buildings

MDPI

Article

Potential Energy Risks of High-Efficiency Dwellings: Lessons from Four Contemporary Rural Housing Cases in Scotland

Wenbo Fang * and John Brennan

School of Architecture and Landscape Architecture, Edinburgh College of Art, University of Edinburgh, Edinburgh EH8 9LE, UK; john.brennan@ed.ac.uk
* Correspondence: s2235087@ed.ac.uk

Abstract

This study, through a hybrid approach to post-occupancy evaluation (POE) of four types of high-energy-efficiency housing in rural Scotland, explores the manifestation, formation mechanism, and mitigation pathways of energy risks in high-energy-efficiency housing from environmental and socioeconomic dimensions. The findings reveal a "high-efficiency paradox": better fabric performance and lower heating demand do not guarantee reduced carbon emissions, fuel poverty alleviation, or energy resilience. Actual energy risks are formed by the combined effects of multiple factors, including building size, energy infrastructure, resident characteristics, energy prices, and policy, exhibiting a clear systemic coupling characteristic. The study further verifies that, in the context of rural Scotland, relying solely on indicators such as EPC may lead to misjudgements of housing sustainability. Heating demand, total energy consumption, carbon emissions, and energy expenditure exhibit a partially decoupled relationship. Thus, rural housing sustainability should shift from a technically efficient approach to a comprehensive strategy integrating design, infrastructure, affordability, and social equity. The study proposes context-specific mitigation pathways including multi-source energy systems, place-sensitive policies, socio-economic support, and a multi-criteria assessment framework, providing empirical references for rural housing energy transition and energy risk governance.

Keywords: high-efficiency dwellings; energy risks; rural Scotland; energy equity; Post-Occupancy Evaluation (POE)

Check for updates

Academic Editors: Mehrdad Rabani, Guilherme Coelho and Mehran Rabani

Received: 17 May 2026
Revised: 14 June 2026
Accepted: 22 June 2026
Published: 25 June 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Scotland has established one of the most ambitious decarbonisation pathways in Europe, legally committing to achieve net-zero greenhouse gas emissions by 2045 [1,2]. Within this transition, the residential sector plays a critical role, accounting for a substantial proportion of national energy consumption and operational carbon emissions. Consequently, high-efficiency housing models, including Passivhaus, have become central to Scottish strategies for reducing building-related emissions and improving energy performance [3].

However, rural Scotland presents a unique combination of environmental and socioeconomic conditions that differentiate it from urban areas. Environmentally, Scotland features distinct climatic variations across its mainland, islands, coastal zones and Highland regions [4,5]. Rural localities are regularly affected by strong prevailing winds, wind-driven rain, high annual precipitation and elevated humidity, alongside extended heating seasons [6]. These harsh climatic characteristics raise air infiltration rates, speed up building

heat loss, and increase the risks of condensation and moisture buildup, all of which directly undermine the thermal performance of building envelopes [7]. Beyond climatic factors, socio-economic conditions and regional energy infrastructure also markedly shape Scottish rural dwellings. Rural Scotland is typified by scattered population distribution, underdeveloped energy networks and a large stock of ageing housing [3,8,9]. The large-scale construction and renovation of energy-efficient housing and the promotion of renewable energy have disrupted the traditional rural energy supply system, triggered a series of emerging energy risks and become a major obstacle to the development of sustainable housing in rural areas [10,11].

1.1. Energy Resources and Supply

For centuries, rural households in the studied regions have relied heavily on fossil fuels. Peat has long been a major domestic fuel in the Highlands due to high coal transportation costs. Four main types of peatlands in Scotland have experienced large-scale degradation: 70% of blanket bogs and 90% of raised bogs are damaged. Although peat extraction is restricted, small-scale local exploitation still persists [12]. Scottish peatlands store approximately 1.6 billion tonnes of carbon, and the Scottish government invested £22 million in peatland restoration in 2022. Official data from 2023 shows that roughly 1000 to 2000 hectares of peat are used for commercial purposes each year [13–15]. The gradual phase-out of peat has created a fuel supply gap in these rural areas, which conflicts with the clean energy requirements of modern high-efficiency dwellings. Along with the national low-carbon transition, local fuel structures have been reshaped by new policies, yet fuel supply shortages remain a prominent challenge in rural Scotland.

Domestic energy accounts for 41.8% of Scotland's total consumption (with heating accounting for 52.6%) [16]. Electricity has decarbonised rapidly, with 87.8% coming from low-carbon sources in 2021 (57% renewables, 29.8% nuclear). In contrast, renewable heating reached only 7.1%, which is dominated by biomass [11,16]. This creates a critical structural imbalance between electricity and heating decarbonisation, and uneven fuel supply across rural areas further worsens this imbalance.

Notably, Scotland missed its 2020 11% renewable non-electric heating target, with over 90% of heat still dependent on fossil fuels despite the Renewable Heat Incentive. A 50% renewable heating target is set for 2045, but rural areas face starkly unequal energy access [17]. Only 53% of rural homes are connected to mains gas [18,19], with near-total absence in Shetland, Orkney, and Na h-Eileanan Siar. Off-gas areas rely heavily on off-grid electricity, which is more costly and raises household energy burdens [20,21]; additionally, grid capacity constraints limit the adoption of new electric heating systems, given that modern low-carbon housing solutions increasingly depend on electric heating, advanced mechanical ventilation and integrated renewable energy technologies, all of which require reliable and affordable energy infrastructure; inadequate infrastructure may also trigger new energy risks, including rising fuel costs, supply outages, and limited flexibility in selecting heating systems [11].

This combination of low gas penetration, weak grid infrastructure, and costly off-grid solutions undermines the energy supply stability of rural high-efficiency dwellings, compounding the energy risks stemming from the transition from past to modern fuels.

1.2. Fuel Poverty

In accordance with the UK Warm Homes and Energy Conservation Act 2000, a household is classified as living in fuel poverty (FP) if it spends over 10% of its total income on heating to maintain standard indoor temperatures (21 °C for living rooms, 18 °C for other spaces). FP stems from fuel costs, housing conditions and household income, and harms

public health and community stability [22]. Rural households often rely on expensive, inefficient energy, resulting in a 19% FP rate compared to 11% in urban areas; remote rural areas saw a 33% rate in 2019 [16]. Rural Scotland still struggles with equitable access to affordable warm housing [10]. Half of rural Scotland lacks gas grid access with 72% in the Highlands. Remote rural living costs are 15–30% higher, with rural households paying some of the UK's highest electricity prices [23]. Actual energy use exceeds official data due to 24 h heating, heat loss and colder northern climates; at the same time, off-grid homes lack energy price cap protection, exacerbating FP during price hikes [24]. Alternative energy technologies exist but are often unaffordable for low-income rural households, leading some to argue FP solutions should focus on broader poverty rather than just fuel costs [8]. Mould and Baker [25] note remote rural households face disproportionate FP from socio-economic factors and isolation, with older housing increasing heating costs and reducing funds for essentials, harming health. Widespread FP weakens community economic stability [26]. Considering income disparities, accessible rural households earn over £40,000, remote ones £10,000–£20,000 [18], and inadequate FP assessments further exacerbate inequalities.

1.3. Carbon and Environment

1.3.1. Carbon Policy and Social Status

Scotland's Energy Performance Certificate (EPC) and related assessment systems (SAP/RdSAP) are mandatory for housing transactions and renovations, serving as core tools for local low-carbon policies [18]. Despite EPC improvements, rural housing remains less efficient: the 2022 Scottish Housing Condition Survey found only 56% of Scottish homes meet minimum EPC C, dropping to 33% in rural areas dominated by F/G-rated homes [27]. Existing support schemes have failed to reverse the rising fuel poverty rate. The Heat in Buildings Bill plans to phase out fossil fuel and biomass boilers by 2045. While the policy expands financial grants, high upfront costs, labour shortages and relocation issues remain major barriers for rural implementation [18,28].

1.3.2. Paying for Emissions Reductions

Scotland adopts the net-zero operational carbon standard, enshrined in national climate legislation [2,29]. However, key challenges include large existing housing stock and new homes facing stricter regulations without a clear pathway. Broader location-specific heating systems are needed, such as decarbonized natural gas (still experimental) for grid-connected areas [30], while heat pumps and solar heating are needed for off-grid areas. Meanwhile, balancing energy efficiency investments with decarbonization for low-income households lacks standardized metrics. No renewable energy (RE) reduces emissions without higher costs; relying solely on energy for housing decarbonization faces contradictions, as seen in Scotland's "Hard to Treat" housing [31].

1.4. Theoretically Potential Energy Risks Associated with Energy-Efficient Housing

For energy-efficient housing, although its energy-saving performance theoretically shows a significant improvement, it is still considered to have potential energy risks, as shown in Table 1 below.

Existing studies on Scottish high-efficiency dwellings mainly focus on individual technical optimisations, single energy performance tests or macroscopic policy analyses (Table 1). Most literature discusses separate energy risks from either technical or policy perspectives. A key research gap is the absence of systematic research that integrates environmental, social and economic sustainability dimensions to explore the overall energy risks and causes of rural high-efficiency dwellings. Many studies adopt a techno-centric mindset, simply equating lower heating demand with reduced carbon emissions and

energy bills, while ignoring combined constraints from rural climate, infrastructure and household economy.

Table 1. Summary of potential energy risks.

Energy Risk Manifestations	Potential Formation Causes	References
Actual energy consumption far exceeds designed values (performance gap)	Overestimation of building performance in design; mismatch between SAP calculation and real occupant behaviour; poor construction quality and air tightness; occupant inexperience with new systems	[11,12,22,25,26,28]
Unstable and/or unaffordable energy supply	Weak grid capacity in remote areas; high cost of grid connection; lack of district heating; lack of mains gas access; low household income	[2,11,12,17,19–21,24]
High cost of low-carbon heating equipment	High upfront cost of renewable heating systems; high installation cost	[23,32]
Inconsistency between renewable electricity and renewable heating	Electricity decarbonises rapidly, but heating still relies on fossil fuels; limited renewable heat penetration	[11,16]
Difficulty in achieving real-world carbon reduction targets	High embedded carbon; performance gap; unsuitable energy source choices	[13,17,31]

To address this gap, this paper draws on selected cases to examine local energy resource characteristics of housing. It investigates the formation processes and multidimensional impacts of fuel poverty, while also exploring the economic and technical challenges associated with achieving a low-carbon transition in high-efficiency dwellings. By analysing the interactions between building design, energy infrastructure, household characteristics, and their insights, the study seeks to uncover the mechanisms through which highly efficient homes may produce unexpected trade-offs among energy efficiency, operational carbon emissions, affordability, and long-term sustainability. The findings contribute to a deeper understanding of what can be described as the "high-efficiency paradox", whereby improvements in building fabric performance and reductions in space-heating demand do not necessarily lead to lower operational carbon emissions, reduced fuel poverty risk, or enhanced energy resilience under the specific conditions of rural Scotland.

This study's significance lies in three aspects: First, it sorts out various energy risks concluded from the studied cases, providing practical empirical evidence for relevant research. Second, through multi-case POE analysis, it reveals the causes and manifestations of energy risks within the sample scope, supplementing current rural energy research. Third, targeted mitigation strategies are proposed according to local realities, which can serve as practical references for low-carbon housing development in similar rural contexts.

2. Materials and Methods

This study adopts a mixed-methods research design, integrating case study and Post-Occupancy Evaluation (POE) of four contemporary rural high-efficiency dwellings in Scotland. The design was specifically constructed to systematically address the two core research questions, namely the manifestations and formation cause of energy risks in such dwellings, as well as effective mitigation paths. Triangulation of theoretical insights and empirical data was employed to ensure the rigor, validity, and reliability of the research findings.

2.1. Case Study and POE

Four rural high-efficiency dwellings were selected for the case study based on strict criteria to ensure representativeness: all meet Scottish high-efficiency standards (SAP

rating $\geq$ 80), had been occupied for at least 12 months to ensure stable operational data, cover diverse rural regions of Scotland, and include different ownership types (social housing and private housing) that are all newly built (Table 2). Due to privacy regulations of the local housing trust, direct face-to-face interviews are not allowed for tenants in Case 3. For Case 1, 2 and Case 4, we successfully conducted direct one-on-one interviews with residents. Qualitative data for Case 3 are sourced from archived interview videos provided by the housing trust, supplemented by interviews with the project architect and trust manager. POE, as the core empirical tool, consisted of complementary quantitative and qualitative components to comprehensively capture actual dwelling performance and energy risks.

Table 2. Basic information of cases.

	Local Council	Ownership Type	Household Structure	Interviewee	Housing Type	House Age
Case 1	Aberdeenshire	Private	Living alone	House owner (self-occupant)	Detached	2011
Case 2	Moray	Social	Living alone	Tenant	Flat (4 studio)	2022
Case 3	Dumfries & Galloway	Social	Young couple with 1–2 children	Architect. Trust Manager [1]	Flat (3 units)	2021
Case 4	Shetland Islands	Private	Young couple with 3 children	House owner (self-occupant)	Detached	2021

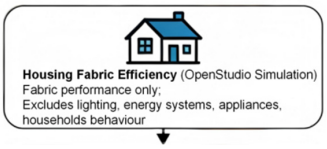
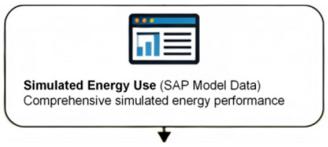
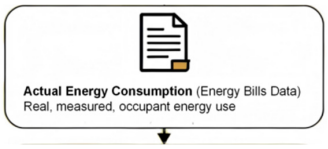
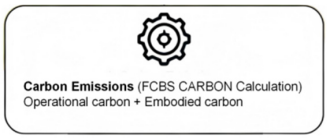
[1] To eliminate data bias caused by differentiated interview access, a multi-source triangulation strategy is adopted for Case 3: interview records (archived videos), interviews with professional architect and Trust manager are mutually verified to guarantee data quality and research robustness.

Quantitatively, a range of indicators related to building energy performance and carbon emissions were collected, including heating demand, simulated total energy use, actual household energy consumption, operational carbon emissions and embodied carbon emissions (Table 3). These indicators represent different aspects of building performance and were obtained from different sources. According to ISO 52016-1:2017, heating demand refers to the annual energy required to maintain specified indoor thermal comfort conditions and reflects the intrinsic thermal performance of the building envelope rather than actual occupant-dependent energy consumption. Since the purpose of the heating demand simulations (openstudio) was to provide a comparative assessment of baseline heating requirements among the four dwellings, calibration against measured utility data was not undertaken. Operational carbon emissions and energy expenditure were derived independently from actual energy use and energy-source characteristics rather than from building simulations. Qualitatively, semi-structured interviews were conducted to explore occupants' experiences, energy use behaviour, and perceptions of energy risks. Interview data were audio-recorded, and transcribed verbatim.

2.2. Data Integration

A comparative analysis was conducted on the four newly built case dwellings. By comparing the quantitative and qualitative data obtained from simulation and POE across the four cases, combined with the theoretical insights from the targeted literature review, the commonalities and differences in the manifestations and formation causes of energy risks were identified. This comparative analysis further supports the proposal of practical and targeted paths to mitigate energy risks in high-efficiency rural dwellings in Scotland.

Table 3. Data collection flow.

Diagram	Data Needed	Indicator	Definition	Source
	Basic housing information: total floors, floor area, door and window dimensions, etc. Housing energy efficiency parameters	Heating demand ($kWh/m^2 \cdot yr$)	Annual energy required to maintain indoor thermal comfort, reflecting the intrinsic thermal performance of the building envelope and ventilation losses	Field work, Documents, SAP Data (UK EPC Database); OpenStudio
	Directly used data	Primary energy demand (EPC) ($kWh/m^2 \cdot yr$)	Standardised estimate of total building energy demand under SAP assumptions, including space heating, DHW and auxiliary loads	SAP Data (UK EPC Database)
	Directly used data	Household energy use (kWh)	Actual delivered energy consumed by occupants during operation	Field work
	Energy consumption and energy types, Materials and quantities of each component of the house	Operational carbon emissions ($kgCO_2e/year$)	Carbon emissions associated with energy use during building operation	Field work; Calculated from energy use and emission factors; FCBS CARBON Calculation
		Embodied carbon emissions ($kgCO_2e$)	Greenhouse gas emissions arising from material production and construction processes	

3. Results

3.1. Potential Energy Risks in the Environmental Dimension

3.1.1. Fabric-First or Size-First? An Excessively Large per Capita Housing Area May Have a More Direct Impact on Energy Consumption

Figure 1 reveals that per capita floor area exerts a more direct and dominant influence on residential energy consumption, environmental impacts, and energy utilization efficiency in high-efficiency dwellings. This is consistent with the conclusion of quantitative research conducted in 2015 [33].

Heating demand simulated by OpenStudio reflects the spatial heating load determined by the fabric performance, including heat transfer through the envelope and heat loss from ventilation and infiltration. This indicator objectively represents the inherent thermal performance of the building and the baseline heating demand. When evaluated on a per capita basis (see Figure 1), clear disparities emerge across cases. Cases 3 and 4 show significantly lower per capita heating demand than Cases 1 and 2. This difference is not driven by superior fabric thermal efficiency alone, but primarily by per capita floor area, which directly impacts the affordability and feasibility of energy integration. The total heating demand is distributed among more occupants, resulting in a much lower per capita energy burden and a smaller, more cost-effective energy system requirement (e.g., Case 3's Passivhaus design with small per capita area allowed for a low-capacity ASHP system with minimal supplementary energy).

Similarly, energy bills represent the actual economic cost experienced by residents for both renewable and fossil fuel energy. While energy cost per unit floor area shows Case 4 as considerably higher, this gap is substantially narrowed when expressed per capita, as per capita costs better reflect household affordability of energy consumption. Notably, as a passive house with a small per capita floor area and cost-effective ASHP system, Case 3 presents clear advantages in reducing fuel poverty risk and improving energy utilization affordability. Together, these results demonstrate that per capita dwelling size plays a

decisive role in actual energy demand, energy-related burden, and the economic viability of the energy system in high-efficiency dwellings.

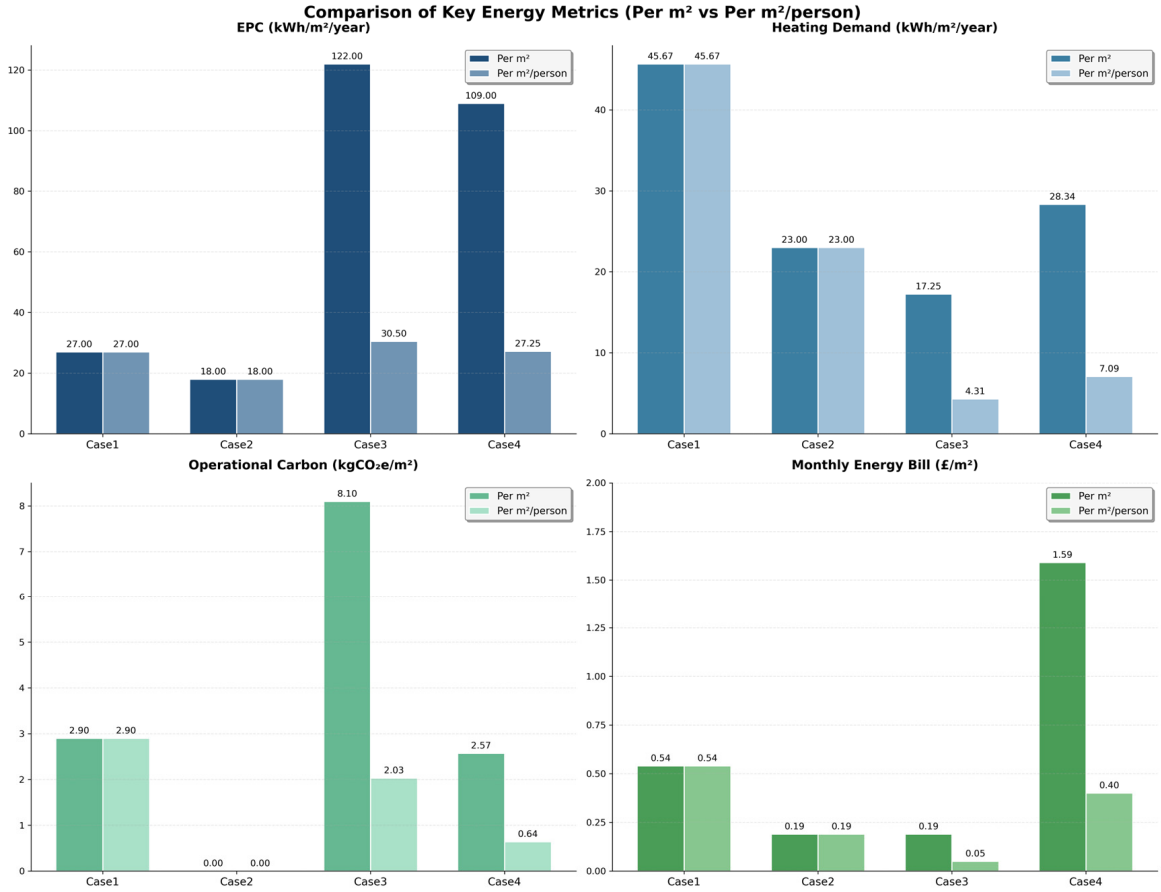


Figure 1. Energy performance, carbon emissions, and cost metrics for four rural Scottish housing scenarios, presented as both per unit floor area (per m^2) and per unit floor area per person (per m^2/person) [1]. The four subplots show: (1) EPC energy, (2) simulated heating demand, (3) operational carbon, (4) average monthly energy bill. [1]. Considering one of the family members in Case 4 is a newborn baby, this person will not be included in the calculation.

3.1.2. Single-Dimensional Indicators Are Partial and Misleading in Assessing Performance

Limitations of EPC Indicators

The core energy indicators of EPC are calculated based on the British Standard Assessment Procedure (SAP), which covers factors such as domestic hot water demand, internal heat input, ventilation rate, and air infiltration rate. Since all four cases in this study are high-performance residences, after standardizing based on the number of occupants, the per capita primary energy indicators calculated from EPC show almost no difference among Cases 1, 3, and 4. This consistency highlights two key limitations of EPC: Firstly, it fails to capture the actual energy burden caused by differences in per capita building area, which creates certain misleading effects on the market, especially considering that EPCs are currently influencing housing values [34]. Secondly, SAP, as the basic calculation method of EPC, is essentially an economic efficiency indicator derived from static general parameters, rather than a physical measurement of building energy performance [3].

Moreover, evaluating housing based on any one-sided energy indicators will lead to structural flaws. Take the heating demand as an example.

Heating Demand Is Decoupled from Operational Total Primary Energy Consumption and Carbon Emissions

Heating demand only measures the energy required to maintain indoor thermal comfort through space heating, while the primary energy demand (EPC) covers the total energy consumption of the entire building, including not only space heating but also domestic hot water, household appliances, ventilation systems, and other non-heating energy services. As shown in the plot, Case 3 achieves an ultra-low heating demand of 17.25 kWh/m^2·year, which is the lowest among all four cases, fully embodying the advantages of passive design in thermal insulation and airtightness. However, its EPC indicator reaches 122 kWh/m^2·year, the highest among all cases; this paradox arises precisely because heating demand ignores the high energy consumption of non-heating links.

Operational carbon emissions are determined by both energy consumption intensity and energy structure, while heating demand only reflects the energy quantity required for heating and cannot account for the carbon intensity of the energy used (e.g., high-carbon fossil energy vs. low-carbon renewable energy) or the carbon emissions from non-heating energy consumption. Taking Case 3 as an example, its ultra-low heating demand does not translate into low carbon emissions; on the contrary, its operational carbon emissions are the highest among all cases. The root cause is that Case 3 uses electricity suppliers with higher carbon emissions to meet both its heating and non-heating energy needs, and the high carbon emissions completely offset the carbon reduction benefits brought by low heating demand. In contrast, Case 2 has a slightly higher heating demand (23.00 kWh/m^2·year) than Case 3, but it achieves zero operational carbon emissions by adopting zero-carbon energy sources.

A Holistic Evaluation Framework Is Needed

The pairwise comparison plot (Figure 2) reveals that the four core indicators (primary energy indicator (EPC), heating demand, operational carbon emissions, and energy bill) have certain inherent connections; for instance, heating demand and EPC are both related to energy consumption intensity, and operational carbon emissions are closely linked to energy structure which also affects EPC and the energy bill. However, these indicators are not fully dependent on each other; instead, they are indirectly made relatively independent by other intervening variables. Specifically, factors such as energy type, price and fluctuations, household performance, and non-heating energy consumption act as intermediaries: for example, Case 4's low carbon emissions (linked to clean energy source) do not correspond to low EPC or low energy bills. Consequently, Case 1, 3, and 4 all have obvious structural defects caused by single-indicator bias, while only Case 2 achieves balanced performance in all indicators.

For Case 3, however, the high-carbon disadvantage is well optimized when evaluated from a per capita perspective. The smaller per capita dwelling area of Case 3 dilutes the total operational carbon emissions among more occupants, resulting in a more favourable per capita carbon emission level, which further confirms the misleading nature of single-dimensional assessment. This fully illustrates that residential energy evaluation cannot rely on a single indicator, which will lead to misleading judgments on the sustainability of housing energy performance [35]; instead, a holistic evaluation framework covering heating demand, total energy consumption, carbon emissions, and energy price must be established.

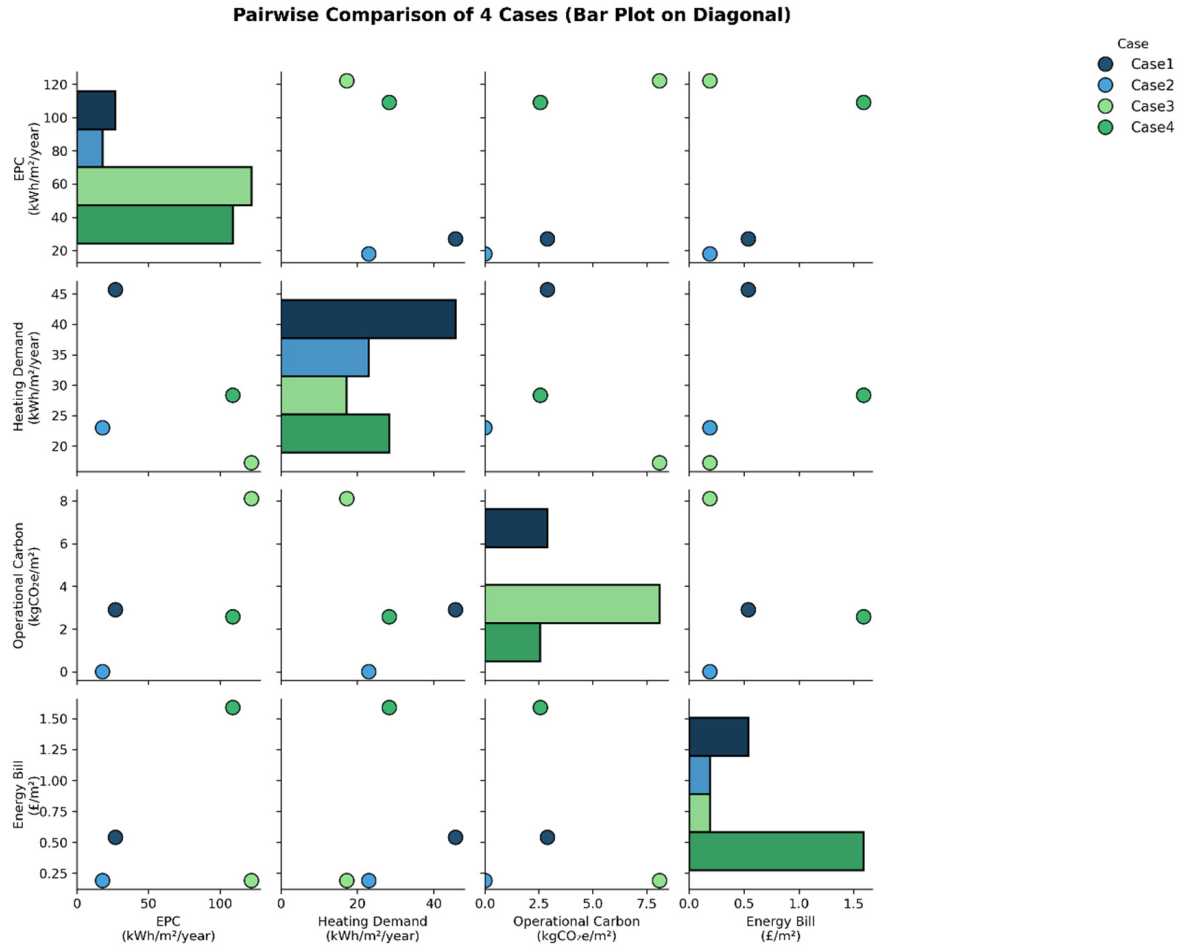


Figure 2. Pairwise comparison of key energy metrics across four rural Scottish residential case studies. The scatterplot matrix illustrates bivariate correlations between EPC primary energy indicator (kWh/m^2/year), heating demand (kWh/m^2/year), operational carbon (kgCO_2e/m^2), and monthly energy bill (£/m^2). Diagonal entries are bar plots showing the distribution of each variable, and off-diagonal entries are scatterplots color-coded by case study to highlight between-dwelling differences.

3.1.3. The Implicit Carbon Emissions of Housing Materials Are Constrained by the Dual Complexity of Both Subjective and Objective Factors

Objective Constraints: Non-Substitutable High-Carbon Materials Based on Functional Necessity

The embodied carbon flow diagrams (Figure 3) reveal that concrete substructures and high-tech service equipment (e.g., MVHR) form a non-substitutable, high-carbon baseline across all four cases. Concrete is universally selected for foundations and floor slabs due to its inherent compressive strength and durability, which are indispensable for structural stability in Scotland's mainland and the lands' climatic conditions. This material choice inherently locks in significant embodied carbon from cement and aggregate production, a baseline that cannot be eliminated by subjective preferences alone.

Similarly, "Services" (such as MVHR) are a top-tier material carbon contributor in every case. The manufacturing of these systems relies on metal alloys and electronic components with inherently high embodied carbon intensities. These high-tech services are functionally required to complement low heating demand, reinforcing their status as a fixed material carbon constraint.

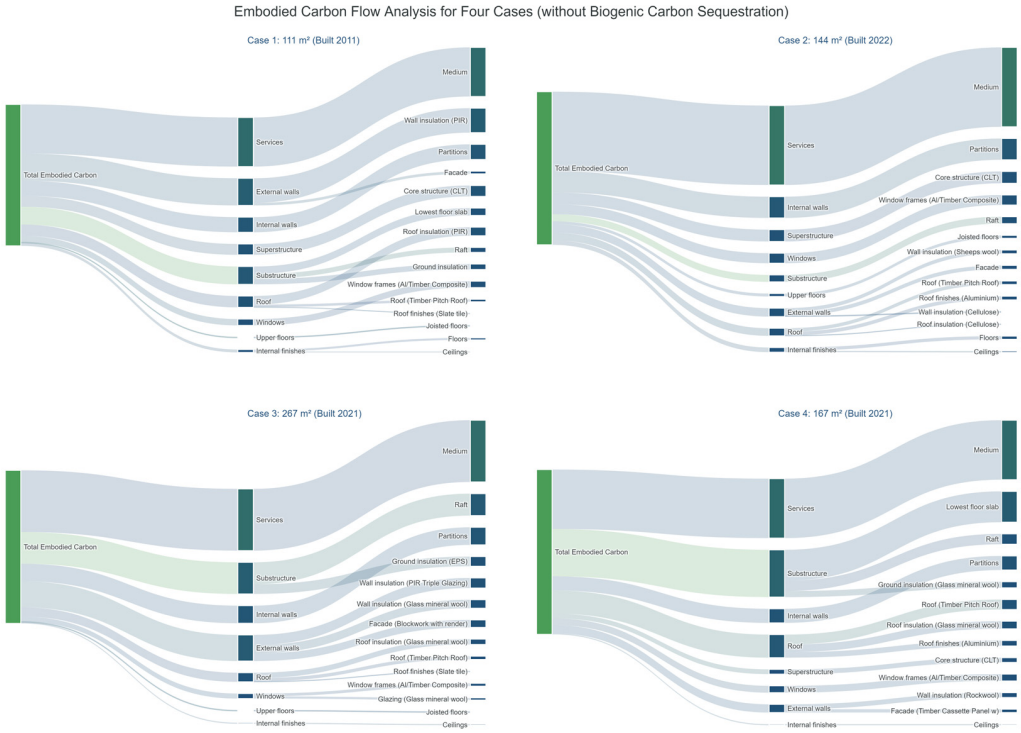


Figure 3. Sankey diagrams illustrating embodied carbon flow and breakdown by building component for four case studies. Each panel corresponds to a case study dwelling, showing the flow of embodied carbon from the total embodied carbon stock, through major structural and non-structural building elements, and finally to specific construction materials. The analysis excludes biogenic carbon sequestration, focusing on the cradle-to-gate embodied carbon impacts of the built fabric.

Subjective Constraints: Ethical Priorities Driving Sustainable Material Choices

Subjective ethical values can significantly mitigate the high-carbon baseline set by objective constraints, as exemplified by Case 2. An interviewee explained that the project "always try to source wood from sustainable forests even if it's more expensive. . . in order to use building materials that don't harm the planet." This ethical commitment to sustainable material production led to the selection of manufactured sustainable materials over cheaper, high-carbon industrial materials, resulting in the lowest embodied carbon and the highest sequestration rate among all cases (Figure 4).

Notably, timber construction is the absolute mainstream in new Scottish housing, and this widespread use of wood plays a pivotal role in increasing carbon sequestration. However, the choice of insulation materials still exerts a major influence on embodied carbon (Figure 3). For example, Case 3's reliance on mineral wool (instead of natural insulation) results in minimal sequestration, even as it benefits from timber's carbon storage potential.

Subjective Constraints: Insufficient Budget as a Barrier to Low-Carbon Choices

Economic constraints act as a critical objective barrier to low-carbon material selection, as demonstrated in Case 3. The architect (Case 3) noted that while the team intended to use Scottish timber and natural insulation, these sustainable materials are "more expensive" than industrial alternatives like mineral wool, and the project's "really tight" margins made this shift economically unfeasible. This cost differential forced a reliance on cheaper, non-local, and higher-carbon materials, overriding the technical potential of sustainable options to reduce embodied carbon.

Across all four cases, the absence of recycled materials in structural and insulation applications can also be traced to this objective cost constraint. Recycled materials often

require more complex processing or have higher upfront costs than virgin alternatives, making them economically unviable within standard construction budgets.

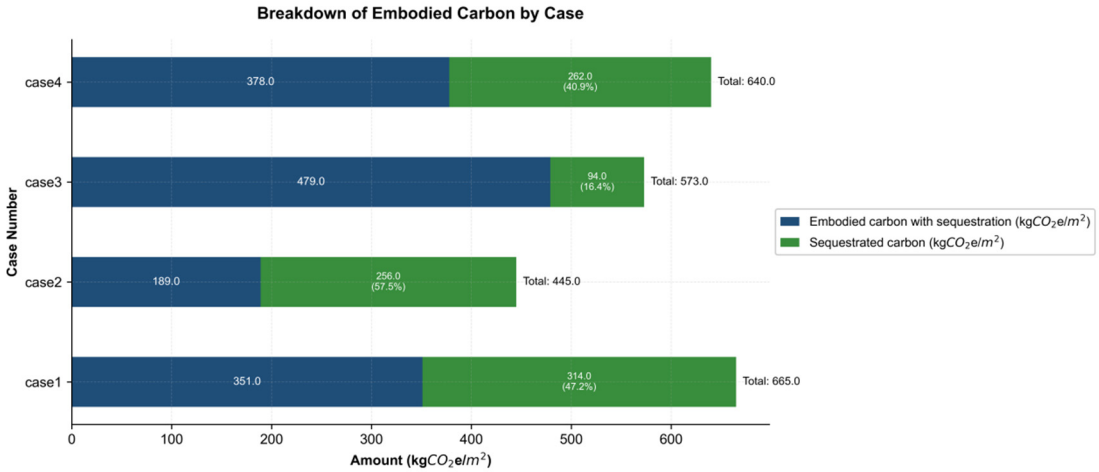


Figure 4. Breakdown of embodied carbon (with and without biogenic sequestration) across four case studies. The stacked bars represent the total embodied carbon per unit floor area (kgCO_2e/m^2), decomposed into embodied carbon emissions (blue) and biogenic carbon sequestration (green). The total embodied carbon and the proportion of sequestered carbon are annotated for each case, enabling direct comparison of net embodied carbon performance across the four scenarios.

3.2. Potential Energy Risks in the Socio-Economic Dimension

3.2.1. Energy Resilience Deficiencies in Single-Source Rural Residential Energy Systems

The POE explores energy resilience deficiencies in single-source residential energy systems through four rural case studies. Table 4 presents the energy systems of the four cases. The findings underscore a critical dichotomy: residential energy systems with built-in redundancy and diversification sustain resilience during disruptions, whereas single-source dependence exacerbates vulnerability. Case 1's resident highlighted grid unreliability through firsthand experience: "we lost power for about 3 or 4 days... maybe once a year, twice a year"; criticizing policy disconnects with rural realities: "They completely failed to understand that if your power supply is not reliable, you have a problem." Case 2's dual-grid system, validated by its resident's account ("once every couple of years" for outages), demonstrated community-scale resilience. Case 4's resident embodied proactive risk mitigation: "We prepared for it... that's just part of living here," with redundant systems mitigating prolonged outages. In contrast, Case 3, reliant solely on grid power, lacked resilience.

Table 4. Energy systems for housing cases.

Cases	National Grid	Mains Gas	Main Heating	Hot Water	Resilience Mechanism
Case 1	On-grid	Without	Wood-burning stove	Solar heating panels + Electric heater	Wood stove and solar heating panels
Case 2	On-grid	Without	District heating system (DHS)	DHS	Dual grid (microgrid + national grid)
Case 3	On-grid	Without	ASHP (radiators)	ASHP (water tank) + Electric heater	None
Case 4	On-grid	Without	ASHP (underground heating)	ASHP (water tank) + Electric heater	Wood stove and gas hob

3.2.2. Internal Factors and External Factors Jointly Contribute to the Complexity and Uncertainty of Fuel Poverty

Table 5 provides detailed data on energy spending and fuel poverty. Internal factors include household structure, energy use behaviour, and economic capacity, which together form the micro-level foundation of fuel poverty's complexity. Among these internal factors, economic capacity exerts the most significant impact on fuel vulnerability. This is clearly reflected in the interview data of Case 1's resident, who, as a financially stable individual, stated that fuel price increases had almost no effect on him. He acknowledged his own monthly fuel bill of around £60 and noted the rising trend, while emphasizing, "for me, fuel prices have almost no effect, but I know for many people, rising energy prices are devastating." This statement highlights the stark disparity in fuel price sensitivity between affluent and low-income households.

Table 5. Fuel poverty characteristics of housing cases.

	Case 1	**Case 2**	**Case 3**	**Case 4**
Primary energy indicator (EPC) (kWh/m^2/year)	27	18	122	109
Heating demand (Openstudio) (kWh/m^2/year)	45.67	23	17.25	28.34
Monthly average energy bill (£)	Approximately £60 per month (wood biomass spending unclear)	Approximately £80 per month	Up to £50	Approximately £270 per month (wood biomass spending unclear)
Floor area (m^2)	111	432 (4 studios)	270 (3 units)	170
Total floor	2	2	2	1
Construction cost total price (£)	185,000	500,000	518,000	285,000
Energy system costs (£) (estimates)	13,000	52,800	32,400	24,500
Energy system investment pressure	None	None (the maintenance costs are borne by the tenants)	None (assuming responsibility by the trust)	Yes
Energy use behaviour	Strong energy-saving awareness	Weak energy-saving awareness	Rising energy-saving awareness and backed by ultra-high energy efficiency	Higher awareness of energy saving
Potential FP	None	Almost no	None	Potential risk

Household structure is another key internal factor affecting fuel vulnerability. Single-person households have inherently lower energy need compared to families, as they require less living space and have fewer people with concurrent energy needs. Case 2 provides direct evidence for this observation. Case 2's resident, with stable finances, reported winter energy costs of £120 to £140 per month for a single room. In contrast, other family residents in the same co-housing project had to limit energy use to control costs, such as "avoiding heating or minimizing how often they wash dishes" and keeping room temperatures at 18 °C, which they found uncomfortably cold. This indicates that the inherently lower energy need of single-person settings still reduces overall fuel burden compared to households with children.

Energy use behaviour is the third internal factor, and its impact is largely moderated by the high energy efficiency of the dwellings and reasonable housing area. High-efficiency

homes provide a certain degree of tolerance for residents' energy use behaviour, meaning that even suboptimal energy practices do not lead to excessive fuel consumption. Case 2 exemplifies this point: its residents had weak energy-saving awareness, with some distrusting new technologies such as shutting down the MVHR system and relying on natural ventilation. However, the high energy efficiency of the co-housing project prevented these behaviours from resulting in prohibitively high fuel bills, though they still contributed to unnecessary energy consumption.

External factors include housing area, housing energy efficiency, and energy prices and their trends, which operate at the macro level and interact with internal factors to shape fuel poverty's complexity and uncertainty. Housing area is a fundamental external factor because objective energy consumption is the product of energy efficiency and housing area. Even with high energy efficiency, a large housing area can lead to substantial energy consumption. Case 4 illustrates this clearly: the house has commendable energy efficiency; however, its 170 m^2 area, combined with other factors, results in high fuel bills.

Although high energy efficiency has made the gap manageable, there are still varying degrees of differences in high-efficiency cases, and they have had certain impacts on energy expenditures. A comparison between Case 3 and 4 demonstrates this variation. Case 3 is a Passivhaus, while Case 4 has an EPC-B rating. With similar household structures (young couples with children), Case 3's housing area is only half of Case 4's, but its monthly fuel bill of £50 is merely one-fifth of Case 4's £270. This gap is even more pronounced when considering that Case 4's bill excludes supplementary fuel costs such as chips for the wood-burning stove. A key distinction between the two cases lies in their ownership and investment models: Case 3 is social housing, with costs related to high-efficiency measures borne by external investors and no rent increases passed on to tenants. In contrast, Case 4 is private housing, and the household's limited budget prevented them from achieving Passivhaus standards, their architect recommended an "80 or 90% passive" compromise to balance efficiency and cost, as full Passivhaus compliance was impractical financially.

Energy prices and their trends are the most uncontrollable and negatively impactful external factor. Scotland's energy prices have increased by approximately 80% since 2020 [36], and this upward trend has exacerbated fuel vulnerability, particularly for households like Case 4. Case 4's fuel bill has risen nearly 300% from £80 per month five years ago to £270 currently, excluding supplementary fuel costs. Despite the dwelling's high energy efficiency, its large area and growing household size have amplified the adverse effects of rising energy prices. The household's proactive plans to install turbines and solar panels are not only environmentally motivated but also economically driven, as they seek to shield themselves from future energy price volatility. This reflects how rising energy prices, as an external shock, interact with internal factors (household size) and other external factors (housing area) to increase fuel uncertainty. Despite strong energy-saving awareness and equipment use, external constraints leave the household feeling powerless.

Collectively, these cases confirm that fuel poverty's complexity stems from the nonlinear interaction of internal household attributes and external systemic conditions. No single factor operates in isolation, and their dynamic interplay generates uncertainty that complicates fuel poverty mitigation.

3.2.3. Energy Conservation and Emission Reduction Become Contradictory Rather than Unified in Housing Investment with a Limited Budget

We have reason to believe that as the professionalism of practitioners improves, the performance of fabrics can be significantly improved at a reasonable cost [37]. However, if improving the energy efficiency of fabrics can reduce energy consumption and thus reduce carbon emissions, then the choice of heating system is entirely a balance between cost and emissions, and this expenditure needs to be borne by every stakeholder. An inevitable

question is, how much do people need to pay to reduce emissions? First, a comparison is conducted to examine the differences in annual carbon emissions and fuel costs among different heating fuels for a typical two-bedroom semi-detached house in Scotland, with mains natural gas as the benchmark. The heating demands for a typical two-bedroom house were taken from the Scottish Household Energy Calculator and were calculated at 11,700 kWh per year, while the various energy types and their prices were referenced from multiple sources [32,38–40]. The efficiency of ASHP is calculated as 300% electrical thermal efficiency, and the efficiency of GSHP is calculated as 400%. Heating efficiencies refer to the different heating systems in Table 4 of SAP 10.2, with the housing default being built after 1998 [38]. Current high-efficiency boilers are more efficient at heating than those listed in SAP, for example biomass gasification boilers can be up to 90% efficient. Because around 85% of Scotland's electricity was renewable in 2023, its carbon emissions will be far lower than those in the rest of the UK. The Scottish electricity carbon emission factors in the table are from the 2023 report [38]. Carbon emission data and fuel unit prices are from the latest Ofgem's Price Cap, valid from 1 July 2023 [32]. Energy consumption for heating a typical house (including space heat and water heat) uses data from the Fuel Cost Calculator [39] for a two-bedroom semi-detached house.

$$\text{Annual fuel use} = \text{Annual heat demand} / \text{Heating system thermal efficiency}$$

$$\text{Annual } CO_2 \text{ emission} = \text{Annual fuel use} \times CO_2 \text{ emission factor}$$

$$\text{Annual fuel cost} = \text{Annual fuel use} \times \text{Unite price}$$

According to Figure 5, the following conclusions can be drawn:

- Natural gas is the most economical fossil fuel with the lowest CO_2 emissions, while coal is the least advantageous fuel due to its low efficiency, high carbon emission factor and expensive price.
- Using natural gas as a reference, both LPG (Bulk) and heating oil are competitive to a certain extent, and efficiency will be further improved with the upgrade of boilers.
- The UK standard electricity carbon emission factor is almost the same as natural gas. However, its cost of nearly three times that of natural gas makes electric heating uncompetitive.
- Electric heating in Scotland is different from other parts of the UK. Due to Scotland's ultra-high proportion of low-carbon electricity supply, electric heating systems have the advantage of low carbon emissions compared to the gas grid, but the cost is still not as advantageous or even higher.
- Even at only 70% efficiency, wood biomass still has the triple advantages of fuel price, low carbon emissions, and suitability for off-grid households.
- Both ASHPs and GSHPs are driven by electricity, and their carbon emissions are dependent on power sources. Heat pumps rely on their high coefficient of performance (COP) to achieve electric heating at an affordable price.

For rural Scotland, a decarbonised mains gas grid is the best option for individuals without increasing fuel costs, while relatively advantageous alternative energy sources such as LPG, heating oil and biomass will be completely banned due to the new policy. One problem is that pure fuel price advantages or carbon emission advantages are still not enough to define the advantages and disadvantages of heating energy. One main reason is that there is a significant gap in the investment costs of equipment corresponding to different fuels. High-efficiency boilers or pumps can significantly improve fuel utilization, but the price will also increase. Table 6 summarizes common fuel equipment and price ranges (including installation fees and excluding installation fees).

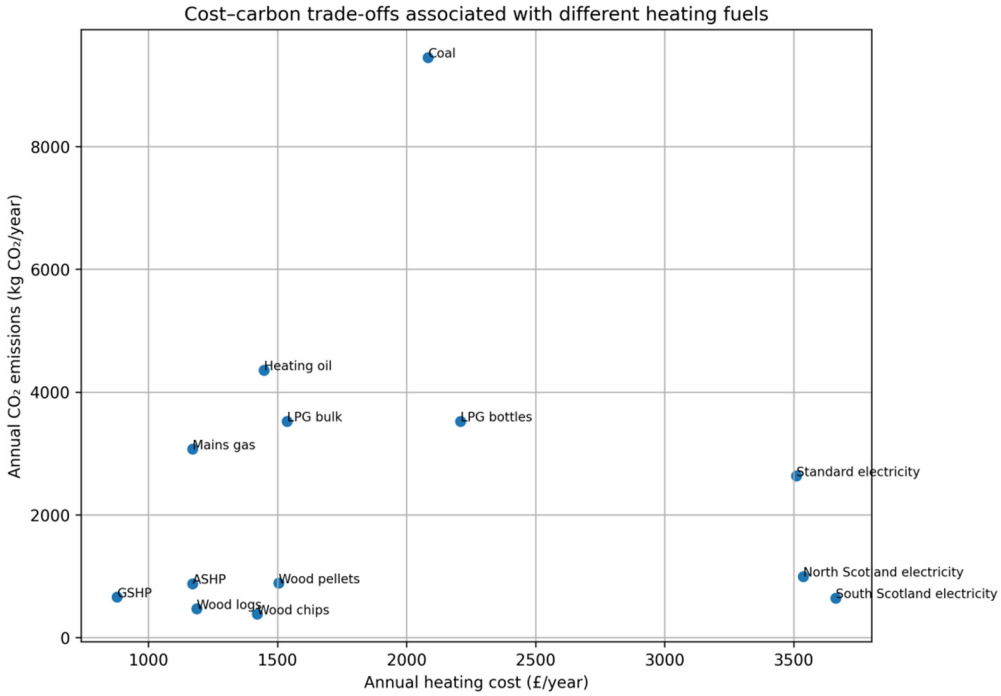


Figure 5. The comparison between different fuel types for heating a two-bedroom semi-detached house.

Table 6. The cost of different boilers and pumps (£).

	Gas (Efficiency from 90 to 94%)		Oil (Efficiency from 87 to 97%)		Electric (99.8%)	
	Exc. Installation *	**Inc. Installation ***	**Exc. Installation ***	**Inc. Installation ***	**Exc. Installation ***	**Inc. Installation ***
Combi	500–2000	1500–3500	1900–3700	3200–5500	1150–2370	1950–3670
System boiler	500–2500	1700–3600	1100–3180	2400–4980	600–2000	1400–3300
Regular boiler	500–3500	1700–3000	1300–2700	2600–4450	500–900	1300–2200
		Exc. Installation			Inc. Installation	
Biomass boiler		7000–15,000			10,000–18,000	
ASHP		7000–13,000			8000–18,000	
GSHP (vertical)		17,000–30,000			19,000–45,000	
GSHP (horizontal)		More than 30,000			More than 45,000	

* For rural area, according to the new Home Energy Scotland Grant and Loan scheme, up to 75% of the combined cost of the improvements and up to the maximum grant amount of £9000 can be involved for supporting heat pump installation.

Combining Figure 5 and Table 6 for analysis, just from a price point of view, natural gas boilers are cheaper compared to other boilers, as well as cheaper than fuel; however, for homes that are not connected to the gas grid, they are useless. Oil or LPG and their boilers are options that can cost almost 20 percent more. Electric boilers are not economical due to the three times higher running costs compared to natural gas.

Biomass boilers entail an initial cost premium of £6400–£16,500 compared to gas boilers. While fuel costs may appear similar, biomass boilers are better suited for off-grid homes, boasting extended lifespans and more cost-effective long-term fuel expenses than oil boilers, which are also suitable for off-grid residences. ASHPs and biomass boilers have similar purchase and installation costs, and the long-term fuel costs for both are not dissimilar; although biomass will be banned, subsidies for ASHPs will enable low-cost replacement. Biomass is suitable for homes with storage space, whereas ASHPs can be compactly installed, but they rely on electricity. Also, biomass boilers are suitable for older buildings with weak insulation, whereas ASHPs are best suitable for airtight buildings. The upfront cost of a GSHP is nearly 10,000–27,000 pounds higher than that of an ASHP, and it requires a wide outdoor space.

If only looking at emissions, then RE heating systems must be competitive. The focus here is on the rates at which households pay for the carbon emissions of different heating systems. Since other fossil fuels have no advantages over natural gas in terms of fuel price and carbon emissions, fossil fuels are excluded here, and electric heating and renewable fuel heating systems are reviewed using natural gas as the benchmark. According to the lifespan of different fuel equipment, taking 20 years as a cycle, it is assumed that gas boilers and electric boilers will need to be purchased twice during the cycle, while RE-type boilers or pumps will only need to be purchased once. A rough measure of the cost of different heating systems for carbon is given by (20-year difference in fuel costs compared to mains gas + difference in boiler or pump costs compared to gas boiler)/20-year difference in carbon emissions (£/tonne). Table 7 can be obtained from the previous data.

Table 7. The cost of different heating systems for carbon—using natural gas as the benchmark *.

	Electricity (The UK Average Standard)	Electricity (North Scotland Standard)	Electricity (South Scotland Standard)	Biomass (Wood Pellets)	ASHP (Scotland Power)	GSHP (Scotland Power)
20 years CO_2 Emissions difference (tonne)	1.95	34.71	41.73	40.82	37.05	41.44
20 years bill difference (£)	−49,400	−52,465.4	−49,938.2	−2600	−2600	3250
Cost of boiler or pump for reducing emissions (£)	20	20	20	−9373.4	−8373.4	−27,373.4
Carbon value (£/tonne/20 years)	−25,323.07	−1510.96	−1196.22	−293.32	−296.17	−582.13

* Gas boiler and biomass boiler efficiency calculated as 90%. The total cost of a boiler or heat pump is calculated as an average (gas boiler: 2313.3; electricity boiler: 2303.3; biomass boiler: 14,000; ASHP: 13,000; GSHP: 32,000).

Finally, a conclusion was drawn based on region, fuel price, carbon emissions and equipment price:

- Electric boiler heating systems outside Scotland will pay for emission reductions nearly 17 times more than in the north of Scotland and nearly 21 times more than in the south of Scotland. There is therefore reason to believe that areas of the UK outside of Scotland are not suitable for electric heating, and that the development of low-carbon electricity in Scotland will play an important role in decarbonizing the future heating system.
- Compared with other low-carbon heating systems, even high-efficiency electric heating in Scotland is not economical. Its carbon reduction cost per ton is about 2–3 times that of GSHP, and 4–5 times that of biomass boilers and ASHP.
- Although GSHPs have the lowest operating costs, their prohibitive installation costs and the additional conditions of outdoor space prevent them from being a priority. While the funds can provide some subsidies to vulnerable groups, the remaining loans may be one to two years' income for many families in remote rural areas.
- Biomass originally had the same advantages as ASHP. However, with the ban on biomass and subsidies for ASHP, ASHP has become the most advantageous heating system under the premise of meeting the conditions of use, especially for households that cannot be connected to the main gas network or heat network.

Back to the cases, the lack of mains gas restricts heating fuel decarbonization options to more expensive alternatives, with costs borne entirely by housing investors (Figure 6). A sufficient budget (Case 1) enables the coordination of environmental goals and economic feasibility, forming a unified relationship, as evidenced by the resident's forward-thinking perspective on energy efficiency: "I thought at some point put in a heat pump, . . . that's the best solution in the future." This willingness to invest in further emission reduction

measures underscores how financial stability fosters the unity of energy and economic goals. However, when the budget is constrained (Cases 2, 3, 4), the pursuit of energy conservation and emission reduction faces unavoidable trade-offs (see Figure 5): for social house, investors must choose between building a small number of ultra-high-efficiency dwellings or reducing energy consumption for more households, as explicitly noted in Case 3: "Because you can build more houses for the same money if they are not Passive houses." Additionally, attempts to balance building fabric efficiency and energy system sustainability (Cases 1, 3, 4) often lead to increased energy consumption or higher infrastructure costs, which are either absorbed by investors or passed on to tenants, as seen in Case 2 where residents bear infrastructure maintenance costs: "Any infrastructure repairs, such as replacing a pump, must be paid for by the residents." For Case 4, the balance fails to offset cost pressures from expensive non-mains gas heating fuels and rising energy prices, leaving the household frustrated: "It's not what we wanted, much more expensive than we imagined. I don't really know what to do about that." This contradiction arises from the inherent cost of high-efficiency technologies, the limited and costly heating alternatives in rural areas without mains gas, and the unavoidable trade-offs under budget constraints, all of which prevent the effective absorption of costs and lead to the breakdown of the unity between energy conservation, emission reduction, and practical feasibility. The integration of residents' firsthand accounts further reinforces this conclusion, as their lived experiences directly illustrate the tension between environmental aspirations and financial constraints.

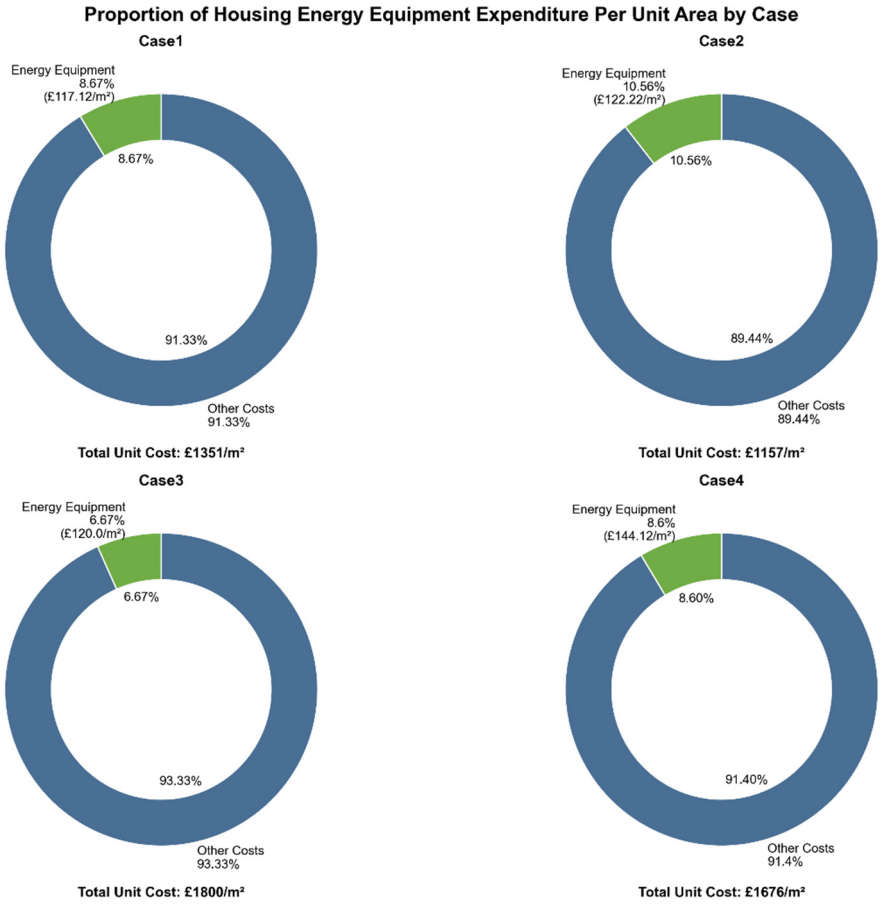


Figure 6. Proportion of housing energy equipment expenditure per unit area across four case studies. These charts show the breakdown of total unit cost (£/m^2) into two categories: energy equipment costs (green) and other construction costs (blue), for each case study. The absolute cost of energy equipment and the total unit cost are annotated, highlighting the relative financial contribution of energy-related systems to the overall dwelling cost.

4. Discussion

This section presents theoretical interpretations of findings derived from four rural housing case studies. This research adopts a multiple case study methodology [41], focusing on analytical generalization rather than statistical representativeness. The conclusions are context-specific and not universally applicable. That said, the identified mechanisms and insights are transferable to rural settlements with similar conditions across Scotland and other comparable regions. Building on the above clarification, this section firstly unpacks the systemic drivers of the high-efficiency paradox identified in the field investigation, then derives theory-based implications for rural low-carbon housing transitions.

4.1. Systemic Mechanisms Behind the High-Efficiency Paradox

The high-efficiency paradox refers to a prevalent phenomenon in the studied rural contexts: improvements in building thermal performance do not necessarily reduce overall energy risks or alleviate fuel poverty. A complete logical framework is established below to interpret its multi-layered root causes.

4.1.1. Increasing Efficiency May Intensify Socio-Technical Dependency

Conventional narratives often assume that improvements in building efficiency enhance household energy autonomy. However, the findings suggest the opposite tendency in rural Scotland.

Modern high-efficiency dwellings are equipped with sophisticated mechanical services, electric heating and integrated renewable systems, which create strong socio-technical dependency on public power grids and complete energy supply networks. Their performance therefore depends not only on building fabric quality but also on external conditions such as grid reliability, energy prices and institutional support mechanisms. Electric-driven high-performance housings become vulnerable when the grid capacity is limited and there are power outages caused by extreme weather conditions. Households lose the flexibility to switch to alternative fuels during supply disruptions. Meanwhile, remote communities are faced with persistently high electricity tariffs, making fully electrified dwellings more susceptible to price fluctuations.

The findings suggest that energy efficiency improvements do not automatically translate into lower energy risks. This observation extends previous studies on the spatial unevenness of energy transitions and the temporal complexity of low-carbon transitions [17,42,43]. While previous research has highlighted infrastructural inequalities, the present study suggests that highly efficient dwellings may paradoxically become more dependent on external infrastructures than conventional homes. Under certain socio-economic and infrastructural conditions, increasing technological sophistication may expose households to new forms of vulnerability, creating what can be described as a high-efficiency paradox. In this sense, reductions in heating demand do not necessarily imply improvements in affordability, resilience or fuel poverty outcomes.

4.1.2. Urban-Centric, Metric Lock-In of Performance Gaps

The current mainstream energy assessment methods overly focus on the thermal performance per square meter, while the significant impact of per capita living area is often overlooked. This structural bias is precisely the core of "indicators locking". This problem is widespread and is influenced by industry standard assessment tools (such as EPC and SAP). These frameworks were originally designed for urban operation scenarios, with heating load and unit area energy consumption as the core indicators, but failed to consider the per capita space indicator. Previous studies have shown that residential energy usage is far more affected by house area and household characteristics than thermal performance [33].

The case of this study further indicates that there is a trade-off between scale and efficiency in high-performance rural housing. Excessive per capita building area continuously offsets the energy-saving benefits brought by high-performance building envelopes, yet this crucial spatial factor is rarely formally included in performance assessment. Guided by such institutional assessment rules, designers tend to optimize residences to meet single-indicator requirements rather than pursuing comprehensive performance that adapts to rural actual conditions [44].

4.1.3. Path Dependency in Rural Scottish Energy and Housing Models

The case evidence indicates that the studied rural communities show noticeable path dependency, which can also be observed across many rural areas of Scotland, manifested in both long-standing energy use patterns and established residential living habits. Local households in the cases have historically relied on biomass and fossil fuels for heating, forming entrenched energy routines that pose challenges to rapid shifts toward full electrification promoted by national low-carbon policies.

Beyond energy systems, occupants in the investigated dwellings have grown accustomed to traditional housing operation modes. Conventional rural homes typically use operable windows for natural ventilation and indoor thermal regulation. In contrast, modern high-efficiency buildings feature airtight envelopes and mechanical ventilation as standard design solutions. Within the cases, this transition from natural window ventilation to mechanical systems has led to perceived discomfort and difficulties in adapting to new operational routines among residents. Combined with long-standing energy practices, these two forms of path dependency help explain local carbon lock-in and associated energy risks seen in the research sites.

4.2. Effective Paths to Mitigate Energy Risks of High-Efficiency Dwellings in Rural Scotland

A core research question of this study is to identify effective, contextually appropriate paths to mitigate the energy risks of high-efficiency dwellings in rural Scotland. Drawing directly from the empirical findings of the four case studies and the systemic mechanisms of risk formation identified above, the following paths are proposed: all tailored to the unique geographic, infrastructural, socio-economic, and policy context of rural Scotland, with feasibility grounded in the study's empirical evidence and existing Scottish policy and institutional frameworks.

4.2.1. Optimizing Rural Energy Systems and Improving Design–Infrastructure Compatibility

The findings suggest that reducing heating demand alone is insufficient to ensure lower operational carbon emissions or improved affordability. Instead, future high-efficiency dwellings should seek to simultaneously balance thermal performance, carbon reduction and energy costs through resilient and context-sensitive system design.

From an architectural perspective, passive design strategies should remain the priority. Compact building forms, appropriate orientation, optimized window-to-wall ratios, thermal zoning, and zone-controlled heating systems can reduce heating loads while limiting the increase in total primary energy demand associated with large per capita floor areas. Such sufficiency-oriented design strategies help alleviate the size–efficiency trade-off identified in Section 4.1.2.

From an engineering perspective, increasing system diversity appears to be more effective than maximizing efficiency through a single technology. The case studies indicate that reliance on a single energy source may increase vulnerability to power outages and price fluctuations. Consequently, multi-source complementary energy systems, such as ASHP combined with biomass stoves, solar thermal systems, photovoltaic panels with battery

storage, or hybrid electric–biomass configurations, may improve energy resilience and reduce exposure to infrastructure failures. Such redundancy-based approaches are consistent with resilience-oriented energy system design and may help mitigate the dependency paradox discussed in Section 4.1.1.

Therefore, rather than pursuing maximum efficiency alone, future high-efficiency dwellings should seek to align heating demand reduction, operational carbon emissions and affordability through integrated architectural and engineering strategies.

4.2.2. Refine Low-Carbon Policies Through Place-Sensitive and Flexible Transitions

The findings suggest that rural low-carbon transitions should move beyond uniform and technology-centred approaches towards place-sensitive and adaptive policy frameworks.

Although the electrification of heating is essential for achieving net-zero targets, abrupt replacement of biomass or fossil-fuel systems with ASHPs may unintentionally increase fuel poverty risks in low-income rural households where electricity prices are high and infrastructure remains inadequate. Therefore, transitional flexibility may be particularly important in rural contexts.

Rather than adopting a single transition pathway, a phased approach may offer greater social and economic feasibility. In the short term, sustainably sourced biomass and hybrid heating systems may continue to provide affordable and resilient heating solutions for remote communities. In the medium term, hybrid systems integrating ASHPs with secondary biomass or thermal storage systems may facilitate gradual decarbonisation while reducing affordability risks. Full electrification may become more appropriate in the long term as grid capacity, renewable generation and energy storage technologies continue to improve.

4.2.3. Addressing the High-Efficiency Paradox Through Socio-Economic and Spatial Considerations

The present findings suggest that high-efficiency dwellings do not automatically eliminate fuel poverty or energy vulnerability. This supports the argument that fuel poverty should be understood as a socio-technical phenomenon rather than a purely technical problem. To address the high-efficiency paradox and fuel poverty risks, targeted measures are needed to alleviate the socio-economic barriers that prevent rural Scottish households from accessing and benefiting from high-efficiency dwellings. First, provide targeted fuel cost subsidies for low-income rural families in high-efficiency private dwellings, ensuring energy affordability. Second, promote affordable high-efficiency rural housing in rural Scotland (with optimized per capita floor area) through planning concessions and capital grants, and capping rent increases for rural social high-efficiency dwellings to ensure low-income households can access the energy savings of these homes. Third, provide rural household energy literacy training: offering free workshops on the operation of high-efficiency systems and energy-saving behaviours, addressing the performance gap caused by low user familiarity with high-efficiency technology.

4.2.4. Establish a Comprehensive and Adaptive Decision-Support Framework

To eliminate the structural flaws caused using a single indicator, a comprehensive and performance-based assessment system for efficient residences in rural areas should be established. This will replace the excessive reliance on energy efficiency certificates with a multi-criteria framework that encompasses social equity, the environment, and economic justice. The core indicators of this system should include: primary energy consumption (kWh/m^2 and $kWh/m^2/person$), operational carbon emissions ($kgCO_2/m^2$ and $kgCO_2/m^2/person$), fuel poverty resilience (to reflect the risk of fuel poverty caused by rising energy prices), energy system resilience (the number of energy sources), and the carbon footprint of key materials. Such approaches would be particularly valuable in

situations where stakeholders' ethical aspirations, for example, preferences for natural materials or local construction traditions, conflict with technical or economic considerations. Multi-criteria decision analysis (MCDA) may therefore offer a more transparent and adaptive basis for balancing competing objectives.

This system should be applicable to all new efficient rural residences in Scotland, and the design guidelines should be updated to prioritize comprehensive performance rather than the optimization of a single indicator, ensuring that efficient residences in rural Scotland are designed for actual energy performance and sustainability.

5. Conclusions

This study conducted a mixed-method Post-Occupancy Evaluation on four high-efficiency dwellings in rural Scotland to explore energy risks, their formation mechanisms and mitigation strategies from environmental and socio-economic perspectives. The results verify the high-efficiency paradox: enhanced building fabric performance and reduced space-heating demand cannot guarantee lower operational carbon emissions, energy costs or better energy resilience. Actual household energy risks are jointly determined by dwelling size, energy infrastructure, household attributes, energy prices and local policies.

The study further reveals that excessive reliance on single performance indicators may lead to misleading assessments of housing sustainability. Heating demand, total energy use, operational carbon emissions and affordability are interconnected but partially decoupled dimensions, mediated by factors such as energy sources, household composition and socio-technical dependencies. The findings suggest that improving rural housing sustainability requires a shift from technology-centred approaches towards more integrated strategies that simultaneously consider architectural design, energy infrastructure, affordability and energy resilience. Rather than pursuing maximum efficiency alone, future low-carbon housing transitions should seek a more balanced relationship among environmental performance, economic feasibility and social equity.

Based on the empirical findings, this study proposes a holistic and adaptive evaluation framework that combines environmental, economic and social dimensions. The framework incorporates multiple indicators, including heating demand, energy consumption, operational carbon emissions, fuel poverty resilience and energy system resilience. Although such a framework would require further methodological development and policy support before large-scale implementation, many of its constituent indicators are already available through existing assessment systems, EPC databases and Post-Occupancy Evaluation methods. Therefore, the proposed framework should be regarded as an evolutionary extension of current assessment practices rather than a complete replacement of existing standards, offering a potentially feasible direction for improving the evaluation and design of rural high-efficiency housing.

Several limitations are noted. First, as a multiple case study, the findings are context-specific to rural Scotland and cannot be universally generalised. The identified mechanisms are therefore context-specific and should not be interpreted as universally applicable to all rural regions. Second, although the study integrates quantitative performance indicators and qualitative interviews, psychological adaptation processes and perceptual responses related to thermal comfort were not explicitly incorporated into the analytical framework. In particular, the interactions between occupant perceptions, behavioural adaptation and energy use remain insufficiently understood. Future studies may benefit from integrating occupant-centred thermal comfort models and psychological coefficients into building performance assessments to further explore how subjective factors influence energy use and carbon outcomes. Third, conclusions on rural energy systems and decarbonisation pathways carry inherent uncertainties due to evolving technologies, energy prices and

policies. The proposed mitigation measures are only context-adaptive directions rather than universal solutions.

Despite these limitations, the present study contributes to a more comprehensive understanding of the relationship between high-efficiency housing and sustainability in rural Scotland. By demonstrating that lower heating demand does not necessarily guarantee lower carbon emissions, reduced fuel poverty risks or greater resilience, the study highlights the need to move beyond efficiency-centred narratives and towards more context-sensitive, socially informed and system-oriented approaches to rural low-carbon housing transitions.

Author Contributions: Conceptualization, W.F.; methodology, W.F. and J.B.; investigation, W.F.; formal analysis, W.F.; data curation, W.F.; writing—original draft preparation, W.F.; writing—review and editing, J.B.; supervision, J.B.; project administration, W.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The datasets used and/or analysed during the current study are available on request from the corresponding author due to privacy and confidentiality restrictions.

Acknowledgments: I would like to express my sincere gratitude to my doctoral supervisors, John Brennan and Simone Ferracina, for their invaluable guidance and constant support throughout the research and writing of this article. Their professional insights and patient advice have been instrumental in the completion of this work.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Harris, P.G. COP26: The Eternally Weak Pulse of Climate Diplomacy, and What Needs to Change. *PLoS Clim.* **2022**, *1*, e0000019. [CrossRef]
2. Scottish Government. *Rural Scotland: Key Facts 2021*; Scottish Government: Edinburgh, UK, 2021. Available online: https://www.gov.scot/publications/rural-scotland-key-facts-2021/pages/2/ (accessed on 1 October 2023).
3. Kelly, S.; Crawford-Brown, D.; Pollitt, M.G. Building Performance Evaluation and Certification in the UK: Is SAP Fit for Purpose? *Renew. Sustain. Energy Rev.* **2012**, *16*, 6861–6878. [CrossRef]
4. Caird, J.B. The Making of the Scottish Rural Landscape. *Scott. Geogr. Mag.* **1964**, *80*, 72–80. [CrossRef]
5. Valley, M. *Geology of Scotland*; Oliver and Boyd: Edinburgh, UK, 1929.
6. Martyn. The Climatology of Scotland—Four Seasons in One Day? Scottish Flood Forecasting Service. Available online: https://floodforecastingservice.net/2015/05/11/the-climatology-of-scotland-four-seasons-in-one-day/ (accessed on 28 October 2025).
7. Foster, J.; Sharpe, T.; Poston, A.; Morgan, C.; Musau, F. Scottish Passive House: Insights into Environmental Conditions in Monitored Passive Houses. *Sustainability* **2016**, *8*, 412. [CrossRef]
8. Baker, K.J.; Mould, R.; Stewart, F.; Restrick, S.; Melone, H.; Atterson, B. Never Try and Face the Journey Alone: Exploring the Face-to-Face Advocacy Needs of Fuel Poor Householders in the United Kingdom. *Energy Res. Soc. Sci.* **2019**, *51*, 210–219.
9. Rennie, F.; Billing, S.-L. Changing community perceptions of sustainable rural development in Scotland. *J. Rural Community Dev.* **2015**, *10*, 35–46.
10. Serin, B.; Kintrea, K.; Gibb, K. *Social Housing in Scotland*; UK Collaborative Centre For Housing Evidence: Glasgow, UK, 2018. [CrossRef]
11. Wood, G.; Baker, K. (Eds.) *A Critical Review of Scottish Renewable and Low Carbon Energy Policy*; Springer International Publishing: Cham, Switzerland, 2017. [CrossRef]
12. Scottish Government. *Delivering Net Zero for Scotland's Buildings—Heat in Buildings Bill: Consultation*; Scottish Government: Edinburgh, UK, 2023. Available online: https://www.gov.scot/publications/delivering-net-zero-scotlands-buildings-consultation-proposals-heat-buildings-bill/pages/5/ (accessed on 25 September 2024).
13. Scottish Natural Heritage. *Annual Report and Accounts 2019/20*; Scottish Natural Heritage: Edinburgh, UK, 2020. Available online: https://www.nature.scot/sites/default/files/2023-07/Annual%20Report%20and%20Accounts%20-%202019-20.pdf (accessed on 27 May 2021).

14. Scottish Government. *Heat in Buildings Strategy—Achieving Net Zero Emissions in Scotland's Buildings*; Scottish Government: Edinburgh, UK, 2021. Available online: https://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings/pages/2/ (accessed on 24 August 2022).
15. Billy, B. Scottish and UK Governments Have No Records on Commercial Peat Digging. Available online: https://theferret.scot/peat-digging-records/ (accessed on 9 May 2024).
16. Scottish Energy Statistics Hub. Scottish Energy Statistics, 2021. Available online: https://scotland.shinyapps.io/Energy/?Section=WholeSystem&Chart=EnConsumption (accessed on 13 September 2023).
17. Bridge, G.; Bouzarovski, S.; Bradshaw, M.; Eyre, N. Geographies of Energy Transition: Space, Place and the Low-Carbon Economy. *Energy Policy* **2013**, *53*, 331–340. [CrossRef]
18. Scottish Government. *Scottish House Condition Survey: 2022 Key Findings*; Scottish Government: Edinburgh, UK, 2023. Available online: https://www.gov.scot/publications/scottish-house-condition-survey-2022-key-findings/ (accessed on 22 May 2024).
19. Markantoni, M.; Woolvin, M. The Role of Rural Communities in the Transition to a Low-Carbon Scotland: A Review. *Local Environ.* **2015**, *20*, 202–219. [CrossRef]
20. Curl, A.; Kearns, A. Housing Improvements, Fuel Payment Difficulties and Mental Health in Deprived Communities. *Int. J. Hous. Policy* **2017**, *17*, 417–443. [CrossRef]
21. McCullough, K.L. Resolving the 'Highland Problem': The Highlands and Islands of Scotland and the European Union. *Local Econ. J. Local Econ. Policy Unit* **2018**, *33*, 421–437. [CrossRef]
22. Mould, R.; Baker, K.; Emmanuel, R. Behind the definition of fuel poverty: Understanding differences between the fuel spend of rural and urban homes. *Queen's Political Rev.* **2014**, *2*, 7–24.
23. The National. Cost of Living Crisis Means Higher Energy Bills for Rural Scotland. 2023. Available online: https://www.thenational.scot/news/23353644.cost-living-crisis-means-higher-energy-bills-rural-scotland/ (accessed on 20 September 2023).
24. Big Issue. What's It Like Living in Rural Scotland During the Cost of Living Crisis? Available online: https://www.bigissue.com/news/social-justice/rural-communities-scotland-suffering-cost-of-living-crisis/ (accessed on 20 September 2023).
25. Mould, R.; Baker, K.J. Uncovering Hidden Geographies and Socio-Economic Influences on Fuel Poverty Using Household Fuel Spend Data: A Meso-Scale Study in Scotland. *Indoor Built Environ.* **2017**, *26*, 914–936. [CrossRef]
26. Bryan, A.; Ellen, J.; Hirsch, D.; Padley, M. *The Cost of Remoteness: Reflecting Higher Living Costs in Remote Rural Scotland When Measuring Fuel Poverty: 2022 Update*; Centre for Research in Social Policy Loughborough University: Leicestershire, UK, 2024.
27. Scottish Government. *New Build Heat Standard: Factsheet*; Scottish Government: Edinburgh, UK, 2024. Available online: https://www.gov.scot/publications/new-build-heat-standard-factsheet/ (accessed on 13 April 2024).
28. Organ, S. Minimum Energy Efficiency—Is the Energy Performance Certificate a Suitable Foundation? *Int. J. Build. Pathol. Adapt.* **2021**, *39*, 581–601. [CrossRef]
29. Torcellini, P.; Pless, S.; Deru, M.; Crawley, D. *Zero Energy Buildings: A Critical Look at the Definition*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2006. Available online: https://www.osti.gov/biblio/883663 (accessed on 3 November 2025).
30. Rosenow, J.; Lowes, R.; Broad, O.; Hawker, G.; Wu, J.; Qadrdan, M.; Gross, R. *The Pathway to Net Zero Heating in the UK*; UK Energy Research Centre (UKERC): London, UK, 2020.
31. Dowson, M.; Poole, A.; Harrison, D.; Susman, G. Domestic UK Retrofit Challenge: Barriers, Incentives and Current Performance Leading into the Green Deal. *Energy Policy* **2012**, *50*, 294–305. [CrossRef]
32. Energy Saving Trust. *Renewable Heat in Scotland, 2020 [Report]*; Energy Saving Trust: London, UK, 2021. Available online: https://energysavingtrust.org.uk/report/renewable-heat-in-scotland-2020/ (accessed on 25 September 2024).
33. Estiri, H. A Structural Equation Model of Energy Consumption in the United States: Untangling the Complexity of per-Capita Residential Energy Use. *Energy Res. Soc. Sci.* **2015**, *6*, 109–120. [CrossRef]
34. McCord, M.; Haran, M.; Davis, P.; McCord, J. Energy Performance Certificates and House Prices: A Quantile Regression Approach. *J. Eur. Real Estate Res.* **2020**, *13*, 409–434. [CrossRef]
35. Guy, S.; Farmer, G. Reinterpreting Sustainable Architecture: The Place of Technology. *J. Archit. Educ.* **2001**, *54*, 140–148. [CrossRef]
36. AgileBuddy. Octopus Electricity Tracker. Available online: https://agilebuddy.uk/historic/tracker/electricity/2018?utm_source=chatgpt.com (accessed on 27 July 2025).
37. Burford, N.; Pearson, A. Ultra-low-energy perspectives for regional Scottish dwellings. *Intell. Build. Int.* **2013**, *5*, 221–250. [CrossRef]
38. Scottish Government. The Government's Standard Assessment Procedure for Energy Rating of Dwellings; Version 10.2 (14 March 2025). Available online: https://bregroup.com/documents/d/bre-group/sap-10-2-14-03-2025/ (accessed on 18 May 2025).
39. Energy Review. Average Gas and Electricity Bill for a Two-Bed House. Available online: https://www.energy-review.co.uk/guides/average-gas-and-electricity-bill-for-a-two-bed-house/ (accessed on 18 May 2025).
40. Ofgem. Energy Price Cap Explained. Available online: https://www.ofgem.gov.uk/information-consumers/energy-advice-households/energy-price-cap-explained/ (accessed on 18 May 2025).
41. Yin, R.K. *Case Study Research: Design and Methods*, 4th ed.; SAGE Publications: Thousand Oaks, CA, USA, 2009.

42. Sharpe, T.; Morgan, C.; Shearer, D. Towards Low Carbon Homes—Measured Performance of Four Passivhaus Projects in Scotland. In *Proceedings of the EuroSun 2014 Conference*; International Solar Energy Society (ISES): Freiburg im Breisgau, Germany, 2014; pp. 1–10. [CrossRef]
43. Terry, N.; Galvin, R. How do heat demand and energy consumption change when households transition from gas boilers to heat pumps in the UK? *Energy Build.* **2023**, *292*, 113183. [CrossRef]
44. Reed, R.; Bilos, A.; Wilkinson, S.J.; Schulte, K.-W. *An International Comparison of International Sustainable Building Tools*; IDEAS Working Paper Series from RePEc; European Real Estate Society (ERES): Amsterdam, The Netherlands, 2009.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.