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Case Study

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Life Cycle Assessment of the Minety Battery Energy Storage System: Environmental Performance, Operational Trade-offs, and Implications for Utility-Scale Energy Storage

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Abstract

Battery energy storage system (BESS) could be a major enabling technology for the successful integration of renewable energy, providing improved grid flexibility, but they are vulnerable from an environmental perspective because of their production, mining and end-of-life processes. The 100 MW / 129 MWh Interface Minety BESS in Wiltshire, UK is one of the largest lithium-ion BESS projects in Europe and this case study applies Life Cycle Assessment (LCA) methodologies (ISO 14040/14044) to look across its cradle-to-grave impacts based on data provided by Carvalho et al. (2021). The study shows that the initial life cycle climate impact of charging electric vehicles with this electricity is 24.2 g CO₂-eq per kWh delivered, where most of the climate impact comes from manufacturing and operational charging losses. Most importantly, the operational electricity mix affects the environmental impact: emissions decrease by more than 50% if the charging is done entirely with renewables. Longevity of batteries, as well as recycling and usage, are also significant factors in the sustainability outcomes. The main thing we learned from the Minety project is the importance of clear environmental reporting. It is suggested in this analysis that existing procurement approaches need to move beyond just operational efficiency to whole-life driven approaches, both for grid-scale storage solutions and for procurement by both policymakers and developers more broadly. Sustainability of BESS is not only dependent on battery chemistry, but also on charging patterns, decarbonization pathways of the grid, material recovery and BESS asset management.

Keywords

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1. Introduction

As a result of the intensifying impacts of climate change, environmental degradation, resource exhaustion and industrial pollution, the operational requirements of modern electricity networks are changing fundamentally with their overall transition to low carbon energy systems. Europe, North America and Asia are now rapidly introducing the use of renewable energy, like wind and solar photovoltaics, at unprecedented levels. These technologies, which can significantly cut down on the greenhouse gas footprints of operations, however, suffer from being intermittent, creating significant issues with grid stability, service balancing and transmission reliability. Battery energy storage systems (BESS) have thus taken center stage in the energy transition higher agenda [\[1\]](#).

Grid-scale storage facilities can carry out several tasks at once. They offer fast frequency response, reserve margin, voltage support, peak shaving, smoothing renewable energy and congestion management. Curtailment losses and optimization of the use of the transmission infrastructure are also reduced due to battery storage in systems where a higher share of renewables is installed. The value of the BESS industry has also increased significantly in the past decade, and it is now commonplace for the industry to be integrated into the national energy infrastructure planning process at the level of full-scale lithium-ion projects [\[2\]\[3\]](#).

Batteries can, however, be complex technologies when looking at their environmental impacts. A lot of nickel, cobalt, lithium, copper, aluminum and graphite are necessary for the production. The extraction and processing of them requires lots of energy, and are not always environmentally friendly, water intensive, or in regard to chains of supply. Furthermore, electricity is used in large quantities in battery production, and so are high-temperature industrial processes. With increased deployment and adoption worldwide, a question that now needs to be addressed by engineers, policy makers, and sustainability researchers is whether the upstream environmental effects of the storage outweigh its long-term environmental benefits [\[4\]](#).

Life cycle assessment (LCA) is becoming the main technique available for answering this question. LCA does not only consider the operational impacts, but also the impacts which can be relevant throughout the lifecycle of a system including raw material extraction, manufacture, transport, operation, maintenance, and end-of-life treatment. This systems perspective is especially

critical in the scope of battery technologies because a significant amount of environmental impact takes place prior to system start-up [5].

One of the most significant battery storage projects for lifecycle analysis is a system at Minety near Salisbury, Wiltshire, United Kingdom. The plant was constructed in 2021 and at the time of deployment became one of the biggest lithium-ion storage facilities in Europe [6]. The public LCA it has carried out, by Carvalho et al. (2021), is particularly interesting for its transparency and engineering level, which are much rarer in the scope of commercial storage projects. The study is one of the most straightforward to-date datasets for looking at the environmental impacts of utility-scale lithium-ion infrastructure in the real grid environment [7].

This article builds the assessment with details to the engineering and sustainability audience. The paper not only presents numerical results, but also critically discusses the methodological assumptions, operational sensitivities, and strategic implications of the Minety project. The case is presented to develop a rationale for discussing wider issues about how sustainable the case is, how the concept of a circular economy could be taken up on the project, how the project could fit in with the decarbonization of the grid and how energy storage infrastructure should be procured in future.

2. Background and Literature Review

Battery energy storage systems are playing an increasing role in the energy sector. Electricity systems were traditionally built to meet varying demand with capacity that can be dispatched by the fuel being used, which is commonly fossil fuel. In contrast, renewable energy technologies involve a certain degree of fluctuation in time, which is not accounted for in conventional infrastructure. Wind generation is dependent on weather forecasts and solar generation is directly proportional to the daytime and seasonal daylight information [8]. When more and more renewable power enters the grid, balancing mechanisms are ever more critical to grid reliability.

This happens because battery energy storage systems can be used to store excess electricity during those times and provide a balancing delivery when it's needed, either due to a greater demand or decreased renewable energy. The current market for utility scale storage is dominated by lithium-ion batteries with their high energy density, quick response times, modular operating and a rapidly declining cost [9].

In the last 10 years, installed battery storage has grown massively around the world. The International Energy Agency sees non-distributed batteries growing by several times by 2030, when countries accelerate decarbonization and coal phase-out plans in their power sector. With a growing need for balancing services and a strong offshore wind investment base in the UK, the country has emerged as one of the biggest markets for battery storage steps in Europe.

2.2 Environmental Concerns Associated with Lithium-Ion Batteries

Lithium-ion systems will lower operating reliance on fossil fuel peaking plants, but still have significant environmental impact during the upstream phases. Nickel, cobalt, lithium, manganese and copper production is closely linked to significant GHG emissions, freshwater ecotoxicity and resource depletion. These effects can tend to be regionalized in areas where environmental laws and energy systems are very different from countries of deployment [\[10\]](#)[\[11\]](#).

Manufacturing the battery itself is another large contributor. Highly controlled dry room environment and thermal processing is required with energy intensive cathode synthesis for cell production. Electricity use in the manufacturing phase is consistently found among the biggest driver of impacts in the lifecycle of lithium-ion systems. This means that battery factories on fossil fuel-based electricity grids have significantly higher carbon footprints compared to those using electricity derived from renewables [\[12\]](#).

Energy and sustainability issues are further complicated by battery disposal and recycling concerns. Efficiency of recovery systems is important – if something is lost to waste streams in the short term, then it will cost in the long term to recover it again. Incorporating recycling technologies (pyrometallurgy and hydrometallurgy processing) has been given greater attention, therefore, in circular economy contexts.

2.3 Life Cycle Assessment: A tool for Energy Storage Research.

LCA is a methodical tool used to assess the environmental effects over the entire life cycle of technological systems. There are four general steps in LCA, which are provided in the ISO 14040 and ISO 14044 standards: Goal Definition, Inventory Analysis, Impact Assessment, and interpretation [\[13\]](#) [\[14\]](#).

Past work looking at the use of lithium-ion battery energy storage systems (BESS) has found a wide range of lifecycle emissions results based on chemistry, manufacturing region, BESS

operating strategy, and electric generation portfolio. The climate change impacts reported from around the world are distributed from less than 10 g CO₂-eq/kWh delivered to over 100 g CO₂-eq/kWh. This variation illustrates the fragility of storage sustainability of contextual operational assumptions.

In many of the published studies, however, the authors made use of simplifying assumptions or systems modeled in the laboratory and not in use at actual operational commercial projects. The Minety assessment is therefore especially useful in assessing a functioning utility-scale installation in an objective way, based on actual engineering data, and with clear boundaries of the methodology used.

3. Case Study Description: The Minety Battery Energy Storage System

3.1 Project Context

The Minety Battery Energy Storage System is located in Wiltshire in southwest England and is connected to the United Kingdom National Grid's 400 kV transmission network. Developed as part of the UK's broader energy flexibility strategy, the project was designed to support increasing renewable penetration while improving frequency stability across the transmission system [\[15\]](#).

At the time of commissioning in 2021, Minety was among Europe's largest operational lithium-ion battery facilities. The project attracted substantial attention within the energy sector because it demonstrated the growing commercial maturity of utility-scale battery infrastructure.

3.2 Technical Characteristics

The facility has a rated power capacity of 100 MW and a storage capacity of 129 MWh, corresponding to approximately two hours of discharge duration under nominal operating conditions. The installation consists of 28 Tesla Megapack units utilizing lithium nickel manganese cobalt oxide (NMC) battery chemistry.

Each Megapack integrates battery modules, inverters, thermal management systems, safety equipment, and digital control architecture within a containerized design. The modular configuration simplifies deployment while enabling rapid scalability and maintenance access.

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The system primarily provides frequency response and balancing services to the Great Britain transmission network. Such applications require high cycling frequency and rapid response capability, both of which significantly influence lifecycle energy throughput and environmental performance.

3.3 Importance of the Minety Project

Several characteristics make the Minety BESS particularly relevant for lifecycle assessment research. First, its operational scale reflects the emerging generation of commercial utility-scale storage infrastructure rather than pilot or demonstration projects. Second, the availability of transparent lifecycle data allows meaningful academic and policy analysis. Third, the project operates within a national grid undergoing rapid decarbonization, making it an instructive example of how storage sustainability evolves alongside electricity sector transformation.

4. Methodology

4.1 Goal and Scope Definition

The primary objective of the lifecycle assessment was to quantify the environmental impacts associated with electricity delivery from the Minety BESS over its operational lifetime. The study adopted a cradle-to-grave perspective, encompassing all major lifecycle stages from raw material extraction through end-of-life recycling.

The functional unit selected was 1 kWh of electricity delivered to the grid over the system's lifetime. This functional unit enables comparison with alternative storage technologies and electricity generation systems.

4.2 System Boundary

The system boundary included four principal stages:

1. Upstream material extraction and processing
2. Manufacturing and construction
3. Operational phase
4. End-of-life treatment and recycling

The upstream stage incorporated mining and refining of lithium, nickel, manganese, cobalt, copper, graphite, and aluminum. Battery cell production, module assembly, Megapack integration, and transportation to the UK deployment site were also included.

The construction stage accounted for civil works, concrete foundations, electrical infrastructure, transformers, cabling, and auxiliary systems.

Operational impacts included charging losses associated with round-trip efficiency, thermal management electricity consumption, maintenance activities, and replacement components where applicable.

The end-of-life stage considered recycling through combined pyrometallurgical and hydrometallurgical pathways, with avoided burden credits allocated for recovered metals.

4.3 Assumptions and Operational Parameters

The study assumed a 20-year operational lifetime and a round-trip efficiency of 86 %. The operational electricity mix reflected the 2019 Great Britain grid carbon intensity of approximately 230 g CO₂-eq/kWh.

Sensitivity analyses examined alternative operational scenarios, including renewable electricity charging, improved round-trip efficiency, and extended operational lifetime.

5. Results and Findings

5.1 Global Warming Potential

The baseline lifecycle global warming impact was calculated at 24.2 g CO₂-eq per kWh delivered. Manufacturing represented the single largest contributor, accounting for approximately 47 % of total emissions.

Cathode material production and cell assembly dominated manufacturing impacts due to energy-intensive industrial processing requirements. Aluminum and copper current collectors also contributed significantly because of their high embodied energy.

Operational impacts represented approximately 44 % of total lifecycle emissions. Importantly, these impacts were driven primarily by charging losses rather than direct auxiliary electricity consumption. This finding highlights the importance of system efficiency and charging source characteristics.

End-of-life recycling generated a net environmental credit equivalent to roughly 9 % of total lifecycle emissions through displacement of virgin metal production.

5.2 Renewable Charging Scenario

One of the study's most significant findings emerged from the renewable charging sensitivity analysis. Under a fully renewable electricity supply scenario, lifecycle emissions decreased from 24.2 g CO₂-eq/kWh to approximately 10.5 g CO₂-eq/kWh.

This result demonstrates that storage sustainability is closely linked to the decarbonization trajectory of the surrounding electricity system. Battery systems do not inherently eliminate emissions; rather, they shift electricity temporally within the grid. Consequently, charging behavior and grid composition become critical determinants of environmental performance.

5.3 Energy Payback Time

The cumulative energy invested during manufacturing and construction was recovered after approximately 1.1 years of operation. This relatively short payback period reflects the system's high utilization rate within frequency regulation applications.

Compared with lower-throughput applications such as energy arbitrage, frequency response services generate larger cumulative energy throughput over the system lifetime, thereby distributing manufacturing impacts more efficiently across delivered electricity.

5.4 Mineral Resource Scarcity

Resource depletion impacts were strongly associated with copper, nickel, and cobalt demand. Although recycling reduced virgin material requirements, substantial dependency on primary extraction remained.

This finding reinforces concerns regarding long-term material availability as global battery deployment accelerates. Diversification toward lower-cobalt chemistries and improvements in material recovery efficiency may therefore become increasingly important for future storage sustainability.

5.5 Freshwater Ecotoxicity and Land Use

Freshwater ecotoxicity impacts originated primarily from mining activities and electricity consumption during cell production. Sulfidic ore processing associated with nickel and copper extraction contributed heavily to these indicators.

Direct land occupation associated with the Minety site itself remained relatively modest due to the compact nature of containerized battery systems. However, indirect land impacts associated with global mining operations were substantially larger.

6. Discussion

6.1 Operational Context Matters

A key lesson emerging from the Minety case is that battery sustainability cannot be evaluated independently of operational context. Storage systems derive environmental value not simply from their existence, but from how and when they are charged, discharged, and integrated into the grid.

The dramatic reduction in lifecycle emissions under renewable charging scenarios illustrates the importance of aligning storage operation with periods of low-carbon electricity generation. Future smart charging algorithms could therefore play an increasingly important role in minimizing environmental impacts.

6.2 Manufacturing Remains the Dominant Challenge

Although operational decarbonization can substantially reduce lifecycle emissions, manufacturing impacts remain difficult to eliminate entirely. Cathode production, particularly for nickel-rich NMC chemistries, continues to require significant thermal processing and material extraction.

Future reductions may depend on renewable-powered battery factories, lower-impact cathode chemistries, and greater manufacturing efficiency. Emerging technologies such as lithium iron phosphate (LFP) batteries may also offer advantages in terms of reduced cobalt and nickel dependency.

6.3 Importance of Lifetime Extension

The sensitivity analysis showed that extending operational lifetime from 20 to 25 years reduced lifecycle GWP by approximately 15 %. This highlights the environmental significance of degradation management strategies.

Advanced battery management systems, improved thermal control, predictive maintenance, and conservative cycling protocols may therefore contribute not only to economic optimization but also to environmental performance.

6.4 Circular Economy Considerations

The Minety assessment demonstrates that recycling can partially offset upstream environmental burdens, although current recovery systems remain imperfect. Future battery policies may increasingly prioritize design for disassembly, standardized module architecture, and traceable material recovery pathways.

Establishing domestic recycling infrastructure within Europe and the United Kingdom may also reduce transport burdens and improve strategic resource security.

7. Policy and Industry Implications

The findings of the Minety case study carry several important implications for policy makers and energy developers.

First, procurement frameworks for publicly supported storage projects should incorporate lifecycle environmental criteria rather than focusing solely on capital cost and operational performance.

Second, grid operators could incentivize low-carbon charging behavior through dynamic carbon-intensity pricing mechanisms. Such systems would encourage storage operators to align charging schedules with renewable availability.

Third, governments should support the development of battery recycling infrastructure and harmonized reporting standards. Transparent lifecycle disclosure would enable more meaningful comparison across storage technologies and supply chains.

Finally, lifecycle metrics should become integrated into long-term energy planning models to ensure that rapid deployment does not inadvertently create new environmental burdens.

8. Limitations

Although the Minety assessment provides valuable insight, several limitations remain. Battery manufacturing data often involve proprietary information, creating uncertainty regarding exact production processes and energy sources. Recycling technologies are also evolving rapidly, meaning that future recovery efficiencies may differ significantly from those assumed in the study.

In addition, the operational electricity mix of the UK grid is expected to continue decarbonizing throughout the system lifetime. Static grid assumptions may therefore overestimate future operational impacts.

Finally, the study focuses primarily on environmental indicators and does not comprehensively evaluate social or geopolitical dimensions associated with critical mineral supply chains.

9. Future Research Directions

Future research should examine comparative lifecycle performance across alternative battery chemistries, including lithium iron phosphate, sodium-ion, and solid-state technologies. Greater

attention should also be given to second-life battery applications and adaptive operational strategies based on real-time carbon intensity signals.

In addition, integrating techno-economic analysis with lifecycle assessment could provide a more holistic understanding of sustainability trade-offs within energy storage deployment.

10. Conclusion

The Minety Battery Energy Storage System represents one of the most important real-world case studies currently available for evaluating the environmental performance of utility-scale lithium-ion storage infrastructure. Its lifecycle assessment demonstrates that battery systems can provide substantial climate benefits when integrated within increasingly decarbonized electricity networks, while also revealing significant environmental burdens associated with manufacturing and material extraction.

With a baseline lifecycle impact of 24.2 g CO₂-eq/kWh and an energy payback period of approximately 1.1 years, the project illustrates both the promise and complexity of large-scale storage deployment. Operational electricity mix, battery lifetime, recycling effectiveness, and service application all emerge as critical determinants of sustainability outcomes.

More broadly, the Minety case highlights the necessity of adopting systems-level thinking within the energy transition. Battery storage should not be evaluated solely as a technological product, but rather as part of an interconnected industrial ecosystem encompassing mining, manufacturing, electricity generation, operational control, and material recovery. As global deployment accelerates, lifecycle assessment will become increasingly important for ensuring that the transition toward low-carbon electricity systems remains environmentally credible, resource-efficient, and socially sustainable.

11. Declaration

11.1 Availability of data and material

Not applicable.

11.2 Funding

Not applicable.

11.3 Acknowledgements

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