RURAL ENERGY AND COMMUNITY HEAT (REACH)

WP4B: Carbon Accounting

Closure Report – M1

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Executive Summary

This report examines regional disparities in carbon emissions across the United Kingdom (UK) and offers a synthesis of the literature on environmental impact of low-carbon heating and transport technologies using Life Cycle Assessment (LCA). Findings reveal significant geographic variations in emissions: the Southeast has the highest total emissions, while Northern Ireland records the highest per capita emissions. In contrast, London, due to its dense urban infrastructure, has the lowest per capita emissions but the highest emissions per square kilometre.

Key differences between rural and urban areas stem from energy access and consumption patterns. One in four rural properties (1.4 million) lacks access to the gas grid, with higher proportions in regions such as Eden and Mid-Suffolk. These rural communities heavily rely on oil heating—used by more than one in ten rural homes, compared to just four in every thousand urban homes— leading to high carbon emissions, and increased energy costs which exacerbates fuel poverty.

Off-grid households require an additional £568 per year on average to escape fuel poverty, facing deeper financial burdens than on-grid households. In 2023, approximately 590,000 rural households in England, Scotland, and Wales experienced fuel poverty, particularly in Cumbria, Yorkshire, Durham, Lincolnshire, East Anglia, the England-Wales border, and north-west Devon.

Energy consumption patterns further distinguish rural and urban areas. Rural households use more electricity due to larger property sizes, a higher proportion of detached homes, and greater reliance on electric heating. In 2022, the median domestic electricity consumption was 2,700 kilowatt-hours (kWh) per meter in rural areas, compared to 2,500 kWh per meter in urban areas. Despite this, both saw reductions in electricity consumption from 2015 to 2022: 23% (800 kWh per meter) in rural areas and 21% (700 kWh per meter) in urban areas.

The effectiveness of low-carbon technologies also varies by region. General Heat pumps achieve the highest carbon dioxide (CO_2) reduction potential in the Northwest due to lower grid carbon intensity. However, thermal energy storage (TES) systems, while reducing localized emissions, have a lower coefficient of performance (COP),

potentially increasing overall energy demand and offsetting environmental benefits. Additionally, lithium-ion battery (LIB) production remains carbon-intensive, requiring 328 watt-hours (Wh) of energy per Wh of storage capacity and emitting 110 grams of CO_2 equivalent (gCO_2eq) per Wh due to reliance on rare metal extraction and fossil-based electricity.

In transport, the environmental benefits of electric vehicles (EVs) depend on energy sources and battery production. Grids reliant on fossil fuels contribute to increased nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) emissions, while heavier EVs lead to higher particulate matter (PM2.5) emissions. Meanwhile, hydrotreated vegetable oil (HVO) provides a lower-emission alternative to fossil diesel, reducing greenhouse gas emissions by 40% to 85%, depending on feedstock sources. Waste-derived HVO offers the greatest environmental benefits, whereas food-based sources like palm oil raise concerns about land-use change and deforestation.

Overall, the results of this review underscore that low-carbon technologies are essential for emissions reduction, but their effectiveness depends on regional infrastructure, resource availability, and sustainability considerations. Addressing disparities in energy access and affordability is crucial to ensuring an equitable transition to a low-carbon future.

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1. Introduction

Space and water heating constitute nearly half of building energy use, making them a major contributor to global emissions, with 4,100 million tonnes of CO_2 emitted in 2022 (IEA, 2023). In the UK, domestic heating alone accounts for 14% of total carbon emissions (Hehar et al., 2025) primarily due to the overreliance on natural gas, which supply 74% of households. This dependency on fossil fuel-based heating systems presents a significant obstacle to achieving net-zero emissions by 2050.

Despite the dominance of mains gas, 15.3% of domestic properties in Great Britain remain off-grid, facing limited access to clean heating alternatives (Stewart & Bolton, 2024). Hehar et al., (2025), highlight that region with a high prevalence of detached housing, often found in suburban areas, hold significant untapped potential for CO_2 reductions through the adoption of low-carbon heating technologies. Furthermore, they establish a direct correlation between technology adoption and emissions reduction, with the Northwest of the UK achieving up to a 33% reduction at a 40% uptake rate, benefiting from lower grid carbon intensity. The uneven distribution of emission reductions underscores the need for immediate and large-scale decarbonisation efforts across all regions.

This report provides an overview of counterfactual carbon emissions in rural communities compared to urban areas. Additionally, it offers a synthesis of the environmental impact of various low-carbon technologies—including heat pumps, heat storage, electric vehicles (EVs), hydrotreated vegetable oil (HVO), and large-scale batteries—through Life Cycle Assessment (LCA) and their role in reducing emissions.

The report is structured as follows: **Section 2** outlines the search strategy. **Section 3** provides an overview of UK energy consumption and regional disparities in energy use between rural and urban areas. **Section 4** presents a detailed analysis of the sustainability and environmental impacts of different low-carbon technologies.

2. Methodology: Search Strategy

This literature review report summarises existing research using two distinct search strategies. i) a systematic literature review was conducted using Scopus as the primary database to identify relevant peer-reviewed studies. ii), a rapid literature search focused on grey literature, employing key terms such as direct household emissions, UK energy consumption, and off-grid heating. This search encompassed

Google Scholar, governmental websites (e.g., ONS, Census, DESNZ), and research reports, ensuring a comprehensive analysis of both academic and policy-related sources.

The systematic literature review followed a structured search strategy based on three key categories: methodological approach, technologies, and geographical context. Studies prioritising Life Cycle Assessment (LCA) were selected to assess the environmental impact of various low-carbon technologies, including heat pumps, electric vehicles (EVs), heat storage, large-scale battery storage, and hydrotreated vegetable oil (HVO). Additionally, the review examined both urban and rural environments to understand how these technologies are deployed across different settings Figure 1.

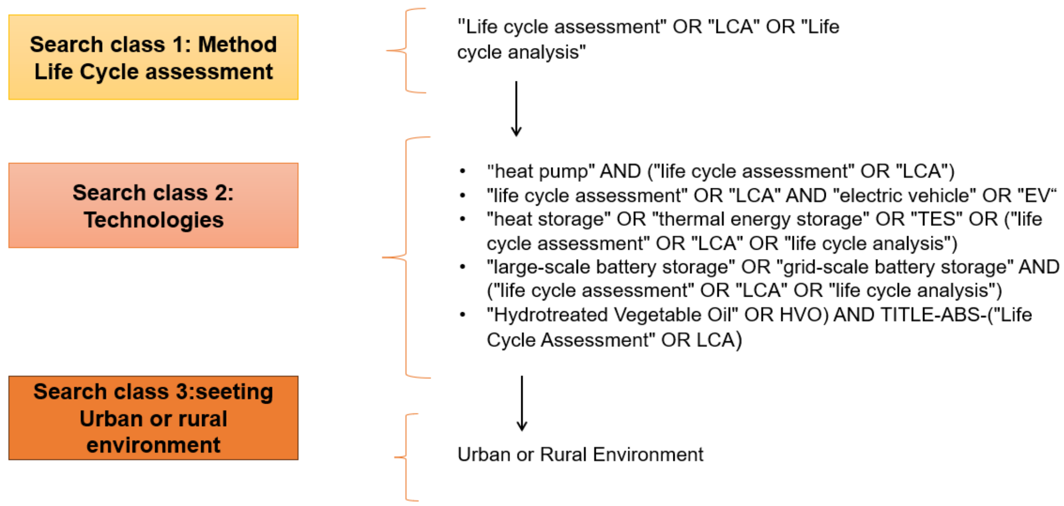

Figure 1: Structured Search Strategy for Systematic Literature Review

Table 1 provides a summary of the search results from Scopus, detailing the number of papers identified for each technology and the number of relevant papers selected based on their applicability to the study. In total, 197 papers were identified, with 40 classified as highly relevant to the research focus. Highly relevant papers refer to those that specifically focus on the technology itself and include an LCA. These papers provide detailed insights into the environmental impact, and carbon footprint of the technology. The search timeframe covered 2010–2025, ensuring that the study captures both historical trends and emerging research on low-carbon technologies.

Table 1: Summary of Identified and Relevant Papers from Scopus Search

Technologies	Number of Papers	Related Papers
Heat pump	45	14
Electric vehicle (EV)	37	8
Heat storage	67	6
Large-scale battery energy storage	40	8
HVO	8	4
Total Papers	197	40

3. Overview of UK's Emissions and Energy Consumption

In 2022, 77.6% of the UK's GHG emissions came from fossil fuels, with natural gas (40.4%) mainly used for heating and electricity, and petroleum (33.3%) primarily for road transport (Figure 2). Coal and other solid fuels accounted for a smaller share. The remaining 22.4% of emissions originated from non-fossil fuel sources, including industrial processes, agriculture, land use changes, and other miscellaneous activities.

While fossil fuel emissions have declined by 46.2% since 1990, they remain a major contributor. Coal emissions have dropped significantly, now making up just 2.3% of UK emissions, a 95.8% reduction since 1990 (Figure 2). Despite these overall declines, regional and housing differences persist, with rural areas still heavily reliant on oil heating and private vehicles, contributing to higher per capita emissions (DESNZ, 2024a).

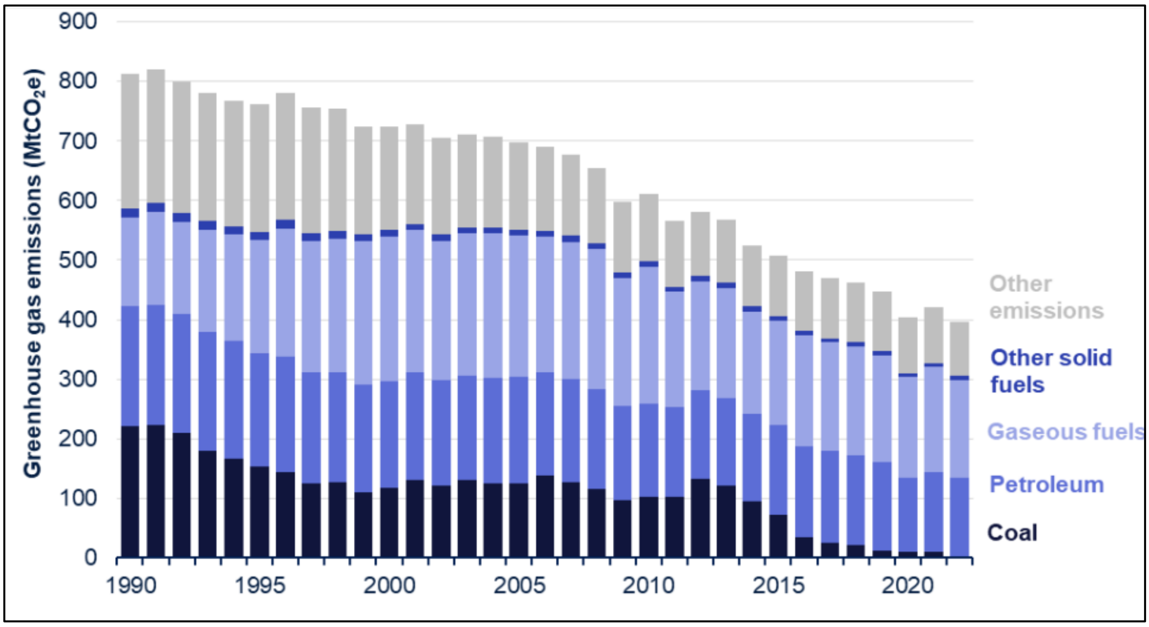

Figure 2 : Territorial UK greenhouse gas emissions by fuel type, 1990-2022
Source: DESNZ, (2024)

Households are the largest contributors to greenhouse gas emissions on a residency basis, surpassing any industry sector, according to the Office for National Statistics (ONS) Environmental Accounts (ONS, 2022). These emissions, categorised as "consumer expenditure," mainly stem from domestic travel and heating (excluding electricity use), accounting for 26% of total residence-based emissions in 2020, with 43% of these emissions linked to travel. While overall household emissions remained relatively stable until 2019—1.7% lower than in 1990—travel-related emissions had been increasing since the mid-1990s but dropped by 23% in 2020 due to COVID-19 travel restrictions (ONS, 2022).

Figure 3 indicates significant regional disparities in territorial greenhouse gas emissions across the UK. The Southeast records the highest total emissions, exceeding 12 $MtCO_2e$, followed by the Northwest and London, both above the UK average of 9.3 $MtCO_2e$. However, when adjusted for population size, Northern Ireland has the highest per capita emissions, while London has the lowest. In contrast, London has the highest emissions per square kilometre, reflecting its high population density and concentrated energy demand, whereas Scotland records the lowest emissions per land area due to its lower population density and extensive rural regions (DESNZ, 2022; ONS, 2022).

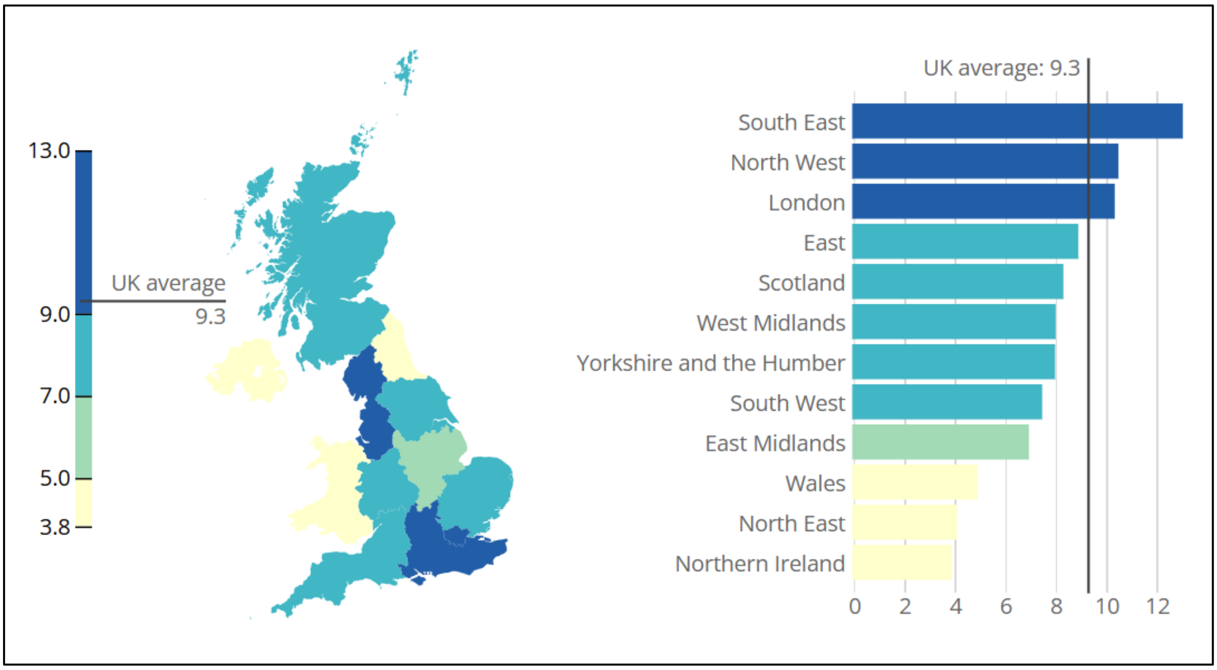

Figure 3: UK Territorial greenhouse gas emissions ($MtCO_2e$) across different regions

Source: DESNZ, (2022)

Slightly lower than UK average emissions are observed in the East, Scotland, West Midlands, and Yorkshire & Humber, representing a mix of urban and rural influences. Meanwhile, the Southwest, East Midlands, Wales, Northeast, and Northern Ireland report the lowest total emissions, likely due to smaller populations, lower household energy demand, and a higher share of renewable energy in some areas. While urban regions have higher total emissions, rural areas may still experience high per capita emissions due to reliance on fossil fuels for heating (DESNZ, 2022).

Housing type also plays a critical role, with existing homes emitting 2.7 times the CO_2 of newly built homes, and rural homes producing 15% more emissions than urban homes. Among housing types, detached rural homes generate 2.4 times the CO_2 of flats or maisonettes, and owner-occupied homes in rural areas emit 1.7 times the CO_2 of social rent homes. In rural regions, Eden (which is now part of Westmorland and Furness) recorded the highest CO_2 emissions for detached homes at 7 tonnes per year (Department for Environment Food & Rural Affairs, 2024).

According to the 2021 Census for England and Wales, 73.8% of households relied on mains gas as their primary heating source. 9.1% used multiple heating sources, while 8.5% depended solely on electric heating. Oil heating accounted for 3.5% of households, and 2.5% used other methods, including renewable energy, solid fuels, wood, and district or communal heating networks. Additionally, 1.5% of households had no central heating, and 1.0% relied on tank or bottled gas (Stewart & Bolton, 2024).

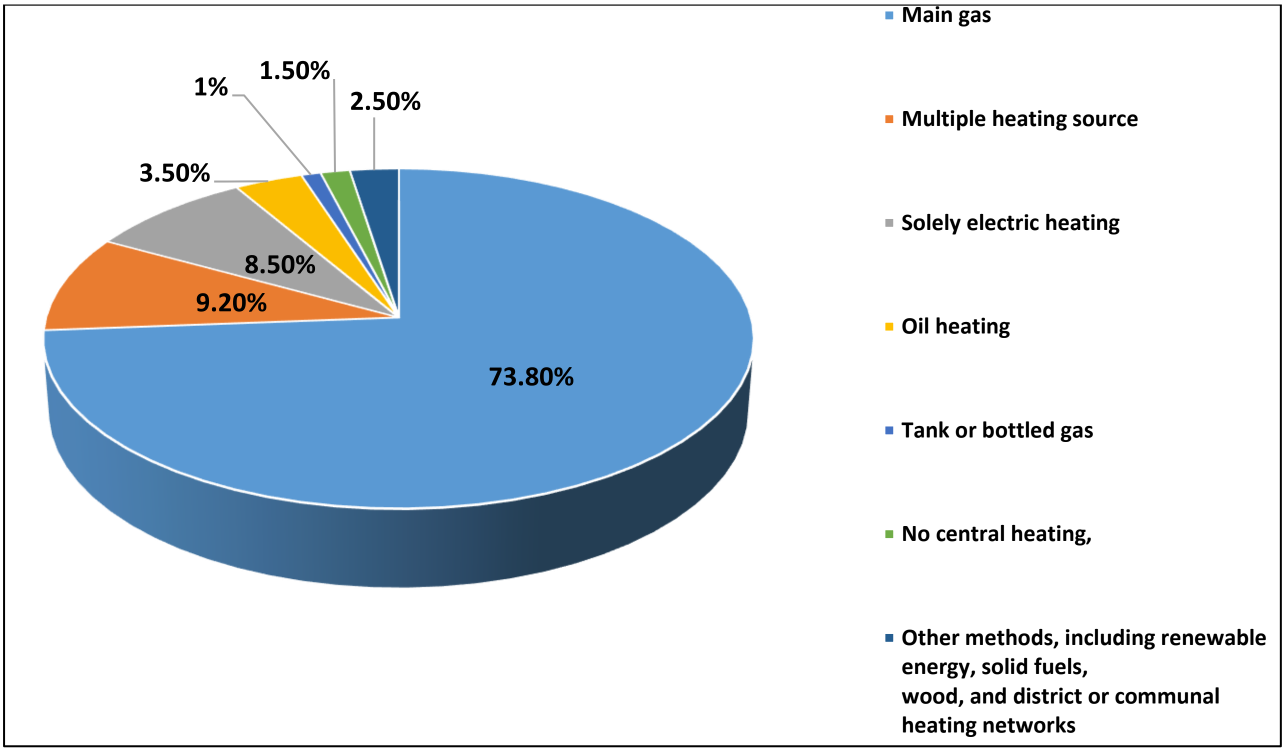

Figure 4: Source of heating across England and Wales

Source: Stewart & Bolton, 2024

Rural areas are disproportionately affected by a lack of gas grid infrastructure, leaving many households reliant on alternative heating fuels. However, off-grid properties are not exclusive to rural settings; some urban dwellings, particularly high-rise flats, also lack gas connections due to safety concerns, despite their proximity to the network. In 2021, an estimated 4.4 million households across Great Britain—15.1% of all domestic properties—were not connected to the gas grid. As Figure 5 presents within this off-grid population, the highest proportions were in Inner London (25.1%), the Southwest (23.6%), and the East of England (19.6%), while the Northeast (7.3%) and Northwest (9.7%) had the lowest rates (Stewart & Bolton, 2024).

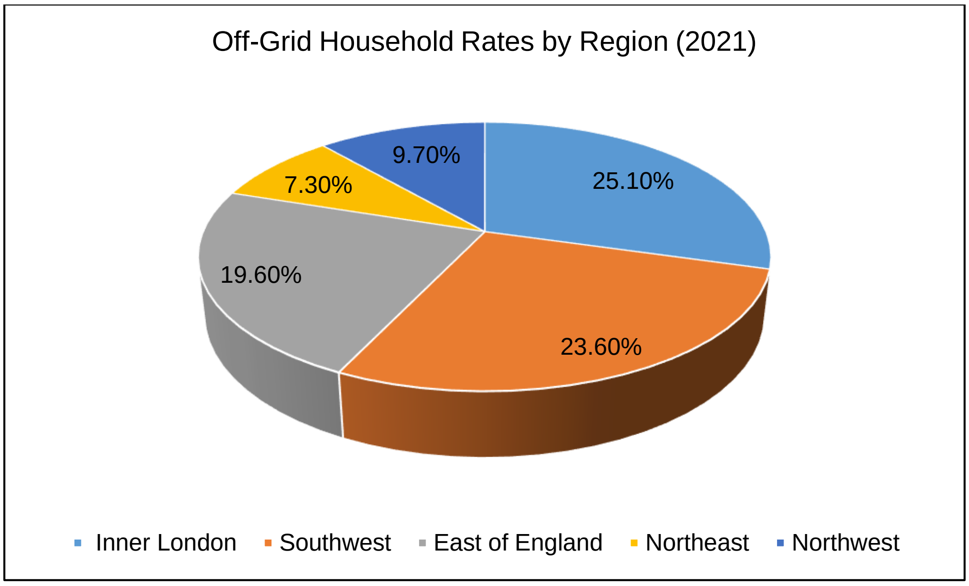

Figure 5:Off-Grid Household Rates by Region (2021)

Households using alternative heating fuels face higher and more severe fuel poverty, largely due to the lower energy efficiency of off-grid properties. This trend is seen across England, Scotland, and Wales, despite differences in how fuel poverty is measured (Stewart & Bolton, 2024). Fuel poverty as defined by (Dogan et al., 2022) occurs when a household struggles to access sufficient energy services to meet basic needs. This issue remains a significant challenge, particularly in rural areas, where 590,000 households were affected by fuel poverty in 2023**.** The issue is most severe in Cumbria, Yorkshire, Durham, Lincolnshire, East Anglia, the England-Wales border, and north-west Devon, where fuel poverty levels are above average.

A key factor is the lack of access to the gas grid, with one in four rural properties (1.4 million) being off-grid, and even higher proportions in areas like Eden and Mid-Suffolk, where more than half of properties lack gas grid access. Consequently, many rural homes rely on oil heating, with over one in ten rural households using oil, compared to just four in every thousand urban homes. The more rural the area, the greater the reliance on oil heating, further driving up energy costs. Off-grid households face deeper levels of fuel poverty than on-grid households, requiring an additional £568 per year on average to escape fuel poverty(Department for Environment Food & Rural Affairs, 2024).

3.1 Regional and Housing Impacts on Energy Use

Urban and rural areas exhibit distinct energy consumption patterns and emission profiles due to differences in urbanisation rates, infrastructure, energy access, and consumption behaviour. One key factor influencing emissions is consumer behaviour, as urban residents typically consume more goods and services than rural populations, leading to higher per capita emissions (Chen et al., 2019; Yuan et al., 2022) . Additionally, differences in energy use, transportation systems, and industrial activities further contribute to the urban-rural emissions gap.

Energy consumption also differs significantly between urban and rural households, particularly in electricity usage. Rural households consistently consume more electricity than urban households due to larger property sizes, a higher proportion of detached homes, and greater reliance on electric heating in off-grid areas. In the UK in 2022, the average median domestic electricity consumption was 2,700 kWh per meter in rural areas, compared to 2,500 kWh per meter in urban areas. Despite this, both areas have experienced a decline in electricity consumption over time (Department for Environment Food & Rural Affairs, 2024). Between 2015 and 2022, rural areas saw a 23% reduction (800 kWh per meter), while urban areas experienced a 21% reduction (700 kWh per meter) (Department for Environment Food & Rural Affairs, 2024). The line graph (Figure 6) illustrates this trend, showing that while rural households consistently consumed more electricity than urban households, both groups experienced an overall reduction in consumption.

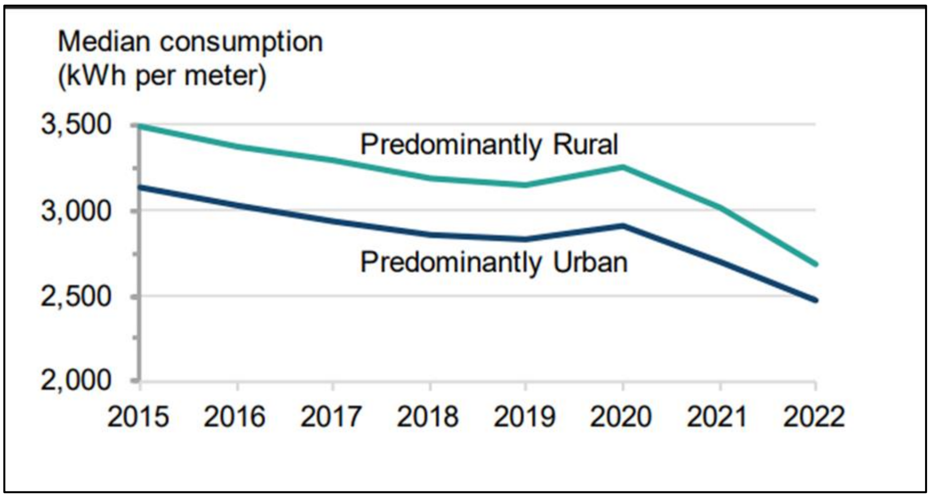

Figure 6: Median Domestic Electricity Consumption in Predominantly Rural and Urban Areas, 2015-2022
Source: *Department for Environment Food & Rural Affairs, (2024)*

However, the proportion of total domestic electricity consumption attributed to rural areas remained stable at 25% throughout this period, indicating that rural areas continue to account for a significant share of overall electricity use. Beyond electricity use, rurality is a key determinant of heating energy choices, particularly in remote and extreme climate regions. While examples from other countries, such as Canada, highlight how geographic isolation and harsh climates reinforce diesel dependency (Gunawan et al., 2020), similar challenges exist in off-grid rural areas of England, where infrastructure limitations restrict access to low-carbon heating alternatives.

Unlike electricity consumption, predominantly rural areas account for a larger share of non-domestic gas consumption, which includes gas usage by businesses, industries, and public sector buildings rather than households (Figure 7). This contrast is likely due to the high number of off-gas grid domestic properties in rural areas, where households rely on alternative heating sources such as oil, LPG, or electricity. In comparison, very few properties lack mains electricity, reducing the reliance on stand-alone generators (Department for Environment Food & Rural Affairs, 2024).

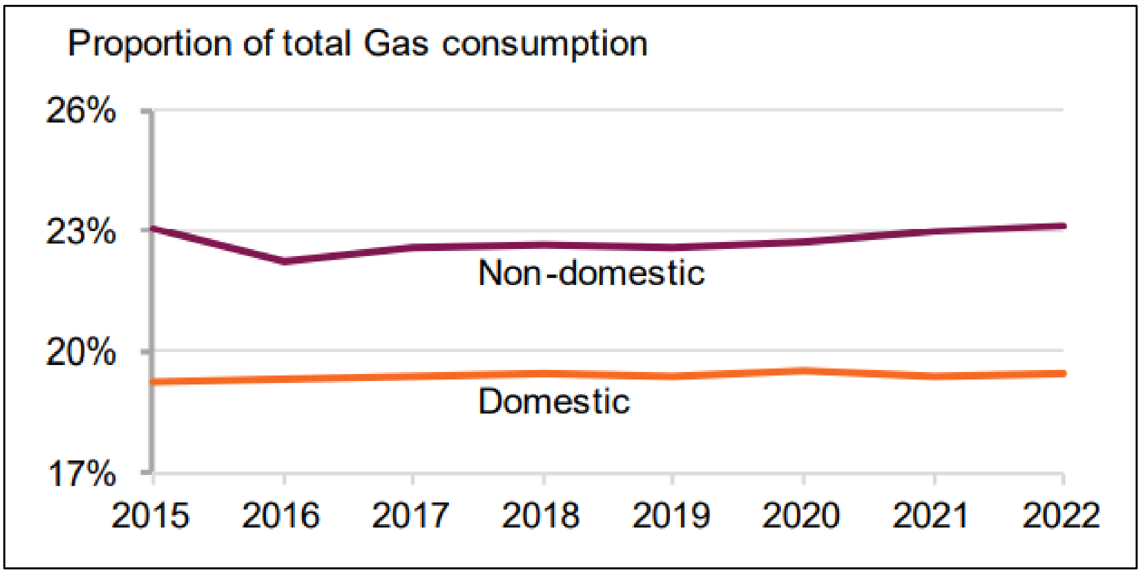

Figure 7: Gas Consumption in Predominantly Rural Areas (2015-2022)
Source: Department for Environment Food & Rural Affairs, (2024)

Energy efficiency levels between rural and urban areas remain largely similar despite differences in infrastructure, heating sources, and property age. In 2023, the average energy efficiency score for rural areas was 66.8, while urban areas scored slightly higher at 67.5. Both scores correspond to an energy efficiency rating of D, indicating moderate efficiency with room for improvement (Department for Environment Food & Rural Affairs, 2024). While both rural and urban areas experienced marginal improvements in energy efficiency over the past two years, rural homes showed a slightly greater improvement:

- **Rural Areas: +2.1 points (3% increase)**
- **Urban Areas: +1.3 points (2% increase)**

Older rural homes remain significantly less efficient than modern constructions, typically three energy efficiency bands lower than newer homes. However, rural properties built in the last decade have energy efficiency levels comparable to urban homes of the same period, demonstrating the impact of modern building regulations. When comparing housing tenure, owner-occupied rural homes were the least energy-efficient, whereas social rental properties had the highest efficiency levels, likely due to government-led retrofitting and energy efficiency programs. Property age plays a crucial role—90% of pre-1930 rural properties have energy efficiency ratings low enough to put low-income households at risk of fuel poverty. Detached rural homes are particularly vulnerable, with only 4 in 10 meeting EPC C standards, compared to 7 in 10 flats in rural areas (Department for Environment Food & Rural Affairs, 2024).

Our analysis estimates heating emissions for 100 urban and 100 rural homes based on fuel mix proportions, system efficiency, and heating demand, incorporating differences in housing type and energy consumption patterns. Rural households, particularly detached homes, have higher average heating demand due to larger property sizes and lower energy efficiency, with small urban flats consuming approximately 9,000 kWh/year compared to 12,000 kWh/year for similar rural properties, and detached rural homes requiring up to 18,000 kWh/year versus 15,000 kWh/year in urban areas. Urban homes primarily rely on natural gas and electricity, whereas rural homes depend more on oil and solid fuels due to limited gas grid access, resulting in higher carbon intensity and greater emissions(Ofgem, 2024). As a result, rural homes emit approximately 54% more CO_2 than urban homes, primarily due to their reliance on high-carbon heating fuels and greater heating demand. Expanding low-carbon heating solutions, such as heat pumps, in rural areas could significantly reduce emissions and help bridge the gap in heating sustainability between urban and rural regions.

Table 2 :Heating emissions Urban vs Rural homes [1]

Heating Source	Urban Homes (tCO_2/yr per 100 homes)	Rural Homes (tCO_2/yr per 100 homes)
Natural Gas	146.7	122.4
Electricity	12.2	24.5
Oil Heating	7.6	93.6
Solid Fuel (Coal, Biomass)	1.8	17.5
Total Emissions	168.3 tCO_2/yr	258 tCO_2/yr

Source: (DESNZ, 2022, 2024a; ONS, 2022)

Transport emissions vary significantly between urban and rural households due to differences in vehicle dependency, public transport availability, and fuel mix. The table *Table 3* presents estimated annual CO_2 emissions for 100 urban and 100 rural homes, highlighting key transport-related disparities .Rural households emit **~91% more CO_2** from transport than urban households, mainly due to greater reliance on private vehicles. Urban areas benefit from extensive public transport, contributing to lower emissions—13.3 tCO_2/yr in urban areas vs. 1.6 tCO_2/yr in rural areas. While EVs help reduce emissions, their impact is lower in rural areas (6.1 tCO_2/yr) than in urban areas (8.2 tCO_2/yr), likely due to longer travel distances, limited charging infrastructure, and continued petrol/diesel use.

Table 3: Transport emissions Urban vs Rural homes

Mode of Transport	Urban (tCO_2/yr per 100 homes)	Rural (tCO_2/yr per 100 homes)
Petrol/Diesel Cars	99.6	224.0
Electric Vehicles	8.2	6.1
Total Transport Emissions	107.8 tCO_2/yr	230.1 tCO_2/yr

Source: (DESNZ, 2024b; ONS, 2024)

These emissions were calculated using UK Government Emission Conversion Factors, based on:

1. Average annual energy use per household for each heating type.
2. CO_2 emission factors for gas, electricity, oil, and solid fuels.

Values represent emissions per 100 homes per year, highlighting urban-rural heating differences.

4.Sustainability and Environmental Impact Assessment of Low-Carbon Technologies

The following section presents the results of a systematic literature review on the environmental impact of low-carbon technologies. Using Life Cycle Assessment (LCA), it evaluates the effectiveness of heat pumps, heat storage systems, electric vehicles (EVs), hydrotreated vegetable oil (HVO), and large-scale batteries in reducing emissions and enhancing sustainability. Immendoerfer et al., (2017) defines LCA, as a method that evaluates environmental, human health, and resource reduction impacts from inputs (materials, energy) to outputs (emissions, waste) across a product's life cycle, including manufacturing, extraction, operation, disposal. LCA helps to identify energy-efficient and environmentally sustainable design choices by comparing the performance of different technologies or products offering the same service. The first step in an LCA analysis involves defining the product and establishing key specifications for the Life Cycle Inventory, which includes factors such as the functional unit, system boundaries (Bonamente & Aquino, 2017). The literature review identifies the most commonly used Life Cycle Assessment (LCA) system boundaries for low-carbon technologies (LCTs).

While various system boundaries exist, only a few were frequently applied in the reviewed literature. These system boundaries define the scope of environmental impact assessments and influence the results of sustainability evaluations. Table 4 provides a summary of the most commonly used LCA system boundaries, highlighting their coverage, key focus areas, and relevant studies. Among these, the Implementation & Operation Phase is particularly relevant as it focuses on Scope 1 and Scope 2 emissions, measuring direct emissions from on-site fuel combustion (Scope 1) and indirect emissions from purchased electricity (Scope 2) during the operational phase. This approach is useful in assessing the environmental impact of technologies based on their energy consumption and emissions during real-world use.

Table 4: Summary of commonly used LCA System Boundaries for LCTs

LCA System Boundary	Description	Key studies
Cradle-to-Grave	The most widely used approach, covering the entire life cycle of LCTs, including raw material extraction, manufacturing, transportation, operation, and end-of-life disposal or recycling	Chowdhury et al., 2020; Costa et al., 2023; Immendoerfer et al., 2017; Violante et al., 2022; Zhang et al., 2019
Cradle-to-Cradle	A circular economy approach that extends beyond Cradle-to-Grave by incorporating material recovery, recycling, and reuse, ensuring that waste is minimised, and products contribute to a closed-loop system	Aberilla et al., 2020b; Bigiotti et al., 2024; Sadhukhan & Christensen, 2021)
Cradle-to-Gate	Assesses the production phase, covering raw material extraction, processing, and manufacturing up to the factory gate, excluding the use phase and disposal	Bahlawan et al., 2019; Ellingsen et al., 2014
Well-to-Wheel (WTW)	A specific LCA approach applied in transportation studies, which evaluates energy use and emissions from fuel production (Well-to-Tank) to vehicle operation (Tank-to-Wheel)	Arvidsson et al., 2011; Soam & Hillman, 2019
Implementation & Operation Phase	Focuses on Scope 1 and Scope 2 emissions, measuring direct emissions from on-site fuel combustion (Scope 1) and indirect emissions from purchased electricity (Scope 2) during operation.	Bonamente & Aquino, 2017; Schollliers et al., 2024

4.1 Impact Categories

In LCA, impact categories define the environmental and health effects of a product or process. Selecting appropriate categories is crucial, as overlooking key factors can lead to incomplete assessments and misrepresentation of environmental impacts. The majority of LCA studies analyse multiple impact categories simultaneously, incorporating a holistic environmental evaluation. However, certain impact categories are more frequently studied than others. Table 5 summarises the most commonly studied impact categories and their relevance in LCA research.

Table 5 Commonly Studied LCA Impact Categories for Low-Carbon Technologies

Impact Category	Description	Key Studies
Global Warming Potential (GWP)	Measures greenhouse gas (GHG) emissions and their contribution to climate change.	(Arvidsson et al., 2011; Chowdhury et al., 2020; Ellingsen et al., 2014; Roux et al., 2024; Yang et al., 2021; Zhang et al., 2019)
Abiotic Depletion Potential (ADP-Fossil)	Assesses depletion of non-renewable resources, primarily fossil fuels, highlighting concerns over energy security.	(Aberilla et al., 2020b; Greening & Azapagic, 2012; Roux et al., 2024;Sadhukhan & Christensen, 2021)
Cumulative Energy Demand (CED)	Quantifies total energy consumption, including fossil-based and renewable energy sources, across a product's life cycle.	(Scharrer et al., 2020; Sunde et al., 2011; Zhang et al., 2019)
Acidification Potential (AP)	Evaluates acid rain and soil degradation impacts caused by emissions of sulphur dioxide (SO_2) and nitrogen oxides (NO_x).	(Arvidsson et al., 2011; Scharrer et al., 2020)
Human Toxicity Potential (HTP)	Assesses the health risks from hazardous emissions and pollutants affecting humans.	(Aberilla et al., 2020b; Nordelöf et al., 2019; Scharrer et al., 2020).

Among the listed impact categories, Global Warming Potential (GWP) measures greenhouse gas (GHG) emissions and their contribution to climate change. Abiotic Depletion Potential (ADP), particularly applied to? fossil fuel depletion is also widely studied due to its relevance to energy security and resource management. Other categories include Cumulative Energy Demand (CED), Acidification Potential (AP), and Human Toxicity Potential (HTP) which highlight the broader environmental and health implications of low-carbon technologies. Together, these categories provide a holistic framework for assessing sustainability.

4.2 Environmental Impact of Heat Pump Technologies

Decarbonisation of heat can be achieved through an efficient whole heating system that combines low-carbon technologies such as heat pumps. Heat pumps, driven by low-emission electricity, play a crucial role in the UK's transition toward secure and sustainable heating solutions. The International Energy Agency, (2022) estimates that global heat pump deployment could reduce CO_2 emissions by at least 500 million tonnes by 2030—equivalent to Europe's current annual car emissions. Additionally, heat pumps are three to five times more energy-efficient than gas boilers, particularly when powered by low-carbon electricity(Hehar et al., 2025).

Despite earlier assessments by Greening & Azapagic (2012) suggesting that heat pumps lacked clear environmental advantages over gas boilers in the UK, the decarbonisation of the electricity grid has since improved their relative benefits, particularly in reducing greenhouse gas emissions and fossil fuel dependence. However, their environmental impact remains nuanced. Among heat pump types, air-source heat pumps (ASHPs) have the highest environmental burden, while water-source heat pumps (WSHPs) perform better (Naumann et al., 2024). The primary contributor to heat pump emissions is electricity consumption during operation, whereas manufacturing and maintenance have a lesser impact.

As the UK continues to expand its renewable energy capacity, the sustainability of heat pumps is expected to improve, reinforcing their role as a viable low-carbon heating alternative (Greening & Azapagic, 2012). However, their full decarbonisation potential is best realised when integrated with solar photovoltaic (PV) systems, further reducing their environmental impact (Naumann et al., 2024).

An LCA comparison of ground-source heat pumps (GSHPs) and ASHPs underscores a trade-off between upfront manufacturing impacts and long-term efficiency (Violante et al., 2022). While GSHPs require more resources for production and installation—mainly due to the environmental cost of closed vertical loop systems—their geothermal probe circuit lasts up to 100 years, supporting multiple system lifecycles. In contrast, ASHPs impose greater environmental impacts during operation due to their reliance on fluctuating external air temperatures (Naumann et al., 2024). Over the long term, GSHPs prove more energy-efficient and environmentally sustainable than ASHPs, as their extended lifespan mitigates the need for frequent system replacements, reducing overall environmental burden (Violante et al., 2022). Table 6 provides a comparative analysis of various heat pump (HP) systems in comparison to gas boilers and condensing boilers, based on four key factors: CO_2 emissions, GHG emission reduction, energy efficiency, and overall environmental impact.

A LCA of domestic gas boilers in Italy found that condensing boilers have a 23% lower environmental impact than traditional models, primarily due to higher fuel efficiency and reduced CO and NOx emissions (Vignali, 2017). However, the use phase remains the dominant contributor to their environmental footprint, accounting for over 90% of total impacts. While condensing boilers are more efficient and emit fewer pollutants than traditional gas boilers, their reliance on fossil fuels limits their long-term viability in a fully decarbonised energy system. Despite efficiency gains, their operational emissions remain tied to natural gas combustion. In contrast, a heat pump unit can reduce total CO_2eq emissions by approximately 19% compared to the baseline electricity mix. When integrated with solar PV systems, it can further decrease grid electricity demand, resulting in a 36% reduction in CO_2eq emissions (Norouzi et al., 2023).

The literature review indicated that strategic deployment of heat pumps can significantly contribute to CO_2 reduction, particularly in regions with favourable grid carbon intensity and housing characteristics**.** Norouzi et al., (2023) suggest that aligning heat pump adoption with the UK's national electricity decarbonisation targets could lower whole life-cycle emissions, reducing the long-term climate impact of buildings by approximately 60%. Hehar et al., (2025) analysed heat pump adoption in the West Midlands and Northwest of the UK regions and assessed CO_2 reductions based on weather data, housing characteristics, and grid carbon intensity. The study found that the Northwest region demonstrated the highest CO_2 reduction potential—up to 33%—due to its lower grid carbon intensity**.**

Regional disparities in electricity generation play a critical role in determining the carbon intensity of energy consumption. To maximise emissions reductions, ASHP deployment must be strategically aligned with regions that have a higher share of renewable energy, such as the Northwest. According to Hehar et al. (2025), the environmental benefits of ASHPs can be significantly amplified by focusing on high-density urban areas, such as Birmingham, where the strong correlation between heating demand, electricity consumption, and household density enables substantial CO_2 reductions. However, limiting ASHP adoption to urban centres fails to account for the high heating demand of detached housing, which presents another opportunity for emissions reduction. Prioritising ASHPs in detached housing-dominant regions, such as Shropshire and West Lancashire, can yield even greater energy savings due to the higher heating requirements of detached homes. Given the differences in heat transfer coefficients between detached and semi-detached houses, targeting these areas ensures greater efficiency gains, reinforcing ASHPs as a viable and impactful low-carbon heating solution.

Table 6: Comparative Life Cycle Assessment of Different Heating Systems

Heating system types	CO_2 Emissions	GHG emission reduction	Energy Efficiency	Overall Environmental impact
General HP	A heat pump unit can reduce total CO_2eq emissions by approximately 19% compared to the baseline electricity mix	Aligning with UK's electricity decarbonisation targets could reduce buildings' life cycle GHG by approximately up to 60%.	Typically, 3 to 5 times more energy-efficient than gas boilers	The primary contributor to heat pump emissions is electricity consumption during operation whereas, manufacturing and maintenance have a lesser impact
GSHP	Higher efficiency reduces CO_2, emissions more effectively than ASHP	Vs ASHP: Higher GHG emissions initially (production & installation) but lower life cycle GHG emissions due to greater efficiency and longevity.	more energy-efficient than ASHP	GSHP has higher manufacturing and installation impacts due to raw material use.
ASHP	Higher efficiency reduces CO_2, emissions more effectively than ASHP	Higher GHG emissions compared to GSHP due to reliance on outdoor temperatures	Less efficient than GSHP, especially in extreme weather	Among heat pump types, air-source heat pumps have the highest environmental but is the most economical one
WSHP	Lowest CO_2, emissions among HP types	Lowest GHG emissions among HP types	Higher efficiency than ASHP due to stable water temperatures	Among all HP types WSHP has the lowest environmental impact
HP with PV	Further decrease grid electricity demand, resulting in a 36% reduction in CO_2eq emissions	Greater GHG reduction by integrating renewable electricity sources	Enhanced efficiency with PV integration, reducing reliance on grid electricity	Maximises decarbonisation potential when integrated with PV
Biomass Heating	Can achieve high CO_2 savings depending on feedstock and supply chain	Net-zero GHG potential when using sustainably sourced biomass	Efficiency varies, based on fuel type and system design	Sustainability depends on feedstock; local biomass reduces transport emissions, but deforestation risks exist for unsustainable sources
Solar Thermal	Zero direct CO_2 emissions during operation	Eliminates GHG emissions associated with heating when fully meeting demand	Highly efficient for water heating, but seasonal variability affects performance	Lowest overall environmental impact when replacing fossil-fuel-based heating, but requires backup heating for reliability
Gas boiler	Higher CO_2, emissions compared to heat pumps	Use phase is the dominant contributor to total GHG emissions	Lower efficiency compared to heat pumps	Use phase remains the dominant contributor to their environmental footprint, accounting for over 90% of total impacts
Condensing boiler	23% lower CO_2, emissions than traditional gas boilers	higher fuel efficiency and reduced CO and NOx emissions	Compare gas boilers are more efficient	Condensing boilers have a 23% lower environmental impact than traditional models

Source: (Naumann et al., 2024; Violante et al., 2022;. Greening & Azapagic, 2012 ;Hehar et al., 2025,DESNZ,2023)

4.3 Environmental Impact of Grid Scale Batteries Technologies

Battery energy storage systems (BESS) play a crucial role in stabilising electricity grids, reducing peak demand, and maximising renewable energy integration. Their ability to enhance grid stability and efficiency makes them indispensable in the transition to a low-carbon energy system. However, despite their potential to reduce emissions, their environmental impact warrants further investigation. In rural micro-grids, battery storage enhances energy autonomy and reliability but also presents sustainability challenges. While batteries enable renewable systems to operate without diesel backup and achieve up to 100% renewable penetration, their production has significant environmental costs (Symeonidou et al., 2021). They optimise diesel generator operations—reducing fuel consumption by 30% and operating hours by 50%—yet contribute to mineral resource depletion, accounting for up to 88% of environmental impacts in home systems and 78% in micro-grids(Aberilla et al., 2020a). Given BESS' dual role in supporting renewable integration while imposing environmental burdens, a comprehensive sustainability assessment is needed. The following section presents our LCA review, offering insights into mitigation strategies and sustainable deployment of BESS.

Our literature review reveals that the majority of research focuses on lithium-based battery technologies, Lithium-Ion (Li-Ion) batteries dominate the field, accounting for 72% of the reviewed studies. This is largely due to their commercial maturity, high energy density, and widespread adoption in grid storage and electric vehicles. Meanwhile, 12 % of the papers examine Lithium-Sulfur (Li-S) batteries, which remain in the trial phase due to ongoing challenges related to stability and scalability. Despite their potential for higher energy capacity, their commercial viability is still uncertain. Another 12% of the studies focus on Lithium-Manganese batteries while 4% explores flow batteries an emerging alternative that offers improvements in performance and cost efficiency.

Pumped hydropower storage has historically played a key role in grid balancing, but its expansion is increasingly hindered by environmental concerns and public opposition. In contrast, lithium-ion batteries (LIBs) provide a more flexible and decentralised alternative, making them a critical component of renewable electricity infrastructure. However, their resource-intensive production raises significant sustainability concerns, particularly regarding their long-term environmental impact (Immendoerfer et al., 2017).

Symeonidou et al. (2021) highlighted the environmental drawbacks of lead–acid batteries compared to lithium-ion alternatives (NCA, NCM), demonstrating battery selection significantly impacts the environmental sustainability of rural micro-grids. Lead–acid batteries, due to their short lifespan and frequent replacements, contribute disproportionately to carbon emissions—exceeding 4.8 million kg over 30 years. They also offer lower storage capacity and efficiency, limiting energy exchange within the micro-grid. Lithium-ion batteries (LIBs), particularly NCA and NCM variants, are a more sustainable alternative, reducing lifecycle emissions by nearly 60% compared to grid-dependent systems (Symeonidou et al., 2021).

Aberilla et al., (2020a) highlight that lithium-ion battery (LIB) production is highly carbon-intensive due to the extraction and processing of rare metals like cobalt and nickel, which depend on fossil-based electricity. Kaya (2022) further emphasises the energy-intensive nature of lithium extraction, raising concerns about resource depletion and supply chain sustainability. Compared to other battery technologies, LIBs have a high embodied energy demand, requiring 328 Wh of energy to produce just 1 Wh of storage capacity, resulting in 110 gCO_2eq emissions per Wh (Peters et al., 2017). Sadhukhan & Christensen (2021) emphasise that for BESS to effectively compete with fossil fuel-based energy systems, their global warming potential (GWP) must be reduced by 13-fold. To achieve a carbon footprint comparable to renewable energy sources, an even more drastic 300-fold reduction in GWP would be required. Addressing these sustainability challenges necessitates a comprehensive strategy to enhance the efficiency, longevity, and recyclability of LIB-based BESS (Table 7).

Key approaches to reducing LIB-related environmental impacts include reducing Scope 2 and 3 emissions through phosphorus recycling, increasing energy density to improve storage efficiency, extending battery lifespan through effective maintenance, enhancing recyclability, and integrating waste materials into battery production to lower resource extraction impacts. Additionally, deploying multi-functional BESS applications can improve grid flexibility and overall system efficiency (Sadhukhan & Christensen, 2021). While LIBs help reduce fossil fuel dependence, their long-term sustainability depends on advancements in material sourcing, recycling, and supply chain management. A balanced approach to battery selection is essential for optimising both energy security and environmental responsibility in rural electrification projects.

Table 7: Comparative Life Cycle Assessment (LCA) of Grid Scale Batteries

Type of batteries	CO_2 Emissions	GHG Emission	Overall environmental impacts
Lead-Acid Batteries	Very High (Over 4.8 million kg CO_2 over 30 years)	Very high GHG emission due replacement requirements	High carbon footprint, low efficiency, and short lifespan contribute to high environmental impact
Lithium-Ion (LIBs - NCA, NCM variants)	High (110 gCO_2eq/Wh)	LIBs must reduce their global warming potential 13-fold to compete with fossil fuel-based energy systems	High carbon footprint due to fossil-based electricity reliance, resource depletion from rare metal extraction, and energy-intensive production (328 Wh per 1 Wh storage)
Lithium-Sulfur (Li-S)	Moderate (Lower than LIBs, but not well quantified)	Low Reduced dependency on rare metals like cobalt & nickel	Present several environmental and resource advantages over traditional LIBs. They offer higher specific energy density and do not require rare metals, apart from lithium,
Lithium-Manganese (Li-Mn)	Moderate	Significant greenhouse gas emission due to Mining and refining of lithium and manganese	The most significant environmental impact occurs during the mining and production phase, with the extraction of lithium and manganese being the primary contributors to the overall carbon footprint.
Flow Batteries (Vanadium, Zinc-Bromine, Iron-Flow)	Low to Moderate	Lower lifecycle emissions compared to LIBs, but higher energy demand in material extraction	Longer lifespan and recyclability reduce long-term environmental impact, but high initial material processing emissions remain a challenge
Pumped Hydropower Storage	Low	Very low GHG emissions compared to battery storage and fossil fuel-based energy systems	Resource-intensive production raises significant sustainability concerns, particularly regarding their long-term environmental impact

Source:(Sadhukhan & Christensen, 2021; Peters et al., 2017; Aberilla et al., 2020a) Symeonidou et al., 2021;Immendoerfer et al., 2017, Dieterle et al., 2022).

Lithium-sulfur (Li-S) batteries present several environmental and resource advantages over traditional LIBs. They offer higher specific energy density and do not require rare metals, apart from lithium, reducing dependence on critical raw materials like cobalt and nickel. However, Li-S batteries have not yet been produced at an industrial scale, leaving significant room for technological development and optimisation (Wickerts et al., 2023). Despite their potential benefits, LCA studies on Li-S batteries remain limited and vary in scope, making it difficult to fully assess their environmental impact. Wickerts et al. (2023) reveal that higher specific energy density and the use of clean electricity sources significantly reduce environmental impacts, making Li-S batteries a promising alternative to LIBs. Additionally, hydrometallurgical recycling can mitigate mineral resource depletion, though it does not necessarily reduce other environmental impacts. While Li-S batteries present a viable low-resource alternative to LIBs, further scalability, recycling advancements, and efficiency improvements are required to establish them as a sustainable large-scale energy storage solution.

4.4 Overview of Thermal Energy Storage and Its Environmental Assessment

Thermal Energy Storage (TES) plays a critical role in enhancing energy efficiency and integrating renewable energy sources. TES can be categorised into three main types, each with distinct operational principles and applications (Roux et al., 2024) :

- **Sensible Storage**: Utilises materials such as water, air, soil, bricks, concrete, or sand to retain heat by increasing their temperature. Due to its technological maturity, sensible TES is the most widely implemented system in residential and industrial applications.
- **Latent Storage**: Uses phase change materials (PCMs) that absorb or release heat during phase transitions, such as melting and solidification, enabling efficient thermal management.
- **Thermochemical Storage**: Involves reversible chemical reactions to store and release energy efficiently, offering high energy densities and long-duration storage potential.

The selection of TES technology depends on factors such as storage duration, temperature range, cost-effectiveness, and operational requirements. While TES systems contribute to improved energy efficiency and grid flexibility, their environmental impact requires further examination.

Existing Life Cycle Assessment (LCA) studies on TES primarily focus on urban settings, leaving rural applications underrepresented in the literature (Karasu & Dincer, 2020). This gap limits the applicability of findings to diverse geographical contexts, particularly in regions where energy infrastructure and demand dynamics differ significantly from urban environments. Expanding LCA research to include rural TES applications is crucial for a comprehensive sustainability assessment and equitable energy transition.

The LCA of TES systems highlights that energy consumption is the most significant environmental impact, primarily influenced by the system's coefficient of performance

(COP). Ozone depletion and metal depletion are associated with the heat pump and the heat pump with TES, respectively; however, overall energy consumption remains the critical factor in determining environmental performance. Although TES can reduce localised emissions, its lower COP often leads to higher overall energy demand, undermining its environmental benefits. Systems with higher COP and lower energy consumption are not only more energy-efficient but also more competitive and environmentally favourable. Therefore, prioritising systems with optimised COP is essential for minimising environmental impact and enhancing sustainability in thermal storage solutions (Bonamente & Aquino, 2017).

As shown in Table 8, TES emits only 8.58 kg CO_2eq per 1000 kWh of stored energy, demonstrating superior carbon efficiency. Additionally, TES offers remarkable sustainability advantages, emitting at least 95% less than battery storage in fossil and metal depletion categories. While TES's fossil depletion is not entirely negligible, it remains significantly lower and highly favourable, with further field studies expected to refine this estimate. Beyond carbon emissions, TES also shows notable resource efficiency, consuming nearly an order of magnitude less water per functional unit throughout its lifecycle. In broader environmental impact categories, TES consistently outperforms battery storage, reducing its overall environmental impact by at least 80% across most ecosystem health categories, except for terrestrial ecotoxicity (David et al., 2021).

Table 8: Overview of alternative thermal energy storage systems

Technology	Thermal Energy Storage (TES)	Solar Latent Heat Thermal Energy Storage (S-LHTES)
Energy Consumption	Primarily influenced by (COP); lower COP leads to higher energy demand	High energy consumption of electricity and heat during the production of raw materials for these components.
Global Warming Potential (GWP)	Emits 8.58 kg CO_2eq per 1,000 kWh of stored energy.	Initially higher GWP compared to natural gas; however, extending the system's operational life to 40 years reduces GWP below that of natural gas
Fossil and Metal Depletion	At least 95% less impact compared to LIPB.	Environmental hotspots include components like solar collectors and PCMs, contributing to resource depletion.
Overall Environmental Impact	Outperforms LIPB by reducing impact by at least 80% across most ecosystem health categories, except terrestrial ecotoxicity.	Extending the system's operational life to 40 years significantly reduces environmental impacts

Source:(David et al., 2021; Bonamente & Aquino, 2017; Bernal et al., 2021).

LCA assessment of solar systems with latent thermal storage (S-LHTES) indicates that the system's main environmental hotspots are the solar collector, the phase change materials (PCM), the PCM tank, and the heat exchanger. The primary cause of most impacts is the extensive consumption of electricity and heat during the production of raw materials for these components. Comparison with other household heat sources (biomass, heat pump, and natural gas) indicates that the S-LHTES-PCM system generates the highest environmental impact. However, sensitivity analysis shows that when the lifetime increases to 40 years, almost all impacts are significantly reduced. In fact, a 40-year S-LHTES-PCM system has a lower global warming potential than natural gas (Bernal et al., 2021).

4.5 Transport Emissions: Regional Disparities

Transport remains a major contributor to household greenhouse gas (GHG) emissions, accounting for 43% of total household emissions. Car travel continues to dominate transport in Great Britain, with road travel making up 90% of passenger kilometres in 2019, a 13% increase since 2000 (ONS, 2022).

Electric vehicles (EVs) offer a sustainable alternative to fuel-powered vehicles, reducing oil dependence and emissions, particularly when powered by decarbonised electricity. However, EV adoption is largely concentrated in urban areas, where charging infrastructure, financial incentives, and accessibility are more developed. In contrast, rural and suburban areas face significant barriers, including limited charging networks, higher upfront costs, and weaker policy support (Ding et al., 2024; Westin et al., 2018).

Despite these challenges, rural communities could benefit from increased EV adoption, particularly through reduced fuel costs and lower oil dependency, which may encourage counter-urbanisation. However, the effectiveness of EVs in reducing emissions in rural areas depends on the electricity grid mix. While the UK has been reducing its dependence on fossil fuels, particularly gas, regional variations in electricity generation still impact EV emissions. In areas where coal or gas-fired power plants remain a significant part of the energy mix, EVs may still contribute to emissions. However, in regions with high renewable energy penetration, EVs can achieve near-zero transport emissions (Ding et al., 2024).

Additionally, rural residents often travel longer distances daily, leading to higher overall transport emissions. Transitioning from conventional vehicles to EVs could significantly lower fuel-related carbon emissions, but widespread adoption will require investment in charging infrastructure and policy interventions to bridge the urban-rural disparity.

The adoption of ultra-low emission vehicles (ULEVs), zero-emission vehicles (ZEVs), and plug-in vehicles (PiVs) is rising rapidly. In Q1 2022, ULEV and PiV registrations increased by 71%, while ZEV registrations doubled compared to Q1 2021. The charging infrastructure has also expanded significantly, with 14 times more electric vehicle (EV) charging points and 30 times as many rapid chargers since 2015 (ONS, 2022).

However, rural areas lag behind in EV infrastructure, making long-distance travel and daily commuting more challenging for EV users. Meanwhile, high-emission vehicles (over 150 g/km CO_2) are steadily declining, with a 4% drop in 2020 and an overall 30% reduction since 2014, reflecting the shift toward cleaner transport solutions (ONS, 2022).

4.6 Environmental Impacts of Electric Vehicles and EV Charging Points

While electric vehicles (EVs) eliminate tailpipe emissions, their full life cycle environmental impact must be critically examined. Advocates often highlight EVs as a cleaner alternative to internal combustion engine (ICEs) vehicles, yet this perspective overlooks the substantial emissions generated during battery production and electricity use. A Life Cycle Assessment (LCA) approach provides a more comprehensive analysis, revealing that while EVs reduce on-road emissions, they still contribute to carbon emissions and resource depletion in other stages of their life cycle. The environmental footprint of EVs is heavily dependent on battery production and charging strategies. A 26.6 kWh, 253 kg lithium-ion battery alone has a global warming potential of 4.6 tonnes of CO_2 equivalent, with the battery cell manufacturing process, positive electrode paste, and negative current collector being the primary contributors (Ellingsen et al., 2014). Shifting battery production to cleaner energy sources is the most effective way to lower emissions, as relying on carbon-intensive grids negates much of the intended environmental benefit of EVs. A comparative analysis of the environmental impact of EVs in urban and rural settings versus ICEs Vehicle is summarised in the table below (Table 9).

Table 9: Environmental Impact Assessment of EVs and ICE Vehicles

Category	**Urban EVs**	**Rural EVs**	**ICE Vehicles**	**Source**
Tailpipe Emissions	Zero direct emissions (CO_2, NO_x, SO_2)	Zero direct emissions (CO_2, NO_x, SO_2)	High emissions (CO_2, NO_x, SO_2, PM)	Mehlig et al., 2022
Battery vs. Fuel Emissions	Battery production emits 4.6 tonnes CO_2 eq.	Battery production emits 4.6 tonnes CO_2 eq.	Fuel extraction & refining produce high CO_2	(Ellingsen et al., 2014)
Life Cycle CO_2 Emissions	Lower over lifetime, but depends on grid mix	Lower over lifetime, but depends on grid mix	Consistently high emissions from fuel combustion	(Huo et al., 2015)
Charging Infrastructure	High charging station density, public & home access	Limited public charging, reliance on home stations	Fuelling stations widely available	(Zhang et al., 2019)
Energy Demand & Efficiency	Lower per capita emissions due to shorter commutes	Higher per capita emissions due to longer travel distances	High fuel consumption, inefficient at lower speeds	(Westin et al., 2018)
Particulate Matter (PM_2.5, PM_{10})	High from tire, and road dust due to heavier weight, but lower vs rural due to shorter commutes	Higher from brake, tire, and road dust due to longer travel distances and more road wear	Lower from non-exhaust sources but significant from tailpipe emissions	(Mehlig et al., 2022) Ding et al., 2024)
Smart Charging Potential	10% CO_2 reduction	Limited smart charging, may increase marginal emissions	No smart charging equivalent	Mehlig et al., 2022
EV Adoption Rates	Higher due to incentives & charging availability	Lower due to infrastructure gaps & high costs	Dominant vehicle type in rural areas	Ding et al., 2024

Charging strategies significantly influence the overall environmental impact of EVs, as emissions depend on the electricity mix used for charging rather than the vehicle itself. In 2019, the electricity required to charge a typical Battery Electric Vehicle (BEV) resulted in 41 g CO_2, 27 mg NO_x, and 0.7 mg $PM_2.5$ per kilometre, based on average grid intensity. Static analyses underestimate these emissions by 4%, as they do not account for daily and seasonal fluctuations in the energy grid. Marginal emissions from **BEV charging** are 25% higher for CO_2 and NO_x compared to average emissions, though $PM_2.5$ emissions are 50% lower, suggesting that the power plants supplying marginal electricity produce less particulate matter than the overall grid mix.

This highlights that while EVs produce no tailpipe emissions, their true environmental impact depends on when and where they are charged, particularly in regions still reliant on fossil fuels for electricity generation (Mehlig et al., 2022).

Smart charging, which aligns charging with periods of high renewable energy availability, can reduce CO_2 emissions by 10%. However, it may also increase marginal emissions, particularly in regions where fossil fuels dominate off-peak electricity generation. The adoption of smart charging with real time pricing that recognises peak renewable energy production is essential to maximising the environmental benefits of EVs and preventing emissions from simply shifting within the energy system (Mehlig et al., 2022).

The environmental impact of EVs is also influenced by the type of charging infrastructure and the electricity mix used for charging. Zhang et al., (2019) analysed four main types of EV chargers in China and found that home chargers have the lowest cumulative energy demand and global warming potential (GWP), while public AC chargers perform better than public DC chargers. The highest environmental impact was associated with mixed public chargers that combine both AC and DC charging. The three main factors affecting the GWP of EV charging systems are the electricity mix, the type of chargers used, and the ratio of vehicles to chargers. In regions with clean energy grids, such as California, EVs significantly reduce greenhouse gas emissions, although they may still contribute to particulate matter (PM) pollution from tire, brake, and road dust due to their heavier weight. In contrast, in coal-heavy regions like parts of China and the U.S. Midwest, EVs still lower overall greenhouse gas emissions compared to internal combustion engine (ICE) vehicles but contribute to increased urban air pollution, particularly through sulfur dioxide (SO_2) and PM emissions. As electricity grids decarbonise, emissions of CO_2, NO_x, and SO_2 from EV use will decline, but particulate matter pollution may persist, driven by increased road wear from heavier EVs (Huo et al., 2015).

As shown in Table 10, as electricity generation becomes cleaner with increased use of solar, wind, and hydropower, the reductions in carbon dioxide (CO_2), volatile organic compounds (VOC), nitrogen oxides (NO_2), and sulphur dioxide (SO_2) from electric vehicles will improve. However, fine particulate matter ($PM_{2,5}$) emissions may rise due to factors such as tire wear, brake dust, and road dust from heavier electric vehicles. When compared to internal combustion engine vehicles, most studies indicate that electric vehicles emit less carbon dioxide over their lifetime but tend to produce higher levels of nitrogen oxides and sulphur dioxide in regions that rely on fossil fuels for electricity generation. This means that while EVs offer significant environmental benefits, their overall impact is directly tied to the carbon intensity of the electricity grid (Eltohamy et al., 2024).

Table 10: Assessment of emissions by BEV & PHEVs

Category	Battery Electric Vehicle (BEV)	Plug-in Hybrid Electric Vehicle (PHEV)
CO_2, Reduction (tons)	6.2	1.4
VOC Reduction (kg)	9.7	6.7
NO_2,Reduction (kg)	2.2	1.2
$PM_{2,5}$ Increase (kg)	4	1.9
SO_2 Increase (kg)	28.5	14.2

Source: Eltohamy et al. (2024)

By 2025, improvements in power generation are expected to enhance the benefits of electric vehicles, although some air pollutants may remain high in certain areas. Studies suggest that using 80 percent renewable energy for charging electric vehicles could cut emissions by up to 85 percent, reinforcing the importance of clean energy integration in maximising the sustainability of electric vehicles. The more we transition to renewable energy sources, the greener electric vehicles will become (Huo et al., 2015).

4.7 Environmental Impact of Hydrotreated Vegetable Oil

Hydrotreated Vegetable Oil (HVO) has emerged as a promising alternative to conventional diesel, offering a renewable solution for both light- and heavy-duty vehicles (Suarez-Bertoa et al., 2019). Its appeal lies in its ability to reduce emissions and enhance fuel performance without requiring modifications to existing diesel engines. However, the true environmental impact of HVO extends beyond tailpipe emissions, necessitating a comprehensive evaluation through LCA. Unlike a simple carbon comparison, LCA considers multiple variables, including feedstock sourcing, land-use changes, processing technologies, and end-of-life impacts, all of which influence the overall sustainability profile of HVO.

Existing LCA studies have highlighted significant reductions in GHG emissions, particulate matter (PM), and nitrogen oxides (NOx) associated with HVO use (Soam & Hillman, 2019b; Suarez-Bertoa et al., 2019). These benefits, however, are highly dependent on the choice of feedstock. Common raw materials such as palm oil, rapeseed, jatropha, tallow, and used cooking oil (UCO) exhibit varying environmental footprints due to differences in land-use impacts, cultivation methods, and processing efficiencies (Ambat et al., 2018). Reported GHG emission reductions range from 40% to 85% compared to fossil diesel, depending on methodological choices within LCA studies, such as system boundaries, functional units, allocation approaches, and the treatment of biogenic carbon (Table 11). These methodological inconsistencies contribute to the ongoing debate about the true climate benefits of HVO (Soam & Hillman, 2019b).

Table 11: Assessment of environmental impacts of HVO vs Fossil Diesel

Category	HVO	Fossil Diesel
GHG Emissions Reduction	40% to 85% reduction compared to fossil diesel, highly dependent on feedstock type	High emissions; no inherent reductions without blending with biofuels
Particulate Matter (PM) Emissions	Lower than fossil diesel	Higher than HVO, contributing to air pollution
NOx Emissions	Lower than fossil diesel	Higher than HVO, associated with acid rain and smog formation
Sustainability Concerns	Sustainability depends on feedstock availability; food-based sources raise ethical and environmental concerns	Contributes to long-term carbon emissions and fossil fuel dependence

Source: (Soam & Hillman, 2019b; Suarez-Bertoa et al., 2019).

A key challenge is ensuring that increased demand for HVO does not shift production toward unsustainable feedstocks. While the current emissions advantage of HVO is largely attributed to waste-derived sources, limited availability could drive reliance on food crops, potentially undermining its environmental credentials (Sunde et al., 2011). Nitrous oxide (N_2O) emissions, though lower than fossil diesel, remain a critical factor in assessing its overall climate impact. Given these complexities, waste-based HVO presents a viable short-term solution, particularly for hybrid buses and other transport applications, as part of a broader transition toward long-term decarbonisation strategies. However, its sustainability depends on strict regulatory frameworks, responsible feedstock sourcing, and consistent LCA methodologies to ensure that environmental benefits are not compromised by shifting market dynamics (Sunde et al., 2011).

5. Conclusion

This report highlights the critical role of low-carbon technologies in reducing emissions while emphasising that their effectiveness is contingent on regional infrastructure, resource availability, and sustainability considerations. Addressing disparities in energy access and affordability is essential for achieving an equitable transition to a low-carbon future.

Regional variations in carbon emissions, energy consumption, and heating fuel reliance present significant sustainability challenges across the UK. The Southeast, Northwest, and London record the highest emissions, while Northern Ireland leads in per capita emissions due to its lower population density and greater reliance on fossil fuels. Despite London's high energy demand, its per capita emissions remain lower, largely due to efficient public transport and widespread use of natural gas. In contrast, rural areas face significant energy inefficiencies, with one in four homes off-grid and heavily dependent on high-carbon heating fuels such as oil and solid fuels. This dependence exacerbates emissions and deepens fuel poverty, particularly in regions such as Cumbria, Yorkshire, and Lincolnshire. Expanding low-carbon heating solutions, including heat pumps, is crucial to closing the urban-rural energy gap and ensuring transition to a more sustainable heating systems.

Heating technologies offer both opportunities and challenges in emissions reduction. Ground Source Heat Pumps (GSHP) provide the highest efficiency but come with greater manufacturing and installation impacts. Air Source Heat Pumps (ASHP) are more cost-effective but have higher operational emissions, while Water Source Heat Pumps (WSHP) offer the lowest environmental footprint. Integrating heat pumps with photovoltaic (PV) systems can further reduce emissions by lowering grid electricity demand. Similarly, alternative fuels like Hydrotreated Vegetable Oil (HVO) present a lower-emission alternative to diesel; however, their sustainability depends on feedstock sources. Waste-derived HVO offers the most significant environmental benefits, while palm oil-based HVO raises concerns regarding deforestation and unsustainable land use.

Battery storage technologies play a crucial role in decarbonisation but vary in sustainability. Lithium-ion battery (LIB) production remains highly carbon-intensive, requiring 328 watt-hours (Wh) of energy per Wh of storage capacity and emitting 110 grams of CO_2 equivalent (gCO_2eq) per Wh due to reliance on rare metal extraction and fossil-based electricity. Emerging alternatives such as Lithium-Sulfur and Lithium-Manganese batteries show potential for reducing emissions but are not yet widely commercialised. Flow batteries, including Vanadium, Zinc-Bromine, and Iron-Flow, offer lower lifecycle emissions than LIBs and improved recyclability, but their high material extraction energy demand remains a challenge.

Transport remains a dominant source of household greenhouse gas emissions, with road travel accounting for 90% of passenger kilometres. EVs significantly reduce CO_2 emissions, but their environmental impact is heavily dependent on the electricity grid mix. In regions where fossil fuels dominate electricity generation, EVs may still contribute to NO_x and SO_2 emissions. Additionally, non-exhaust emissions from tire, brake, and road dust remain a concern, particularly for heavier EVs. Expanding clean electricity generation and optimising EV charging infrastructure are key to maximising the environmental benefits of transport electrification.

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