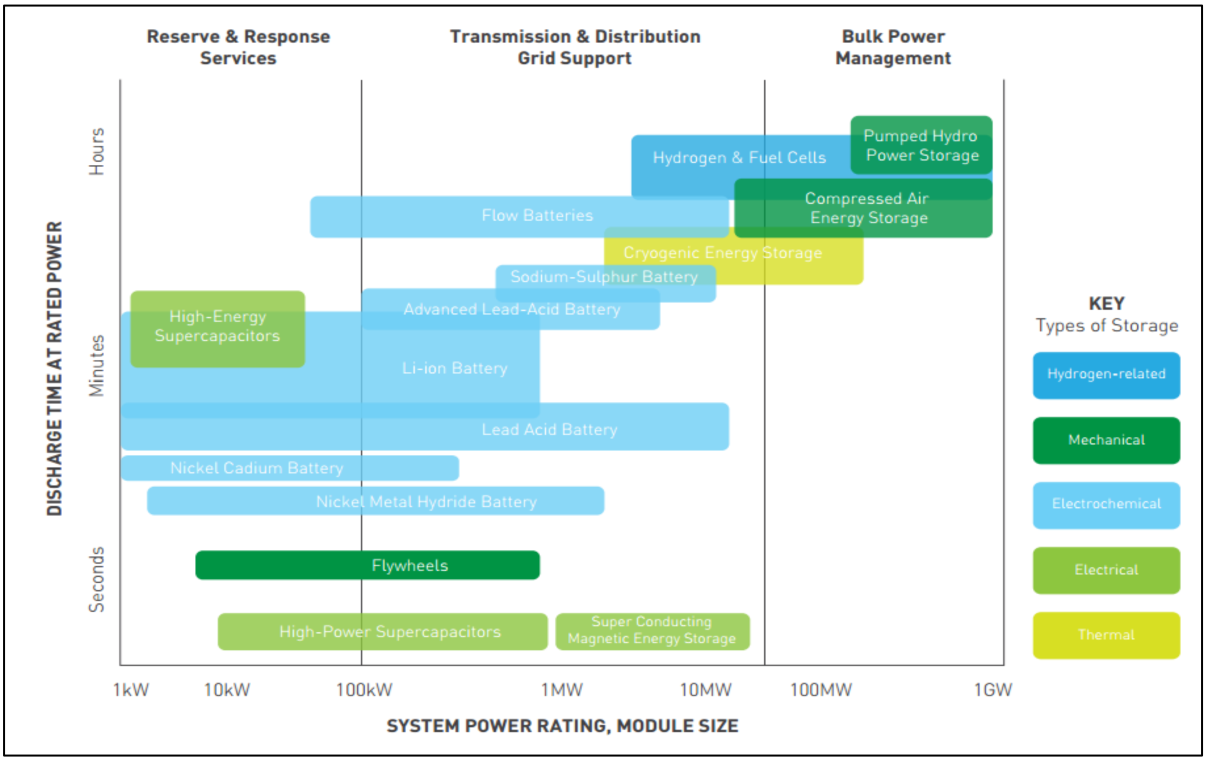

Figure 3: Applications for the different energy storage technologies (Taylor *et al.,* 2012).

As presented in Figure 3, EES is suitable for different applications based on their power rating and discharge time. More specifically, the techniques in the left side of the scale like flywheels and supercapacitors are more sufficient for smoothing short-term fluctuations such as those caused by line faults. On the other side, PHS and CAES can easily store excess electricity produced by renewables for potential future use (Taylor *et al.*, 2012).

2. Literature Review

In this chapter are going to be addressed the characteristics of the eight technologies examined in this study as well as the findings from previous reports in the literature.

2.1. Technologies Review

PHS

As we mentioned earlier Pumped Hydroelectric Energy Storage (PHS) is the overwhelmingly established bulk EES technology and has been an integral part of many markets since the1960s. PHS stores gravitational energy by elevating water. During the charging process, it converts electrical energy into mechanical energy by pumping water from a lower reservoir to a higher reservoir and the discharging process is the reverse. Pumped storage schemes can either operate using reversible pump-turbines or hydro turbines and separate pumps depending on the site. It is commonly used for peak load generation, but it can also be used for black staring electricity grids in the event of failure (Zini and Tartarini, 2012; Gimeno-Gutiérrez and Lacal-Arántegui, 2013; Brandon *et al.*, 2016).

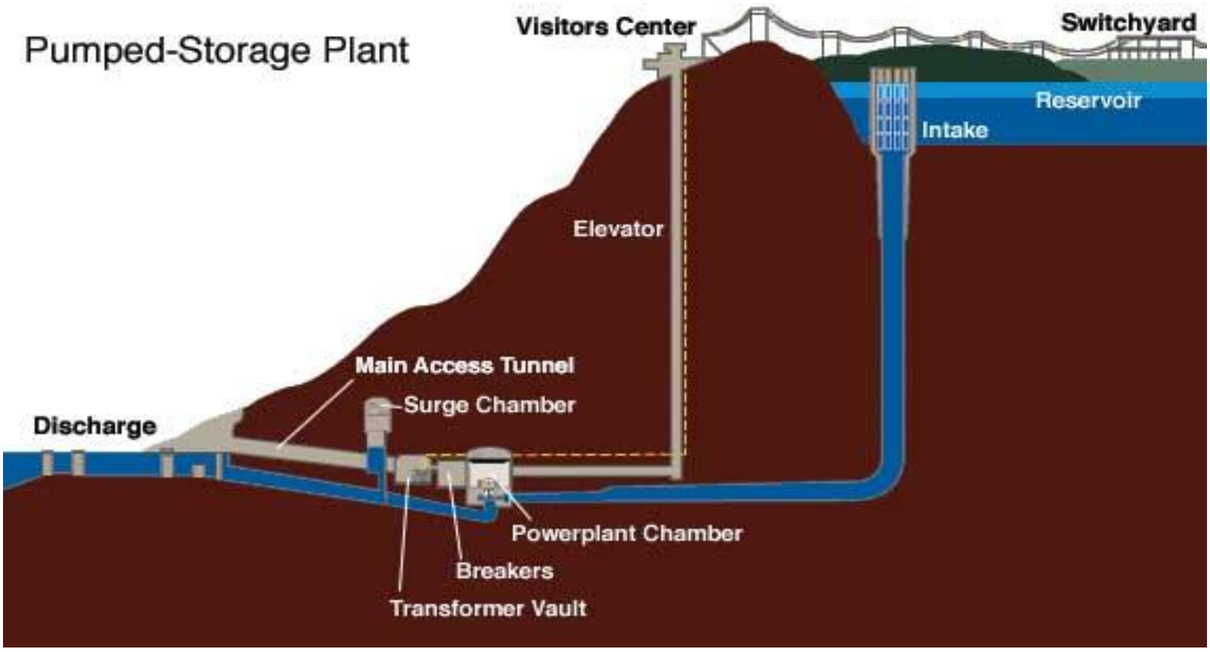

Figure 4: Conceptual model of Pumped Hydroelectric Energy Storage (Wikipedia).

Table 2: Advantages and Disadvantages of Pumped Hydroelectric Energy Storage.

Advantages	Disadvantages
Mature technology	Geographically constrained
Large power and energy capacity	Limited potential for further plants
Fast response	Centralised grid application

CAES

Compressed Air Energy Storage (CAES) is another type of commercialized EES technology which can provide a power output of over 100MW with a single unit. During low demand periods, the surplus electricity drives a reversible generator in order to run one or two compressors which are injecting air into an air storage cavern. This cavern can be either underground or over ground tanks depending on the size of the plant. The power is stored in the form of high-pressure air. When the demand for electricity is high, the air is released and heated via combustion using natural gas in order to drive a gas turbine to generate electricity. In the recent years, a lot of research is being performed into the use of adiabatic CAES, in a way of minimizing the energy losses through thermal energy storage and consequently to increase the total efficiency of the system (Zini and Tartarini, 2012; Lott and Kim, 2014; Luo *et al.*, 2015).

Table 3: Advantages and Disadvantages of Compressed Air Energy Storage.

Advantages	Disadvantages
Mature mechanical technology	Geographically constrained
Large power and energy capacity	Low round trip efficiency
Long lifetime	Demand for natural gas

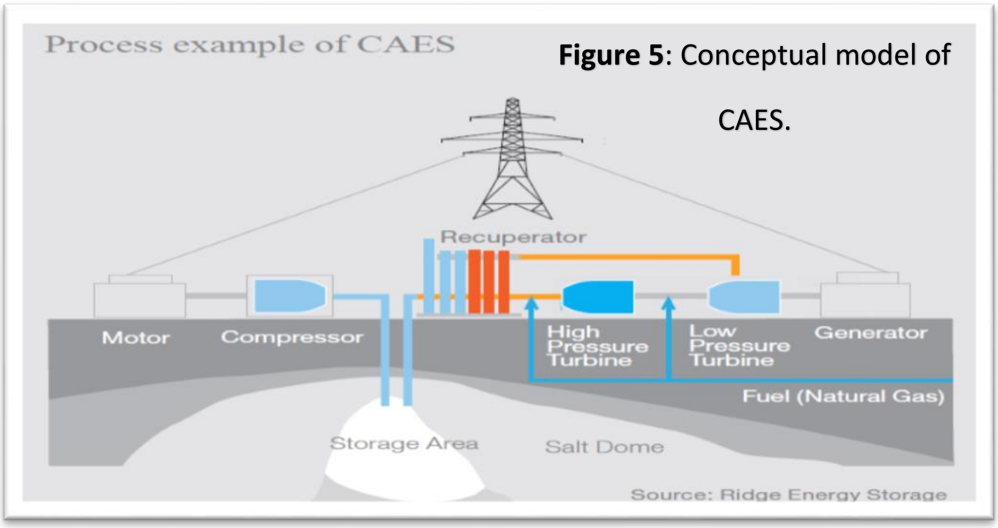

Figure 5: Conceptual model of CAES.

Hydrogen Electrolyser/Fuel Cell

Another very promising EES technology has developed extensively the last decades called Hydrogen storage with Fuel Cells. Hydrogen energy storage systems use two separate processes for storing energy and producing electricity. During charge, water is electrolyzed to produce hydrogen and oxygen. The hydrogen can either be stored as compressed gas in tanks or as liquid in very low temperatures, while the oxygen is released to the atmosphere. When needed, fuel cell can convert the chemical energy to electricity by recombining the stored hydrogen with oxygen. Heat and water are also released as by-products during this process (Ashby and Polyblank, 2012; Zini and Tartarini, 2012; Luo *et al.*, 2015; Few, Schmidt and Gambhir, 2016; Munoz, Garcia and Gerlich, 2016). The chemical reactions taking place are the following:

1. Charging: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ & $2H^+ + 2e^- \rightarrow H_2$
2. Discharging: $H_2 \rightarrow 2H^+ + 2e^-$ & $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Table 4: Advantages and Disadvantages of Hydrogen/Fuel Cell energy storage.

Advantages	**Disadvantages**
Easily transported to the demand point	Fuel cell technologies are expensive
Multiple uses (Power vehicles)	Low round trip efficiency
Absence of self-discharge	Potential safety concerns over hydrogen

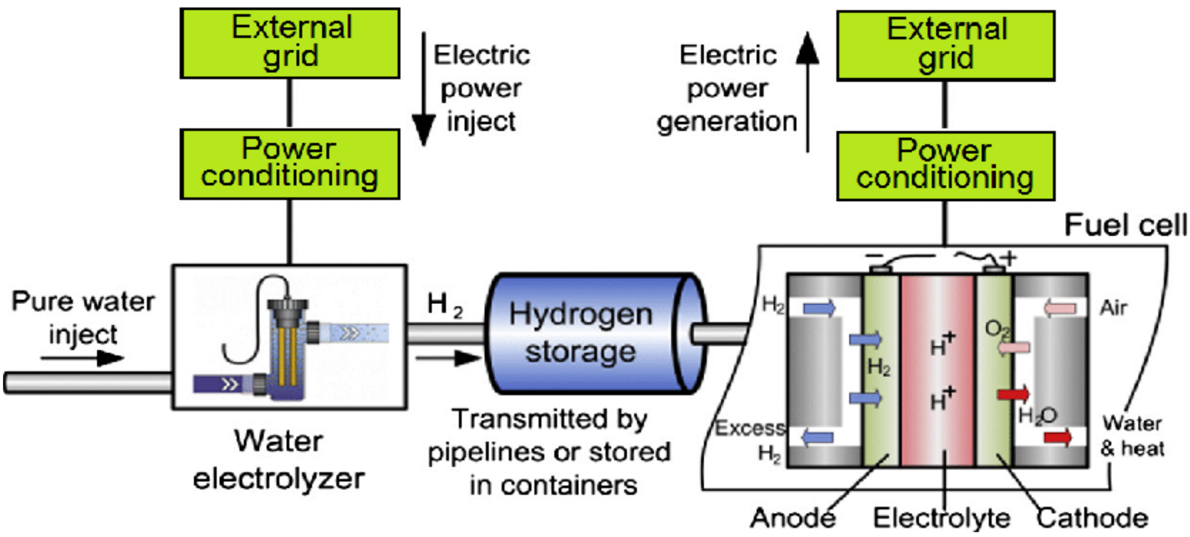

Figure 6: Conceptual model of Hydrogen Electrolyser/Fuel Cell Energy Storage system (J.Kleperis, 2016).

Flywheels

Flywheels use electricity to accelerate a low-friction wheel in order to take advantage of the mechanical inertia and manage to store energy. During discharge, the wheel is decelerated and the energy is transferred to the coupling generator which produces electricity.

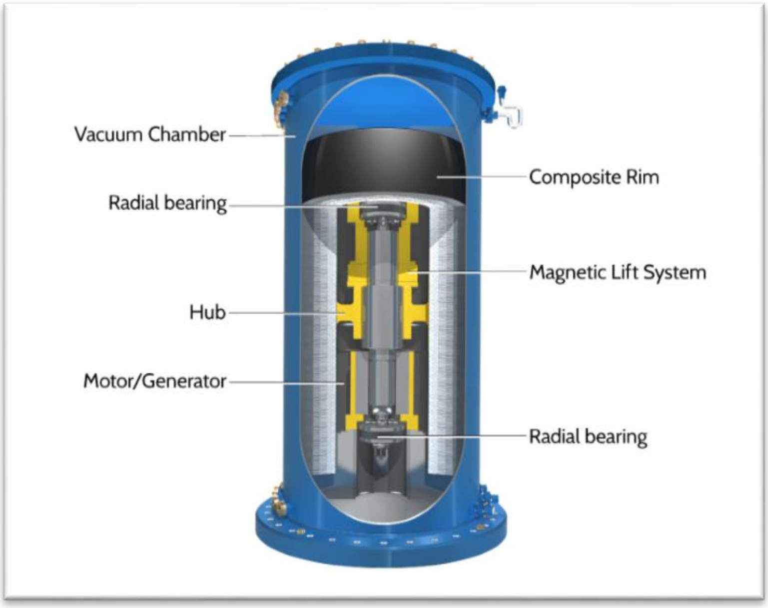

Figure 7: Conceptual model of flywheels (Beacon Power).

At the same time, the flywheel is placed inside a vacuum where the rotor is levitated by superconducting magnetic bearings in order to minimize the frictional losses. There are two groups of flywheels: a) the low speed and b) the high speed with the first group commonly used for short term storage (Ashby and Polyblank, 2012; Zini and Tartarini, 2012; Luo *et al.*, 2015; Few, Schmidt and Gambhir, 2016).

Table 5: Advantages and Disadvantages of Flywheels energy storage system.

Advantages	Disadvantages
Low maintenance cost	High price
Rapid response times	Potentially hazardous failure
Unlimited number of charges in theory	Mechanical stress and fatigue limits

Lithium-Ion Battery

The term lithium-ion battery refers to an electrochemical device in which lithium ions shuttle between electrodes. For instance, during discharge lithium ions move from the negative electrode/anode (carbon, typically graphite) to the positive electrode/cathode (usually lithiated metal oxides or phosphates). This type of battery is widely used for portable devices as well as electric vehicles due to its high energy density, whereas is expected to play a fundamental role for larger scale energy storage as cost is constantly reduced (*Lithium Ion (LI-ION) Batteries | Energy Storage Association*, accessed: 13/08/2017; Ashby and Polyblank, 2012; Zini and Tartarini, 2012; Luo *et al.*, 2015; Few, Schmidt and Gambhir, 2016).

Table 6: Advantages and Disadvantages of Lithium-Ion Battery energy storage.

Advantages	Disadvantages
Very high energy density	High price
High efficiency	Deterioration during its lifetime
Relatively high number of discharge cycles	Potentially hazardous failure due to overheating

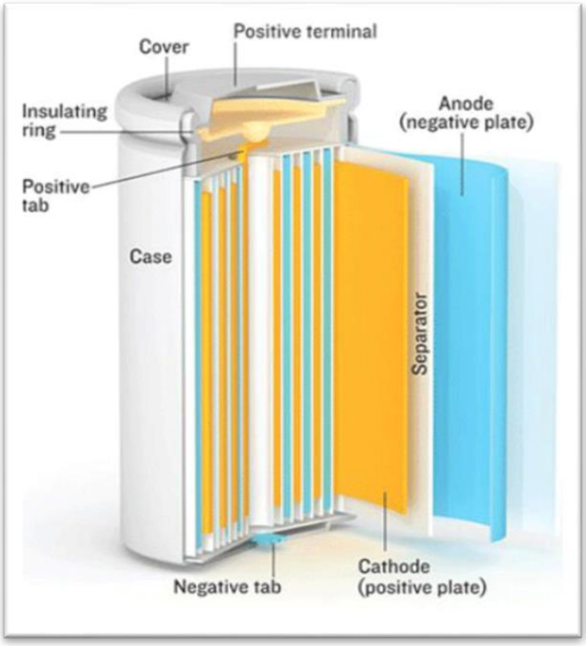

Figure 8: Conceptual model of Lithium-Ion Battery

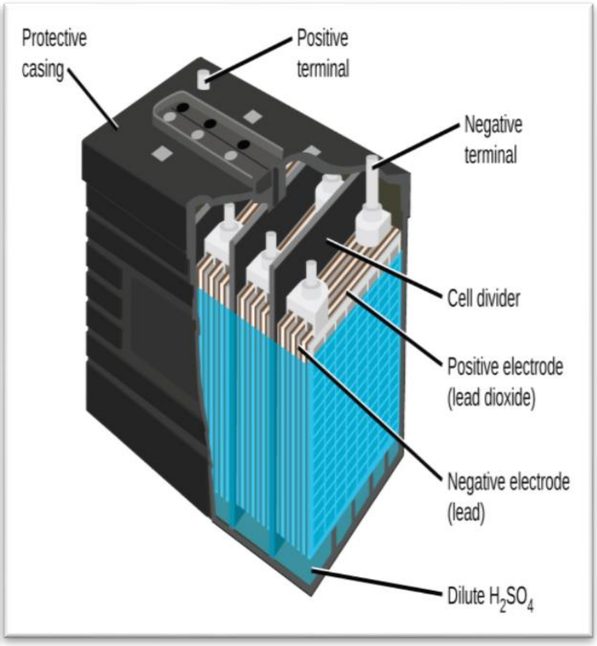

Figure 9: Conceptual model of Lead-Acid Battery

Lead-Acid Battery

One of the most well established electrochemical energy storage technologies is the lead-acid batteries. Lead-acid batteries are composed of a lead-dioxide cathode, a sponge metallic lead anode, and a sulphuric acid solution electrolyte. During discharge, the lead dioxide (positive plate) and lead (negative plate) react with the electrolyte of sulfuric acid to create lead sulfate, water and energy and conversely over charging. They are predominately used for backup power supplies, energy management applications, as well as for staring vehicle engines (Ashby and Polyblank, 2012; Zini and Tartarini, 2012; Luo *et al.*, 2015; Few, Schmidt and Gambhir, 2016).

Table 7: Advantages and Disadvantages of Lead-Acid Battery energy storage.

Advantages	Disadvantages
Low self-discharge rates	Low energy density
Relatively efficient	Hazardous materials
Low cost and well established	Sensitive to high depths of discharge

Sodium - Sulphur Battery (NaS)

Another renowned battery type for stationary storage application called sodium-sulphur battery. It is a molten state battery constructed from sodium (Na) and sulphur (S). On discharge, the sodium is oxidized and the ions pass through an alumina electrolyte to reduce the sulphur and create sodium polysulfide. During charging this process is reversed. This type of battery usually operates at high temperatures of between 300-350°C to ensure that electrodes are in liquid state. Most of the current applications of NaS are located in Japan (Ashby and Polyblank, 2012; Zini and Tartarini, 2012; Applications and Battery, 2015; Luo *et al.*, 2015; Few, Schmidt and Gambhir, 2016).

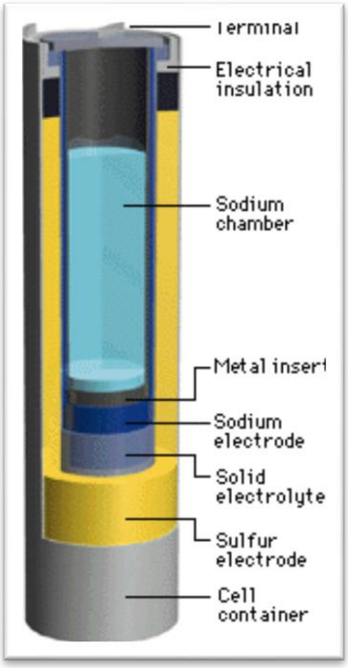

Figure 10: Conceptual model of Sodium - Sulphur Battery.

Table 8: Advantages and Disadvantages of Sodium-Sulphur Battery energy storage.

Advantages	Disadvantages
High energy density	Safety issues of the molten sodium
Quick response	Challenge to keep high temperature
Long life cycle & high efficiency	Potential corrosion of the insulators

Vanadium Redox-flow Battery (VRFBs)

The last type of rechargeable battery examined in this report is the vanadium redox-flow, which utilizes vanadium ions in different oxidation states in order to store chemical energy. The electrolytes are stored in two different tanks and during charge or discharge are pumped through the battery cell where they are undergoing reversible chemical reactions such as reduction or oxidation. The two electrolytes are separated by a proton exchange membrane while the normal operating temperature is approximately between 10 – 40 °C. Even if VRFBs consist one of the most mature technologies among flow type batteries, such as uranium redox flow battery, polysulfide bromide battery, iron chromium flow battery and zinc bromine battery, they still bear some risks (*Vanadium Redox (VRB) Flow Batteries | Energy Storage Association*, no date; Ashby and Polyblank, 2012; Alotto, Guarnieri and Moro, 2014; Luo *et al.*, 2015; Few, Schmidt and Gambhir, 2016).

Table 9: Advantages and Disadvantages of Vanadium Redox-flow Battery snergy storage.

Advantages	Disadvantages
Relatively high efficiency	High capital cost per capacity
Quick response times	Low energy density
Very high cycle life	Strict operating temperature window

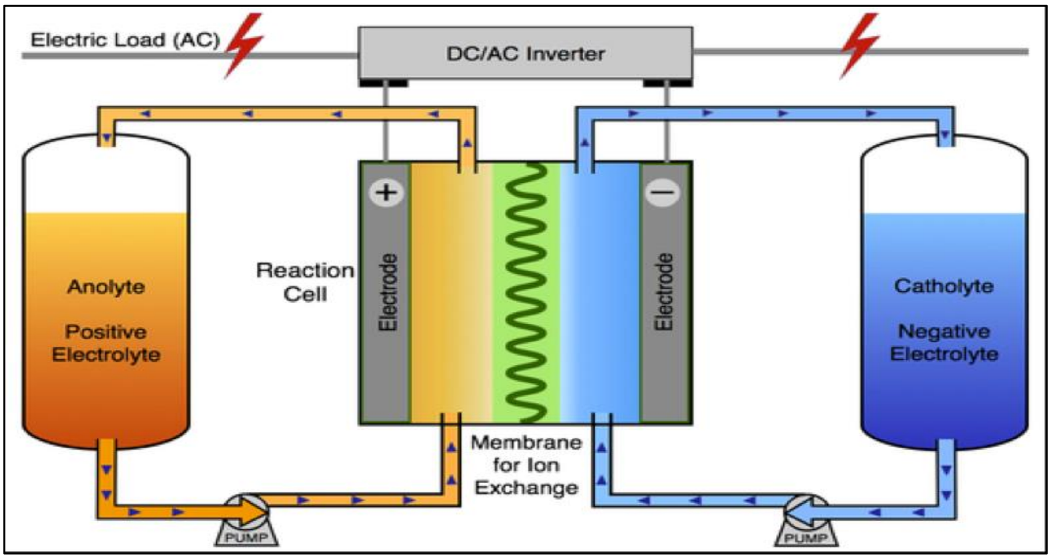

Figure 11: Conceptual model of Vanadium Redox-flow Battery Energy Storage.

2.2. Results of previous studies

As societies seek to move towards renewable energy the last decades, it has been created a very extensive research field around energy storage. Although most of the studies focus on the performance and the efficiency of the different energy storage technologies there are still several studies considering the environmental impacts of each energy storage method and its contribution to the climate change.

The most recent report on energy storage from world energy council clarifies that PHS is the only technology which burdens the land use and the water reserves. At the same time, it was mentioned that PHS and CAES are likely to produce significant ecosystem modification due to large scale installations. Based on the literature batteries utilize considerably more energy in their manufacturing stages than other forms of energy storage. Furthermore, batteries require an extensive load of materials for their manufacture and this creates pressure on the environment on a local level where mining takes place (World Energy Council, 2016).

Another integrated report by L. Oliveira et al. which includes almost all the technologies considered in this dissertation indicates that sodium-sulphur batteries (NaS) and pumped hydro energy storage (PHS) demostrates the lowest environmental impact, while the energy storage in hydrogen has the highest contribution to the climate change and more precisely almost ten times higher influence on the particulate matter formation than all the others. On the other hand, as for the CO_2 emissions at the infrastructure stage, the lead-acid batteries have the higher impact followed by the lithium-ion batteries, in contrast to the hydrogen energy storage and the PHS which have the lower emissions. It's important to mention that in this report it a cradle-to-grave LCA was conducted, so the outcome may differentiate from our results (Oliveira *et al.*, 2015).

One year earlier, a very comprehensive comparative life cycle assessment of battery storage systems for stationary applications was conducted by Mitavachan Hiremath et al. As they concluded lithium-ion batteries are more environmentally friendly than all the other types due to its very high cycle life and round-trip efficiency. The cradle to gate impacts showed that lithium-ion and vanadium redox flow batteries exhibit the lowest cumulative energy demand and the lowest contribution to the global warming than all the other batteries, while lead acid demonstrates almost five times higher impacts per MWh_d of electricity. When the usage stage is considered the results are even more favourable for lithium-ion batteries. Moreover, a qualitative analysis of Li-Ion revealed that the most environmentally harmful feature of them is the positive electrode, especially regarding the metal depletion impact category (Mitavachan, 2014).

One of the few LCA studies for flywheels energy storage carried out by Schneider Electric in 2015 focused only on cradle to grave carbon footprint of the technology and not on other categories such as fossil fuel depletion, human health or climate change. As the analysis demonstrated, even if the raw materials and the maintenance requirements for the lifecycle of the flywheels are fewer than VRLA batteries, VRLA display a lower total carbon footprint than flywheels. This is due to the difference in operating energy over the lifetime of the two technologies (Torell, 2015).

Finally, Charles J. Barnhart and Sally M. Benson quantified the energy and material resource requirements for lithium ion (Li-ion), sodium sulphur (NaS), lead-acid (PbA) and vanadium redox (VRB) flow batteries as well as pumped hydroelectric storage (PHS) and compressed air energy storage (CAES). As they clarify in their report, electrochemical energy storage technologies are very energy intensive and they will stretch the global energy supplies, especially in conjunction with future large-scale installations. Their research indicated that CAES and PHS are by 100 fold less intensive that batteries, however, when material resources are considered NaS and CAES are the two leading technologies with the minimum material requirements (Barnhart and Benson, 2013).

In table 10 below are presented some aggregated results from the literature. The findings cover two main categories that are going to be examined in this study. Although, the majority of the numbers are expressed in kWh of electricity produced which does not correspond to the functional unit of this report. Only (Paul Denholm et. al findings are normalized per kWh of storage capacity. It appears that the findings are highly variable something that relates to the particularities of each study.

Table 10: Literature results for the performance of the different applications regarding the GHG emissions and the CED per kWh of electricity produced.

System	GWP/GHG emissions (kg CO_2 eq./kwh)	CED (MWh/kwh)	Reference
PHS	35.7*	0.103*	(Paul Denholm et. al)
	0.006	-	(L. Oliveira et. al)
CAES	19.4*	0.073*	(Paul Denholm et. al)
	0.008	-	(L. Oliveira et. al)
Flywheel	12	-	(Wendy Torell)
Hydrogen/Fuel cell	8.3	-	(Nadia Belmonte et. al)
	0.003	-	(L. Oliveira et. al)
Li-Ion	0.01	0.042	(Mitavachan H.)
	0.063	-	(L. Oliveira et. al)
Lead-Acid	0.091	0.226	(Mitavachan H.)
	0.11	-	(L. Oliveira et. al)
NaS	0.031	0.123	(Mitavachan H.)
	0.023	-	(L. Oliveira et. al)
VRFB	0.011	0.044	(Mitavachan H.)

*These numbers are expressed per kWh of storage capacity.

2.3. Literature Gap

Taking into account all the previous studies as well as the importance of a fast transition towards sustainable energy forms, we decided to conduct an extensive study about the environmental burden of some of the most promising technologies for stationary energy storage based on their energy and material requirements from cradle-to-gate. This study tries to fulfil the literature gap regarding the environmental performance of mechanical and electrochemical storage techniques by combining the findings or available data in the literature and comparing several technologies for stationary applications under the same assumptions. The main objective lies on the importance for decision makers and investors to identify easily the best available solution for future installations considering also the environment.

3. Methodology

3.1. Life Cycle Analysis overview

The objective of achieving "sustainable development" requires methods, which will help in the quantification and comparison of the environmental impacts of various products and services present in our societies. Life cycle analysis is a decision support tool supplying information on the environmental effects of products. It furnishes information on the environmental effects of all stages of a product's life cycle. This information can be used by governments, NGO's and companies when making decisions related to products. Climate change, depletion of stratospheric ozone, smog formation, eutrophication, and toxicological impacts on humans and the ecosystem, resources depletion, water consumption and land use, as well as noise, are some of the impacts assessed by the LCA. Its objective is the final assessment of the potential for reducing the existing environmental impacts, always alongside with the rational use of energy and raw materials (Unep, 2003).

There are four phases in a life cycle analysis:

1. Goal and scope definition
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Analysis (LCIA)
4. Interpretation of results

3.1.1. Life Cycle Analysis Stages

<u>Goal and Scope</u>

This stage includes initially the purposes of the study, followed by the description of the system and determination of its boundaries. The functional unit, which is a quantitative measure of the functions provided by various goods, is defined at this stage. Furthermore, the target audience is determined, as well as the type of report required for the study. All the above help us ensure that a comprehensive and correct life cycle assessment has been performed (Rebitzer *et al.*, 2004).

<u>Life Cycle Inventory</u>

Life Cycle Inventory is a methodology to assess resource consumption and quantity of waste flows and emissions created by a product's life cycle. Resource consumption and waste or emissions generation may take place in multiple areas of the world and at different time points or even during different time periods. For example, landfill could impact both the existing and future generations. The processes within the life cycle, the corresponding material, and energy flows, as well as various other processes, are modelled so as to reflect the production system and its overall flow from and towards the natural environment. Therefore, at this stage data collection and recording is required, which is usually the most time-consuming part of the life cycle analysis (Finnveden *et al.*, 2009).

Life Cycle Impact Assessment - LCIA

At this stage, correlation indices are provided between the resources exploitation-waste/emissions and the environmental impacts of various categories. Categories like climate change, noise, and land use. According to ISO 2006, the following are included in this stage:

1. Selection of environmental impacts' categories that will be examined and their classification resulting from their study.
2. Selection of characterisation methods. For example, the global warming potential for a time horizon of 100 years is often a characterisation factor of climate change.
3. Normalisation - Standardisation in order to facilitate results' interpretation.
4. Grouping
5. Weighting

The last two stages are optional (Rebitzer *et al.*, 2004).

Interpretation

In this final stage, the product's life cycle analysis results are recorded and interpreted, together with assessments for any improvements to reduce the potential environmental impacts.

3.1.2. SimaPro8

SimaPro8 software is developed and supplied by PreConsultants B.V. It is a well-known software, for conducting Life Cycle Assessments as it provides the right communication tools for enhancing facts that can lead in solid sustainable decisions. Furthermore, it contains some of the latest science-based methods for analysis as well as a great variety of databases that can be used for the characterization of the system.

SimaPro8 enables data exploitation through their use, either as a data system or as separate units, both for input and for output data. Moreover, it helps the user to identify possible hotspots in all aspects of a product supply, from raw material extraction to disposal. Finally, the results produced are really transparent and easy to understand for all the different impact assessment methods such as carbon footprint, water footprint, global warming potential etc.

3.2. Goal and Scope definition

The goal of this study is to carry out a comparative life cycle assessment for eight different energy storage technologies in possible stationary applications and rank their performance from an environmental point of view. Thus, a cradle-to-gate analysis for their construction phase was conducted and then their results were assessed based on their cumulative energy demand, their contribution to global warming as well as regarding three additional impact categories (human health, ecosystem and resources). The eight techniques examined are namely:

- Lithium-Ion batteries
- Lead-Acid batteries
- Sodium-Sulphur batteries
- Vanadium redox-flow batteries
- Pumped Hydropower energy storage
- Compressed air energy storage
- Hydrogen storage/ Fuel cell

3.3. System Boundaries

Probably the most important element to understand the scope of this LCA, as well as its applicability, is the system boundaries. First of all, it needs to be clarified that in this cradle-to-gate study only the manufacturing-assembling phase was considered and not the operation or end-of-life stage. More precisely, the eight technologies were assessed based on their material inputs and energy demand during construction phase as well as for their land use requirements. For the four batteries as well as the flywheel application it was also included an inverter in the modelling as it is required for such stationary systems. Moreover, emissions during the assembling were not considered. Finally, it's important to be mentioned that for batteries and flywheel potential needs for factory deployment are not accounted in this study. The reason for these strictly limited boundaries was initially the lack of available data in the literature review and secondly the attempt to minimize the error and the uncertainty in the results. In the following flow diagram are presented the boundaries for the CAES/PHS/Hydrogen-Fuel Cell and the Li-ion/PbAc/NaS/VRFB/Flywheel systems respectively.

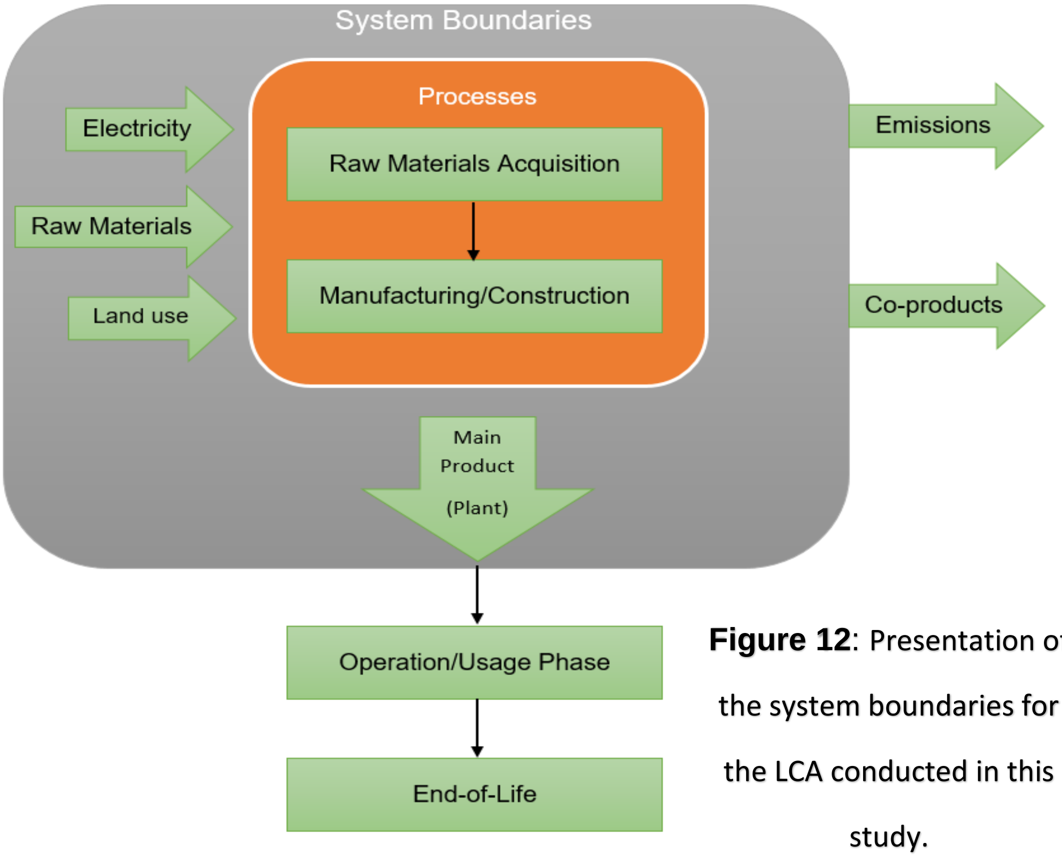

Figure 12: Presentation of the system boundaries for the LCA conducted in this study.

As the supplier of the different materials and equipment was unknown, the global market processes were chosen in SimaPro8. These market processes include inputs from production in several countries as well as inputs of average transportation. However, as we consider a stationary application in the UK, it was decided to utilise the UK electricity mix (medium or high voltage depending on the case).

At this stage, it should be mentioned that despite the extraordinary effort to gather primary data from several companies dealing with energy storage technologies, there wasn't any substantial response and so we relied only on literature data.

3.4. Functional Unit

The functional unit sets the basis for any comparison in a Life Cycle Assessment. In order to succeed an equal and trustworthy comparison, all the data must be normalised in relation to the unique functional unit of each project. In this LCA the one Kilo Watt-hour (1 kWh) of storage capacity was defined as functional unit. This choice was made because storage capacity is probably the most significant characteristic of any energy storage plant and simultaneously allows the interested parties to calculate very easy the total amount of energy that a system can store by just multiplying the storage capacity with the number of cycles in its lifetime. Nevertheless, the way of data normalisation was slightly different for some of the technologies. In the following two paragraphs, each unique method of normalisation is explained thoroughly.

For PHS and CAES systems the storage capacity per cycle was calculated based on the operating assumption made by Karin Flury et. al and by Foteini Rafaela Tsaousi in their studies regarding the corresponding installations.

In this way, the 95 MW PHS plant is operating for 5.5 hours per day and has an average number of 360 cycles per year. Therefore, the storage capacity is:

$$Storage\ capacity = rated\ power * operating\ hours = 95MW * 5.5h = 522.5MWh$$

Suchlike the CAES plant has a rated power of 113 MW and operates for 3 hours per day. In addition, it carries out approximately 300 cycles every year. That gives a storage capacity of:

$$Storage\ capacity = rated\ power * operating\ hours = 113MW * 3h = 339MWh$$

Afterwards, all the material inputs, the electrical energies, and the land uses were divided by the values mentioned above for each system in order to calculate the per kWh of storage capacity contribution.

On the other hand, the batteries and the flywheel systems were normalised in a different way. After the composition and the manufacturing energy per kilogram (kg) of its system was gathered, a specific energy for each technology was selected based on the literature review. Specific energy refers to the amount of energy (Wh) that can be potentially stored in a given system per unit mass (kg). Thus, the necessary amount for the storage of 1 kWh in each one of the systems was estimated according to the following calculations.

For instance, Lead-Acid batteries have an average specific energy of 35 Wh/kg meaning that for the storage of 1 kWh it is required:

$$Total\ PbAc\ battery\ mass: \frac{1000}{35} = 28.5714\ kg$$

Following the same procedure, the masses of the systems presented in table 10 were calculated.

Table 11: Specific energies and total mass of batteries and flywheel storage systems (Rydh, 1999; Sullivan and Gaines, 2012; Luo *et al.*, 2015).

System	Specific Energy (Wh/kg)	Total Mass (kg)
Lithium-Ion	114	8.7719
Lead-Acid	35	28.5714
NaS	170	5.8823
VRFB	20	50
Flywheel	50	20

Finally, the percentages of the material inputs and the electricity were rescaled in relation to each system's exact mass. However, the land use for the batteries and flywheel installation was relatively difficult to estimate for every individual system. After a careful research in the literature and in different databases such "DOE Global Energy Storage Database", we concluded that the average land occupation per kWh of storage capacity for the majority of the operating plants around the world is 0.1 m^2. Consequently, it was made the assumption that all the battery and the flywheel systems have the same land requirements per kWh of storage capacity (0.1 m^2) (*DOE Global Energy Storage Database*, no date).

As for the Hydrogen storage/Fuel cell application, it will be discussed further in Chapter 3.5, because the methodology for this system introduces some particularities.

3.5. Life Cycle Inventory

Lithium-Ion Battery

According to the literature, Lithium-Ion batteries have the lowest environmental impacts among the different types of batteries. At the same time, they present a great variety in the composition, depending primarily on the composition of the cathode.

Some of the most conventional Li-ion types are: a) NMC, b) LMO, c) LFP, d) NCA e) LCO. In this study, a Lithium manganese oxide (LMO) was modelled as it is the one included in ecoinvent 3 database. Table 12 shows that almost 55% of the total battery mass consists of the anode and the cathode. Due to the high specific energy of Li-ion batteries only, 8.77 kg are required for the storage of 1 kWh.

Table 12: Material inputs for the production of a Lithium-Ion cell (*ecoinvent 3*, no date).

Components	Materials	Total Mass(kg) per kWh of storage capacity	Wt.% per kg of battery
Cathodes	**Lithium Ion Manganese Oxide**	2.1722	24.76
Anodes	**Graphite**	2.6657	30.39
Electrolyte	**Ethylene Carbonate**	1.0601	12.09
	Lithium Hexafluorophosphate	0.1265	1.44
Separator	**Battery Separator**	0.3564	4.06
Case	**Lithium Ion Case**	1.7421	19.86
Other	**Polyethylene**	0.4872	5.55
	Liquid Nitrogen	0.0661	0.75
	Aluminium	0.1090	1.24
	Total	8.7719	100

Lithium-Ion Battery case consists of three main components. The module pack, the battery retention, and the battery tray. In table 13 below are presented the aggregated material inputs for the whole battery case (Ellingsen et al, 2014).

Table 13: Material inputs for the production of a Lithium-Ion battery pack (Ellingsen et al, 2014).

Materials	Total Mass (kg) per kg of battery case
Steel	0.3592
Aluminium	0.3492
Polypropylene	0.0668

Nylon 6-6	0.1708
Synthetic rubber	0.11
Acrylonitrile butadiene styrene	0.0165

As for the manufacturing electricity per kg of Li-ion battery, we have to mention that the amount of energy consumption varies for every different battery chemistry. For instance, NCM requires 88 MJ/kg for assembling, while LMO manufacturing is the less energy intensive process with an average 30 MJ/kg (Sullivan and Gaines, 2012).

Table 14: Land use and manufacturing electricity for a Lithium-Ion battery per kWh of storage capacity (Sullivan and Gaines, 2012).

Input	Unit	Per kWh of storage capacity
Land Use	m^2	0.1
Electricity	kWh	59.5253

Lead-Acid Battery

The three main components of a lead-acid battery are the anode, the cathode, and the electrolyte. The first two are made out of lead, while the electrolyte is a mixture of water and sulphuric acid. Together they represent 74.6% of the total battery mass as table 15 shows. The total mass required for the storage of 1 kWh is 28.5714 kg. Nevertheless, the electricity needed for the manufacturing is relatively low due to the fact that lead-acid batteries present a mature technology.

As for the modelling, two things should be mentioned:

- The percentages for the grid alloys Antimony (Sb), Tin (Sn), and Arsenic (As) are 85%, 10% and 5% respectively (Hebbar et al., 1979).
- The expander in PbO_2 consists of carbon black and lignosulphonates in different percentages. However, this material is not included in SimaPro8 and therefore 100% composition of carbon black was assumed.

Table 15: Material inputs for the production of a Lead-Acid battery (Rydh, 1999).

Components	Materials	Total Mass(kg) per kWh of storage capacity	Wt.% per kg of battery
Active material, grids, and poles	**Lead**	17.5095	61.3
Electrolyte dilution to 1.295 s.g.	**Water**	3.8116	13.3
Electrolyte	**Sulphuric Acid**	2.7396	9.6
Cases and Covers	**Polypropylene**	2.3155	8.1
Grid alloys	**Sb, Sn, As**	0.6027	2.1
Separators	**Polyethylene**	0.5717	2.0
Tubular Mats	**Polyester**	0.0858	0.3
Connectors	**Copper**	0.0774	0.3
Expander and oxygen in PbO_2	**Liquid Oxygen**	0.4288	1.5
	Carbon Black	0.4288	1.5
	Total	28.5714	100

Table 16: Land use and manufacturing electricity for a Lead-Acid battery per kWh of storage capacity (Rydh, 1999).

Input	Unit	Per kWh of storage capacity
Land Use	m^2	0.1
Electricity	kWh	76.1904

Sodium-Sulphur Battery

This type of battery has the highest specific energy of all the other types (170 Wh/kg). Hence, it presents automatically a very promising competitor regarding the environmental impacts of its installation. Moreover, many previous studies indicated that NaS batteries cause a small burden on the environment. However, there are not many sources for the material composition of NaS in the literature. All the data for our modelling were acquired from a report conducted by J.L. Sullivan in 2012 regarding the available inventories for different type of batteries.

Table 17: Components of a Sodium-Sulphur battery (Zini and Tartarini, 2012).

Components	
Terminal	Sodium Electrolyte
Electrical Insulation	Sodium Sulphur Electrolyte
Molten Sodium	Sulphur Electrolyte
Ion Selective Conductor	Cell Container

In the following tables 18 and 19 you can observe the material inputs for the Sodium-Sulphur battery as well as the land use and the energy requirements per kWh of storage capacity. NaS batteries have the highest manufacturing energy per kg of battery with an amount of 17.41 kWh/kg. However, their high specific energy keeps the total energy consumption for the storage of 1 kWh low.

Table 18: Material inputs for the production of a Sodium-Sulphur battery (Sullivan and Gaines, 2012).

Materials	Total Mass(kg) per kWh of storage capacity	Wt.% per kg of battery
Sulphur	0.7353	12.5
Sodium	0.4706	8
b-Alumina	0.7353	12.5
a-Alumina		
Steel	0.7529	12.8
Aluminium	1.3353	22.7
Copper	0.2000	3.4
Glass	0.2529	4.3
Sand	0.8941	15.2
Miscellaneous	0.5118	8.7
Total	5.8823	100

Table 19: Land use and manufacturing electricity for a Sodium-Sulphur battery per kWh of storage capacity (Sullivan and Gaines, 2012).

Input	Unit	Per kWh of storage capacity
Land Use	m^2	0.1
Electricity	kWh	102.4501

Vanadium Redox-flow Battery

This type of battery has shown in previous studies a potential, especially for stationary use due to advantages like high cycle life. The material composition for the modelling was relatively more difficult to obtain than other technologies, as only a few report present data. Specifically, the inventory is based on an environmental assessment of vanadium redox and lead-acid batteries for stationary energy storage by Carl Johan Rydh. Nevertheless, some of the data might be outdated as this study was conducted in 1998.

In table 20 are introduced the components, the materials and the contribution of each one of them to the total mass. It is obvious that over 80% of the VRFB is composed by the electrolytes. At the same time VRFBs have the lowest specific energy, therefore it requires the largest quantity of mass (50kg) for the production of 1 kWh among the other battery types.

Table 20: Material inputs for the production of a Vanadium redox-flow battery(Rydh, 1999).

Components	Materials	Total Mass(kg) per kWh of storage capacity	Wt.% per kg of battery
Electrolytes	**Water**	23.8359	47.7
Electrolytes	**Sulphuric Acid**	12.9295	25.9

Electrolytes	**Vanadium Pentoxide**	5.0189	10
Pumps, motors, racks	**Steel**	5.3303	10.6
Electrolyte containers	**Polypropylene**	1.2711	2.5
Flow frames, bipolar plates	**Polypropylene, rubber, carbon black**	0.6949	1.4
Connectors	**Copper**	0.3898	0.8
Ionic membranes	**Polysulfone & Fluoride (Polystyrene)**	0.2203	0.4
Electrodes	**Graphite**	0.1271	0.3
	Total	50	100

Finally, in table 21 are included the land requirements and the energy construction for the VRFBs. It is important to mention that the land use has been assumed the same for all the types of batteries. Although, VRFBs might require some more area due to the large storage tanks for the electrolytes.

Table 21: Land use and manufacturing electricity for a Vanadium redox-flow battery per kWh of storage capacity (Rydh, 1999).

Input	Unit	Per kWh of storage capacity
Land Use	m^2	0.1
Electricity	kWh	39

Flywheels

Moving towards other forms of energy we tried to model an electromechanical form of energy storage called flywheels. This technique has not been extensively examined in any comparison in the literature review. One of the main suppliers currently for flywheels is Beacon power, which has also built the two world largest installations in New York (20MW) and Pennsylvania (20MW).

The data for the flywheels have been collected by a study produces by Wendy Torell for a private company in 2015, while the modelling follows the same principles with the methodology for the batteries. Therefore, the inventory includes only the material composition per kg of flywheel, the manufacturing energy and the required land use for one kWh of storage capacity.

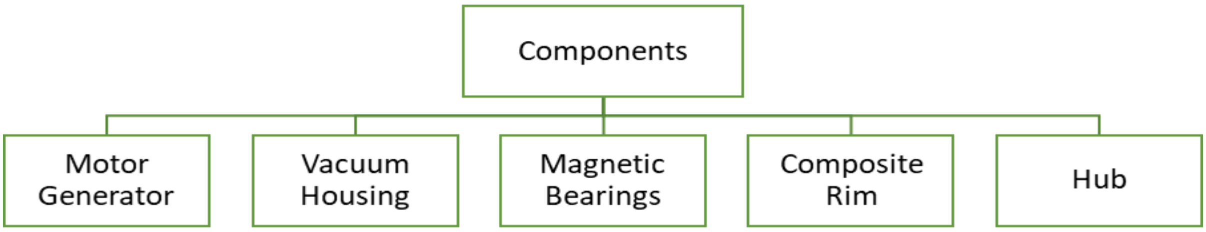

Figure 13: Components of a Flywheel storage system (Zini and Tartarini, 2012).

In table 22 is presented the material composition of the flywheel system. It is remarkable that almost 96% of the flywheel consists out of Iron. The total flywheel mass for storage of 1 kWh is 20 kg considering an average specific energy of 50 Wh/kg. In the literature can be found quite higher specific energies for flywheels, however the low-speed steel flywheel system examined in this report justifies the relatively low specific energy.

Table 22: Material inputs for the production of a Flywheel (Torell, 2015).

Materials	Total Mass(kg) per kWh of storage capacity	Wt.% per kg of battery
Iron, Fe	19.1	95.5
Nickel, Ni	0.366	1.83
Chromium,	0.16	0.8
Manganese, Mn	0.14	0.7
Carbon, C	0.08	0.4
Molybdenum, Mo	0.05	0.25
Silicon, Si	0.04	0.2
Sulphur, S	0.008	0.04
Phosphorous, P	0.007	0.035
Total	20	100

The electricity presented in table 23 is an estimation based on the literature review due to the lack of available data. More specifically, based on a study about manufacturing energy for different materials it was assumed that during fabrication 29 MJ per kilogram of flywheels are required (Ciceri, Gutowski and Garetti, 2010). However, this uncertainty might not influence the results very much as it represents only a small percentage of the total impacts. As for the land use, it is considered the same with the batteries, because of the similar specific energies and the sizes of the currently operating plants.

Table 23: Land use and manufacturing electricity for a Flywheel per kWh of storage capacity (Torell, 2015).

Input	Unit	Per kWh of storage capacity
Land Use	m^2	0.1
Electricity	kWh	161.11

PHS

As we mentioned earlier the mechanical energy storage technologies have been modelled in a slightly different way than the electrochemical techniques. In contrast with the batteries where only the manufacturing materials and energy requirements were considered, here all the civil works for the plant were taken into account since they are necessary for the operation of the unit. At the same time, Pumped Hydro system is very complex and the quantification of all impacts is almost impossible or it can lead to unequal comparison with the rest of the technologies. Thus, biological aspects of the plant have not been considered, but only discussed at the results.

For PHS our report was conducted based on the 2012 study by Karin Flury et. al about the life cycle inventories of Hydroelectric Power Generation. Initially, they indicate that the construction and demolition of storage hydropower stations and pumped storage hydropower stations can be modelled identically due to the fact that the two installations differentiate only during the operation phase. The construction, as well as the material requirements, are almost the same for both plants. In this case, the PHS has 95 MW rated power and an expected net production of 190 GWh per year. It operates 5,5 hours per day and the expected lifespan of the plant is 150 years. It's important to mention that the PHS station operates only with natural water. However, there are plenty of stations around the world which utilize artificial water. Moreover, it is assumed that the most convenient location has been chosen. The data inputs for this inventory are mostly been collected by previous studies between 1990 and 2000 as PHS presents a mature technology for several years now. On the other hand, newer plants have definitely fewer material requirements and lower energy consumption as technological development increases the efficiency equipment constantly.

There are multiple possible reasons for energy losses in pumped hydro storage stations such as inefficiencies in the turbines as well as friction in the galleries. In our case, we estimated that the average total efficiency of the plant is approximately 80%.

Materials

In terms of construction, cement and gravel are the most important materials used in PHS plants. They are used for the water catchment, the dam, the tunnels, the buildings etc. The total cement consumption in this case, is $1.02*10^8$ kg. Considering that 1 m^3 of concrete consists of 0.8 m^3 gravel, 0.127 m^3 water and 0.073 m^3 cement our final results convert into 8,89* 10^8 kg of gravel 5.65*10^7 kg of water, and 1.02*10^8 kg of cement.

Another very important material for the construction of the PHS is steel. It has many different applications such as reinforcement, pressure pipes, generators, turbine etc. The total consumption of the plant in reinforcing steel, chromium steel, and low-alloyed steel is 1.74*10^6 kg 1.82*10^6 kg 4.07*10^6 kg respectively. Furthermore, a total amount of 2.96*10^5 kg of copper is used mainly for parts like generator, turbines as well as electric cables.

During the construction and excavation phase explosives are usually used. However, due to lack of data, the amount of the explosives is an approximate proportion of the excavation load. Specifically, 5.95*10^5 kg of explosives were considered for the whole plant (Flury and Frischknecht, 2012).

Electricity

The construction of a PHS station is a very intensive process and requires an extensive amount of energy. In this study, apart from the electricity consumption, it has also been considered the fuel requirements for the buildings machines. The total electricity reaches up to 2.73*10^7 kWh, while the fuel (diesel) consumption is 5.97*10^7 MJ (Flury and Frischknecht, 2012).

Land Use & Reservoir Occupation

Finally, one of the potentially greatest impacts of PHS stations comes with the land use and the reservoir occupation. The average PHS station covers a total area of 1.16*10^6 m^2. However, the largest part is occupied by the reservoir. Specifically, 7.21*10^5 m^2, while the area covered with buildings and infrastructure accounts only for 1% of the total area. This can be explained by the fact that much of the infrastructure is built inside the rocks (e.g. The penstock).

The volume of the two reservoirs is not only considered about the water management aspect but also for its ecological footprint. During operation, the system withdraws a huge amount of water which can cause several implications to the natural circulation of the water and subsequently to the biomass of the catchment. The reservoir modelled in this study has a total volume of $3.27*10^7$ m^3 (Flury and Frischknecht, 2012).

The following figure 14 shows the main components of the PHS plant, while table 23 presents the material inputs in total and per kWh of storage capacity.

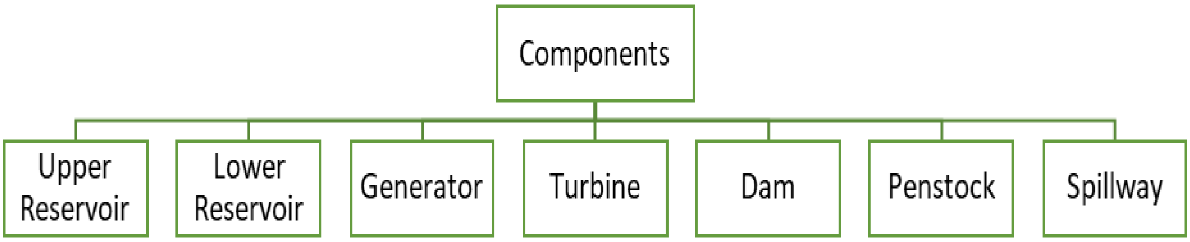

Figure 14: Components of a Pumped Hydro energy storage plant (Torres, 2011).

Table 24: Material inputs, construction electricity and land use per kWh of storage capacity for a PHS plant (Flury and Frischknecht, 2012).

Input	Unit	Total	Per kWh of storage capacity
Cement	kg	1.02E+08	1.95E+02
Water	kg	5.65E+07	1.08E+02
Gravel	kg	8.89E+08	1.70E+03
Reinforcing Steel	kg	1.74E+06	3.33E+00

Chromium Steel	kg	1.82E+06	3.48E+00
Low-alloyed Steel	kg	4.07E+06	7.79E+00
Copper	kg	2.96E+05	5.67E-01
Explosives	kg	5.95E+05	1.14E+00
Construction Energy	kWh	2.73E+07	5.22E+01
Diesel	MJ	5.97E+07	1.14E+02
Occupation of water bodies	m^2	7.21E+05	1.38E+00
Land use	m^2	1.16E+06	2.22E+00
Reservoir Volume	m^3	3.27E+07	6.26E+01
Water	m^3	4.19E+10	8.02E+04

CAES

Similar to PHS the Compressed air energy storage plant has been modelled considering two main elements, which are the civil works and the major equipment of the installation. CAES is currently the second biggest form of energy storage after pumped hydro storage. However, the technology is still immature as only two installations are operating worldwide. The first one was constructed in 1978 in Huntof, Germany with a rated power of 290MW and the second is operating in in McIntosh, USA (110 MW). This was built relatively more recent, in 1991.

The data used in this report were based on two different studies. The first one is by Foteini Rafaela Tsaousi who conducted a research about Advanced Adiabatic

Compressed Air energy storage. The basic equipment has been modelled in the same way, while the data for the civil works have been collected from another report handed over by WorleyParsons group. The primary equipment consists of the two air compressors, the turbine, the recuperator/heat exchanger, and the storage cavern. The lifetime of the plant is defined as 60 years, while the rated power is 113 MW. Moreover, an average of 300 cycles per year has been set. As one cycle is considered one charge and discharge taking place in one day. Finally, the plant is operating for 3 hours per day and has an average efficiency around 50%. There are certainly many additional components in the system like the cooling system, the emergency generator etc. as well as the demand in natural gas for the operation, however, in order to preserve an equal comparison among the different techniques, these data are not included in this analysis. In the following chapters, the inventory for the CAES modelling is reviewed in detail.

Compressor

The two compressors are constructed in the best available technique in order to minimize the heat losses and to keep the temperature steady during the compression. The first one is an adiabatic air compressor with a rated power of 117MW, while the second one has 95MW power and is an isothermal air compressor. Their efficiency reaches up to 85%. In order to model both of them in SimaPro8, we rescaled the existing compressor included in the software, which has 300kW nominal power.

Air Storage Cavern

Afterwards, the air is stored in an underground cavern in order to produce electricity whenever is needed. For the storage caverns can be used existing underground formations such salt mines or they can be constructed from scratch. In our study and in most cases the first option is considered as it can result in much lower capital cost as well as lower environmental impacts due to limited material use. The underground cavern modelled has a total volume of 170,000 m^3 and the pressure is maintained at 100 bars. At the same time, the cavern must secure no pressure losses during storage and minimize the variation in the temperature. The better that these two factors are controlled, the lower the storage volume required.

For the construction of the cavern the following materials were used:

1. 20,000 ton of concrete
2. 100 ton of reinforcing steel
3. 50 ton of foam glass for thermal insulation
4. 16,725 kg of abrasive material (blasting) for thermal insulation

<u>Turbine</u>

The turbine of the CAES plant has a rated power of 113 MW and an estimated efficiency of 95%. However, such turbine is not included in SimaPro8. Thus, the gas turbine existing in SimaPro8 has been rescaled for the purpose of this project. Moreover, a basic assumption that air and gas turbines are operating under the same principles has been made.

<u>Heat Exchanger</u>

In order to sustain the air temperature in certain limits throughout the process and minimize any possible energy losses, a heat exchanger/recuperator is required after the air storage cavern. This device increases the temperature of the air coming out of the cavern in order to eliminate the demand for natural gas and increase the total efficiency of the plant. Based on the following calculations presented, a 4.5 MW heat exchanger was selected.

As the air exits the storage cavern is approximately 298 Kelvin (24.85 C^{o}), while the desired temperature for a proper combustion to take place before the turbine is around 986 Kelvin (712.85 C^{o}). This space in practice is partially filled by the heat exchanger as natural gas provides extensive energy. In our scenario, this could not be modelled with accuracy and therefore it was assumed that the total energy is supplied by the heat exchanger unit. The amount of heat energy required to raise the temperature of one gram of air by one degree Celsius can be measured by the following equation:

$$Q = m * c * \Delta T = 0.001746 \frac{kg}{sec} * 1.052 \frac{kJ}{kg * Kelvin} * (986 - 298) Kelvin = 1.263 \frac{kJ}{sec}$$

Mass Flow: 0.001746 kg/sec

Specific heat of air assumed: 1.052 kJ/(kg*K)

As 1.263 kJ/sec equals to 1.263 kW it was concluded that a 4.578 MW unit is mandatory.

Generator/Motor

The generator and the motor presented in the conceptual as separate units are actually comprised in the air compressor and the turbine systems respectively. In that way, they were not modelled separately but assumed incorporated in the pre-existing database of SimaPro8 software.

Table 25: Major components of CAES plant per kWh of storage capacity (Bauer, 2015).

Components	Unit	Total	Per kWh of storage capacity
Compressor 1	p	1	0.0011
Compressor 2	p	1	0.00024
Storage Cavern	p	1	0.0000029
Recuperator/Heat Exchanger	p	1	0.0078
Turbine	p	1	0.0333

In the table 26 below are presented the materials for the civil works of the whole CAES plant including all the necessary works for the buildings and the foundation. As expected the materials with the highest consumption are the concrete and the steel with 7,979.6 m3 and 2,827 ton respectively.

Table 26: Material inputs for civil works in a CAES station (WorleyParsons Group, 2011).

Input	Unit	Total	Per kWh of storage capacity
Crushed Stone	m^3	1,660.6	0.0048
Concrete	m^3	7,979.6	0.0235
Excavation	m^3	7,757.9	0.0228
Rebar	ton	678	0.0020
Heavy Steel	ton	1,031	0.0030

Medium Steel	ton	538	0.0015
Light Steel	ton	561	0.0016
Base Plate	ton	19	5.6E-05

Above Grade Conduit

Another important feature of complex installations like CAES is the several conduits. Some of them are constructed above grade and some others are embedded. The total length reaches up to 42,744.4 meters including both steel and PVC pipelines. Furthermore, it is clear that the weight per meter of conduit is significantly different as the size increases.

Table 27: Material inputs per kWh of storage capacity for above ground conduit in a CAES plant (WorleyParsons Group, 2011).

Size	Unit	Total	Kg/m	Per kWh of storage capacity
3/4"	m	13,645.9	1.69	0.0680
1"	m	3,621	2.5	0.0267
1 1/2"	m	905.2	4.05	0.0108
2"	m	6,705.6	5.44	0.1076
2 1/2"	m	3,352.8	8.63	0.0853
3"	m	3,352.8	11.29	0.1116
4"	m	1,207	16.08	0.0572
5"	m	335.2	21.77	0.0215
Total	m	33,125.6	-	0.4889

Embedded Conduit

Table 28: Material inputs per kWh of storage capacity for embedded conduit in a CAES plant (WorleyParsons Group, 2011).

Size	Unit	Total	Kg/m	Per kWh of storage capacity
4''	m	9,618.8	2.8	0.0794

Electricity

Construction energy for huge projects like CAES plants is really difficult to estimate and most of the times impossible to calculate based on the literature. Thus, the assumption that CAES has similar construction energy to extensive natural gas power generation projects was made. After communication with a Greek construction company (METKA) we were informed that for the construction of a 100 MW plant are required approximately two to three GWh of energy. Based on this information and the acknowledgment that CAES projects present certain particularities such as the modification of the storage cavern we assumed a total energy demand of 3.1 GWh.

Table 29: Electricity consumption per kWh of storage capacity for the construction of CAES plant (METKA).

Input	Unit	Total	Per kWh of storage capacity
Electricity	GWh	3.1	9.1582

Land use

Finally, the last key aspect of the CAES is the extensive land use which is required for the construction of the plant. The same as with PHS the occupation of the land is much higher than all the others electrochemical techniques. The total size of the plant was estimated based on the average area of the currently operating projects around the world such as the McIntosh in Alabama. It is important to mention that during modelling a clear assumption has been made, considering only 15% of the site will be transformed into industrial building area.

Table 30: Land use for the construction of a CAES plant (McIntosh, Alabama).

Input	Unit	Total	Per kWh of storage capacity
Land use	m^2	230,000	0.6784

Hydrogen Electrolyser/ Fuel Cell

Despite the relatively low efficiency the interest in hydrogen energy storage is growing because it has a much higher storage capacity compared to other technologies such as batteries or mechanical energy storage plants. Thus, we decided to include the technology by modelling a theoretical system similar to the one introduced by Nadia Belmonte et. al in their study earlier this year. More specifically, the system consists of three main parts:

1. The alkaline electrolyser with a nominal power output of 4 kW and approximately 66% efficiency.
2. The 815 m^3 gas storage tank for the hydrogen storage at 30 bars.
3. The 2 kW PEM fuel cell modelled according to the ecoinvent 3 database. Its total efficiency reaches up to 50 % (*Energy Storage Association (Hydrogen)*, no date).

A clear assumption has been made that the whole system is operating for 10 hours every day. However, electrolyser and PEM fuel cell are working in different times during the day so as to always have enough hydrogen stored in the tanks. Moreover, an inverter is needed in order to follow the same criteria with the other technologies.

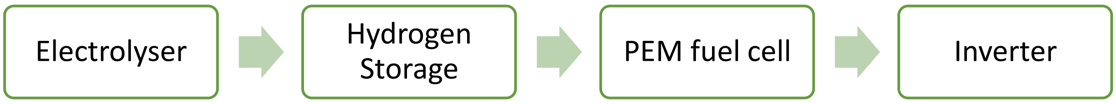

Figure 15: Components of a Hydrogen/Fuel Cell energy storage plant (Belmonte *et al.*, 2016).

For the purpose of the project, an alkaline electrolyser according to a report by Koj et al. was modelled. The basic components of electrolyser are: a) the membrane, b) the anode, c) the cathode, e) the cell frame and f) the gasket. It is interesting to mention that as table 30 shows 83% of the alkaline electrolyser consists of steel, while the total mass of the 4-kW unit is 143.26 kg.

The methodology followed for the calculation of the required materials per kWh of storage capacity is the same for the electrolyser, the PEM fuel cell, and the auxiliary materials. All the data were divided by the storage capacity of the system in one cycle. This capacity can be measured by multiplying the power output of the whole system (2kW) with the operating hours in a cycle (10 hours).

$$Storage\ capacity = rated\ power * operating\ hours = 2kW * 10hours = 20kWh$$

Table 31: Material inputs per kWh of storage capacity for the electrolyser of the system (Koj *et al.*, 2015).

Input	Unit	Total	Per kWh of storage capacity
Steel	kg	118.89	5.9445
Nickel	kg	17.77	0.8889
Copper	kg	1.1428	0.0571
Polytetrafluoroethylene	kg	0.0502	0.0025
Aluminium	kg	0.2569	0.01284
Asbestos	kg	4.8237	0.2411

Polyester Resin	kg	0.2413	0.0120
Dimethylformamide	kg	0.0644	0.0032
Tuluol	kg	0.0137	0.0007
Styrol	kg	0.0036	0.0002
Total	kg	143.26	7.1633

PEM Fuel Cell

The PEM fuel cell was modelled based on the 2kW unit which is included in ecoinvent 3 database. As we can see from table 32, steel occupies 87% of the total fuel cell mass meaning only 4% more than at the electrolyser. This makes clear sense because PEM fuel cells and electrolyser have pretty similar composition.

Table 32: Material inputs per kWh of storage capacity for the PEM fuel cell of the system (Ecoinvent 3 database).

Input	Unit	Total	Per kWh of storage capacity
Steel	kg	39.4	1.97
Chromium Steel	kg	46.2	2.31
Aluminium	kg	4.6	0.23
Cast Iron	kg	1.6	0.08
Titanium Dioxide	kg	0.14	0.007
Charcoal	kg	0.5	0.025
Polyethylene	kg	4.8	0.03
Polypropylene	kg	0.5	0.00006
Polystyrene Foam	kg	0.6	0.0007

Platinum	kg	0.0012	0.0002
Water	m^3	0.146	0.0073
Stack for PEM fuel cell	p	1	0.05

Auxiliary materials

Table 33: Material inputs per kWh of storage capacity for the auxiliary equipment of the Hydrogen/Fuel Cell system (Belmonte *et al.*, 2017).

Input	Unit	Total	Per kWh of storage capacity
Gas storage tank	kg	220	11
Connection cables	m	145	7.25
Pipes-(Steel)	kg	358	17.9
Polyethylene	kg	6	0.3

Land use & Electricity

Finally, the total size of the plant was estimated based on the average area of the currently operating projects around the world such as the Energiepark in Mainz, Germany. It is important to mention that during modelling a clear assumption has been made, considering only 80% of the site will be transformed into industrial building area.

Table 34: Land use and construction electricity for a Hydrogen Electrolyser/ Fuel Cell system (Koj *et al.*, 2015; Belmonte *et al.*, 2017).

Input	Unit	Total	Per kWh of storage capacity
Land use	m^2	10,000	0.25
Electricity	kWh	15.6	0.78

4.Results

4.1 Results Analysis Methods

SimaPro8 software includes various impact assessment methods. The main structure of impact assessment methods is as follows:

1. Characterisation
2. Damage Assessment
3. Normalisation
4. Weighting
5. Addition

Apart from the first step, the other four are optional according to ISO standards, and therefore the five steps are not available in all methods offered for the evaluation (Pre' Consultants, 2014).

Characterisation

The substances that contribute to a broad impact category are multiplied by the corresponding Characterisation Factor, which expresses the relative contribution of each substance to the corresponding impact category. For example, the characterisation factor for CO_2 in the Climate change impact category can be equal to 1, while the characterisation factor of methane can be 25. This means the release of 1 kg methane causes the same amount of climate change as 25 kg CO_2. The result is expressed as Impact Category Indicators.

Damage Assessment

The purpose of this step is to combine a number of impact category indicators into a broader Damage Category. By adding the burdens in specific broader categories, it is easier to assess the overall burden caused by each broad impact category to damage categories.

Normalisation

This step allows the comparison of broad impact category indices with a specified reference point. This comparison is made possible by dividing the indices with the reference point, by reducing all indicators to the same measurement unit. This step can be applied both on the results of the first step and on the results of the second step. Average annual environmental load per country or continent divided by the corresponding population is widely used as a reference point.

Weighting

In this stage, broad impact category indicators of the corresponding damage category indicators are multiplied by weighting factors. This step can be applied on normalised or non-normalised data.

Addition

In this final step, the results are added to establish one final single score.

There are many methods for the comparison and presentation of results, which differ based on the different regulations of countries concerned, and their specialisation in particular damage categories. Europe Recipe Endpoint was the method we selected. This is one of the most widely known methods related to European Directives. It is actually the combination of two other methods, Eco-indicator 99 and CML-IA. It also allows the use of all five steps above. This method has the capability to export an intermediate stage (midpoint) and a final stage (endpoint). In the first case, we end up with many different impact categories with relatively small uncertainty for the results, but at the same time drawing conclusions is more complicated. In the second case, impact categories are limited to three wider categories, leading to greater uncertainty but much easier to understand results. Our model's results were processed based on the final stage (endpoint). Therefore, environmental impact categories are as follows.

A) Damage to Human Health

The effects are expressed as the number of life years lost and the number of life years with disability. The combination of these gives the corresponding DALY (Disability Adjusted Life Years) measurement unit.

B) Damage to Ecosystem Quality

The effects are expressed as the number of extinct species in a specified area for a specified time.

C) Damage to Resources

The effects are expressed as the surplus energy required in future to extract fossil fuels.

The Pt unit, which appears in the environmental impact diagram, is equal to one thousandth of the environmental footprint of the average European citizen in a period of one year.

Furthermore, the eight storage technologies were compared regarding two additional methods. The first one called cumulative energy demand (CED) analyses the sum of the energy demand of all resources required for the production of a product. In our case the one-kilowatt hour of energy storage. The second one, which is also worldwide established, is the global warming potential (GWP) for 100 years horizon designed by IPCC. The 100–year GWP indicator is based on the concentration of greenhouse gases in the atmosphere. The total GHG emissions for a product inventory is calculated as the sum of GHG emissions, in kg of CO_2 equivalent, of all foreground processes and significant background processes within the system boundaries (Pre' Consultants, 2014).

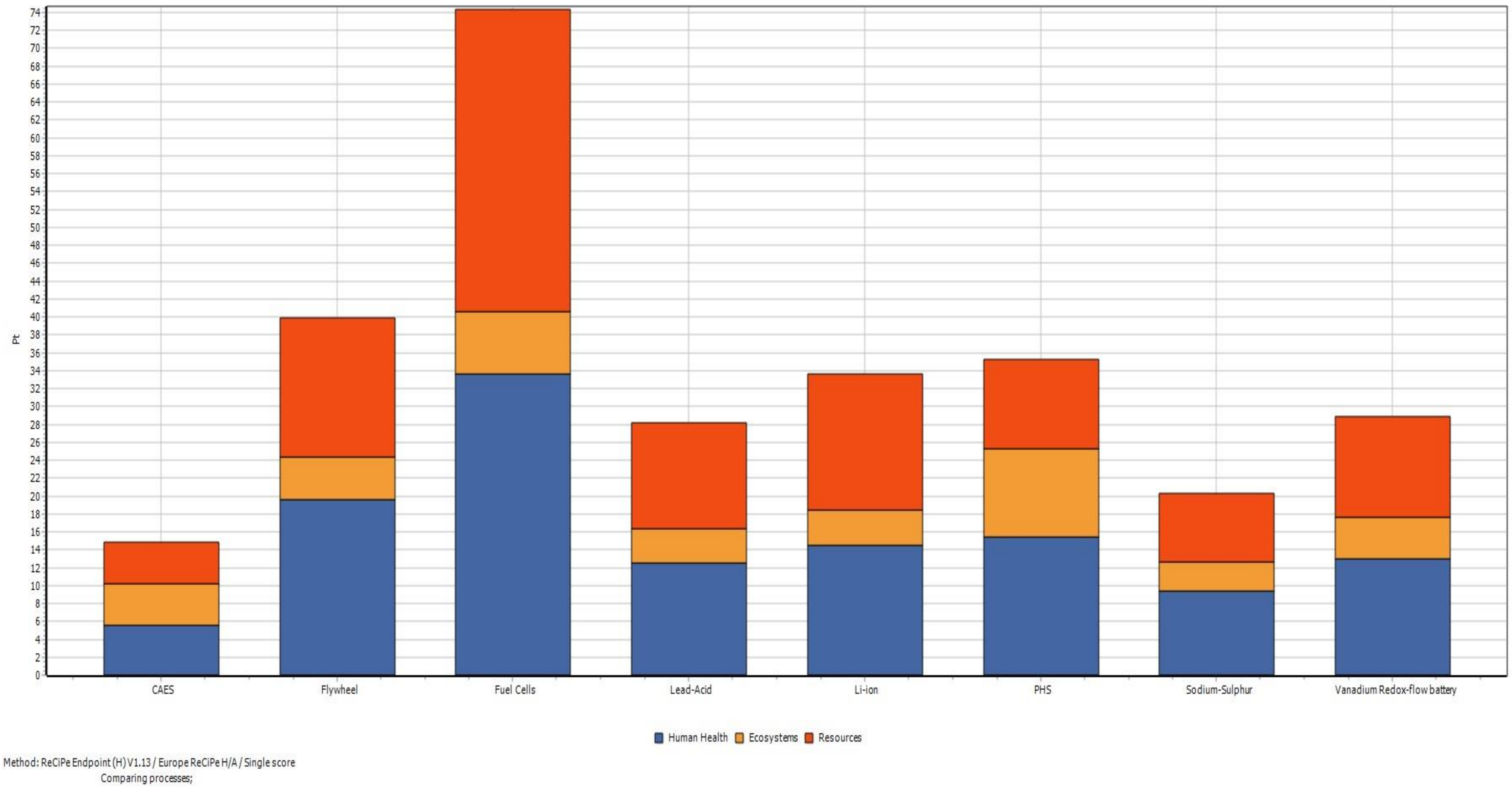

Figure 16: Comparison of environmental impacts per kWh of storage capacity between the eight different storage technologies.

The above diagram compares the environmental impacts of the eight different energy storage technologies examined in this study. The results for all the techniques are normalized per kWh of storage capacity and characterized by Recipe method. As it can be observed, Hydrogen storage/Fuel cells have the worst performance among the different competitors with almost double environmental burdens than all the other systems. More specifically, hydrogen storage application reaches up to 74.3 Pt per kWh of storage capacity with 33.6 Pt and 33.7 Pt of the impacts corresponding to human health and to resources depletion respectively. Flywheel system presents the second highest environmental impact with a number of 39.9 Pt per kWh of storage capacity. At the same time, all the batteries are performing at relatively similar levels with Sodium-Sulphur (NaS) battery being the best one from an environmental point of view. Despite expectations, Lithium-Ion battery shows the worst performance between the batteries, something that can be explained by the functional unit as well as the highly noxious substances containing in it. The particularities of the functional unit will be discussed further in chapter 5. On the other hand, mechanical storage techniques differentiate considerably. CAES for example has the best performance among all systems with only an impact of 14.9 Pt per kWh of storage capacity. Moreover, the individual charges on human health, ecosystem, and resources are all fluctuated at 5 Pt. Finally, PHS introduces relatively high environmental burdens (35.2 Pt) considering the fact that represents almost 99% of the global storage capacity. It is interesting that PHS shows worse performance per kWh of storage capacity than all the battery systems. However, this might also correspond to the particular functional unit. Furthermore, PHS is the technology which has the greatest impact on the ecosystems despite the total effect. Due to the high land and water occupation, PHS contributes to the ecosystem deterioration more than all the other systems with a number of 9.9 Pt. In the following table are presented the different charges in more detail.

Table 35: Analytical environmental impacts of the systems per kWh of storage capac.

	Unit	CAES	Flywheel	Fuel Cells	Lead-Acid	Li-Ion	PHS	Nas	VRFB
Total	Pt	14.9	39.9	74.3	28.2	33.6	35.2	20.3	28.9
Human He.	Pt	5.59	19.6	33.6	12.5	14.5	15.4	9.35	13
Ecosystems	Pt	4.56	4.85	7.01	3.84	3.95	9.9	3.28	4.73
Resources	Pt	4.7	15.5	33.7	11.9	15.2	9.95	7.69	11.2

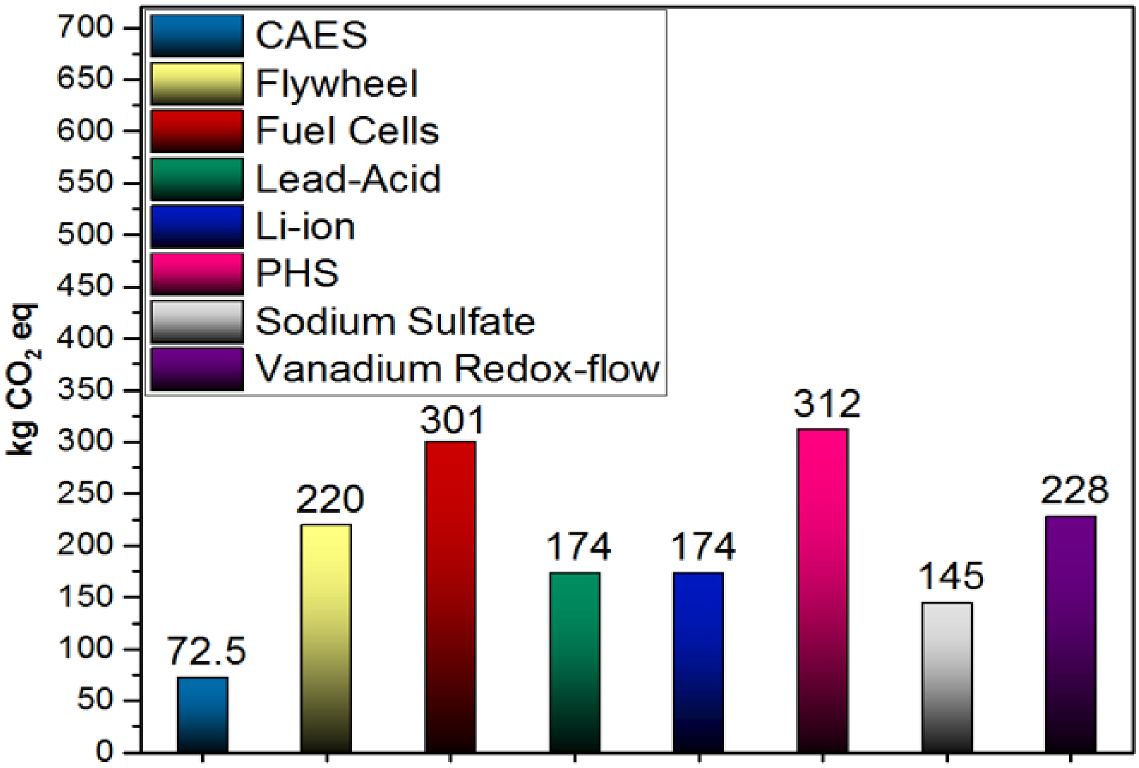

Figure 17: Comparison of GWP per kWh of storage capacity among the 8 systems.

Another characterization method examined was the Global Warming Potential with a one hundred years horizon. All the values are again normalized per kWh of storage capacity. As figure 17 shows the contribution is measured in kilograms of CO_2 equivalent (kg CO_2 eq.). The trends look similar to the previous diagram. Nevertheless, PHS presents a great increase and in that case, has the highest contribution to global warming (312 kg CO_2 eq.), followed by hydrogen/fuel cell with 301 kg of CO_2 equivalent. Once again, CAES shows the best performance and has the lowest environmental impact with 72.5 kg of CO_2 equivalent. Furthermore, flywheel and VRFB produce 220 and 228 kg of CO_2 equivalent respectively. Simultaneously, VRFB displays the worst results among the battery applications with NaS battery remaining the most environmentally friendly (145 kg CO_2 eq.). Finally, Lithium-Ion and Lead-Acid batteries have similar effect to global warming based on the results (174 kg CO_2 eq.). As PHS was the less environmental friendly technique, it was interesting to analyse the contribution of each input to the final result regarding the GWP. The conclusion was that the cement, the electricity for construction and the gravel had the highest impacts with 173, 50.2 and 31.3 kg of CO_2 equivalent respectively. These three elements account for 81% of the PHS plant's total GWP value.

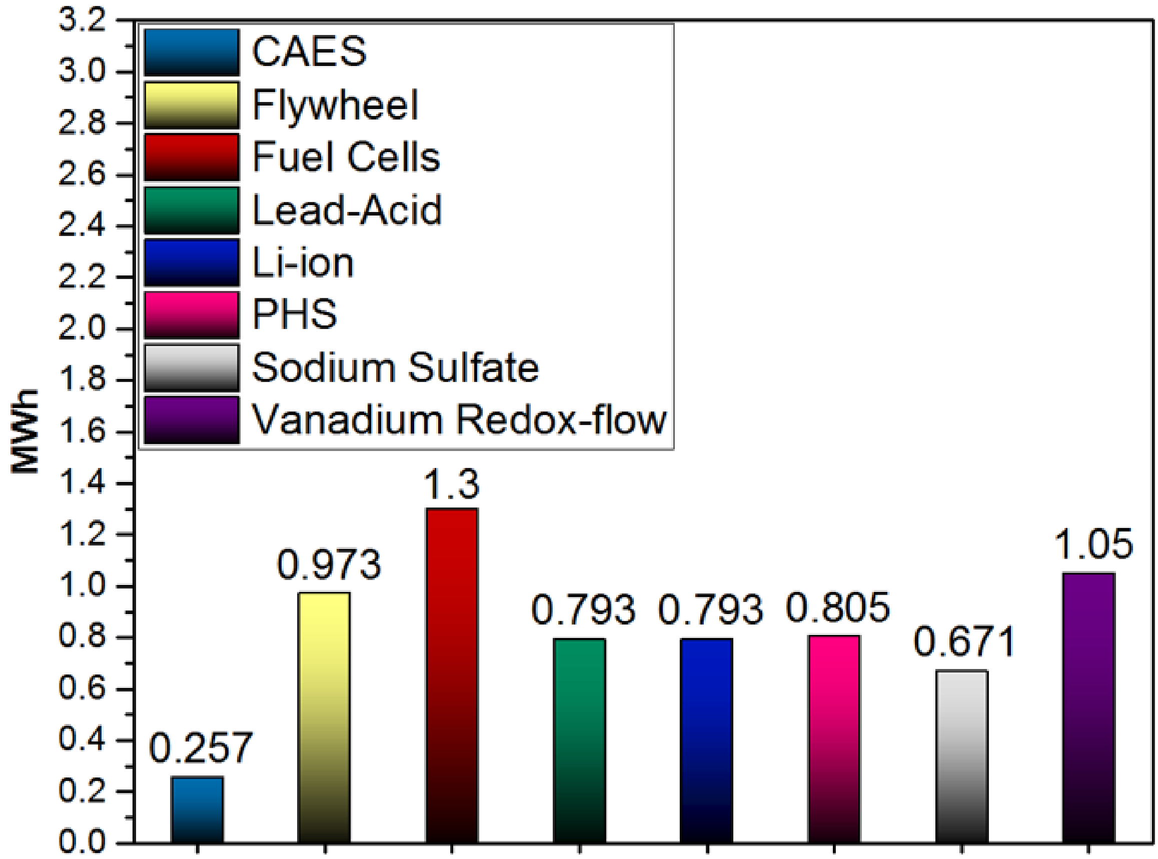

Figure 18: Comparison of the CED per kWh of storage capacity among the 8 systems.

The final characterization method analysed for the comparison of the different energy storage applications was the Cumulative Energy Demand. In y-axis, it is shown the MWh which is the measurement unit for the CED. Initially, it can be observed a slightly closer competition than the previous figures. CAES continues to perform better than all the other techniques and consumes only 0.257 MWh per kWh of storage capacity. It might not seem less enough, but compared to the others is less than one-third of their demand. Then, lead-acid, lithium-ion and PHS show quite similar results with 0.793, 0.793 and 0.805 MWh of energy consumption respectively. NaS battery remains the best solution between the batteries with an amount of 0.671 MWh, while VRFB rises up to 1.05 MWh. Somewhat better flywheel system presented a total CED of 0.973 MWh. Although, the input data for the manufacturing energy of this system were not quite robust due to lack of available data in the literature. This makes the final result for the CED of flywheel a bit less transparent. Finally, hydrogen/fuel cell seems to be the applications with the highest energy demand (1.3 MWh per kWh of storage capacity) and therefore the most environmentally unfriendly.

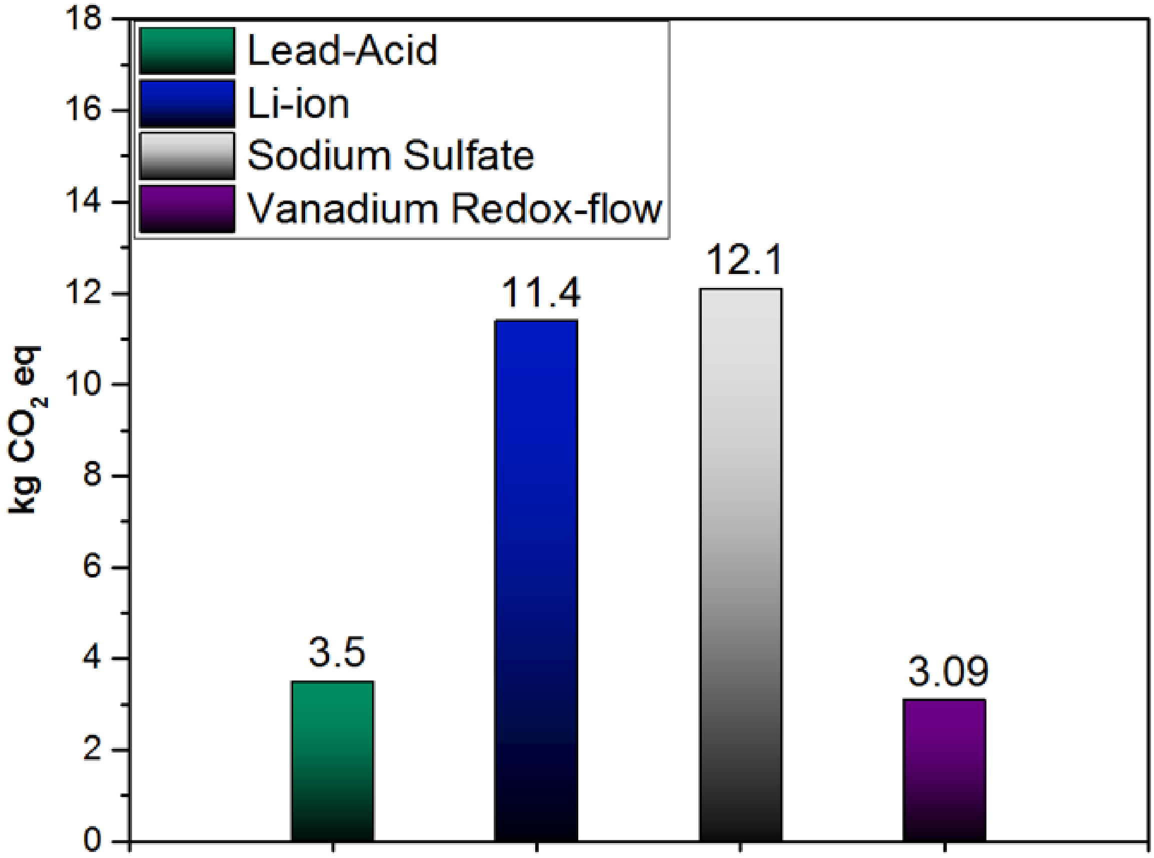

Figure 19: Comparison of GWP per kg of battery between the four batteries.

Furthermore, it was considered useful to examined the GWP and the CED separately for the four batteries in order to compare the results with the literature. As functional unit, here was applied the one kilogram of the battery system and subsequently all the data were normalized regarding to that. It is obvious from the diagram, that the results are quite different from all the previous outcomes and this is due to the different functional unit. More precisely, lead-acid and VRF batteries have the lowest environmental burden with 3.5 and 3.09 kg of CO_2 equivalent. Quaintly, the two most promising batteries (Li-Ion and NaS) present extremely higher contribution to global warming. Especially the NaS battery system shows a production of 12.1 kg of CO_2 equivalent per kilogram of battery. This differentiation in the results can be explained by two factors: 1) Lithium-Ion and NaS battery contain environmental hazardous materials in high percentages per kg of battery. 2) These materials/inputs are becoming negligible as the high specific energy of these two battery types allows a really high cumulative storage energy throughout battery's lifetime.

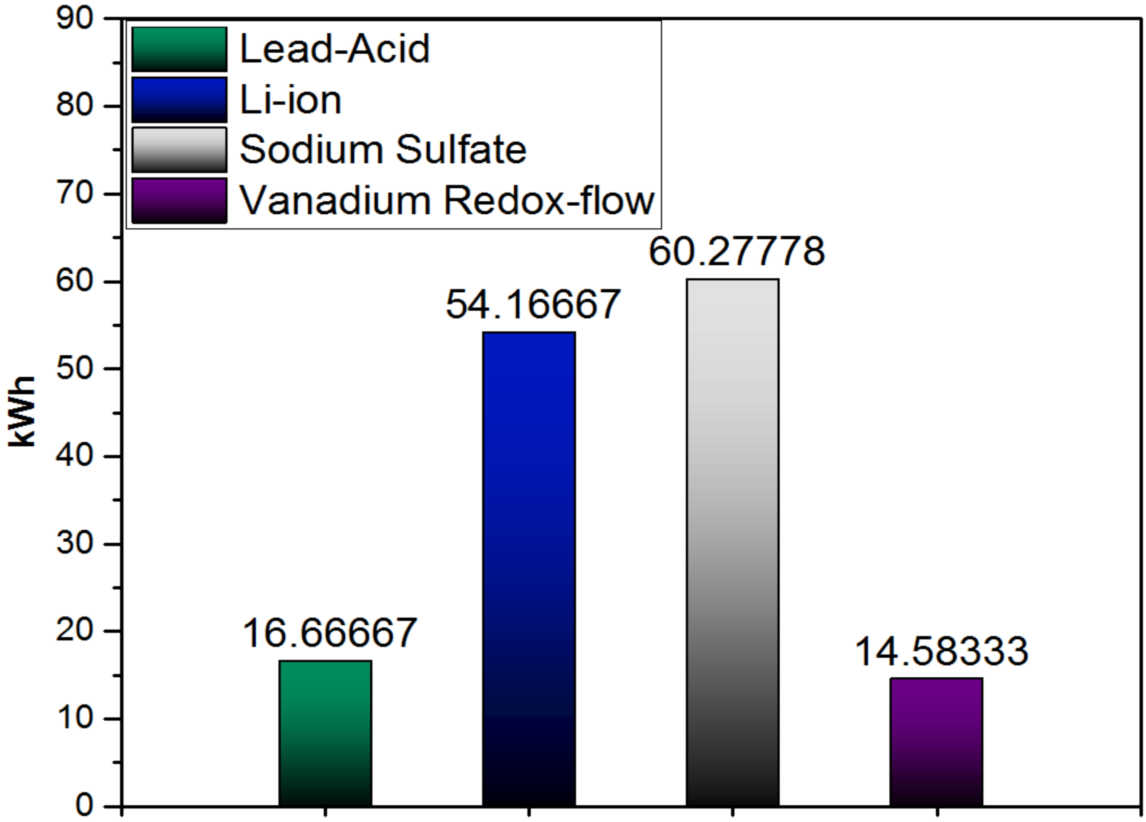

Figure 20: Comparison of CED per kg of battery between the four batteries.

The same as before, the results for the CED per kg of battery are in conflict with the ones per kWh of storage capacity. Its cause lies on the same reasons mentioned before about the batteries characteristics. Here the CED is expressed in kWh as the values are sufficiently lower. VRFB shows the least energy demand with 14.583 kWh per kg of battery, followed by the lead-acid battery (16.66 kWh). Over three times higher, lithium-ion battery consumes approximately 54.16 kWh for the manufacturing of one kilogram of battery. Finally, NaS battery application requires the highest energy among the systems (60,27 kWh) and turns out to be the most environmentally hazardous per kilogram.

5. Discussion

From the results presented in the different diagrams, it is clear that the outcome is strongly correlated to the characterisation method examined as well as the functional unit. Nevertheless, it seems undeniable that CAES system has the best performance per kilowatt hour of storage capacity regarding all three methods, while Hydrogen/PEM Fuel Cell has the highest environmental impacts in two out of three cases. Only in terms of global warming potential (GWP), PHS shows greater environmental burden than all the other technologies. Quaintly, all the performance results are by some hundreds higher than all the literature values. This fact can be explained by the particularity of the functional unit used in this study. In most of the studies, the functional unit used is the one-kilowatt hour of electricity produced and therefore all the input data are divided by the total number of kWh produced during the system's lifetime. In an effort to minimize the error that occurs in the assumptions made for the lifetime of the plant or the number of cycles of the battery, the 1 kWh of storage capacity was considered ideal. Specifically, any interested who wants to calculate the environmental impacts of any particular system just has to apply its characteristics and multiply the data by the total number of cycles and the rated power of his unique storage method.

For instance, L. Oliveira's results using the same characterization method (Recipe Endpoint (H), Europe Recipe H/A) look quite similar with the paired system of fuel cell-electrolyser performing much worse than all the other technologies. However, its total impact accounts for less than 0.07 Pt per kWh of electricity produced explaining so the functional unit issue. Moreover, NaS battery shows also very low environmental burden distinguishing itself from all the other battery types. Finally, PHS and CAES are demonstrating similar results to our study with CAES appearing slightly worse. This might be due to assumptions and different boundaries that cannot be clarified. In the following table can be observed the differences between the two studies mentioned above.

Table 36: Comparison of the findings for Recipe method with L. Oliveira et. al report.

System / Report	PHS	CAES	Li-Ion	PbAc	NaS	Hydrogen/Fuel Cell
Current study	35.2	14.9	33.6	28.2	20.3	74.3
(L. Oliveira et. al)	0.023	0.027	0.029	0.03	0.021	0.067

Charles J. Barnhart and Sally M. Benson findings are in line with the results presented above. More precisely, they concluded that CAES and NaS have the lowest environmental impacts when both energy and materials are considered through the whole life cycle of the applications. However, they indicate that PHS has also quite good environmental performance especially when it comes to the CED. This contrast is subject to the same causes mentioned before, as their study considers the total amount of kWh produced during a battery's or a plant's lifetime.

Only an old reference by Paul Denholm et. al presents comparable data as it uses the same functional unit. However, the uncertainty about the boundaries and the method of calculations undermining the comparison and the possible differentiations in the findings. Specifically, they demonstrated that PHS and CAES produce 35.7 and 19.4 kg of CO_2 equivalent respectively, while their cumulative energy demand is 0.103 and 0.073 MWh per kWh of storage capacity. It is obvious that these numbers are more relevant to our results, although not quite precise. Still, the fact that the key findings are in accordance and conclude that CAES is performing better in both categories strengthens our results.

The results per kilogram of battery, on the other hand, allow a more accurate comparison with literature findings as this functional unit is used by quite a few authors. One of the most recent and comprehensive studies about environmental impacts of different battery types conducted by Mitavachan H. includes models for CED and GWP per kilogram of battery. The findings look almost identical with Lithium-Ion and Sodium-Sulphur (NaS) batteries presented the highest contribution to global warming reaching up to 22 and 14 kg of CO_2 equivalent, while all the other types have a GWP indicator under 4 kg of CO_2 eq. per kg of battery. Compared to figure 19 two key features can be observed: 1) The sodium-sulphur in this current study overcome the

Lithium-Ion environmental impacts and 2) Both Li-Ion and NaS batteries present slightly higher values. The same principles apply to the results regarding the cumulative energy demand per kg of battery. These marginal variations for both methods examined are probably caused by differences during the modelling such as system boundaries or preside composition of batteries.

Another important feature of an LCA is to locate the materials and the processes which present the highest contribution to the total environmental footprint so that those responsible can seek to optimize them. In the following table are presented some of the key drivers of the environmental performance of the tested systems. It should be mentioned that inverter unit has also a relatively high contribution in all the systems incorporated. Finally, we can observe that electricity is a clear driver for many technologies.

Table 37: Key drivers for the environmental performance of every system examined.

System	Driver 1	Driver 2
PHS	Cement	Electricity
CAES	Ait compressors	Turbine
Flywheel	Molybdenum	Electricity
Hydrogen/Fuel Cell	Steel	Inverter
Li-Ion	Anode	Cathode
Lead-Acid	Lead	Electricity
NaS	Electricity	Copper
VRFB	Electrolytes	Electricity

Finally, a further recalculation of the of the results for PHS and CAES was conducted, considering the kWh of electricity as a functional unit. The purpose of this action was to justify our findings regarding the literature review. Based on table 37 it seems that our results for the GWP indicator are quite similar to L. Oliveira et. al conclusions about the kilograms of CO_2 equivalent produced by the two mentioned techniques.

Table 38: Comparison of GWP results with L. Oliveira et. al report from the literature.

System	PHS	CAES	Reference
Units	GWP (kg CO_2 eq.)	GWP (kg CO_2 eq.)	-
Per kWh of storage capacity	312	72.5	Current Study
Per kWh of electricity	0.0057	0.00805	Current Study
Per kWh of electricity	0.006	0.008	(L. Oliveira et. al)

In general terms, the findings look quite accurate and transparent giving an aggregated perception about the environmental impacts of energy storage technologies. Nevertheless, the lack of available data either primary or secondary and the necessity for assumptions to be made create some uncertainty about the accuracy but not for the general trend of the results.

6.Conlusion/Recommendations

The aim of this project was to analyse eight different technologies from an environmental perspective. Therefore, a cradle-to-gate LCA was conducting considering all the systems for a potential stationary application. After the data were gathered and normalized per kWh of storage capacity, the systems were modelled and assessed based on three separate characterization methods. The key findings from this study indicate that CAES plant dominated all three methods performing better not only with the lowest environmental impact based on the Recipe approach but also regarding the cumulative energy demand (CED) and the contribution to global warming (GWP). On the other hand, Hydrogen/Fuel cell system shows the highest environmental burden for two out tree methods. Specifically, only when GWP was examined PHS plant presented higher environmental pollution with 312 kg of CO_2 equivalent against 301 of Hydrogen/Fuel Cell application. Among batteries, NaS proved to be the most environmental friendly from all aspects. Furthermore, when only batteries were compared using for functional unit the 1 kilogram, the findings were more clearly, with Lead-Acid and VRF batteries performing greatly better than the other two battery systems concerning the CED as well as the GWP indicators.

Even if the particularities of the functional unit make it slightly difficult for the results to be compared with other studies, the benefits from this LCA are sufficient as the methodology can easily be applied to different occasions and storage systems. Simultaneously, the conclusions for the environmental impacts of the technologies can be used either by decision makers as an informative tool or by researchers as data inventory.

Simultaneously, there are plenty possibilities for further investigation of this study by researchers. First of all, a more analytic modelling of the different technologies can be performed including more accurate data for material and energy inputs. These data can only be acquired in cooperation with the industry and private companies as the literature seems quite limited. Furthermore, an extension of the boundaries could be carried out in order to comprise in the modelling the usage phase and the end-of-life of the installations. It would also be interested to examine a different functional unit and probably compare the environmental impacts between the renewable electricity stored and delivered by a storage system and the electricity from conventional coal.

However, something like this requires an extensive amount of time and very precise modelling in the software. Finally, more energy storage technologies like TES and SMES, which were not considered in this study, could be investigated.

In conclusion, this study presents the superiority of CAES technology as a potential energy storage method from an environmental perspective and gives a clear hint for the performance of some of the most promising EES regarding the environment. It is also a solid base for further investigations that can provide very accurate and robust results. In a world were transition to renewable energy seems inevitable in order to create a sustainable future, EES will play a dominant role. Therefore, their selection must be made not only based on the economic profit and the different interests, but also on the environmental performance. Because a green future cannot be established in non-sustainable solutions.

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