Sustainability Challenges and Circular Economy Solutions for Lithium in the Transition to Clean Energy: A UK Perspective

P.A. Fletcher, T.K. Olaniyi
Glasgow Caledonian University
London, United Kingdom

Abstract

This paper assesses the degree of sustainability of lithium as a key commodity in the transition to clean energy focusing on the challenges associated with its supply and value chain, environmental impacts, the potential for circular economy solutions and makes recommendations for future directions. The world relies heavily on fossil fuels for urbanisation and development causing significant environmental damage. To combat climate change, a global shift to renewable energy and decarbonisation is essential. Reliance on renewable energy is invariably prone to power fluctuations based on availability of renewable energy sources such as solar or wind energy which underscores the importance of lithium-ion batteries in providing grid stability, energy storage and enabling the widespread adoption of electric vehicles. Existing literature has explored energy consumption, the role of lithium in energy transitions, supply chain vulnerabilities and the socio-economic implications of critical raw materials. However, there exists limited research that focuses on the circularity and sustainability of lithium-ion batteries, particularly in the UK, where decarbonisation efforts are gaining momentum. Through expert interviews and an analysis of current practices, this study highlights that while lithium is abundant, its extraction processes are energy-intensive, water-intensive environmentally damaging, and socially problematic in vulnerable regions. This study makes significant contribution to literature by establishing that the current approaches to lithium use undermines long-term sustainability. The study emphasises the need to extend the lifespan of lithium products by integrating circular economy principles and the waste hierarchy into the lithium value chain. Key recommendations include securing stable and diversified supply chains, implementing early carbon-saving measures, advancing research into alternative battery materials and technologies, fostering collaboration among stakeholders, and enacting robust policies to promote reuse, refurbishment, and recycling. Future research should prioritise strategies for improving lithium sustainability through circular economy frameworks, waste prevention efforts and technological innovations. Additionally, the socio-economic impacts of lithium extraction in vulnerable regions must be addressed to create a more sustainable and ethical supply chain. Coordinated efforts across policy, industry, and research will be crucial in achieving these goals and ensuring the equitable and enduring transition to a clean energy future.

1. Introduction

Sustainable development depends on managing resources, technology, investment, and market engagement. The Industrial Revolution, fueled by fossil energy, caused environmental harm. In response, the 2015 Paris Agreement committed 196 nations to reducing greenhouse gas (GG) emissions to mitigate climate change. Fossil fuel reliance is unsustainable and renewable energy sources (RES) like solar and wind are being prioritised, especially in urban areas, to support a greener economy. However, RES are intermittent and can cause fluctuations in electricity production, so energy storage systems (ESS) like lithium-ion batteries (LIB) are critical for capturing and distributing renewable energy. LIBs are versatile electrochemical ESSs, used in devices, electric vehicles, and grids to provide power and stabilise electricity production.

Raw materials are the fundamental building blocks of manufacturing and industry. Safeguarding the supply chain of strategically important raw material is essential to reducing disruptions and negative impact to consumers. With the global shift to clean energy technologies (CET), the demand for lithium will rise, but its supply chain is complex, involving geopolitical, environmental, and social issues. The UK has pledged to shift towards a robust carbon restrained economy and aims to prioritise domestic energy sources, promote resource efficiency in line with Waste Hierarchy principles, and ensuring sustainability in order to curate a sustainable energy future. Sustainability, defined by the 1978 United Nations Brundtland Commission as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.”, is an integrated approach to development that protects the requirements of future generations through a framework of Sustainable Development Goals (SDGs) [1]. The circular economy model differs from the traditional linear economy model in that it is a closed loop of production and consumption based on the concept of regenerating resources, reducing waste and extending the lifespan and value of products and

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materials through reuse, refurbishment, recycling and resource efficiency thereby minimising reliance on finite natural resources [2]. Waste Framework Directive 2008/98/EC sets out a priority order for waste prevention and management as follows: prevention, reuse, recycling, recovery and disposal. This waste management strategy embodies sustainability and circular economy principles and is based on environmental impact and gives top priority to waste prevention and the least priority to disposal such as landfill [3].

This research examines the sustainability of lithium as a vital commodity in the transition to renewable energy by evaluating the significance of energy consumption to socio-economic development, available technologies and obstacles to the transition from fossil energy to RES and CET, supply chain complexities and challenges associated with an increased dependence on lithium and the interplay between waste hierarchy principles, the circular economy model and the sustainable management of lithium resources. The study uncovers nuanced insight and perspectives for advancing the degree of sustainability of lithium reliance through semi-structured interviews of experts in relevant sectors.

2. Literature Review

Transition to a sustainable energy future hinges on the ability to produce, store and use energy as efficiently as possible. Central to this evolution is lithium, a critical raw material that is indispensable to the energy storage sector. This chapter explores the pivotal role of energy consumption in driving economic and technological advancement, increasing importance of lithium to modern energy solutions and the challenges inherent in its value chain. Finally, this chapter examines the dynamic market trends that underscore lithium's surging demand as industries worldwide intensify their reliance on this essential resource. Together these sections highlight both the opportunities and complexities of building a sustainable lithium-powered future.

2.1. Energy Consumption

Energy consumption is essential for the manufacture, production, transportation, and use of products. Continued urbanisation and growing population increase the demand for energy and energy consumption. Since the 1800s, fossil fuels have been the primary energy source for industrial and socio-economic development [4], though their extraction harms the environment and human health. Fossil fuel combustion generates GGs contributing to climate change and, as a finite resource, poses risks to energy security. Transitioning to RESs like solar, wind, and hydro is crucial for sustainable energy supply.

2.1.1. Economic Benefit and Social Development. Energy consumption drives industrial growth, infrastructure, and technological advancement, essential for basic human needs and social development. Efficient, affordable energy enhances quality of life [5], but disparities in energy access highlight social inequalities and repressed development, especially in rural and marginalised communities where lack of access to healthcare and education, unsanitary living conditions and malnourishment are prevalent. The UN aims for universal energy access by 2030; however this effort is impeded by infrastructural issues predominantly in sub-Saharan Africa and South Asia. Off-grid energy solutions like ESSs help close these gaps stimulating local economies and strengthening social cohesion [6]. However, countries with petroleum-based economies in the Middle East and Central Asia face little incentive or urgency to shift to renewables, as their economic growth relies on fossil fuel exports [7].

2.1.2. Transitioning to renewable energy sources. Fossil fuel use leads to significant GG emissions, necessitating the decarbonisation of the energy sector to protect the environment. RESs like solar and wind are key alternatives, but their intermittent supply poses challenges. ESTs, such as compressed air and electrochemical storage, help stabilise energy flow and store excess power for use when needed [8], facilitating the shift away from fossil fuels [4]. Sustainable renewable energy consumption has been shown to positively influence economic growth, direct foreign investment, inflation, and population growth [9].

2.1.3. The UK net zero target. The UK has reduced its reliance on fossil fuels from 90% in the 1970s to below 80% and aims to achieve net zero emissions by 2050. This will be done through carbon reduction and offsetting via natural sequestration and carbon capture [10]. The UK government's energy policy, outlined in the white paper Our Energy Future, emphasises the role of renewable energy in reducing CO2 emissions and fostering sustainable development [10], [11]. From 1990 to 2021, the UK cut carbon emissions by 48%, outpacing other G7 nations while growing its economy by 65% [12]. The current government policy, Powering Up Britain further emphasises securing the country's energy supply from volatile international energy markets by aiming for net zero carbon electricity generation by 2035 and net zero economy by 2050. RES accounted for 43% of electricity in 2020, up from 2% in 1991. However, while current projections suggest progress, some experts [10] believe the 2035 target may be difficult to achieve without significant financial burdens on consumers and taxpayers.

Coal reliance in the UK decreased from 39.6% in 2013 to 1% in 2023, while zero-carbon electricity

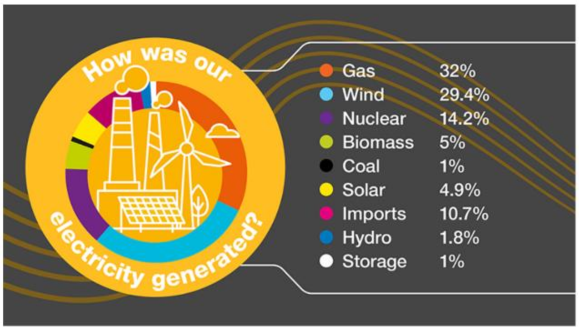

Figure 1. Total electricity generated in the UK in 2023 by energy source [13]

generation rose to 51% in 2023. Figure 1 shows that although natural gas remained the largest single source of electricity (32%) in 2023, over half (51%) of the electricity supplied to the national grid came from zero-carbon sources like wind, nuclear, solar, and hydro, with coal and gas combined making up 33% [13]. The UK's Zero Emission Vehicle (ZEV) mandate, enacted in January 2024, is a key part of the government's net zero strategy. It requires 80% of new cars and 70% of new vans to be zero emission by 2030, increasing to 100% by 2035 to coincide with the government's ban on the sale of new diesel and petrol cars in the UK. This aligns with international commitments but positions the UK with the world's most ambitious regulatory framework for transitioning to electric vehicles [12].

2.2. Lithium as a Critical Raw Material

Raw materials, including metals and rare earth elements, are essential for manufacturing and technological advancement. Their supply chain uncertainties can affect profitability [14]. The European Commission (EC) tracks these materials through a Critical Raw Materials (CRM) list, updated every three years to reflect their strategic importance and associated risks. Recent updates also focus on trade dynamics, substitution, recycling, and circular economy principles [4], [15], [16]. Lithium, the lightest metal and with high electrochemical potential, is vital for modern technology. Lithium is a key component of rechargeable LIBs, which were conceptualised and developed in the late 1970s and have become essential for portable devices and electric vehicles (EVs) alike [17]. Lithium was first included on the EC's CRM list in 2020 due to its importance to automotive and energy storage sectors and the risks in its supply chain. The EU's lithium demand is expected to increase 18-fold and 60-fold by 2030 and 2050 respectively [15], with a projected 1,000% rise in demand for electric storage batteries to meet climate goals [18]. This highlights lithium's critical role in supporting green and digital transitions, leading the EC to also classify it as a Strategic Raw Material (SRM) due to it is strategic significance and anticipated supply-demand gap [16].

2.2.2. Lithium sources and extraction technologies. Lithium is extracted primarily through two methods: mining hard rock deposits, such as spodumene, and evaporating lithium-rich brine from drying ponds [19], [20]. The extracted lithium is then refined to produce market grade lithium carbonate and lithium hydroxide [19]. Lithium, the 33rd most abundant element, has newly discovered reserves, including what is now considered to be the largest deposit (an estimated 20 to 40 million tonnes) of lithium in the mineral-rich claystone in the McDermitt caldera along the Nevada-Oregon border [17], [21]. In the UK, lithium is found in granite at the St Austell clay quarry, with ongoing exploration by companies like British Lithium and Cornish Lithium, though this mining is costly and energy intensive [17]. Innovative extraction technologies are being developed to improve efficiency and reduce environmental impact. Direct Lithium Extraction (DLE) is a leading method and uses selective adsorption, ion exchange, or solvent extraction to achieve a 70-90% lithium yield in hours, compared to the 30-50% yield from conventional evaporation ponds over up to two years. DLE uses less water and land and returns the brine to the aquifer with minimal alteration [20]. Ongoing research is also focusing on extracting lithium from clay reserves using inorganic acid leaching.

2.3. Challenges Associated with the Lithium Value Chain

Lithium is essential for clean energy technologies (CET), but its supply chain faces challenges due to geopolitical, environmental, and social issues. Although lithium is abundant, demand is outpacing supply. In 2021, 107,000 tonnes of lithium were produced globally for a demand of 95,000 tonnes, but by 2022, production (130,000 tonnes) fell short of demand (134,000 tonnes). The International Development Agency predicts a 40-fold increase in lithium demand by 2040, intensifying pressure on supply [17].

2.3.1. Geopolitical complexities. Geopolitical complexities in the lithium supply chain arise from the concentration of reserves and processing capabilities in a few nations. In 2016, Chile led lithium production, but by 2017, Australia took over, supplying lithium concentrates mainly to China [19]. By 2020, the top processed lithium producers were Chile (44%), China (39%), and Argentina (13%), with China dominating global lithium processing (75% of global capacity) and refining (56% of global output) [16], [22]. This control over the mid- and downstream lithium supply chain creates geopolitical risks, particularly for regions like the EU and UK, which rely heavily on imported lithium, mostly from Chile and the U.S. The EU lacks sufficient capacity to extract, process, or refine lithium to meet its growing demand, relying on external suppliers [15]. Similarly, the UK's imports of lithium carbonate surged between 2019 and 2022. China's dominance in lithium refining introduces geopolitical risks, potentially threatening the UK's lithium supply security [14], [16]. The situation parallels the energy market volatility seen in the UK following the 2022 Russian invasion of Ukraine, which disrupted fossil fuel imports. This underscores the importance of developing domestic energy sources to safeguard energy security.

2.3.2. Environmental impact. Lithium mining is generally not considered environmentally sustainable due to its significant ecological impacts, though efforts are being made to improve its sustainability. In brine mining, large areas of land are destroyed to create drying ponds [17], and the evaporation process releases harmful elements into the atmosphere. The leftover contaminants pollute both land and water, and the depletion of water resources [19][20], especially in arid regions like the Andean Salars, threatens ecosystems and wetland species. Brine extraction also consumes a great deal of energy, contributing to carbon emissions and water loss. Hard rock lithium mining is even less sustainable, as it requires energy-intensive processes involving heavy machinery, high-temperature ore roasting, and acid leaching [17]. This leads to significant carbon emissions, further contributing to environmental degradation. While these methods are harmful, there are ongoing efforts to make lithium extraction more sustainable. For instance, DLE and environmentally friendly organic sieves aim to reduce the environmental impact by lowering air, water, and land pollution. However, these technologies are still in development, meaning the sustainability of lithium mining remains limited overall.

2.3.3. Social issues. Until the discovery of the McDermitt caldera lithium deposits, the world's largest lithium reserve was believed to be in South America beneath the Bolivian salt flat – Salar de Uyuni. This lithium rich region is known as "lithium triangle" [21] and shown in Figure 2. The lithium triangle holds 60% of the world's known lithium brine reserves and is an ecologically sensitive area with water sustainability crisis.

The increasing global demand for lithium has significant sustainability challenges, particularly in regions like the Salar de Atacama in Chile. Mining in this severely arid environment strains already scarce water resources, which are critical for local ecosystems and indigenous communities. These communities have historically relied on sustainable farming practices, but the water-intensive demands of lithium mining, coupled with climate change, are threatening their traditional way of life and exacerba-

Figure 2. The Lithium Triangle [23]

ting the region's hydrological vulnerabilities [19][20]. Political instability in resource-rich countries like Bolivia further complicates sustainable lithium mining. These nations, with a history of colonial exploitation, face risks of economic and social destabilisation due to competition over natural resources [14], [17]. Such instability could lead to exploitation of less-developed nations by more powerful countries seeking to secure lithium supplies. Though the discovery of a large lithium reserve in the McDermitt caldera could alleviate pressure on ecologically sensitive areas, it presents new challenges. The area is sacred to Native American communities due to historical events, and potential legal action could prevent mining, raising concerns about respecting cultural heritage alongside environmental sustainability [21]. Thus, while new lithium reserves may ease supply pressures, they introduce complex social, environmental, and ethical issues.

2.4. Analysing Lithium Demand: Market Trends and Distribution Analysis

Lithium has a range of uses in aerospace/defence, electronics, mobility/automotive, energy intensive industries, renewable energy, health and digital industrial ecosystems. The metal also has applications in the glass, ceramic, polymer and lubricant industries. As modern technology becomes more reliant of clean energy generation and storage, the demand for battery grade lithium becomes more relevant to a myriad of industries.

2.4.1. Smart devices. Electronic devices such as smartphones, laptops, tablets and body worn gadgets allow easy digital communication around the globe, convenient internet access, aid in navigation and exploring of the environment, provide entertainment and are useful in health and fitness monitoring. Advances in technology and modern lifestyle have increased dependency on LIB powered electronic devices. Processing capabilities such as the interactivity and computing power of smart devices support advancement in medical research and disease intervention. Smartphone apps assist with medical diagnosis, monitoring, and treatment of substance use disorders [24]. A scoping review found that adults born between 1946-1964 were embracing the use of smartphones and tablets in chronic disease self-management techniques such as self-monitoring, automated feedback, and learning more about their diseases which in turn improve the quality of life [24].

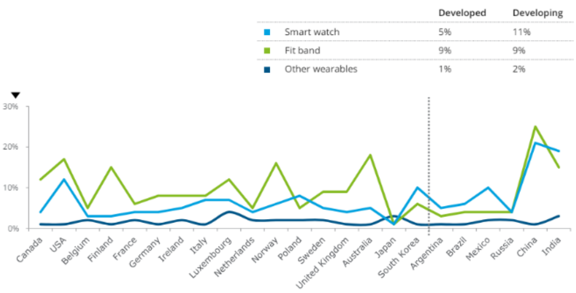

Figure 4. Wearable Device Ownership [26]

As dependency on smart EEE increases so will the pressure on LIBs. Smartphone adoption rates have increased across all global regions. By 2022, North America had registered the highest global adoption rate, it is however anticipated that the region's smartphone adoption rate would be overtaken by Greater China by 2025 and by all other global regions with the exception of Middle East/North Africa (MENA) and sub-Saharan African by 2030 [25] as depicted in Figure 3. The key trends driving the use of

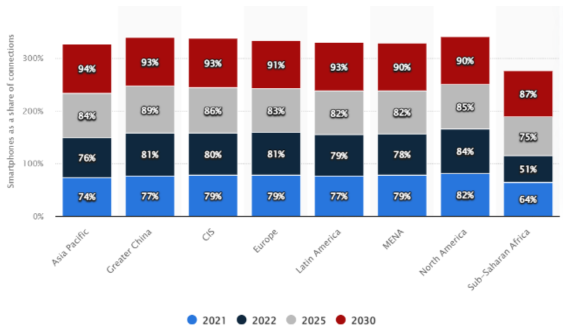

Figure 3. Smartphone adoption rate worldwide in 2021, 2022, 2025 and 2030, by region [25]

smartphones include better networks consumer addiction, functionality, affordability, safety and security [26]. A consumer survey showed that wearables such as smart watches and fit bands showed increasing popularity with consumers [27] as depicted in Figure 4. Fit bands showed a market penetration of 9% in most countries generally ahead of smartwatches. Both items however showed a high market penetration in China. Following a surge in demand for personal computers (PCs) and laptops for virtual learning and working from home during the COVID 19 pandemic lockdowns, global shipments of PC slumped on average by a third in the first quarter of 2023 [28]. Apple Inc, followed by Dell Technologies Inc saw the biggest decline in sales of 40% and 31% respectively. The slump in sales has been attributed to a post-pandemic decline in spending due to rising costs and estimates are conservatively cautious that sales recover in due course.

2.4.2. The automotive and mobility industry. *"The ZEV mandate coming into force is a significant moment which will help to drive down the costs of EVs and increase supply – accelerating the uptake of EVs over the next decade." Andrew Brem, General Manager of Uber UK.* There is an increased reliance on electric battery powered vehicles due to the global effort to electrify transportation which has led to increased investment and progress in LIB technologies [8]. EVs are predicted to make up over a quarter of new passenger cars sold worldwide by 2023. An electric vehicle battery (EVB) can consist of up to 30kg of lithium which corresponds to approximately 80% of lithium use causing a surge in demand for the metal [17]. The demand for EV in China has continued to increase since 2015 [22] with China retaining dominance over the global EV market since 2016 [29] as shown in Figure 5 with an electric battery drivetrain preferred over plug-in hybrids as depicted in Figure 6.

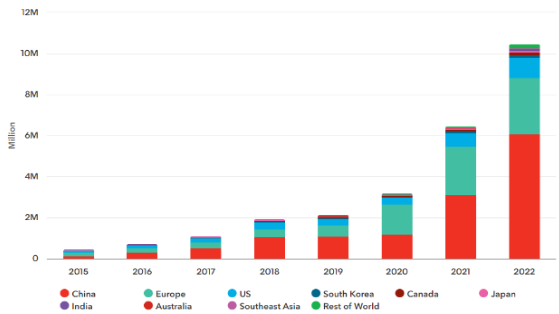

Figure 5. Global passenger Electric Vehicle sales by market [29]

The UK government is heavily invested in becoming a world leading location for the manufacture of EVs with an end-to-end zero emission supply chain. With over a million EVs licensed to drive on public roads and the governments ongoing investment is charging infrastructure the UKs ZEV mandate will serve to further influence motorists to switch to ZEVs. By 2022 the UK recorded the second highest number of EV sales in Europe and saw a 41% increase in number of ZEVs registered compared to the previous year. Publicly available charging portals have increased from 10,300 in 2019 to 38,700 in 2023 with the government determined to reach a target of

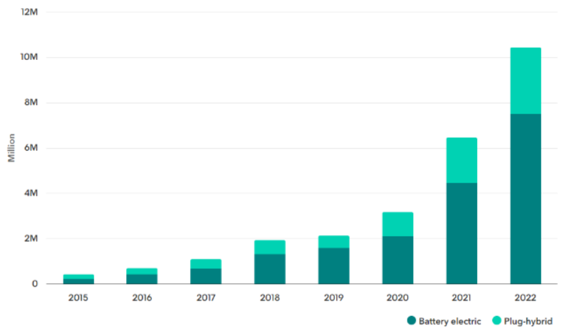

Figure 6. Global passenger Electric Vehicle sales by drivetrain [29]

300,000 charging points by 2030 [30]. This impressive target still falls behind efforts of China who had over 1.5 million publicly available charging connectors for use by motorists by 2022 [29]. In addition to the ZEV mandate, policy changes such as the expansion of London's ULEZ and creation of CAZs geared at the increased seclusion of high polluting automobiles from high traffic highly populated areas, will undoubtedly influence motorists in choosing less pollution EVs for transportation. The UKs commitment to clean transportation is mirrored in other developed countries including Canada, France, Germany and Sweden who are increasing investments in electric and hybrid vehicles, imposing regulations, subsidies and policies to adopt EV for commercial and personal use [12].

LIBs are suitable for powering electric and hybrid vehicles as they are characteristically lightweight, rechargeable with a high-power density and output making them fuel efficient and better for the environment. In a material flow analysis of raw material consumption, Scholars [22] have noted that from 2015 the demand for lithium and cobalt for the manufacture of LIBs for EVs surpassed the demand for LIB used in mobile phones and laptops and has continued to rise. The increasing demand for EVs has strengthened efforts to bring high performance battery technologies, that can compete with the characteristics of LIBs, from the research phase into the reality but LIBs remain the frontrunner [31].

2.4.3. Energy storage systems. Urbanisation and renewable energy driven industrialisation are increasing the demand for electricity and more robust power grids. ESSs are needed for grid modernisation to meet the demands of a carbon constrained future [8].

Estimates show that by 2050 the UK and Europe will require an energy storage capacity of 50GW and over 400GW respectively to meet supply and demand [8]. It is considered that despite the higher cost, LIBs provide the best technology for grid scale energy storage applications owing to their high energy density, high power density, lightweight and relatively compact nature, high cycle efficiency, low daily self-discharge rate, rapid response time and low environmental impact.

The LIB share of the battery energy storage systems (BESS) market has been increasing steadily over the years and is expected to retain the lion share of the market [32] as depicted in Figure 7. The is little consensus over the global market size of BESS. The BESS market is estimated [32] to be valued at USD 5.4 billion in 2023 rising at a compound annual growth rate (CAGR) of 26.4% to USD 17.5 billion by 2028. This evaluation is conservative compared to an estimate of USD 24.5 billion in 2022 rising to USD 199.5 billion by 2032 at a CAGR of 24% [33] or estimate of USD 30.63 billion in 2024 rising to USD 50.70 billion by 2029 at a CAGR of 10.61% [34].

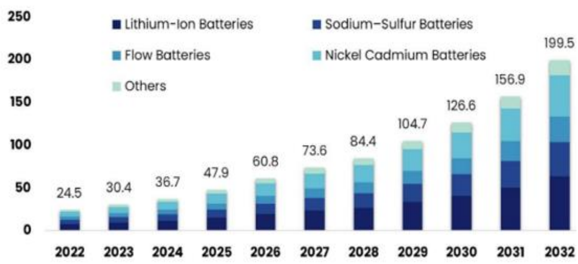

Figure 7. Battery Energy Storage System market size in USD billion by battery type, 2022 to 2032 [32]

Even though initial investments in BESS are expensive and technologies are still developing, there are many factors that drive the market including:

- Grid integration of renewable energy: solar radiation and wind speed cannot be stockpiled like fossil fuels and energy generated from RES need to be stored for use when required.
- Grid stability: BESSs are needed to provide voltage support, reduce fluctuations in power output and stabilise the power flow in the network and preventing power outages particularly during periods of peak demand to minimise the strain on grid infrastructure.
- Cost saving: allows consumers to store energy during abundant supply when tariffs are low for use during peak periods when energy rates are high.
- Clean energy transition: global commitments to mitigation of climate change have led to the electrification of transportation and the subsequent increase in demand for EVs, motorcycles and bicycles powered by LIBs. As regulatory framework of economies adapts to align with global climate change goals and technology advances, the BESS market will receive further boosts [33].

Due to the supportive regulatory framework and government incentives, North America dominates the BESS by extensively modernising electricity grids to integrate RES. American multinational automotive and clean energy company Tesla Inc. deploys the most BESSs worldwide. However, Europe takes the lead for adopting BESSs in compliance with clean energy standards [33]. Germany and the UK have been investing in grid scale storage in order to decentralise their respective energy systems. The Pillswood project located near Hull in the UK is the biggest BESS by power output in Europe. It was developed by Harmony Energy Limited to support the UK national grid and employs a Tesla 2-hour megapack system to store enough electricity capacity (up to 196 megawatt hours of electricity) to power approximately 300,000 UK homes for 2 hours in a single cycle [35].

Asia Pacific is the fastest growing market for BESS as depicted in Figure 8. This is due a high demand for sustainable energy driven by investments from and policy changes in China, India, Japan and Australia. The Middle East is an emerging market with rising interest particularly in storing solar energy. Africa is a developing market with potential to offer battery energy storage solutions but faced with infrastructural and financing challenges [33], [34].

Figure 8. Battery Energy Storage System Market Growth Rate by Region, 2023 to 2028 [34]

BESS have applications in the residential setting and is expected to be the fastest growing segment of the market. Due to advancing technologies, increasing supply and to an extent governmental incentives such as California's Self-Generation Incentive Program, prices of LIB have reduced enough to make the residential ESSs more affordable to consumers. There is also a rising trend of hybrid working styles with employees able to work from home leading to a rise in energy use in residential settings [33], [34]. On 2 June 2022, Toyota Motor Corporation launched the O-Uchi Kyuden System as its first residential BESS. The system was designed with Toyota's EVB technology, to store solar energy from a rooftop photovoltaic system at a rated capacity of 8.7kWh and a rated output of 5.5 kWh to power an entire home. The system is configured as depicted in Figure 9 to also use electricity stored in electrified Toyota vehicles as a backup energy source for instance in the event of prolonged power outages caused by natural disasters [36].

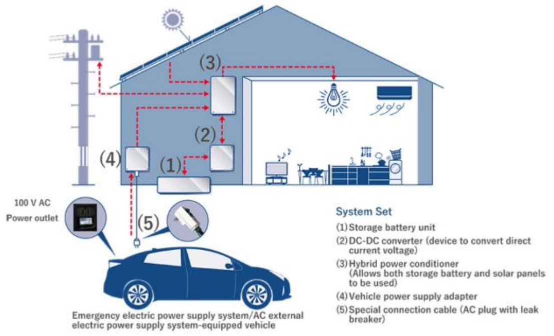

Figure 9. O-Uchi Kyuden System Configuration [36]

2.5. Circularity of lithium in the UK

The principles of circular economy, waste hierarchy, and sustainability are interconnected and form the foundation of efficient resource management and environmental protection. These concepts aim to minimise resource depletion, reduce pollution, and build economic resilience by promoting closed-loop systems. In the management of LIBs in the UK, adopting circular economy and waste hierarchy principles is crucial for achieving sustainable development goals while addressing existing technological and legislative gaps.

2.5.1. Waste Prevention. Injecting the concept of waste prevention at the product manufacturing and formulation stage is the most effective approach to resource conservation. Technological advancements should focus on extending the lifespan and power output of batteries, while modular designs with standardised components can simplify dismantling, refurbishing, and recycling processes, reducing waste generation for disposal [37]. Sustainable design practices, such as integrating durability and upgradability into battery manufacturing, are essential to improving battery longevity and efficiency.

2.5.2. Reuse. LIB reuse provides significant opportunities to extend the lifecycle of batteries. For example, over 25% of mobile phones are resold in secondary markets, highlighting the growing demand for durable devices [26]. Additionally, end-of-life (EoL) EVBs, which retain up to 75% of their capacity after 10 to 15 years of use [38], can be repurposed for stationary ESS or backup power solutions [39]. UK initiatives, such as battery refurbishment programs and secondary market platforms, demonstrate progress in promoting reuse. However, challenges including brand compatibility and regulatory barriers remain. Establishing standardised protocols and certification schemes is vital to unlocking the full potential of battery reuse and extending battery lifespans.

2.5.3. Recycling and Resource Recovery. Recycling reduces dependence on virgin raw materials, alleviating environmental impacts while retaining economic value. WEEE offers a resource-rich supply of CRMs, including lithium, that can be reintegrated into production processes [40], [41]. Advanced infrastructural investments in manufacturing have driven down the manufacturing cost of rechargeable LIB cells enough that LIBs are used in disposable EEEs such as vapes. However, technological barriers continue to hinder the efficient recovery of lithium compared to other metals like nickel and cobalt. For instance, while pyrometallurgical methods recover metals, they are energy-intensive and inefficient for targeted lithium extraction. Emerging technologies such as bioleaching, biosorption and bioelectrochemical systems show promise in improving recovery yields [40], [41], but further investment is needed to scale these innovations.

Current practices in the UK highlight the gap between recycling targets and implementation. In 2022, approximately 90 tonnes of lithium from disposable vapes were discarded without recovery—a quantity sufficient to power 1,000 EVs [37]. Moreover, compliance with the Waste Batteries and Accumulators Regulations (2009) remains alarmingly low, with only 10% of producers and retailers meeting obligations as of 2023 [42]. Enforcement of producer responsibility to finance the cost of collection, invest in advanced treatment and recycling technologies and the recycling of its share of all waste portable batteries in the UK are imperative to improve lithium recovery rates and reduce environmental harm. The yield of battery grade lithium from recycling must be high enough to make the process economically viable even in light of fluctuating metal prices.

2.5.4. Energy Recovery. Recovery of energy from waste (EfW) through high-temperature incineration (HTI) is a last-resort strategy when prevention, reuse, and recycling are not viable. Although facilities like ATM Moerdijk in the Netherlands use HTI to generate combined heat and power, this process incurs significant environmental costs, including GG emissions and the economic loss of valuable CRMs. To align with circular economy principles, priority must be given to battery-to-battery recycling technologies, which enable the recovery of functional materials from spent waste batteries and reduce the need for incineration.

2.5.5. Circular Economy Principles. Transitioning to a circular economy is essential for achieving SDGs by decoupling economic growth from resource depletion and environmental degradation. Principles such as extended producer responsibility (EPR), product ownership, and eco-design promote efficient resource use and waste minimisation throughout LIB lifecycles. In the UK, initiatives like the Circular Economy Package [43] and the Resource and Waste Strategy [44] aim to embed circularity into key industries. However, collaboration among policymakers, industry stakeholders, and consumers is critical to foster innovation and systemic change.

2.5.6. Technological Advancements and Legislative Gaps. Significant technological and legislative gaps hinder progress in battery reuse and recycling. On the technological front, scaling up cost-effective and environmentally sustainable CRM recovery methods remains a challenge. Innovations such as solid-state batteries, aluminium-graphite models, and green solvent-based recycling techniques show promise [8], [31] but require further research and investment to scale upwards. Alternatives to conventional battery technologies, such as energy storage in compressed gases for release via turbines, are also being explored but lack practical application [8]. Legislative inconsistencies across battery collection, recycling targets, and EPR create barriers to cohesive waste management systems. Harmonising national and international regulations and enforcing stricter compliance measures are essential to ensure accountability along the lithium value chain. Policymakers, industry leaders, and civil society must collaborate to address these gaps and raise awareness of sustainable practices. Strengthening legislative frameworks and advancing technological solutions will enable the UK to fully realise the potential of lithium circularity, driving progress toward sustainable development.

3. Methodology

This research explores the transition from fossil fuels to renewable energy, focusing on the sustainability of lithium within ESS and the battery industry. It employs a mixed-methods approach, integrating a comprehensive literature review with semi-structured interviews of experts across academia, industry, and government.

3.1. Research approach and data analysis

The literature review addressed critical areas:

- The importance of energy consumption for social and economic development.
- The urgent need for a timely shift to renewable energy sources to combat climate change.
- Challenges and complexities in the lithium supply chain, essential for sustainable battery technology.
- Market trends, projected lithium demand, and the

role of sustainable practices in extending lithium's lifecycle through reuse, recycling and sustainable resource and waste management.

This review identified gaps and inconsistencies that informed the development of qualitative research questions. The main qualitative research methods are interviews, focus groups and observation. Semi-structured interviews were conducted with experts in sustainable development, battery technology, electric vehicles, and waste management. Participants were selected based on their extensive experience and were recruited via LinkedIn and professional networks. Interviews were held virtually, ensuring flexibility to delve into issues like barriers to sustainability, technological advancements, and the policy landscape affecting lithium's sustainable use. Thematic analysis, a relevant quantitative research method for gathering meaningful and useful information [45] was applied to uncover patterns and insights from the interview data. These findings were compared with literature to provide a comprehensive understanding of sustainability challenges and opportunities in the lithium value chain. This analysis led to recommendations for enhancing sustainable battery management and reducing environmental impacts.

3.2. Delimitation and ethical considerations

Due to time constraints, the study involved a select number of participants with deep expertise in sustainability, resource and waste management, and lithium supply chains. The diversity of perspectives from different sectors ensured a thorough investigation of the key sustainability challenges. Ethical standards were strictly followed, including obtaining informed consent, ensuring confidentiality, and addressing any conflicts of interest. These measures upheld the integrity of the research and the validity of its findings, contributing valuable insights into the sustainability of lithium in the global energy transition.

4. Research findings

This section presents the findings from the research, which combined a comprehensive literature review with semi-structured interviews of experts in sustainable development, circularity, battery technology, and resource and waste management.

4.1. Lithium’s role in renewable energy transition

From the interviews, it became clear that lithium is critical to the transition from fossil fuels to renewable energy, specifically in the development of ESSs and EVBs. Participants consistently emphasised the increasing global demand for LIBs and the associated sustainability challenges, particularly in the sourcing and supply chain of lithium. The adoption rate of EVs) in the UK has slowed compared to the rapid growth experienced 2 years ago. This decline persists despite the fact that diesel and petrol vehicles are less energy-efficient and more polluting than EVs. One key factor is the insufficient charging infrastructure, which exacerbates range anxiety among consumers.

The lack of accessible and reliable charging ports undermines confidence in EV ownership, particularly in the second-hand market, further impeding adoption. While EVs are marketed as a cleaner alternative, some argue that their carbon footprint is underestimated due to the manufacturing impact of EVBs. However, over their intended lifespan, EVs still outperform fossil fuel powered vehicles in terms of emissions. Moreover, unlike fossil fuels, which cannot be reused once consumed, EVBs offer the potential for reuse and recycling. CRMs can also be recovered from used EVBs, reducing long-term environmental impact and supporting a circular economy.

A common misconception fueled by social media is that EVs pose a greater fire hazard than traditional vehicles. In reality, diesel and petrol vehicles are approximately ten times more likely to experience combustion incidents. EV fires, while rare, tend to attract attention due to the rapid escalation of battery fires once ignited. These incidents typically occur when EVBs are damaged, improperly disposed of, or charged with incompatible equipment. Improper disposal of lithium-ion batteries poses significant fire risks, causing damage to waste collection vehicles, household waste recycling centres (HWRCs), and recycling plants, leading to costly repairs and higher insurance premiums. Similarly, charging damaged EVBs, particularly in enclosed spaces like underground parking structures, is a high-risk activity. Ensuring that compromised EVBs are repaired or replaced before charging is essential for safety. While newer automotive technologies like EVs face heightened scrutiny, the risks associated with them can be mitigated with proper handling, maintenance, and public education. By addressing misconceptions and improving infrastructure, the UK can reignite its transition to cleaner and more sustainable transportation.

4.2. Environmental impacts of lithium mining

The research identified significant environmental concerns related to lithium extraction, particularly in water-scarce regions. Interviewees noted the growing strain on water resources, especially in regions like South America’s Lithium Triangle, where lithium is primarily extracted from brine. Social issues arising from the potential use of slave or child labour under arduous conditions in mines particularly in less regulated developing nations and personal health and safety and environmental degradation in mining areas where regulation is inadequate and/or not properly enforced due to the economic dependency of the local populace on mining as a source of income. Literature corroborated these findings, highlighting the environmental degradation and social issues caused by mining of lithium and other metals and the need for more sustainable extraction methods.

4.3. Technological innovations and sustainable practices

Interviews revealed a broad consensus on the need for technological advancements to improve the sustainability of lithium use. To ensure more sustainable use, lithium should be recovered from secondary sources to promote a circular economy, and LIBs should be replaced with alternative high-performance batteries like liquid sodium nickel chloride or graphene batteries to reduce dependence on lithium and other CRMs. Innovations such as solid-state batteries and alternative materials were frequently mentioned as potential ways to reduce dependence on lithium and enhance battery efficiency. Participants also discussed the importance of investment in research and development (R and D) to foster breakthroughs in sustainable battery technologies.

4.4. Supply chain sustainability

The sustainability of the lithium supply chain was another major theme. Participants stressed the importance of transparency and ethical sourcing practices particularly from more vulnerable countries. The dominance of China in the lithium market, driven by significant investments in mining and processing of battery-grade lithium, has raised concerns about market stability and supply chain sustainability. China's ability to influence global lithium carbonate prices and compel companies like Tesla to adjust EV pricing highlights its significant control over the market. This dominance poses risks for nations increasingly reliant on lithium battery production, as political tensions with China could create instability similar to the fossil fuel market disruptions caused by geopolitical conflicts arising from the invasion of Ukraine by Russia.

To mitigate these risks, countries such as Argentina and Bolivia are forming alliances to protect their interests and diversify the market. Simultaneously, ensuring the sustainability of the lithium supply chain is critical. Transparency, ethical sourcing practices, and the potential for certification schemes are being emphasised to align sustainability goals, reduce social and environmental harm, and create a more resilient and equitable lithium supply chain.

4.5. Policy and regulatory frameworks

The research highlighted a gap in robust regulatory frameworks for sustainable lithium production and use. The reuse and recycling of lithium devices and equipment are occurring but lag behind the pace of product manufacturing. Interviewees frequently cited the need for stronger government regulations and policies to drive sustainable practices across the lithium value chain. This was supported by literature, which pointed to the need for policy incentives to promote greener technologies and more sustainable mining practices. Additional drivers to improve the reuse and recycling of LIBs include: standardising manufacturing at a modular level, incorporating environmental damage costs into the price of primary raw materials and establishing recycling targets based on CRM and SRM content rather than arbitrary metrics like weight or product percentage. The findings revealed critical sustainability challenges, including environmental impacts from mining, technological needs for improving battery efficiency, and the importance of supply chain transparency.

5. Discussion

Halting energy consumption is neither practical nor realistic [5] therefore, the transition to clean energy is essential for reducing carbon emissions. This study confirms that socio-economic development, and sustainable development is stimulated by energy consumption [4] and the shift to more efficient, less environmentally damaging RES is necessary. LIBs play a key role in this transition, powering everything from disposable devices to large-scale energy storage systems. However, while lithium appears abundant and its use currently sustainable in the short term, long-term sustainability is a concern due to the supply chain issues associated with being a CRM and SRM to the energy sector. The use of lithium as a key commodity in CET is not without its challenges. Although lithium is abundant and new resources are continually discovered, its extraction is expensive, energy-intensive and harmful to the environment, particularly due to its water-intensive processes [17], [19], [20]. Additionally, lithium extraction can exacerbate social issues in less developed or vulnerable countries with abundant reserves [20]. Research is ongoing to develop more efficient and eco-friendly extraction methods but progress in this area is largely dependent on market demand for lithium.

The UKs transition to net zero energy generation relies on drastic carbon emission reductions [10] which in principle is achievable. However, there is little focus on early carbon saving and delays in carbon-saving measures, like the postponement of the ZEV mandate [12] may hinder the country from meeting its targets as predicted [10]. The ZEV mandate and the 2035 ban on sale of fossil fuel [12] is expected to boost EV adoption rate, but misinformation on social media, including exaggerated concerns about the safety of EV charging infrastructure, fire hazards and range anxiety, is slowing progress. It is encouraging the devices containing LIBs such as mobile phones are being resold and used. However, legislation could drive the standardisation of product manufacturing at the modular level to foster compatibility across different brands in order to promote the reuse, refurbishment and repair of products. Extended producer responsibilities would also ensure that CRMs and SRM contained in single use devices are recovered and recycled instead of loss as residual waste to disposal.

China's dominance in the processed lithium market introduces geopolitical complexities and potential instability in the energy, renewable energy technology, and energy storage system sectors [14], like the volatility seen in global energy markets during political conflicts arising from the Russia - Ukraine war [17], [30]. However, this dominance could also encourage countries, including the UK, to focus on domestic energy resources and promote the sustainable use of renewable energy and lithium.

This study highlights that advancements in battery research have led to the development of alternative technologies, such as solid-state, aluminium-graphite, iron-air, e-Zinc, and redox flow batteries [8], [31], which reduce reliance on lithium. However, continued innovation is essential to ensure the sustainability of these alternatives, as there is a risk of shifting the resource dependency problem rather than solving it comprehensively. For lithium to be used sustainably in CET, addressing supply chain issues, environmental impact concerns and public misconceptions is crucial, alongside exploring alternative materials and technologies to ensure long-term viability.

6. Conclusion and Future Work

Energy consumption is a pivotal driver of social and economic advancement, underpinning the foundations of sustainable development. As societies grow, the demand for energy will increase, making the transition to CETs crucial to combating climate change. LIBs play a vital role in powering EVs and ESSs, reducing dependence on fossil fuels and supporting the shift to clean energy. However, to ensure the sustainable use of lithium, early adoption of carbon-saving measures, advances in extraction methods, market-driven innovation, and legislative efforts to promote reuse, refurbishment, recycling of lithium and other CRMs and the exploration of alternative battery technologies are necessary to conserve lithium resources. The UK's commitment to its net zero carbon emissions targets hinges on timely and effective carbon saving measures. Delays in mandates such as the ZEV initiative coupled with misinformation about EVs, risk slowing progress. Policy interventions, public education, and collaboration with industries are essential to overcoming these barriers and fostering widespread adoption of clean energy technologies.

Reliance on international lithium markets creates vulnerabilities due to geopolitical tensions and market fluctuations. To address this, the UK must strengthen its resilience to external disruptions by fostering innovation and diversification of RETs and economic independence. Alternative battery technologies, such as solid-state and redox flow batteries, are emerging, but sustained innovation is necessary to avoid merely shifting resource dependency. Governments should incentivise sustainable development through the regulatory framework and introduction of certification schemes that ensure lithium is sourced responsibly, minimising environmental and social harm. Collaboration among stakeholders is key to promoting the responsible management of lithium resources. In conclusion, a sustainable energy future hinges on responsible energy consumption and resource management.

It is the recommendation of this study that future works prioritise three key areas: firstly, stakeholder engagement of responsible energy and resource consumption; secondly, addressing the socio-economic impacts of lithium extraction and processing in vulnerable regions to safeguard indigenous communities and environmental sustainability; thirdly extending the lifespan and circularity of LIB products and devices through increased reuse and recycling and finally, exploring alternative battery technologies as sustainable substitutes for LIBs for a more sustainable energy future.

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