



Life Cycle Assessment of Cryobattery Energy Storage

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Citation for published version (APA):

Jones, C. (2019). *Life Cycle Assessment of Cryobattery Energy Storage*.

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Life Cycle Assessment of Cryobattery Energy Storage

Research report

Document Reference: LCA LAES ERv1
Version: 1.0
Date: March 2019
Prepared by: Dr Christopher Jones

***NB:** All views contained with this report are attributable solely to the authors and do not necessarily reflect those of researchers within the wider Tyndall Centre.*

This research was funded as part of the UK Engineering and Physical Sciences Research Council MY-STORE: Multi-energY storage-Social, TechnO-economic, Regulatory and Environmental assessment under uncertainty project (EP/N001974/1).

Executive Summary

The United Nations Paris Agreement 2016 requires rapid decarbonisation of energy systems and this implies electricity grids that are increasingly made up of intermittent generators such as wind and solar photovoltaics and increased electrification of energy services (UNFCCC, 2015). This is likely to mean a greater demand for balancing and flexibility services in the electricity system. Currently these services are typically provided by natural gas generators, diesel electric generators (DEG) and pumped water storage. However these approaches are either direct emitters of greenhouse gases (GHG) or spatially constrained. New forms of energy storage will therefore be relied upon for short-term operating reserve capacity, frequency response, demand management and peaking services. Many new forms of energy storage do not have direct GHG emissions but do however entail upstream resource consumption and operational energy losses (with associated GHG emissions) (Denholm and Kulcinski, 2004, Hiremath et al., 2015). A life cycle assessment (LCA) approach is required therefore to determine the net contribution energy storage devices can have for decarbonising the electricity sector.

Cryobattery energy storage, also referred to as liquid air energy storage (LAES) is a form of thermo-mechanical energy storage for electricity grid scale applications. It is based on the liquefaction of air through cooling and compression for charging and a turbine powered by re-expansion during discharge and developed for large scale grid application. The goal of this study is to apply a LCA method to determine the life cycle impact of a 20MW/80MWh scale cryobattery system. A comparison is also made with equivalent DEG and natural gas turbine generator alternatives to determine the net GHG emissions savings potential of the cryobattery system. The study finds that for a range of use phase and end of life scenario assumptions GHG emissions per unit of electricity supplied to the electricity grid are between 30 kg CO₂eq/MWh to 232 kg CO₂eq/MWh. This compares favorably with equivalent GHG emissions values for DEG and open cycle gas turbines of 955 kg CO₂eq/MWh and 701 kg CO₂eq/MWh respectively.

Contents

1 Goal and Scope.....4

1 Goal and Scope

The goal of this assessment is to evaluate the potential contribution of cyrobattery technology to the decarbonisation of electricity supply through the provision of electricity system services such as balancing, reserve and black-start, under different use phase and end of life assumptions. The aim is to investigate how decarbonisation potential can vary under different use phase circumstances and where recycling at end of life is considered. The scope therefore includes full attributional life cycle assessments of a transmission grid-scale cyrobattery system and it includes equivalent assessments of DEG and OCGT alternatives to determine relative GHG emissions savings where a cyrobattery displaces fossil fuel generation. The functional unit for the attributional impact assessment is 1MWh of electricity output to the electricity system. For the comparative change in GHG between cryobattery, DEG and OCGT, net change in CO_{2e} over the lifetime of the system is used.

A cradle-to-grave system boundary is applied the storage system and the fossil fuel generators (Figure 1). This includes material and energy inputs into manufacturing, assembling and transportation to site (upstream), use-phase energy and material inputs, and end of life processing and products. The scope includes ancillary components for connection to the electricity network or grid, such as transformers and inverters. The system boundary incorporates upstream impacts for electricity generation used to operate and charge the storage devices and the fuel extraction, refining and transport to diesel electric and natural gas generators, in the use phase. Recycled and reused products recoverable from the ESS and fossil fuel systems are accounted for as a credit for displaced primary materials. The energy and material input to, and waste from, recycling or disposal processes are included also.

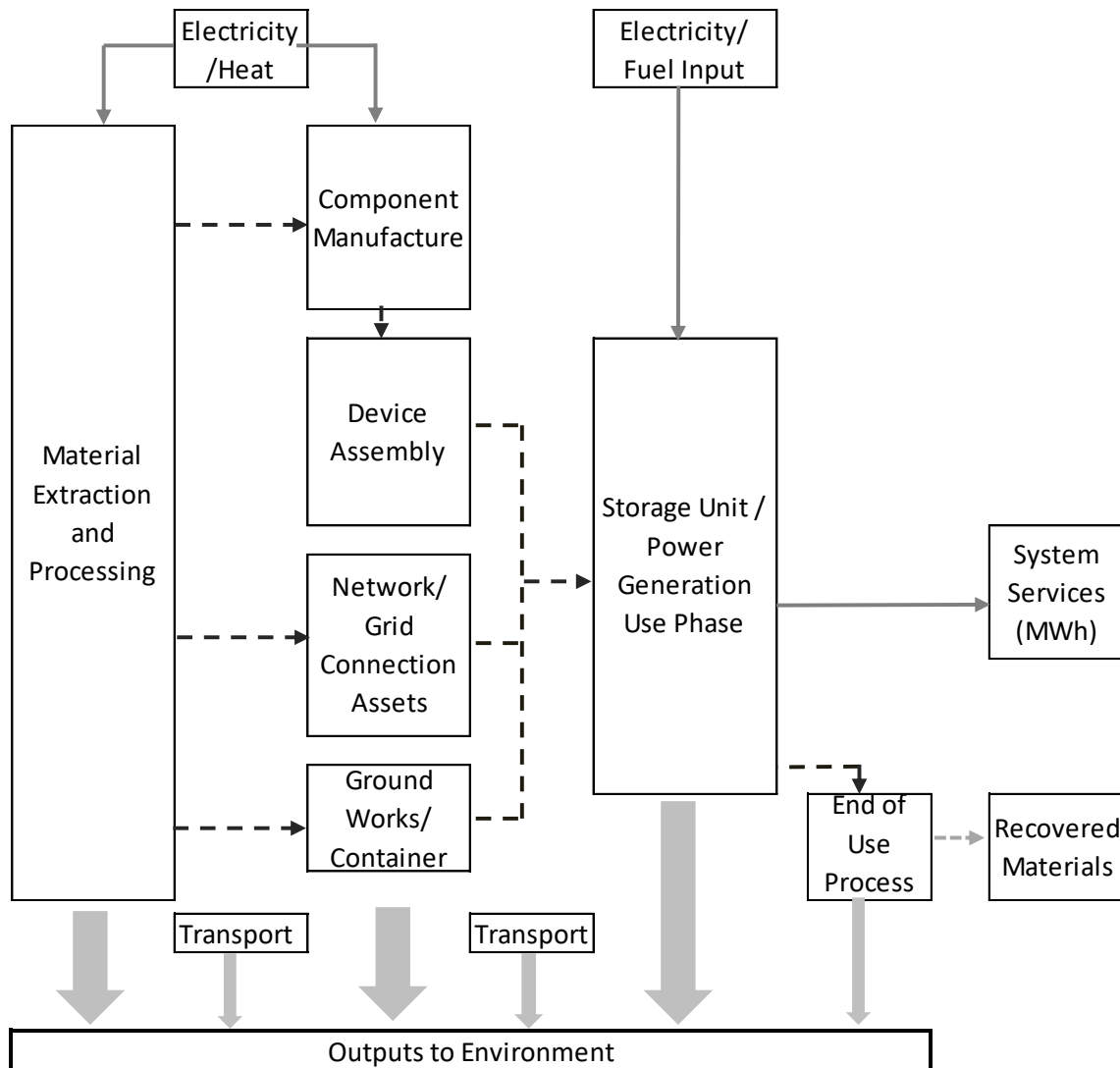


Figure 1: Generalised system boundary for the cryobattery, the diesel-electric generator and the gas turbine generator

1.1 System Definition

The following system definitions were used to determine the system boundary, use phase parameters (round trip efficiency, source of input energy, operating lifetime and the total MWh of electricity provided back to the electricity grid over this period) and end of life processes. The key components of the cryobattery are the liquefaction, power recovery and cryogenic storage units. The liquefaction unit consists of two air compression assemblies, cryogenic expander unit and cold store. The power recovery unit includes an enclosed synchronous generator. The cryogenic storage unit comprises large steel cryogenic tanks with a perlite medium, heat exchangers, thermal generators, thermal stores, insulation and pipework

Energy storage systems can provide a number of specific and combination (stacked) grid services, leading to different use profiles for the frequency and duration of discharge and charge. These different uses have implications for the frequency and duration that a system is used for, which in turn can affect the total output of useful electricity supplied to the grid over the asset life and the roundtrip efficiency of the system. An energy storage system may also operate within different electricity system contexts, meaning that input energy source to charge and operate the system can vary by use case. This study adopts the approach of Hiremath et al. (2015) in applying a range of assumptions on utilisation, round trip efficiency and energy input source to provide a more comprehensive picture of how GHG emissions from energy services provision can vary by use phase context.

Utilisation rate: Utilisation rate is used here to characterise the variation in frequency and duration of energy storage usage over its lifetime. The utilisation rate figures of 5% to 15% are applied to represent the variation in potential utilisation of storage over its lifetime. This equates to 262,800 MWh (5% utilisation) and 788,400 (15% utilisation) electricity supply to the grid over the 30year period. The 15% upper range for the utilisation factor in this assessment equates to frequent usage with nearly full discharge of available stored energy. This figure was based on consultation with energy storage providers. The 5% utilisation was considered a typical average for medium to large stationary energy storage device in the current electricity systems with some intermittent renewables uptake.

Use Phase Electricity Input: The source of energy for charging and operating an energy storage device has a significant effect on the overall impact of discharged electricity (Hiremath, Derendorf et al. 2015). Two representations of likely sources of electricity during the use phase are considered. Firstly, an average grid mix is applied. The average electricity grid mix for Great Britain, decarbonising over time is used. A projected decarbonising electricity mix is based on Great Britain (GB) based electricity grid scenarios from National Grid, specifically their high renewables uptake scenario, 'Two Degrees'. National Grid data is used for an annualised projection of electricity generated per year by generation technology (National Grid, 2017). Secondly, a wind energy only scenario is applied. This reflects a situation where the energy storage unit is charged primarily by low marginal cost and intermittent generators. Ecolnvent v3 data specific to GB is used to provide the impacts associated with this grid electricity mix (Wernet et al., 2016). The average emissions factor for the electricity grid under the National Grid decarbonisation scenario between 2018 and 2047 is calculated to be 101 kg CO₂/MWh. For the wind only scenario Ecolnvent v3 life cycle data for 1-3MW capacity onshore wind turbine located in GB (15 kgCO₂e/MWh) is used.

Round Trip Efficiency: Round trip efficiency is defined here on the basis of useful electricity exported to the grid relative to energy inputs to charge and operate the cryobattery. An efficiency range of 50% to 60% is used here based on interviews with technology provider Highview Power. While this may not necessarily represent the realised performance range of the cryobattery it is used here as the best estimate available and is consistent with the expected round trip efficiency for liquid air energy systems calculated by Morgan (2016).

Life Span and Replacement parts: The assumed asset life for the cryobattery system is of 30 years. This is based on the typical serviceable lifetime of the components involved in the liquid air plant and from interviews with technology developer Highview Power. The consumption of antifreeze, lubricant oil and water by the cryobattery is also included in the assessment.

End of Life Phase: End of life processes are often excluded from most LCAs of energy storage systems as it is typically assumed that this does not add additional detriments to the impact assessment (Hiremath et al., 2015). It is however necessary to consider the extent to which material inputs into storage devices can be recovered and recycled or reused as more energy storage is deployed. This study looks at two options; direct disposal to landfill and recycling of components. Direct disposal includes impacts from transferring components to landfill site only. For recycling, 95% of metals (steel, aluminium and copper) and plastics are assumed to be recovered from the cryobattery, with 90% of material mass entering recycling processes after scrap handling and process losses are accounted for (Paraskevas et al., 2015). Steel, aluminium and copper scrap handling and reprocessing processes and plastics recycling processes are characterised based on Ecolnvent data (Wernet et al., 2016). End products from the recycling process are credited to the ESS as displaced production of primary sourced materials equivalent to the sources of materials assumed in the impact assessment. It is possible that components such as cryogenic tanks could be reused for similar or other purposes; however it is not within the scope of this study to investigate component reuse scenarios.

1.2 Diesel-Electric Generator

For the comparative assessment LCA of a 20MW peak power DEG was undertaken. This analysis is based on the 'Diesel-electric generation set 10MW' Ecolnvent v3 dataset in SimaPro (Wernet et al., 2016). Due to the non-linearity of generation capacity and component mass, it is possible that the impacts of the 20MW unit are slightly overestimated. However, as DEG impacts are dominated by operational emissions, this limitation, due to the availability of data does not materially affect the impact assessment results. Diesel to electricity conversion efficiency of 34% is applied to reflect the stop-start operating profile assumed for electricity grid services. A 240m x 48m x 0.5m concrete plinth is included in the assessment. For comparison with the cryobattery a 30 year life span is assumed, with the generators replaced after 20 years operation.

1.3 Open Cycle Gas Turbine

A LCA for an open cycle gas turbine (OCGT) was undertaken as the second reference case. This assessment is based on data scaled from a 100MW open cycle gas power station in Ecolnvent v3 dataset in SimaPro (Wernet et al., 2016); therefore the same caveats on scaling component impacts apply as with the DEG. The thermal efficiency of the OCGT is assumed to be 37% and is taken from Turconi et al. (2014) who investigated the OCGT performance with a utilisation profile nearer to peak following as opposed to baseload. Ecolnvent v3 (Wernet et al., 2016) data for sweet gas is used and accounts for gas extraction, refining and transport based on global averages. A 30 year lifespan is also applied to this reference case.

1.4 Ancillary Components

Ancillary components included in this study are electricity transmission grid interface assets. For the Cryobattery DEG and OCGT systems a motor control centre kiosk, a 160 kVA transformer, a medium voltage switchgear, a lead acid uninterruptable power supply (UPS) and a low voltage switchboard are included in the scope.

2 Inventory

Inventory data for the cryobattery was provided by Highview Power. For main plant and cryogenic components inventory values were based on scaling up from data for a 5MW/20MWh sized cryobattery to the 20MW/80MWh reference case studied. A power law relationship of 1:0.6 volume to surface area was applied for scaling up the system. Data for the liquefaction components are based on a 20MW/80MWh unit,

Material	Unit	Total
Aluminium	kg	1.20E+04
Aluminium Alloy	kg	1.69E+04
Bronze	kg	6.00E+01
Carbon Steel	kg	6.30E+05
Cast Iron	kg	2.44E+04
Concrete	kg	3.00E+04
Copper	kg	4.71E+04
Copper Alloy	kg	1.57E+03
Foam Glass	kg	2.46E+03
Glass Reinforced Plastic	kg	1.40E+04
Mineral Wool	kg	8.09E+03
Perlite	kg	3.35E+05
Polyurethane	kg	2.17E+02
Quartz Gravel	kg	5.74E+04
Stainless Steel	kg	3.93E+05
Process	Unit	Total
Metal Working	kg	1.09E+06
Transport	Unit	Total
Freight Train	tkm	1.92E+05
Freight Lorry	tkm	9.05E+05
Sea Freight	tkm	9.01E+05

Table 1: Data on the inventory for a 20MW/80MWh Cryobattery system, based on information provided by Highview Power for a 5MW/20MWh compression and generator units and 20MW/80MWh liquefaction unit.

Inventory data for the transformer and enclosure is based on mass balance data from Schneider Electric (2014). The switchgear mass balance is from EICo (2016), inventory data presented in Ghonge and Hakalahti (2012) is used for the UPS and inventory of the switchboard is based on GE Industrial (2016) and Schneider Electric (2016).

3 Impact Assessment Results

The LCA impact assessment was conducted in SimaPro with impact assessments based on Ecolvent version 3 (Wernet et al., 2016) and Plastics Europe databases in SimaPro. In many instances the country of origin for components is not known therefore global average values are used for raw materials and energy inputs into manufacturing generic plastic and metal products.

Figure 2 presents the global warming potential (GWP) impact per MWh of electricity output from the cryobattery under different use phase energy input, utilisation rate assumptions. The results, with and without recycling, are shown as side by side columns. The variation in results due to the range in round trip efficiency estimates are shown as error bars.

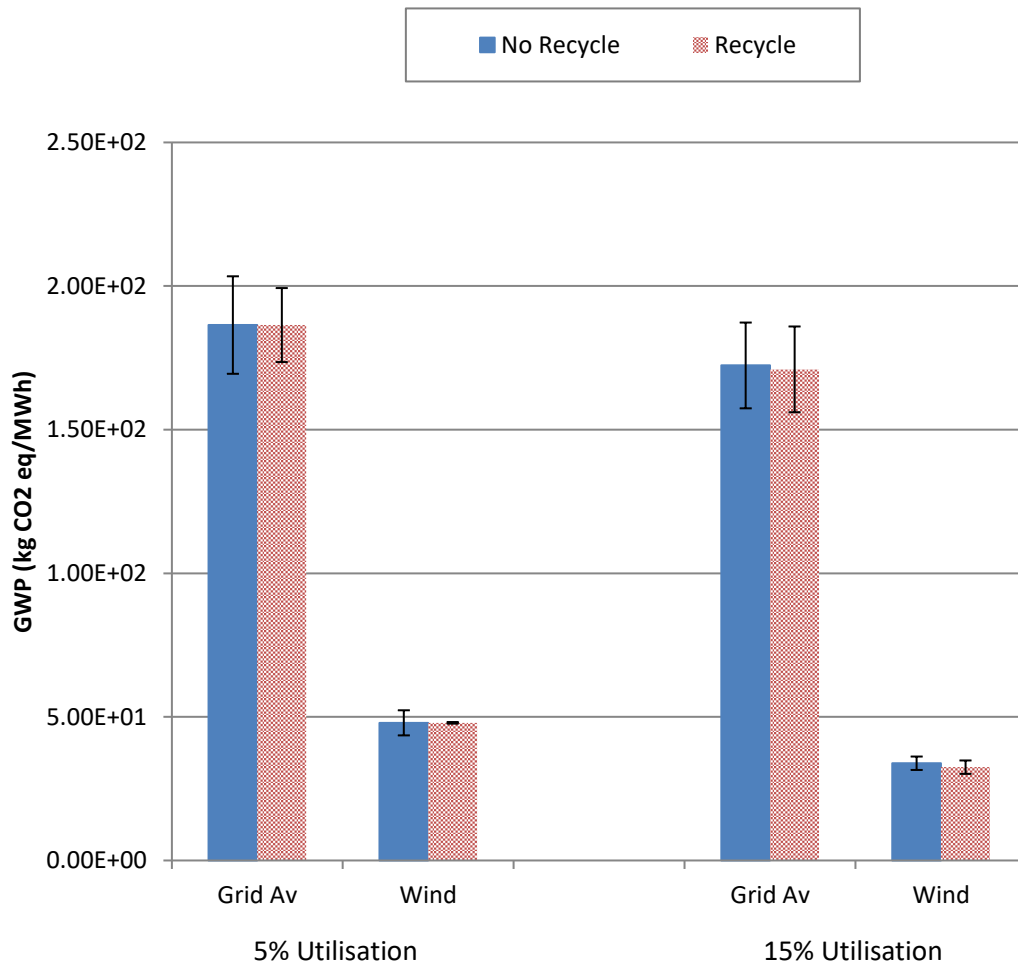


Figure 2: Impact assessment results for 20MW/80MWh Cryobattery system. Variation in results from round-trip efficiency are shown as the error bars.

The results for GWP range from ranging from 30.2 kg CO₂eq/MWh to 232 kg CO₂eq/MWh. Overall life cycle GWP is dominated by the use phase (49% to 97%). The most significant variable

in the life cycle GWP impact results is electricity input source during the use phase. GHG emissions impacts are 73% to 82% lower for the wind-only scenarios compared to the grid average scenarios. The majority of upstream impacts are from raw material and manufacturing inputs for steel and copper components of the system. Key components, including cryogenic storage tanks, pipe work, generators and heat exchangers are predominately steel, with some key elements assembled from copper and aluminium. Steel product production and manufacturing elements of the components account for 80% of upstream impacts. Other bulk products in the system such as the perlite thermal storage medium have minimal effect on the impact metrics. Recycling achieves 1% to 9% reduction in total lifecycle CO₂eq depending on use phase assumptions.

The impact assessment for the DEG and OCGT show GWP values for 946 kg CO₂eq/MWh to 955 kg CO₂eq/MWh and 698 kg CO₂eq/MWh to 701 kg CO₂eq/MWh respectively, varying by utilisation rate. In a comparative assessment the net change in GHG emissions for replacing DEG and OCGT with the cryobattery was found to be in the range of 135 kt CO₂e and 719 kt CO₂e, varying by utilisation rate, input electricity source and type of fossil fuel generator displaced (Fig 3)

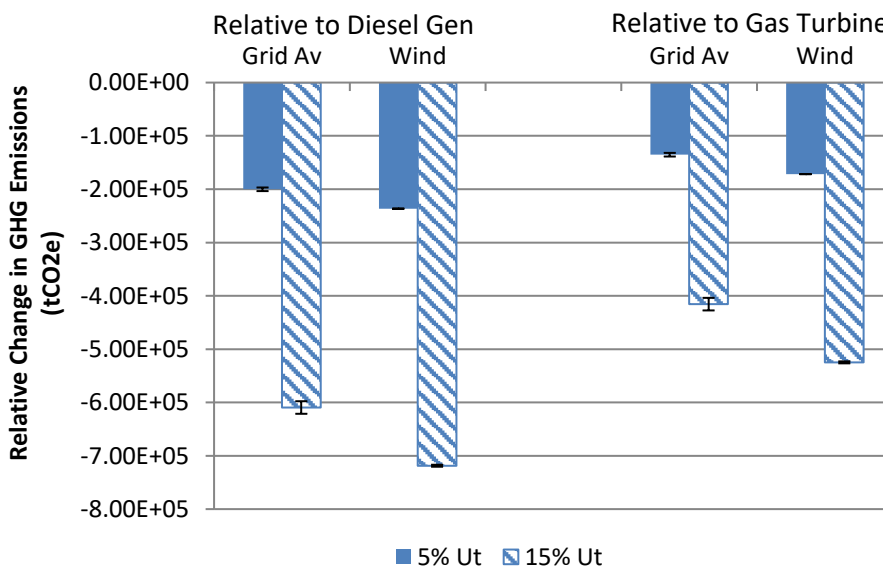


Figure 3: Change in comparable GHG emissions where Cryobattery displaces Diesel-electric Generator or Open Cycle Gas Turbine

4 Conclusions

The results of the life cycle impact assessment show that the cryobattery system studied can provide electricity grid services with low life cycle GHG emissions. The cryobattery has relatively low upstream emissions, owing to types of material inputs (primarily steel) required for its components and long asset life. The relative ease of recycling these components, in comparison with systems with more challenging recycling pathways such as lithium-ion batteries (Chen et al., 2015) means that overall emissions are reduced further where comprehensive recycling is applied. Round-trip efficiency assumptions are shown to be a less significant factor in life cycle GHG results where wind energy is assumed for charging and operating the unit. This supports a recommendation not to balance a focus on efficiency with other factors such as demand for primary materials and recyclability when evaluating energy storage options. A key advantage for the cryobattery is that as the system increases in scale, a power law relationship of 1:0.6 volume to surface area means that upstream impacts relative to the energy capacity of the system will reduce even further as less steel is required per MWh capacity increase.

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