Uneven Paths to Net-Zero: A Review of Rural-Urban Gaps in Low-Carbon Heating in the United Kingdom

By

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Background: Why decarbonising heat matters

- Heating accounts for about 37% of UK emissions.
- The domestic sector is the second-largest emitter (~18%) after transport.
- Natural gas produces around 40% of heating emissions, with rural areas still relying on oil
- Heat pumps and heat networks are expected be backbone of low-carbon heating for the next decade.
- The role of hydrogen and the gas network is uncertain.
- The **Heat and Buildings Strategy aims to:**
  - Phase out new fossil fuel boilers by 2035.
  - Expand heat pump installations.
  - Determine hydrogen's role in heating by 2026.

Proportion of Off-Grid Households by Region in the UK

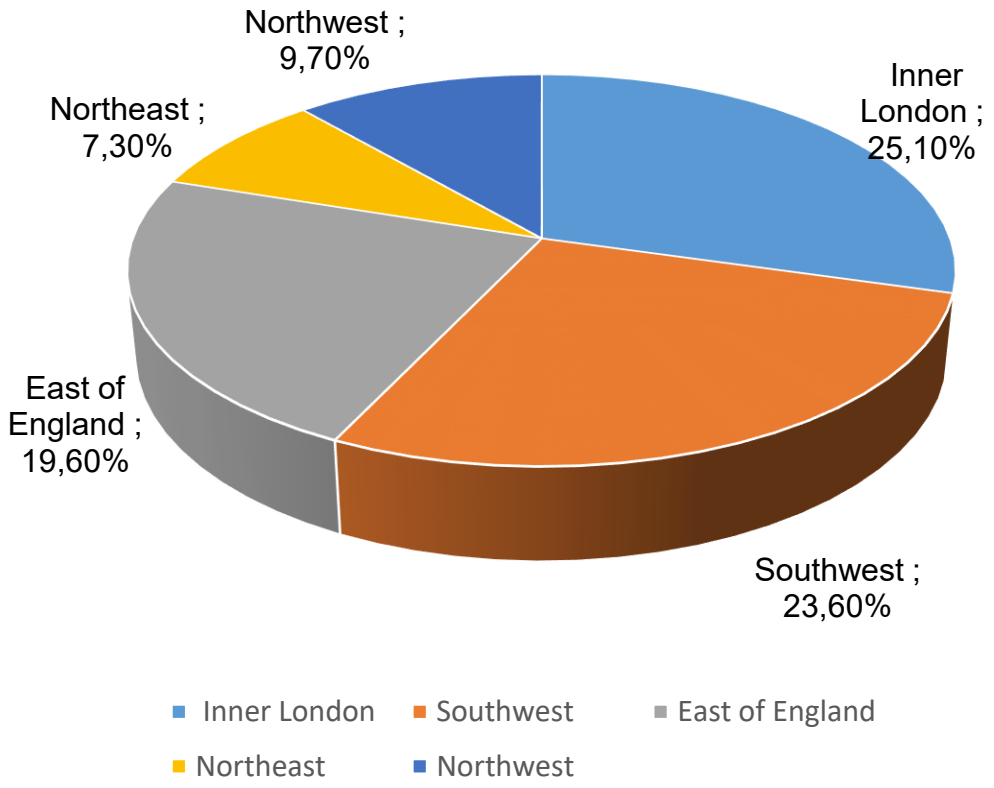
- In 2021, 4.4 million GB households (15.1%)—were not connected to the gas grid.
- Off-grid homes exist in rural areas and high-rise flats without gas links.

Regions with the highest off-grid proportions:

- Inner London (25.1%)
- Southwest (23.6%)
- East of England (19.6%)

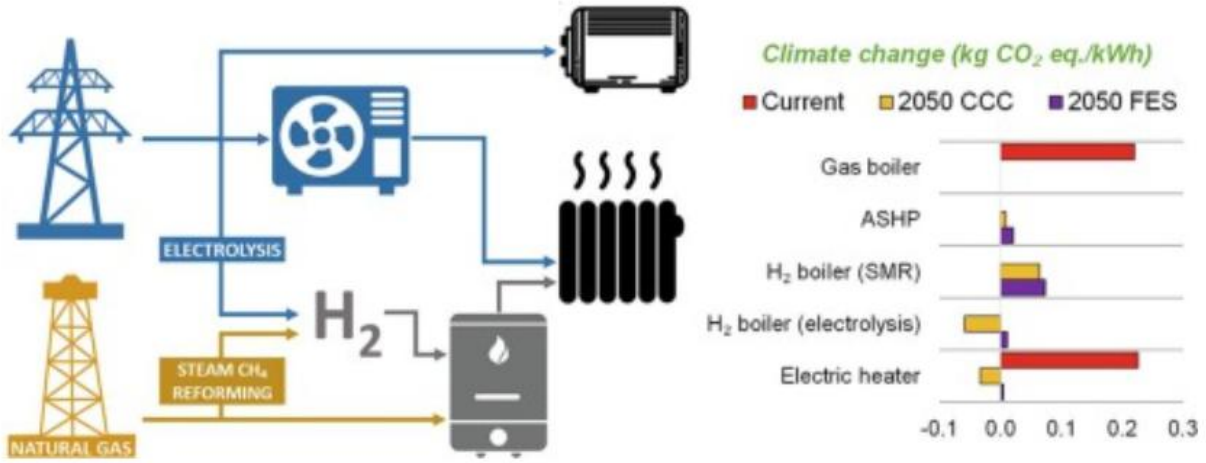
- Off-grid households, often reliant on oil, face higher energy costs and severe fuel poverty
- Mainly due to the lower energy efficiency of off-grid properties.

Off-Grid Household Rates by Region (2021)



Research Gap:

- Net zero requires heating decarbonisation, but risks burden shifting to other resources (e.g., material extraction).
- Large-scale heat pump rollout may increase raw material demand and embodied emissions.
- LCA provides a full-system view, covering manufacturing, operation, and end-of-life.
- Current studies focus narrowly on operational emissions, overlooking full life-cycle costs and impacts.



Aim and Objectives

Aim

Examine how differences in **rural and urban energy infrastructure** shape UK emissions and identify the most suitable **low-carbon heating technologies** using life-cycle assessment (LCA).

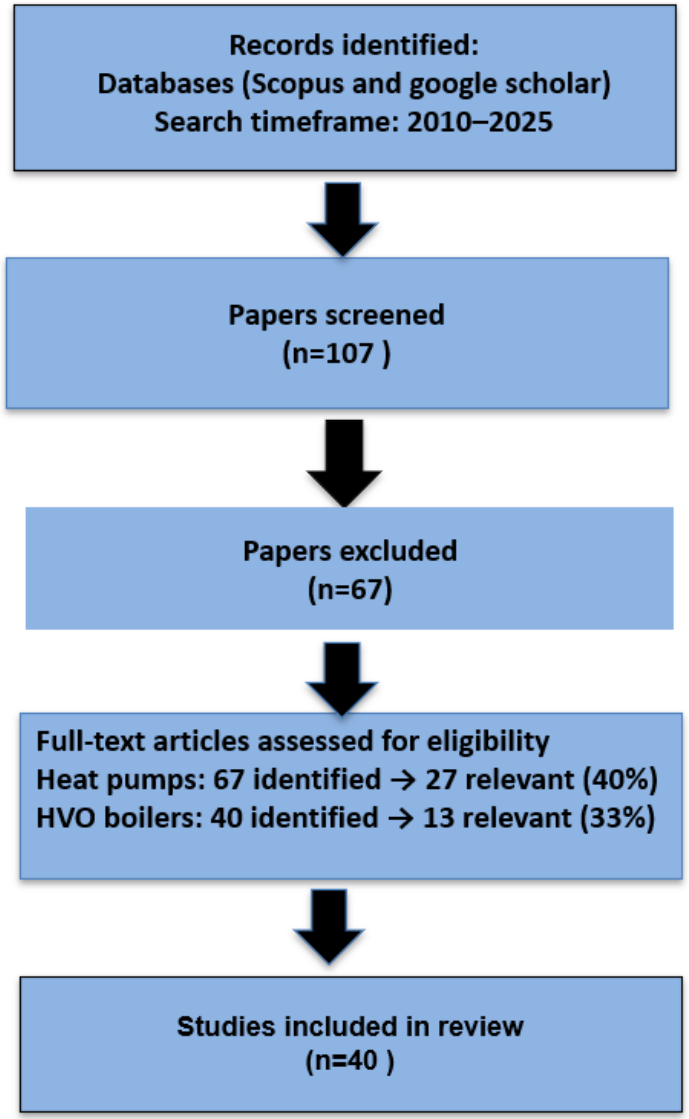
Objectives

1. Compare carbon emissions **rural vs urban** communities to highlight UK's regional disparities.

2. Analyse UK energy use & infrastructure impacts on emissions.

3. Systematic review of Life Cycle Assessment of low-carbon heating (e.g., heat pumps, HVOs).

Methodology



Search class 1: method – life cycle assessment

"life cycle assessment" OR "LCA" OR "life cycle analysis"

Search class 2: technologies

"heat pump" AND ("life cycle assessment" OR "LCA")
"ground source heat pump" OR "GSHP" AND ("life cycle assessment" OR "LCA")
"air source heat pump" OR "ASHP" AND ("life cycle assessment" OR "LCA")
HVO boiler" OR "Hydrotreated Vegetable Oil boiler" AND ("life cycle assessment" OR "LCA")

Search class 3: setting urban or rural environment

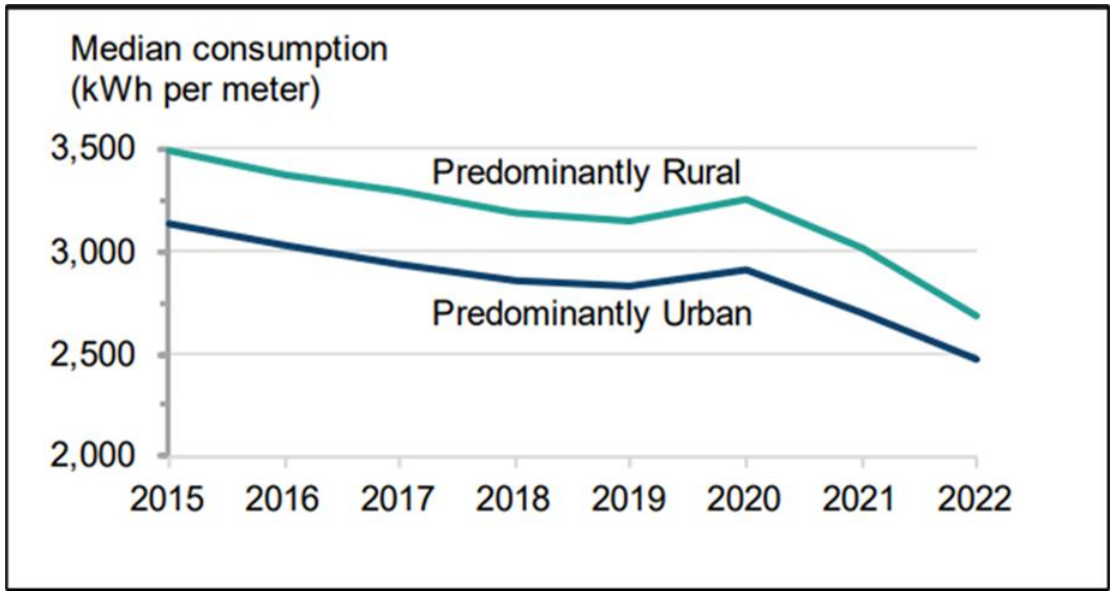
"Urban" OR "Rural" Environment

Key Results: Why GHG Emissions Vary Across Regions

- Urban: Higher total emissions (industry, services, concentrated demand).
- Rural: Higher per-person emissions (fossil fuel heating, bigger homes, fewer alternatives)
- Infrastructure & energy access are key drivers

Electricity Consumption Trends (2015-2022)

- Rural: ↓23% (800 kWh/meter),
- Urban: ↓21% (700 kWh/meter).



Median Domestic Electricity Consumption in Predominantly Rural and Urban Areas, 2015-2022

Regional Emissions: Through Different Metrics

Highest Emitting Regions

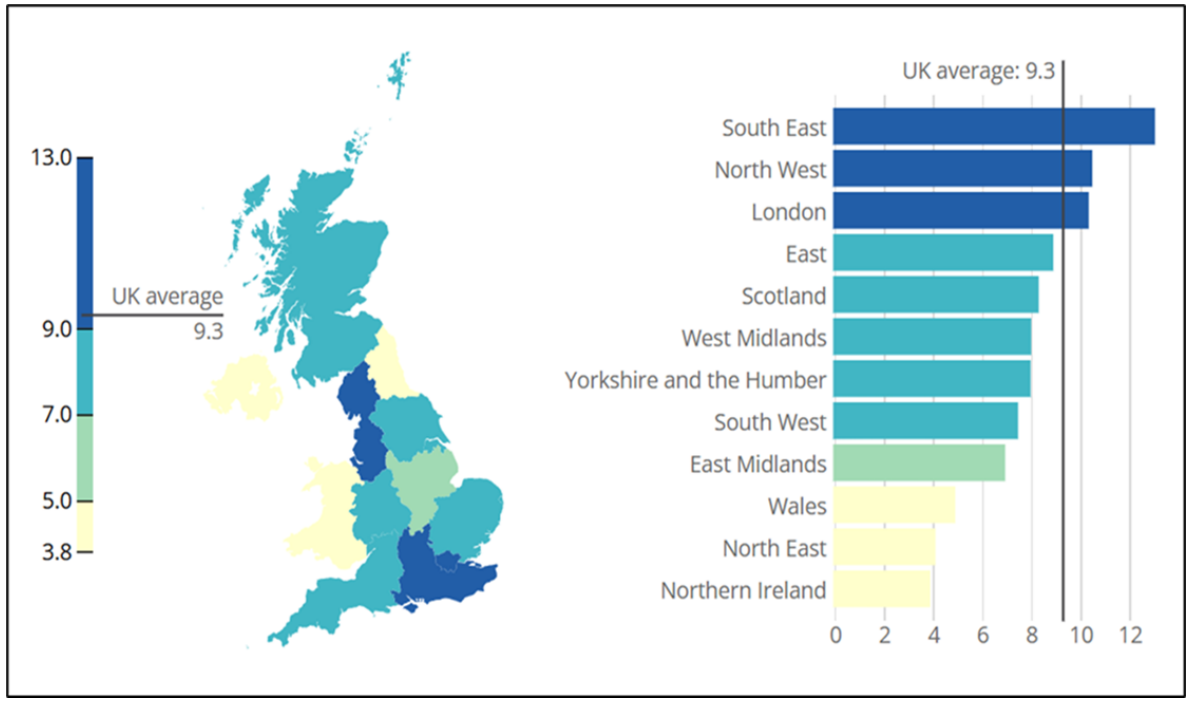
- ❑ Southeast: Highest
- ❑ Northwest & London above UK average

Emissions Per Capita

- ❑ Highest: Northern Ireland.
- ❑ Lowest: London (dense population, lower energy use per person).

Emissions Density (per km)²

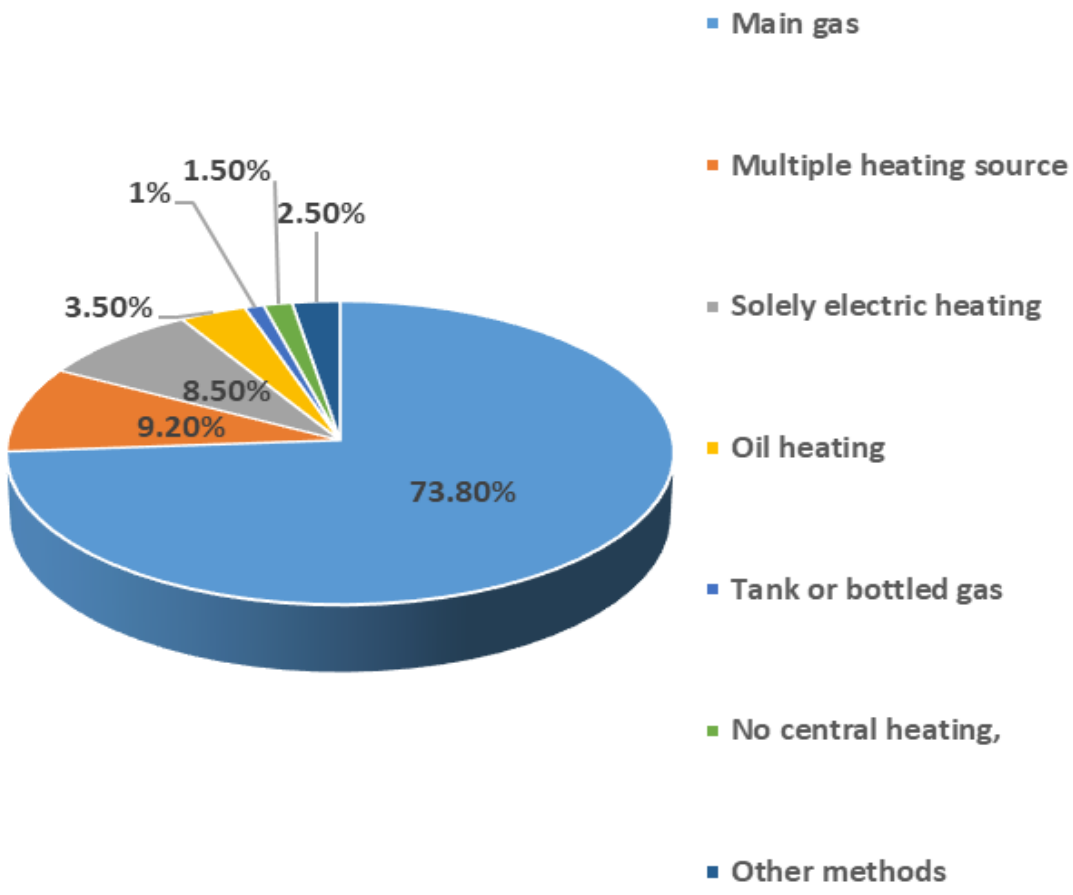
- ❑ London dominates (concentrated demand).
- ❑ Scotland lowest (low density, rural).
- ❑ Rural emissions vary by metric — cities need infrastructure decarbonisation areas need cleaner heating.



UK Territorial greenhouse gas emissions ($MtCO_2e$) across different regions Source: (DESNZ, 2022)

Rural–Urban Divide in Heating Dependence

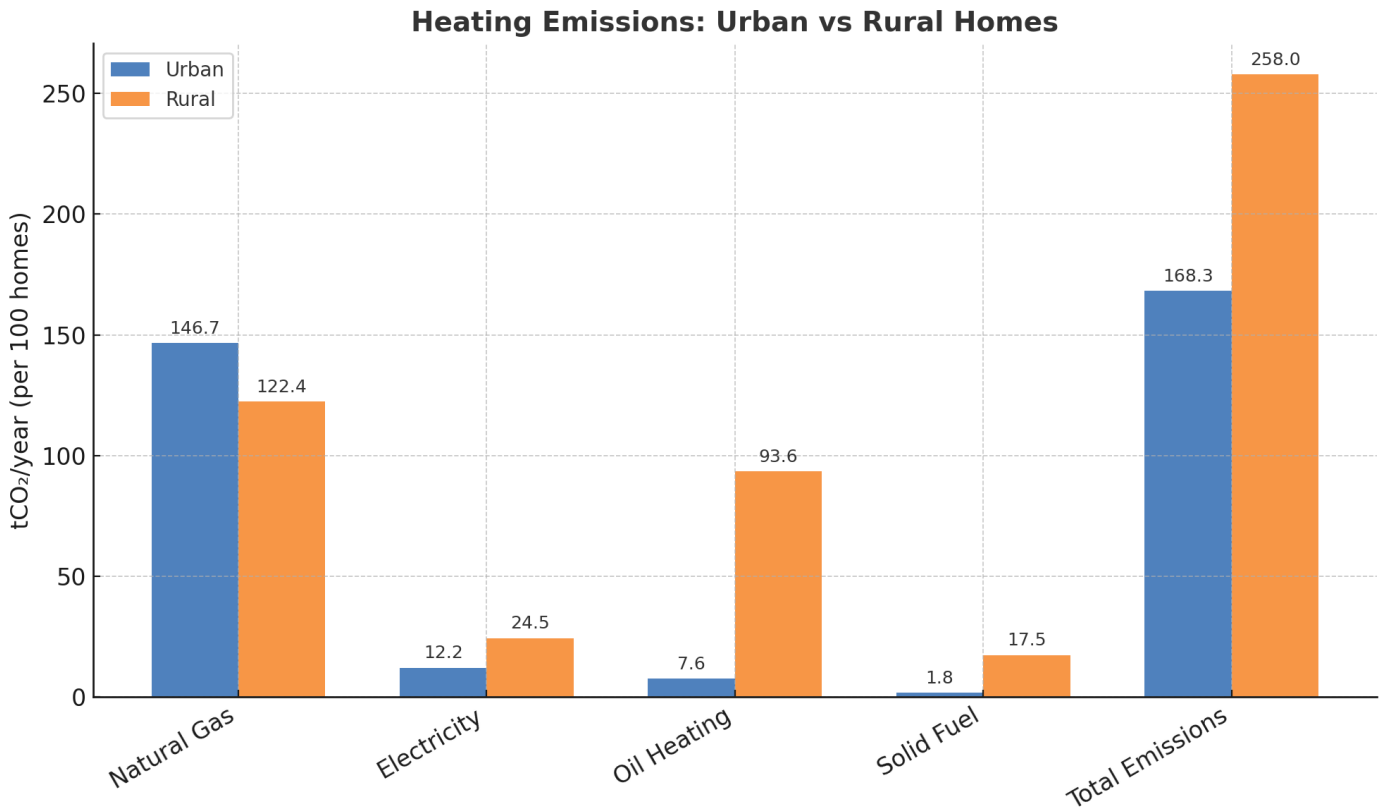
- Rural areas remain disproportionately reliant on oil heating, a legacy of limited grid access.
- >10% of rural homes depends on oil as main source of vs <1% of urban homes.
- Non-domestic gas use dominates in rural regions, driven by businesses, public buildings, and the prevalence of off-gas-grid homes.
- Off-grid households face deeper fuel poverty, needing ~£568 more per year to escape it

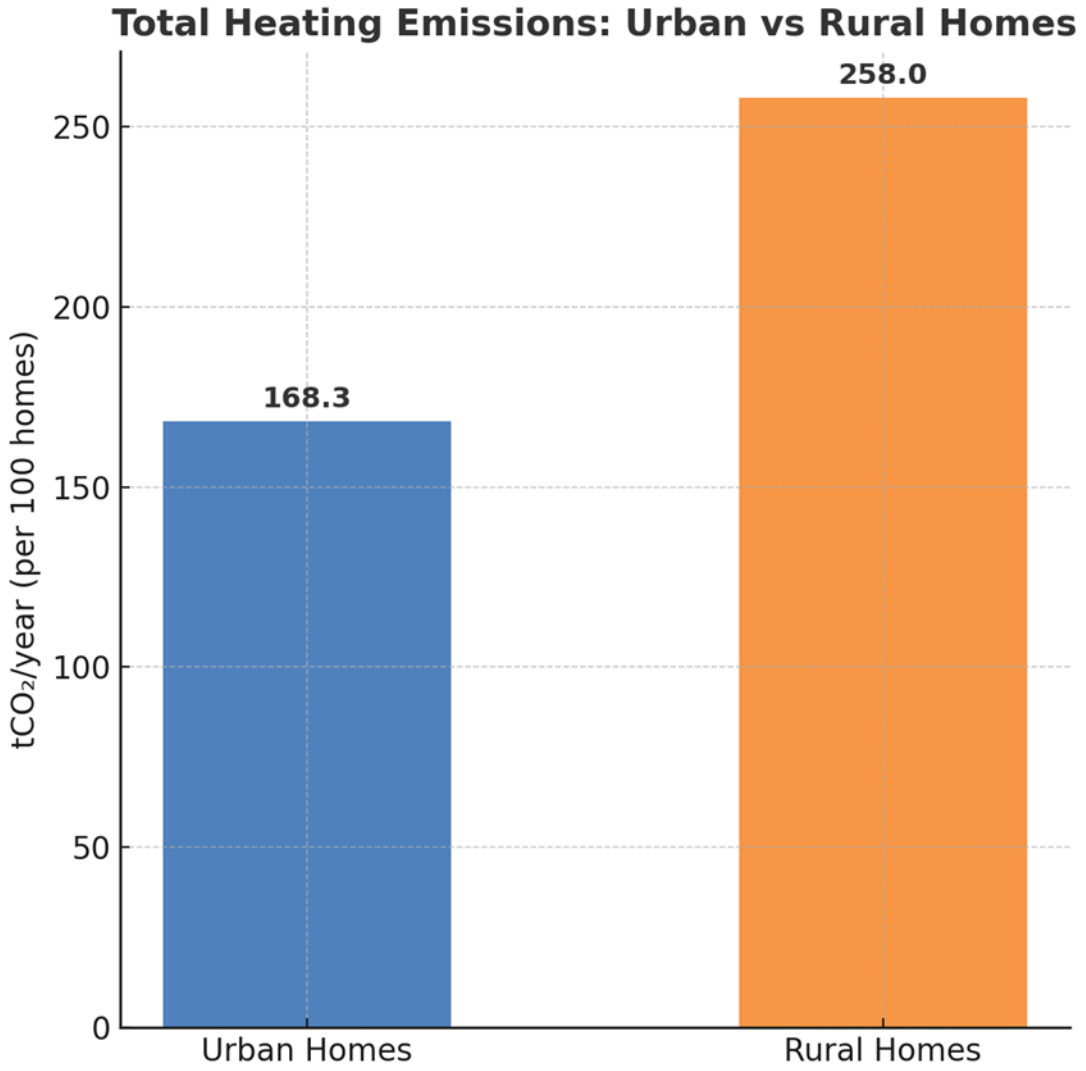


Source of heating across England and Wales

Source: Stewart & Bolton, 2024

Comparing Rural and Urban Emissions in the UK





Life Cycle Assessment Definition

- Assesses impacts across a technology's full life cycle – from materials and production to use and disposal.
- Most studies assess **multiple impact categories** for a holistic evaluation.

Most Studied Impact Categories:

- **Global Warming Potential (GWP):** most common, linked to climate change and GHG emissions.
- **Abiotic Depletion Potential (ADP-Fossil)** & **Cumulative Energy Demand (CED):** common in energy system studies.
- **Acidification Potential (AP)** & **Human Toxicity Potential (HTP):** less frequent but important for ecosystem health and human well-being.

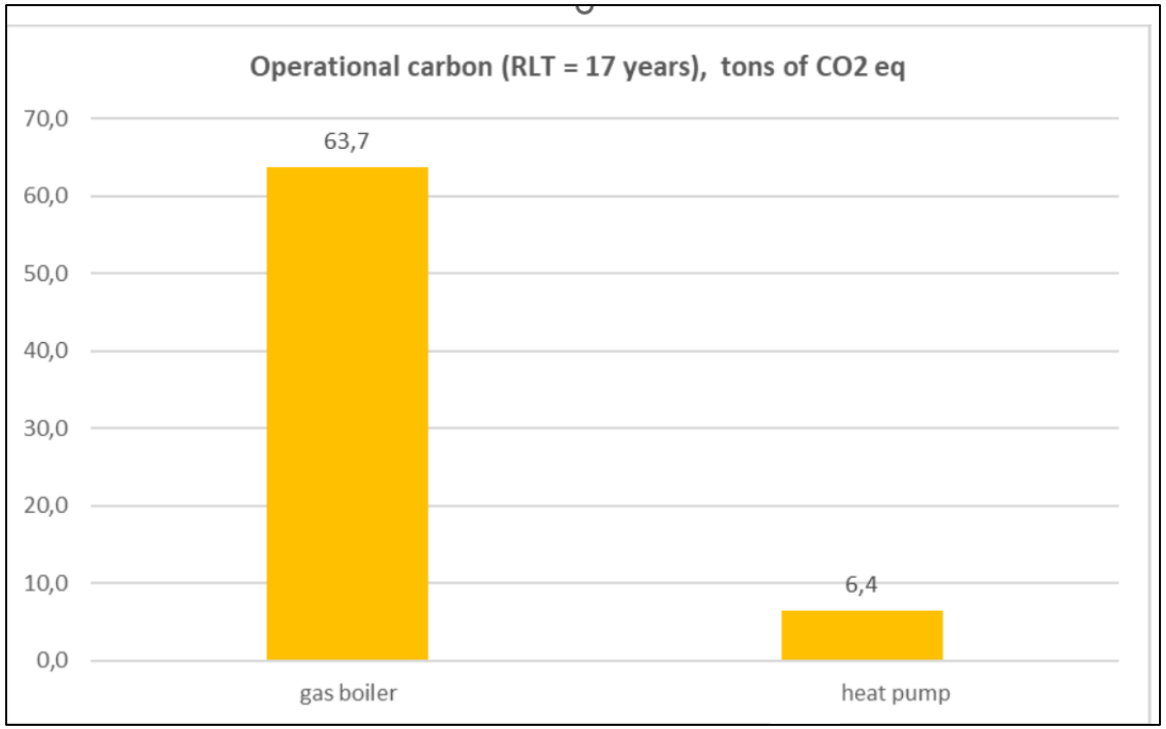
Environmental Impact of Heat Pumps Vs Gas Boilers

Gas Boilers:

- ~23% lower environmental impact than traditional boilers
- Use phase dominates ~90% of total impacts
- Energy supply constraints limit progress toward full decarbonisation.

Heat Pumps:

- 3–5× more efficient than gas boilers.
- Operation phase accounts for ~60% of total impacts.
- **Heat pumps outperform gas boilers**, achieving ~19% CO_2eq reduction (depending on the electricity mix).
- With PV integration, emissions reductions can reach up to 36%.



LCA of Different Types of Heat Pumps

GSHP (Ground Source)

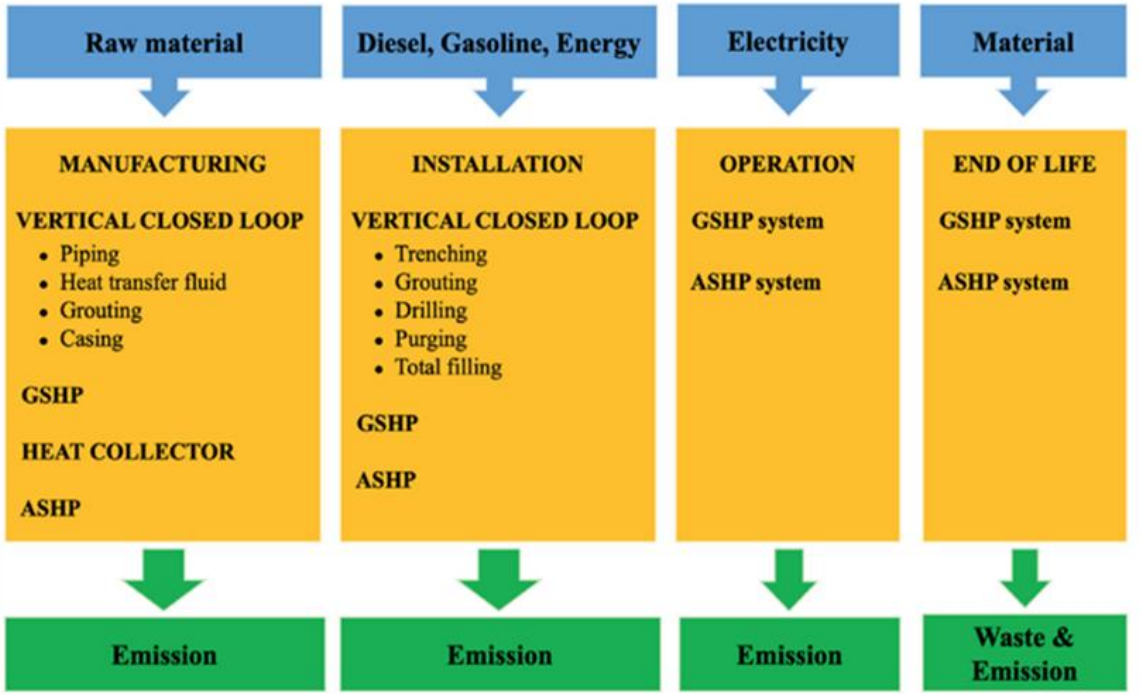
- ❑Most efficient, durable (up to 100 years).
- ❑Higher upfront impacts (drilling & materials).
- ❑Lower lifetime CO_2 than ASHP.

ASHP (Air Source)

- ❑Cheapest and most common.
- ❑Efficiency drops in cold weather → higher emissions.
- ❑Highest environmental impact of heat pumps.

WSHP (Water Source)

- ❑Lowest CO_2 and GHG impact among HP types.
- ❑Very efficient (stable water temps).
- ❑Limited by water access.



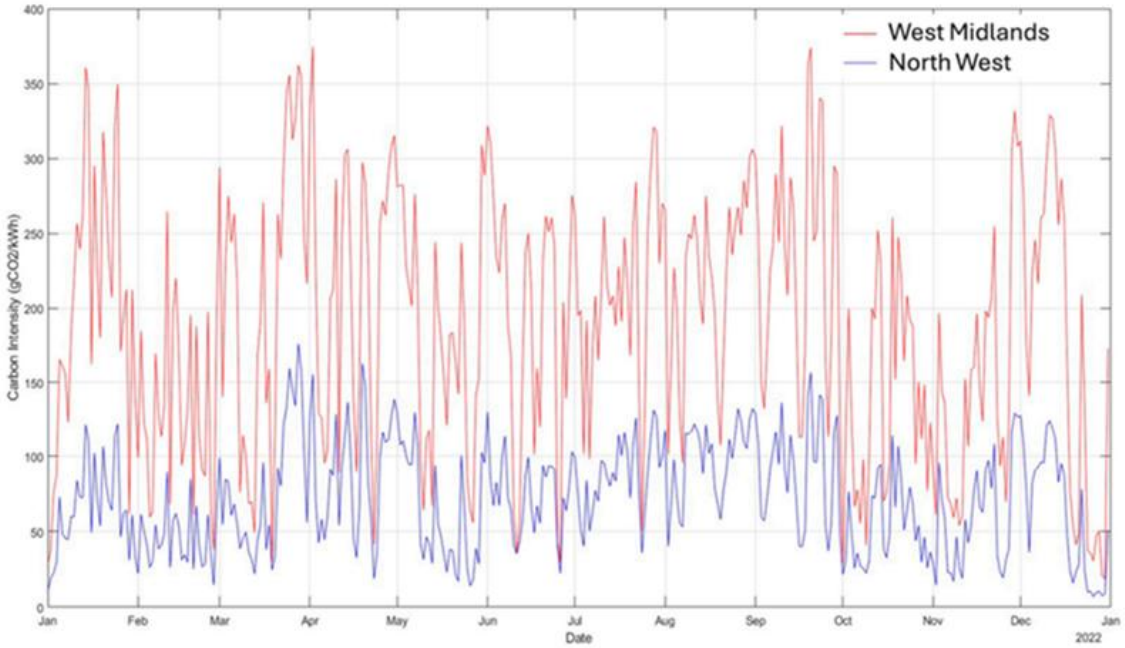
Life cycle stages of heat pump systems

Regional Disparities in Heat Pump Effectiveness

- CO_2 savings depend on grid carbon intensity and housing stock — regions with more renewables achieve greater reductions.
- Aligning rollout with UK grid decarbonisation could cut life-cycle building emissions by ~60%.
- Northwest shows highest CO_2 reduction (~33%) due to a cleaner grid.

Regional Opportunities:

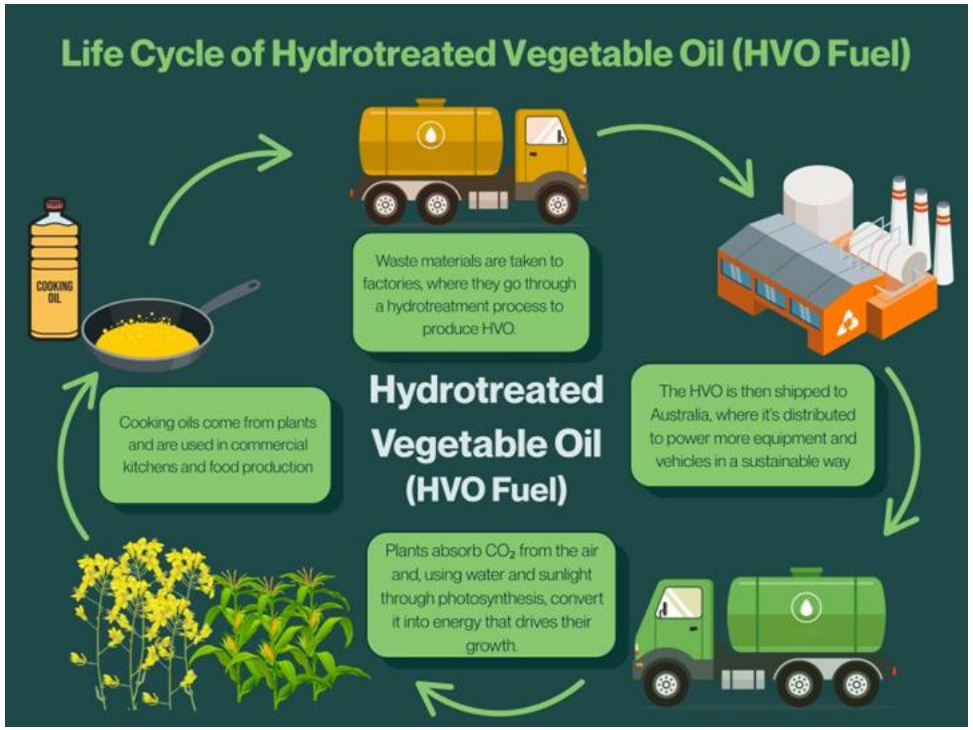
- **Urban centres (e.g., Birmingham):** High density & demand → substantial reductions.
- **Detached housing (West Midlands & Northwest):** Higher heating demand → greater energy savings with ASHPs.



Average carbon intensity (gCO_2/kWh) in 2022: West Midlands vs North West (Hehar et al., 2025)

Environmental Impact of Hydrotreated Vegetable Oil (HVO)

- HVO approved for heating in England & Wales, usable in domestic and commercial boilers
- Drop-in fuel: works in **diesel vehicles and oil-fired boilers**
- Emerging as a promising fossil diesel substitute and a bridge for short- to medium-term decarbonisation.
- **Significant Reductions :**
- 40–85% lower GHG emissions compared to fossil diesel
- Reduced particulate matter (PM) and nitrogen oxides (NOx)
- Nox from soils → >50% of HVO's climate impact
- Nox & ammonia → drive acidification and eutrophication.



Key Challenges & Considerations for HVO

- HVO's emissions advantage relies on limited waste-based feedstocks.
- Rising demand could shift feedstocks from waste to food crops, undermining sustainability.
- HVO is currently more expensive than conventional oil, making adoption less attractive.
- Sustainability of HVO hinges on robust regulation, ethical feedstock sourcing, and uniform LCA standards

Category	HVO	Fossil Fuels
GHG Emissions Reduction	40% to 85% reduction	High emissions; no inherent reductions
PM Emissions	Lower than fossil diesel	Higher than HVO
NOx Emissions	Lower than fossil diesel	Higher than HVO
Sustainability Concerns	Sustainability depends on feedstock availability;	Contributes to long-term carbon emissions

Key Takeaway

- Low-carbon technologies are essential, but their effectiveness depends on regional infrastructure, resource availability.
- Urban areas often have efficient infrastructure, while rural/off-grid communities — remain reliant on high-carbon fuels, deepening energy poverty.
- Heat pumps are globally promoted, yet cost, grid carbon intensity, and manufacturing impacts vary across contexts.
- Alternative fuels like HVO highlight broader sustainability debates —, while crop-based pathways risk deforestation and land-use conflicts

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