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Do feasibility-stage decarbonisation conclusions survive tariff and carbon-factor drift? A controlled current-data rebasing audit of four calibrated UK primary-school retrofit cases

Harshul Singhal *

University of Lancashire, Preston, Lancashire PR1 2HE, UK
Brunel University of London, Uxbridge, Middlesex UB8 3PH, UK

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ABSTRACT

Feasibility studies can remain in public-estate investment pipelines after the tariffs, emission factors and cost levels used to produce them have changed. This study develops a controlled current-data rebasing audit that first reconciles a completed feasibility dataset, then freezes its physical energy quantities and retrofit configuration while updating only explicitly identified exogenous accounting variables. The audit is applied to four anonymised 2022 primary-school retrofit cases from one UK local-authority estate. Their baseline OpenStudio/EnergyPlus models were calibrated to 12 monthly utility observations and met the ASHRAE Guideline 14 monthly NMBE and CV(RMSE) criteria, although the retained evidence package does not recover the exact calibration dates or several model-input assumptions. Under the 2022 source-report basis, the combined packages reduce reported operational CO_2 by 56.7–67.8% (case mean 62.6%), leaving a 32.2–43.3 percentage-point residual within the stated location-based accounting boundary. Rebasing the same physical quantities to the 2026 UK Government conversion factors raises the case reductions to 72.5–78.8% (mean 76.3%) and narrows the residual to 21.2–27.5%. Whole-package utility-cost comparisons are tariff-contingent: the three gas-fired cases change from 13.3 to 16.4% cost increases under the 2022 tariffs to 5.1–13.1% savings under Q1 2026 average electricity and gas tariffs, while the oil-fired case saves 33.0% when Q1 2026 electricity is paired with the retained source-case oil price of £0.085/kWh. A small-consumer-band gas test remains mixed (−0.6% to +5.4%). A separate output-level heat-system counterfactual shows why these package results must not be labelled as ASHP-only effects: at $\eta = 0.85$ and SCOP = 3.0, the current-price incremental ASHP cost remains positive for the gas cases (£4.3–10.5 thousand/yr) while the oil case saves about £1.6 thousand/yr. Recasting sequencing as cumulative emissions gives 1283 tCO_2 avoided over eight years for the carbon-led sequence, compared with 1106 tCO_2 for fabric-first and 912 tCO_2 for cost-led sequencing. The contribution is therefore a reproducible, bounded method for distinguishing durable physical conclusions from tariff-, factor- and accounting-vintage effects; it is not a statistically representative assessment of the UK school stock.

1. Introduction

The Climate Change Act 2008 (as amended in 2019) imposes a legally binding obligation on the United Kingdom to reach net-zero territorial greenhouse-gas emissions by 2050 [1], and the Committee on Climate Change has repeatedly identified the existing building stock as one of the most difficult sectors of that target [2]. Within the building stock, the public sector occupies a position of particular importance: although it is responsible for approximately 2 % of national emissions [2,3], it operates buildings that are publicly accountable, centrally funded, and procured under standardised frameworks. Of the public estate, schools constitute the largest single subset by floor area and the largest cohort of pre-1980 stock with documented fabric and services deficits [4]. Successive rounds of the Public Sector Decarbonisation Scheme (PSDS) have concentrated capital on this cohort [5], requiring local authorities to submit feasibility-led project pipelines as a precondition of grant allocation. The UK Green Building Council framework definition of operational net-zero carbon (ONZ) underpins many such pipelines [6]. In this context, school estates are not only individual buildings requiring energy upgrades, but also public built-environment assets through which local authorities translate net-zero

* Corresponding author at: University of Lancashire, Preston, Lancashire PR1 2HE, UK.
E-mail address: harshul.singhal@brunel.ac.uk.

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Nomenclature

Abbreviation

ASHP	Air-source heat pump
BEIS	Department for Business, Energy and Industrial Strategy
BMS	Building management system
BSRIA	Building Services Research and Information Association
CCL	Climate Change Levy
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CPI	Consumer Prices Index
DALI	Digital Addressable Lighting Interface
DEC	Display Energy Certificate
DESNZ	Department for Energy Security and Net Zero
DNO	Distribution network operator
EUI	Energy use intensity
GHG	Greenhouse gas
LETI	Low Energy Transformation Initiative
CAAR	Capital-to-annual-abatement ratio
ONS	Office for National Statistics
ONZ	Operational net-zero carbon
PAS 2038	Specification for retrofitting non-domestic buildings for improved energy efficiency
PSDS	Public Sector Decarbonisation Scheme
PV	Photovoltaics
QEP	Quarterly Energy Prices
RIBA	Royal Institute of British Architects
kWh/yr	Kilowatt-hours per year
kWh/m^2/year	Kilowatt-hours per square metre per year
$kgCO_2$/yr	Kilograms of carbon dioxide per year
$kgCO_2e$/kWh	Kilograms of carbon dioxide equivalent per kilowatt-hour
£/($kgCO_2$ yr^{-1})	Capital cost per unit of one year of operational CO_2 abatement
£/% CO_2	Capital cost per percentage point of operational CO_2 saved
p/kWh	Pence per kilowatt-hour
kWp	Kilowatt-peak
W/m^2K	Watts per square metre kelvin

commitments into capital programmes, procurement decisions and operational outcomes. Their retrofit therefore provides a useful test case for the wider challenge of moving from feasibility-stage carbon accounting to deliverable net-zero carbon built-environment transition planning.

School buildings are also unusually sensitive building-science environments. Their high occupancy density, scheduled use, safeguarding constraints, mixed construction ages, and dependence on low-disruption maintenance windows mean that energy retrofit cannot be assessed only as a carbon-accounting exercise. Classroom ventilation, overheating, lighting, acoustics and user control influence comfort, attendance and learning conditions, while the same interventions that reduce operational energy can change indoor environmental quality (IEQ) in beneficial or adverse ways [7–9]. Reviews and field studies have shown that poor indoor air quality, adverse thermal conditions and inadequate ventilation in schools can affect pupil performance, attention and wellbeing [7–9]. UK and European studies further show that children's comfort responses can differ from adult-based thermal-comfort assumptions, making school retrofit a distinct building-science problem rather than a simple extension of office or housing retrofit evidence [10–12]. These findings matter for decarbonisation because fabric upgrades, airtightness, heat electrification and controls can only be considered successful if they also preserve or improve the occupied educational environment. This sensitivity is also reflected in school-specific overheating and ventilation guidance [44,45].

School retrofit evidence is developing but remains fragmented across stock-level modelling, overheating and indoor-air-quality analysis, individual retrofit case studies, and wider non-domestic optimisation studies. Recent work on the English school stock shows that rollout order can materially affect cumulative emissions and interim-target performance [13], while classroom-stock modelling demonstrates interactions between energy retrofit, overheating risk and air quality [14]. Reviews of low-emission school retrofit in cool-temperate climates reinforce the need to treat fabric, services and climate adaptation as coupled decisions [15]. Case-study and building-performance evaluation work has similarly shown that educational-building retrofit must balance measured energy use, comfort, indoor-air-quality outcomes, controls and user behaviour rather than treating energy efficiency as an isolated technical output [16–18]. International studies of school and educational buildings in France, Italy, the United States and the UK further demonstrate that retrofit outcomes are highly dependent on baseline condition, occupancy, ventilation strategy, passive measures, and post-retrofit operational management [11,16,17,19]. This wider evidence base supports the need for whole-building retrofit appraisal, but comparatively little peer-reviewed analysis has examined how an industry feasibility methodology behaves when applied across a small portfolio of heterogeneous UK public buildings and then carried forward under changed tariff, carbon-factor and cost-index conditions. Whole-life carbon studies of public campus retrofits likewise reinforce the need to retain intervention and accounting-boundary provenance [22].

Four linked gaps motivate the study. First, feasibility-led project pipelines are rarely re-audited after the external variables used in their carbon and cost calculations have changed. Second, package-level outputs are often discussed as though they isolate the effect of individual technologies, particularly heat pumps, even when non-ASHP measures and photovoltaics are embedded in the same end state. Third, annual endpoint percentages obscure the cumulative carbon consequence of implementation order [13]. Fourth, small case portfolios are sometimes used to support claims about economies of scale or funding design that exceed their inferential strength. The present study addresses these gaps within a deliberately bounded four-case dataset rather than claiming national representativeness.

The temporal comparison is implemented as a controlled exogenous-input rebasing protocol. The reconciled physical energy quantities, measure configuration and source-report package outputs are held fixed; only named emission factors, tariffs and cost indices are updated [23–26]. This restriction differs from an unconstrained scenario study, which may vary physical and accounting assumptions together. It allows each conclusion to be classified as durable, reversed, narrowed or unresolved when the vintage of its external inputs changes, while also identifying the point at which a new model run is required.

The analysis draws on calibrated-simulation practice, whole-building retrofit guidance, sequencing research and abatement-cost literature [13,20,27,30,31,37]. The conventional marginal abatement cost literature is relevant as a terminological benchmark [27], but the source dataset does not contain measure lifetimes, maintenance, replacement, discounting or complete operating-cost streams. The cost metric used here is therefore explicitly limited to capital cost per unit of one year of reported operational-carbon abatement and is not presented as a lifecycle MAC. The multi-objective retrofit literature further cautions that measure allocations need not be physically additive [20]; the study consequently separates package outputs, source-report allocations and the simplified incremental ASHP counterfactual. Evidence on prebound, rebound and energy-performance gaps further cautions against treating modelled savings as automatically realised outcomes [28,29].

The study asks four questions: (1) which 2022 feasibility conclusions survive a controlled rebasing to the latest official data available at the analysis date; (2) how do whole-package utility-cost outcomes differ from an explicitly bounded incremental heat-system counterfactual; (3) how does implementation order change cumulative rather than merely endpoint carbon delivery; and (4) which findings remain robust under transparent tariff, COP, occupancy, capital-cost and grid-factor scenarios? The contribution is analytical and procedural: a reproducible audit applied to four heterogeneous schools produced by one consultancy for one client. The results characterise this case set and this feasibility methodology; they do not establish a UK-wide scaling law or national funding prescription.

2. Methodology

2.1. Research design

A multiple-case study design after Yin was adopted [32], with the building-level feasibility report as the unit of analysis. The four reports are treated as literal replications of one consultancy methodology across different buildings. This design supports analytical examination of the method and its internal consistency, not statistical generalisation to the national school estate [33].

All four reports were prepared by one engineering consultancy for one local-authority client during 2022 using a common template. Similarities between cases may therefore reflect shared modelling, costing and reporting conventions as well as building characteristics. Every cross-case claim is consequently framed as an observation within this controlled case set, and the distinction between case-set evidence and wider transferability is retained throughout.

2.2. Case selection and anonymisation

The four cases summarised in Table 1 were extracted from an anonymised 2022 feasibility-report series and selected by the commissioning local authority as representative of typical and atypical school typologies within its estate [34]. They span a 5.4-fold range of internal floor area, three principal construction eras, two heating-fuel baselines, Display Energy Certificate ratings from D to F, and metered energy-use intensities from 134 to 187 kWh/m^2/year. Two cases are heritage-period buildings with multiple historical extensions (School A, originally 1849; School C, originally 1953 with extensions to 2008), and two are post-war or late-twentieth-century purpose-built structures (School D, 1952 with 1995 extension; School B, 1994 with 1995 extension). The cases are anonymised as Schools A-D throughout this manuscript, ordered by ascending treated floor area (see Data Availability).

Table 1
Anonymised case-study buildings and baseline characteristics within a single UK local-authority public estate.

Case	Year built	Floor area (m^2)	Peak occupancy	Heating fuel	DEC score / band	Survey period
School A	1849 (renov. to 2007)	860	80	Oil	131 / F	Jul 2022
School B	1994 (ext. 1995)	1610	90	Gas	93 / D	Jun 2022
School C	1953 (ext. to 2008)	2642	450	Gas	76 / D	Aug 2022
School D	1952 (ext. 1995)	4620	920	Gas	86 / D	Aug 2022

2.3. Data extraction and reconciliation

Six variable families were extracted and harmonised: annual baseline electricity and heating-fuel demand; baseline operational carbon; package and source-report measure allocations; capital cost; annual energy and carbon savings; and simple payback where reported. Each value was classified as measured, modelled, reported, reconciled or newly derived in Supplementary Data S1. Source variants were retained rather than silently standardised. The 2022 source reports use CO_2 terminology, whereas calculations using the later UK Government conversion factors are reported as CO_2e; this distinction is retained in the relevant tables and scenarios.

The paper is a secondary synthesis and does not rerun the original EnergyPlus models. All extracted values were first subjected to arithmetic reconciliation against package totals and stated calculation bases. Exact package reductions were calculated from unrounded baseline and post-package emissions; rounded per-measure percentages were treated as source-report allocations. The resulting interaction/reconciliation terms are −0.05 to +0.05 percentage points, which is consistent with rounding but is not evidence that the physical effects of the measures are additive. The complete provenance and reconciliation register is provided in Supplementary Data S1.

The retained evidence confirms that the baseline OpenStudio/EnergyPlus models used 12 monthly utility observations and met the ASHRAE Guideline 14 monthly calibration criteria (NMBE within ±5% and CV(RMSE) ≤15%) [35–37]. Electricity NMBE/CV(RMSE) values were −3.20/6.90%, +1.23/14.20%, −3.92/5.67% and + 1.23/3.78% for Schools A–D; the corresponding heating-fuel values were + 4.32/11.70%, +4.71/6.20%, −0.94/2.34% and − 0.76/2.01%. The exact calibration dates, occupancy- and weather-normalisation procedures, ventilation and infiltration assumptions, and detailed ASHP performance curves were not recoverable from the retained project records. These items are reported as unavailable rather than reconstructed. The analysis therefore treats the reported package energy outputs as fixed feasibility-stage quantities and uses explicit output-level stress tests where a model rerun is not possible. Table 2 summarises the available school-level calibration statistics and identifies the unrecovered model inputs.

Table 2
Available school-level calibration evidence and unrecovered model-input information.

School	Electricity NMBE / CV (RMSE)	Heating-fuel NMBE / CV(RMSE)
School A	−3.20% / 6.90%	+4.32% / 11.70%
School B	+1.23% / 14.20%	+4.71% / 6.20%
School C	−3.92% / 5.67%	−0.94% / 2.34%
School D	+1.23% / 3.78%	−0.76% / 2.01%
Evidence boundary	12 monthly observations; ASHRAE 14 monthly criteria met	Exact dates and several occupancy/ weather/ventilation/infiltration/ ASHP inputs not recoverable

2.4. Derived techno-economic indicators

Nine linked analytical steps were used. Equations, source values and reproducible calculations are provided in Supplementary Data S1.

1. Package reduction and residual: exact operational-carbon reduction was calculated as (Cbase − Cpost)/Cbase; the location-based residual to the stated operational-net-zero endpoint was 100% minus that reduction.
2. Capital intensity and source allocations: portfolio capital cost was divided by the exact percentage-point reduction. Per-measure percentages were retained as source-report allocations and were not interpreted as independent simulation runs. The package-minus-

allocation difference was reported only as an arithmetic reconciliation term.

3. Whole-package utility comparison: pre-retrofit purchased electricity plus heating fuel was compared with the reported post-package electricity quantity. Because the latter embeds the combined package and does not separately report gross load, PV self-consumption or export, this is termed a whole-package electrified end-state comparison, not an ASHP-only effect.
4. Capital-to-annual-abatement ratio: feasibility-stage capital cost was divided by one year of reported operational-carbon abatement and expressed as £/($kgCO_2$ yr^{-1}). It excludes operating costs, lifetime, discounting, maintenance, replacement and cumulative emissions and is therefore not a conventional lifecycle marginal abatement cost.
5. Whole-package tariff-ratio sensitivity was calculated over electricity-to-gas ratios of 2:1–10:1 and oil prices of £0.020–£0.180/kWh. For the reported package end state, revenue neutrality satisfies:

$$E_{post}\, p_e = E_{pre}\, p_e + H\, p_h \quad (1)$$

where E_{pre} and E_{post} are the source-report pre- and post-package purchased-electricity quantities, H is baseline heating-fuel input and p_e and p_h are unit prices. Rearrangement Eq. (1) gives the package-level break-even ratio:

$$r^{*} = p_e/p_h = H/(E_{post} - E_{pre}) \quad (2)$$

This ratio is useful for testing tariff contingency, but it must not be interpreted as an isolated ASHP threshold because Epost includes the combined effects represented in the source package.

Controlled rebasing holds E_{pre}, E_{post}, H, measure scope and 2022 capital quantities fixed while updating only exogenous variables. The controlled audit uses the 2026 UK Government company-reporting factors [23], DESNZ Q1 2026 non-domestic tariffs including the Climate Change Levy [24], and an illustrative CPI uplift from April 2022 to May 2026 of 142.4/123.2 = 1.156 [25]. CPI is used only as a transparent index-controlled sensitivity; procurement decisions require construction-specific indices and current tender evidence [26].

Operational-carbon boundary: the current reporting calculation is location-based and covers annual purchased energy at the site. The source-report post-package electricity value is treated as net annual grid import because gross electricity demand, PV self-consumption and exports are not separately available. No export credit, transmission and distribution loss, well-to-tank emissions, refrigerant leakage, embodied carbon or market-based green-tariff claim is included. The ONZ residual is therefore unbalanced annual operational emissions within this boundary. The 2040 and 2050 Green Book factors are instead consumption-based appraisal factors that include transmission and distribution losses; they are reported as a separate scenario and are not boundary-equivalent to the 2026 Scope 2 generated-electricity calculation.

2.5. *Controlled rebasing workflow and decision rule*

Step 1 – provenance and reconciliation: identify the physical quantities, accounting quantities, tariff values and cost bases used by the original study; resolve arithmetic inconsistencies without altering the physical design.

Step 2 – freeze the physical case: retain the calibrated/modelled annual energy quantities, measure scope and package configuration. A change to schedules, weather, occupancy distribution, fabric properties, equipment sizing or controls triggers a new model run rather than a rebasing calculation.

Step 3 – define the accounting boundary: state whether the calculation is location- or market-based and document the treatment of grid import, on-site generation, export, losses, offsets and excluded lifecycle modules.

Step 4 – update only named exogenous inputs: apply dated official emission factors, tariffs and transparent cost indices, retaining both the historical and rebased results.

Step 5 – classify each conclusion: durable if its direction survives, contingent if its magnitude or sign changes with external inputs, unresolved if the required physical counterfactual is unavailable, or superseded if the original conclusion depended on an obsolete input.

Step 6 – procurement gate: before implementation, replace generic tariffs and index uplifts with the site contract, DNO evidence, tendered capital cost and a rerun of any physically changed design.

2.6. *Incremental ASHP counterfactual and bounded uncertainty*

Because measure-only EnergyPlus runs were not retained, an output-level heat-system counterfactual is used to avoid attributing the whole-package comparison to the heat pump alone. Baseline delivered heat is approximated as $Q_{heat} = \eta_b H$ and ASHP electricity as $E_{ASHP} = Q_{heat}/SCOP$. The incremental annual cost is $E_{ASHP}p_e - Hp_h$ and the location-based carbon saving is $Hf_h - E_{ASHP}f_e$. The central assumptions are $\eta_b = 0.85$ and SCOP = 3.0, with $\eta_b = 0.80$–0.90 and SCOP = 2.5–4.0 used as a bounded sensitivity. The calculation excludes distribution redesign, auxiliaries, defrost, part-load curves and fabric-load interaction; it is a diagnostic counterfactual, not a recovered source-model result or procurement design.

2.7. *Sequencing and cumulative emissions*

The three sequences retain the same final package but vary the assumed commissioning year of each source-report allocation. Measures commissioned at the start of a programme year deliver their allocated annual saving during that year. Cumulative avoided carbon to year T is the sum of the annual achieved reduction multiplied by the four-school baseline of 306,876 $kgCO_2$/yr. This converts an endpoint-percentage comparison into tCO_2 avoided over time. No physical interaction correction is imposed because the necessary independent and combined model runs are unavailable. Supplementary Data S1 provides a formula-linked commissioning matrix: the annual achieved reductions and cumulative tCO_2 values are calculated from the stated scenario tranches rather than entered independently.

2.8. *Quantitative scenario tests*

Uncertainty is represented by transparent bounded scenarios rather than a probability distribution unsupported by the source evidence. Tests cover Q1 2026 average and small-consumer tariff bands; SCOP 2.5–4.0; boiler efficiency 0.80–0.90; a proportional whole-building demand uplift of 5%, 10% and 15%; CPI-rebased capital cost ±20%; and current plus projected grid factors. Uniform demand scaling changes absolute energy, cost and carbon quantities but leaves percentage reduction unchanged because both baseline and post-package states receive the same multiplier. U-value uncertainty and physical measure interaction cannot be propagated without the original model and are explicitly classified as requiring rerun. For School A, the current-price tests retain the source-case oil price of £0.085/kWh while updating electricity; they are not presented as a Q1 2026 oil-tariff observation.

2.9. *Methodological limitations*

Nine methodological qualifications delimit the interpretation.

1. All four reports came from one consultancy, one local authority, one year and one template; observed convergence cannot be separated cleanly into building-stock and consultancy-method effects.
2. Baseline U-values were inferred from age-banded guidance rather than measured. The reported ±0.25 W/m^2K range cannot be

propagated credibly without the original geometry and end-use model, so no fabricated output elasticity is applied [39].
3. The 2021–22 metered baselines may reflect COVID-related occupancy disruption. The available evidence does not support end-use-specific normalisation. A proportional 5–15% whole-building demand stress test is therefore reported; it scales absolute quantities but does not change percentage reductions.
4. Although monthly calibration statistics meet ASHRAE Guideline 14, exact calibration dates and several model-input assumptions are unavailable. Calibration supports the baseline fit but does not validate the projected retrofit performance or recover missing inputs [40].
5. Per-measure percentages are source-report allocations. Independent and combined measure runs were not retained, so physical interactions among fabric, plant, controls and PV cannot be quantified.
6. The incremental ASHP analysis is an explicit η/SCOP output-level counterfactual, not a recovered EnergyPlus measure-only run. Its ranges are scenario bounds rather than probabilistic confidence intervals.
7. Capital costs are 2022 budget estimates. CPI and ± 20% tests are transparent sensitivities, not tender-price forecasts. The sample size is four, so regression, national economy-of-scale and funding-policy claims are not inferentially supported.
8. The operational boundary excludes embodied carbon, refrigerant leakage, upstream fuel effects, transmission losses, PV export credit and market-based procurement instruments; conclusions apply only to the stated location-based annual operational boundary [46,47].
9. Future grid factors are externally determined, consumption-based appraisal scenarios that include transmission and distribution losses [43]. They can illustrate how an all-electric end state may evolve under the projected power-sector trajectory, but they are not an additional building measure, a guaranteed asset outcome or a boundary-equivalent continuation of the 2026 Scope 2 reporting result.

3. Results

3.1. Baseline energy and carbon profile

Table 3 summarises the baseline purchased site energy, carbon emissions, and energy-use intensity (EUI) of the four cases prior to intervention. Three of the four schools rely on natural gas for space and water heating; School A remains on heating oil, a residual condition of its rural location and early construction date. The carbon-emission intensity per square metre of treated floor area is highest at School A (38.4 $kgCO_2/m^2$), reflecting the higher emissions factor of heating oil, and lowest at School C (26.0 $kgCO_2/m^2$), which exhibits the lowest EUI of the sample at 134 kWh/m^2/year. All four EUI values lie above the CIBSE Guide F good-practice benchmark for UK primary schools of approximately 113 kWh/m^2/year [41], with School B exceeding the benchmark by 65% notwithstanding its status as the youngest building in the sample.

Table 3
Baseline purchased site energy and carbon emissions across the four cases (2021–22 metered data).

Case	Electricity (kWh/yr)	Heating fuel (kWh/yr)	EUI (kWh/m^2/yr)	Baseline CO_2 (kg/yr)	CO_2 intensity (kg/m^2)
School A	33,071	98,928 (oil)	154	32,981	38.4
School B	43,133	258,211 (gas)	187	57,541	35.7
School C	74,339	278,582 (gas)	134	68,567	26.0
School D	138,768	627,675 (gas)	172*	147,787	32.0

* The source report states 172 kWh/m^2/yr; the underlying metered inputs imply 165.9 kWh/m^2/yr. Conversion factors follow BEIS 2022 [38].

3.2. Proposed intervention portfolio and per-measure outcomes

All four reports converge on a common six-measure intervention portfolio: external wall insulation (with roof insulation in three of four cases); glazing replacement to modern low-E double glazing targeting U-values below 1.4 W/m^2K; replacement of fluorescent luminaires with LED fittings under DALI-based occupancy, presence, and daylight-dimming control; replacement of the existing gas or oil boiler plant with an air-source heat pump feeding the existing hydronic distribution, with selective radiator upsizing as required [21]; installation of a building management system where one is absent; and installation of a rooftop monocrystalline photovoltaic array of 12–40 kWp depending on available roof area. Three secondary technologies are screened in every report and uniformly rejected: ground-source heat pumps (rejected on capital-cost grounds), small-scale wind generation (rejected on planning and acoustic grounds), and biomass (rejected on fuel-supply and maintenance grounds). School C introduces one additional measure, a CO_2-refrigerant heat pump dedicated to service hot water, reflecting its higher hot-water demand from a 450-person occupancy.

Table 4 reports feasibility-stage capital cost and source-report carbon allocations. The allocated percentages reconcile to the exact package reductions within −0.05 to +0.05 percentage points, consistent with rounding. They are not treated as independent additive simulations. Within the source allocation, ASHP plus distribution is the largest category in each case (23.6–30.5% of baseline), while lighting and controls have the lowest capital cost per allocated percentage point (£1179–£6544/%). Fabric measures retain long simple paybacks, but that observation is distinct from lifecycle cost-effectiveness.

3.3. Portfolio-level reduction and convergence

Table 5 summarises the exact package-level carbon outcomes, residuals and capital costs. Across the four cases, the exact package reductions are 56.7–67.8% under the 2022 source-report accounting. Baseline operational carbon of 306,876 $kgCO_2$/yr falls to 118,412 $kgCO_2$/yr, an aggregate reduction of 61.4%, at an indicative capital cost

Table 4
Per-measure capital cost and operational CO_2 saving by case.

Measure	School A £ (% CO_2)	School B £ (% CO_2)	School C £ (% CO_2)	School D £ (% CO_2)	£/% range
Wall (+ roof) insulation	14,175 (10.4%)	65,726 (22.6%)	80,222 (19.2%)	99,450 (15.7%)	1363–6334
Glazing	25,313 (11.2%)	39,724 (10.0%)	n/a	60,480 (7.3%)	2260–8285
Lighting + controls	4128 (3.5%)	4730 (2.6%)	5284 (1.0%)†	22,250 (3.4%)	1179–6544
ASHP + distribution	75,000 (30.5%)	95,000 (23.6%)	196,000 (24.0%)	360,000 (25.9%)	2459–13,900
BMS	n/a	10,000 (2.4%)	15,000 (1.9%)	20,000 (2.9%)	4167–7895
Photovoltaics	25,000 (12.2%)	15,300 (4.2%)	33,000 (7.8%)	45,000 (5.45%)	2049–8257
Service-HW CO_2 HP	n/a	n/a	18,000 (2.8%)	n/a	6429
Portfolio total (reported/modelled estimate)	143,616 (67.8%)	230,480 (65.4%)	347,506 (56.7%)	607,180 (60.6%)	2118–10,016

Note: Values in parentheses are source-report allocations relative to each site baseline. They reconcile arithmetically to package outputs but are not evidence of physical additivity.
† School C lighting covers controls only because LEDs were already installed.

Table 5
Portfolio-level carbon reduction outcomes and residual gap to ONZ across the four cases.

Case	Baseline CO_2 (kg/yr)	Post-retrofit CO_2 (kg/yr)	Reduction (%)	Residual to ONZ (%)	Total capital (£)
School A	32,981	10,618	67.8	32.2	143,616
School B	57,541	19,938	65.4	34.6	230,480
School C	68,567	29,657	56.7	43.3	347,506
School D	147,787	58,199	60.6	39.4	607,180
Sample mean	–	–	62.6	37.4	–
Sample SD (n − 1)	–	–	4.96	4.96	–
Portfolio total	306,876	118,412	61.4 (aggregate)	38.6	1,328,782

of £1,328,782. The unweighted case mean is 62.6% and the residual is 32.2–43.3 percentage points. These are direct case-set results; the narrow range is not interpreted as a national school-stock distribution. At portfolio level, annual purchased site energy decreases from 1,552,707 to 507,531 kWh/yr, equivalent to an aggregate reduction of 67.3% in purchased site energy. Fig. 1 visualises the source-report measure allocations and the remaining unbalanced ONZ residual for each school.

3.4. Exploratory capital intensity and floor area

Capital cost per exact percentage point of operational CO_2 saved rises monotonically across the four observations: £2118/% at School A, £3527/% at School B, £6124/% at School C and £10,016/% at School D. A descriptive log–log guide across the four observations is reported in Supplementary Data S1 (sheet Capital_Intensity); with $n = 4$ it is not inferential, and no population scaling law or absence of economy of scale is claimed. The pattern may reflect scope, plant capacity, baseline carbon and common costing conventions as well as floor area. Fig. 2 plots treated floor area against capital cost per exact percentage point of operational CO_2 saved.

3.5. Capital-to-annual-abatement screening ratio

Fig. 3 orders the source-report measure groups by capital cost per one year of allocated operational-carbon abatement. The ratios are £4.35/(kgCO_2 yr^{-1}) for lighting and controls, £4.92 for wall and roof insulation, £5.96 for photovoltaics, £6.20 for glazing, £6.46 for BMS and £9.27 for ASHP plus service-hot-water heat pump. The portfolio-weighted ratio is £7.05/(kgCO_2 yr^{-1}). The ASHP grouping accounts for 80.3 tCO_2/yr of the 188.5 tCO_2/yr allocated portfolio abatement.

This is a feasibility-stage capital-efficiency screen, not a lifecycle MAC. It cannot establish economic priority over the asset life because operating-cost change, measure life, maintenance, replacement and discounting are absent. Its valid use is narrower: comparing how much 2022 budget capital was associated with one year of reported operational abatement within the same source methodology.

3.6. Whole-package economics and incremental ASHP counterfactual

The source reports provide baseline and final package energy quantities but not a complete set of non-ASHP and ASHP-only model runs. Table 6 therefore retains the baseline-to-final comparison and labels it correctly as a whole-package electrified end state. It includes the combined effects embedded in the reported post-package electricity quantity and must not be attributed to the heat pump alone.

Under the 2022 tariffs, the oil case has a 27.9% whole-package cost saving, while the three gas cases show increases of 13.3–16.4%. Under the current scenario, the gas cases use Q1 2026 average non-domestic electricity and gas tariffs and show savings of 5.1–13.1%. School A combines Q1 2026 electricity with the retained source-case oil price of

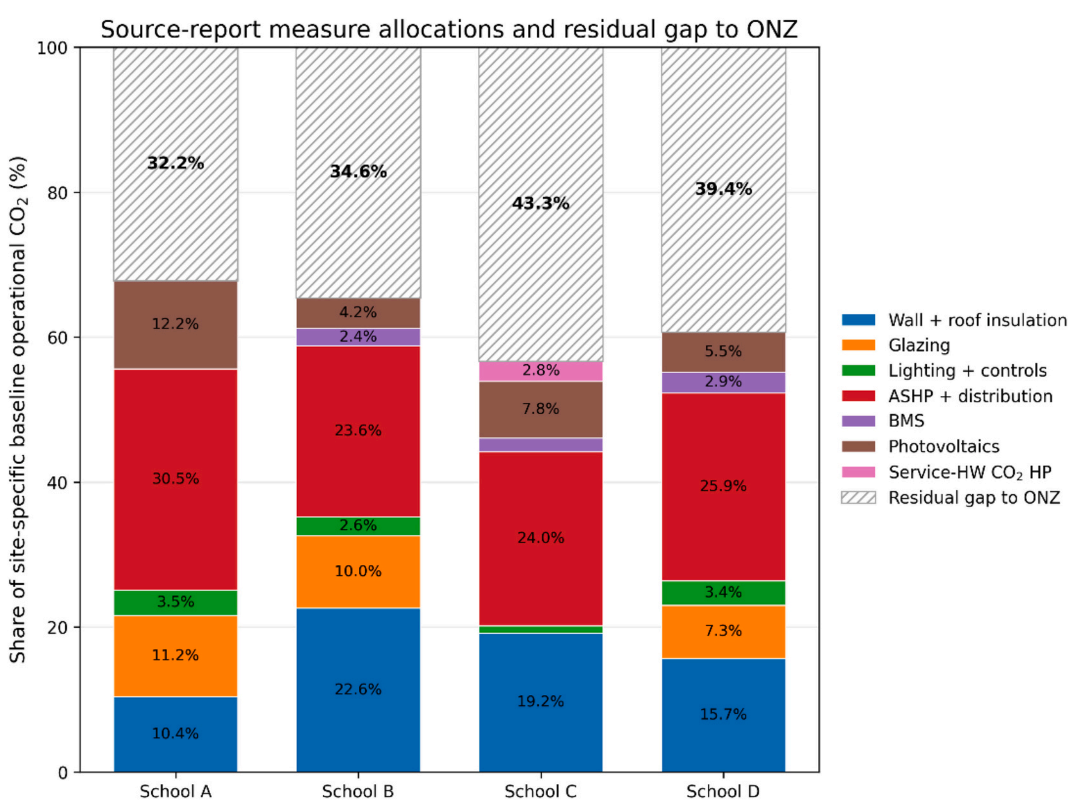

Fig. 1. Source-report measure allocations and residual gap to ONZ. The coloured segments reproduce the reported allocation percentages; the hatched segment is the unbalanced location-based residual.

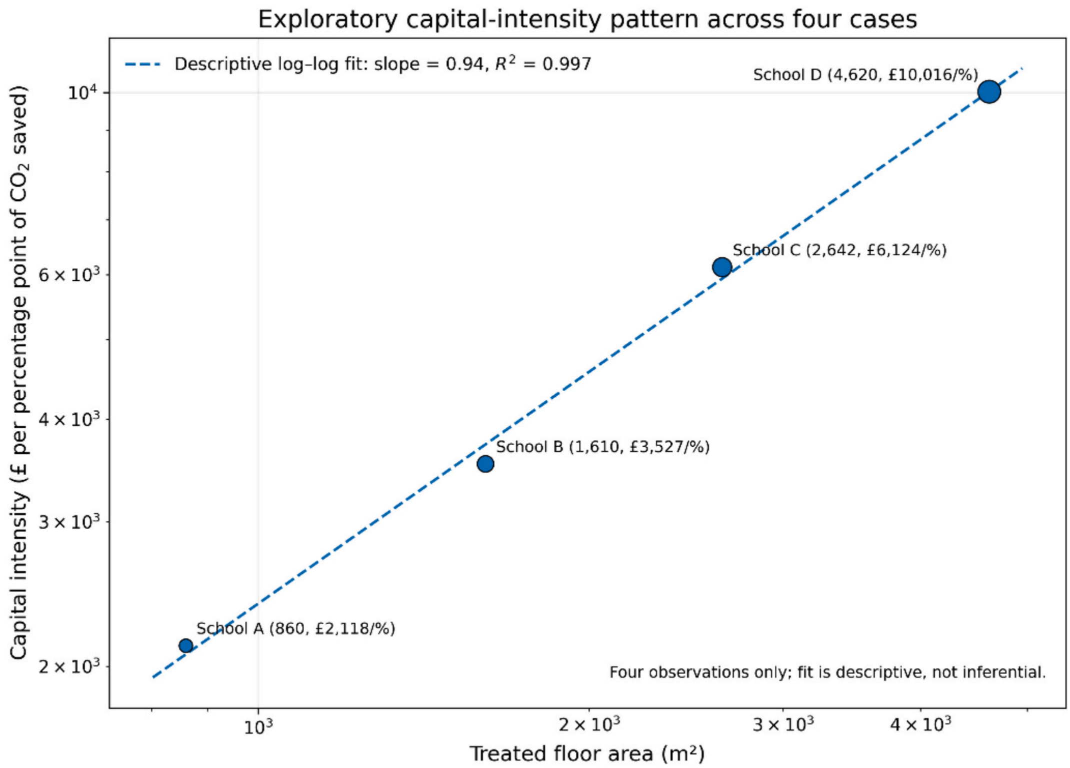

Fig. 2. Exploratory relation between treated floor area and capital cost per exact percentage point saved. The dashed line reproduces the descriptive guide detailed in Supplementary Data S1 (sheet Capital_Intensity) and carries no inferential weight.

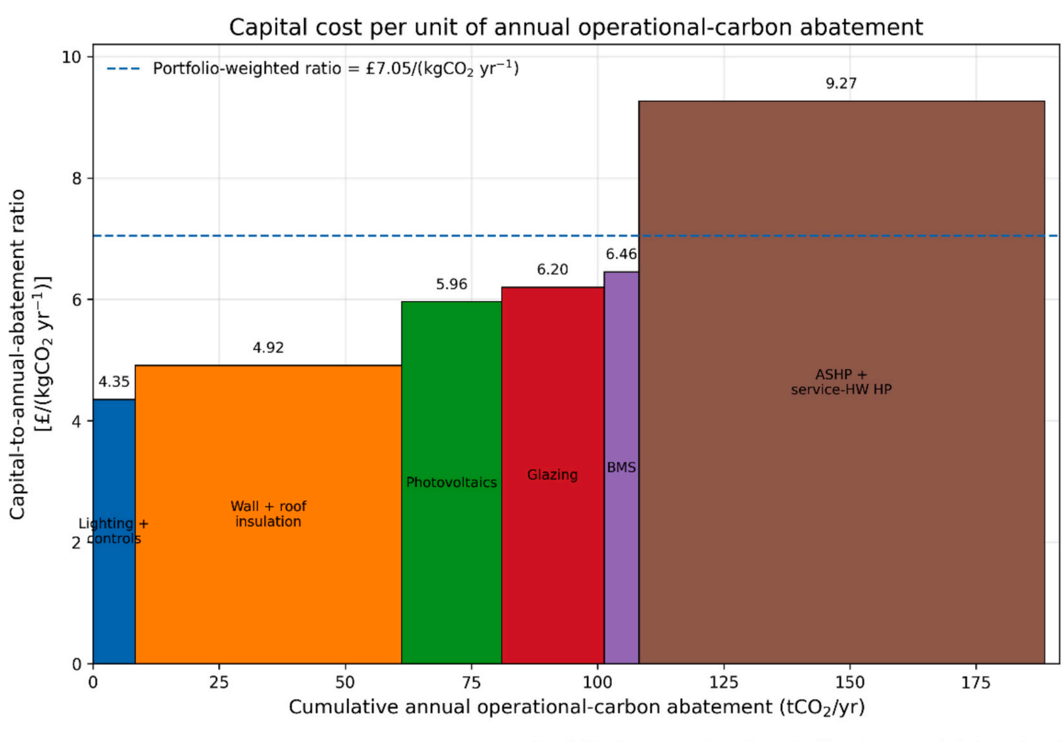

Fig. 3. Capital-to-annual-abatement screening curve. Width represents allocated annual operational-carbon abatement (tCO_2/yr) and height represents £/(kgCO_2 yr^{-1}). The metric excludes lifecycle costs and is not a marginal abatement cost.

£0.085/kWh and shows a 33.0% saving; this is not a measured Q1 2026 oil-tariff result. The Q1 2026 small-consumer bands remain mixed for the gas cases: −0.6% at School B, +5.4% at School C and + 2.7% at School D. The sign reversal is therefore tariff- and boundary-contingent rather than evidence of a physical change to the package.

The package-level tariff-ratio curves in Fig. 4 identify break-even

Table 6
Whole-package electrified end-state utility-cost comparison under the 2022 basis and current tariff scenarios.

Case	2022 pre-cost (£/yr)	2022 post/ change	Current pre-cost (£/yr)	Current post/ change	Small-band gas change	Scope
School A (oil)	17,669	12,746 (−27.9%)	16,393	10,990 (−33.0%)	n/a	Package*
School B (gas)	21,115	23,927 (+13.3%)	23,753	20,630 (−13.1%)	−0.6%	Package
School C (gas)	30,565	35,591 (+16.4%)	32,340	30,687 (−5.1%)	+5.4%	Package
School D (gas)	60,824	69,844 (+14.8%)	65,930	60,220 (−8.7%)	+2.7%	Package

Note: Post-package electricity is the source-report net annual quantity and is not an isolated ASHP load. For gas-fired schools, the current scenario uses Q1 2026 electricity and gas tariffs including the Climate Change Levy. For School A, Q1 2026 electricity is paired with oil retained at £0.085/kWh. The small-consumer band is a transparent proxy, not a measured school contract. The reported post-package purchased-electricity quantities used in these calculations are 45,521, 85,454, 127,112 and 249,444 kWh/yr for Schools A–D, respectively.

electricity-to-gas ratios of 5.28 for School C, 5.67 for School D and 6.10 for School B. The 2022 ratio of 8.0 lies above all three thresholds; the Q1 2026 average ratio of 4.67 lies below them, while the small-band ratio of approximately 6.03 lies close enough to produce mixed outcomes. For School A, the package break-even oil price is about £0.035/kWh when electricity is £0.28/kWh. These curves diagnose package tariff exposure and are not ASHP-only thresholds. Table 7 reports the simplified incremental ASHP counterfactual under the central efficiency assumptions and bounded sensitivity range.

The separate counterfactual in Table 7 and Fig. 6 gives a materially different interpretation. At ηb = 0.85 and SCOP = 3.0, the current-scenario incremental heat-system cost is approximately −£1642/yr for oil-fired School A but +£4321/yr, +£4662/yr and + £10,505/yr for gas-fired Schools B–D. The gas cases use Q1 2026 electricity and gas; the oil case uses Q1 2026 electricity with oil retained at £0.085/kWh. Across the stated η/SCOP bounds, each gas case can cross cost neutrality, showing that performance and tariff uncertainty remain decisive. The central 2026 location-based carbon savings are 19.6–91.1 tCO_2e/yr.

3.7. Sequencing scenarios

Three heuristic sequences were retained to test timing while holding the final source-report package unchanged. S1 is fabric-first, S2 prioritises short-payback measures, and S3 prioritises the largest reported annual carbon allocations. The scenarios are not alternative physical designs and do not correct for unquantified interactions. The fabric-first logic is consistent with PAS 2038, LETI and RIBA sequencing guidance [30,31,42].

Measures are assumed to be commissioned at the start of the stated programme year. Fig. 5 integrates the annual achieved reduction against the four-school baseline of 306,876 $kgCO_2$/yr, while Table 8 reports cumulative tCO_2 avoided at years 1, 3, 5 and 8. This cumulative framing answers the timing question without implying that the final 61.4% package reduction differs between sequences.

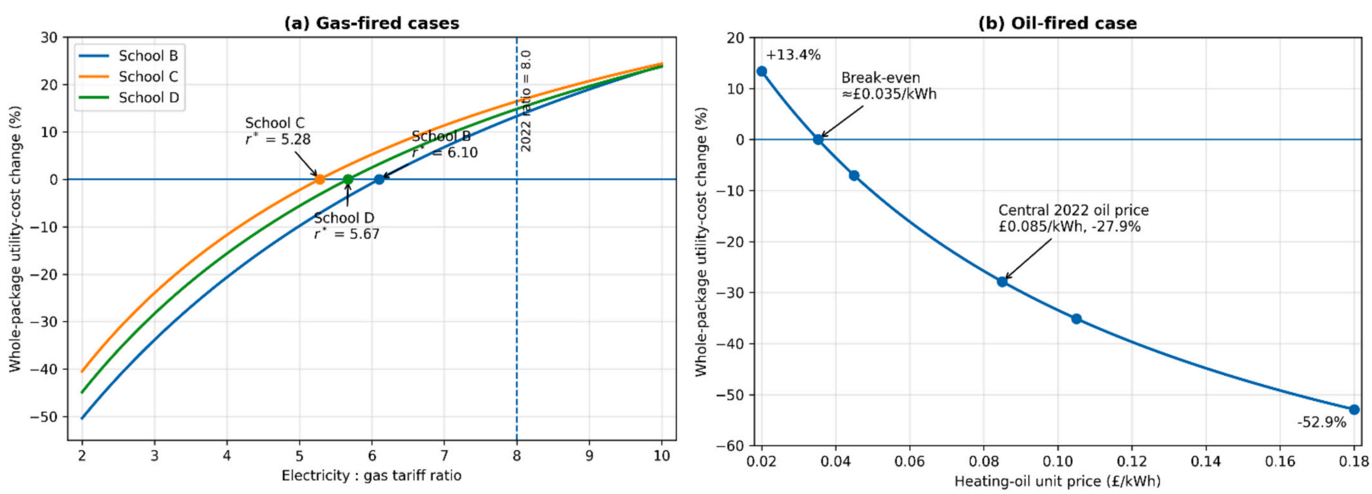

Fig. 4. Whole-package electrified end-state tariff sensitivity. Panel (a) varies the electricity:gas ratio for the three gas cases; panel (b) varies heating-oil price for School A. The curves use the reported final package electricity quantity and must not be interpreted as isolated ASHP economics.

Table 7
Simplified incremental ASHP counterfactual using ηb = 0.85 and SCOP = 3.0.

Case	Heat input (kWh/yr)	Implied ASHP electricity (kWh/yr)	2022 incremental cost (£/yr)	Current incremental cost (£/yr)	Current range (£/yr)	2026 carbon saving ($kgCO_2e$/yr)
School A (oil)	98,928	28,030	−561	−1642	−3632 to +189	19,602
School B (gas)	258,211	73,160	+11,447	+4321	−873 to +9101	37,493
School C (gas)	278,582	78,932	+12,350	+4662	−942 to +9819	40,451
School D (gas)	627,675	177,841	+27,827	+10,505	−2123 to +22,122	91,141

Note: The sensitivity range uses ηb = 0.80–0.90 and SCOP = 2.5–4.0. The calculation isolates a heat-system counterfactual from baseline fuel input; it is not a recovered measure-only EnergyPlus run and excludes fabric-load interaction, auxiliaries, defrost and distribution redesign.

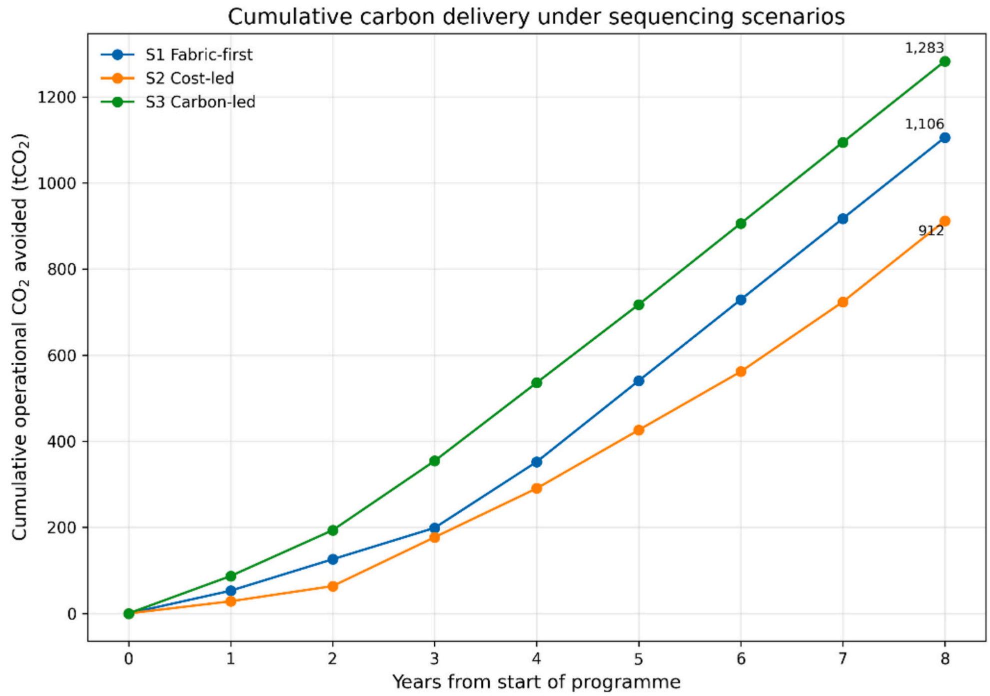

Fig. 5. Cumulative operational CO_2 avoided under the three sequencing scenarios. Values integrate each year's achieved source-report reduction against the four-school baseline.

Table 8
Cumulative operational CO_2 avoided under the three sequencing scenarios.

Scenario	Logic	Year 1 (tCO_2)	Year 3 (tCO_2)	Year 5 (tCO_2)	Year 8 (tCO_2)
S1 Fabric-first	Fabric and glazing before ASHP	52.8	198.9	540.7	1106.0
S2 Cost-led	Short-payback measures first	28.2	177.1	426.3	912.3
S3 Carbon-led	Largest reported carbon allocations first	86.8	354.4	717.8	1283.0

Note: tCO_2 values integrate annual achieved reduction against the 2022 four-school baseline. Commissioning is assumed at the start of each programme year; all scenarios reach the same final annual package reduction.

By year 3, cumulative avoided emissions are 199 tCO_2 under S1, 177 tCO_2 under S2 and 354 tCO_2 under S3. By year 8, the totals are 1106, 912 and 1283 tCO_2, respectively. S3 therefore avoids about 371 tCO_2 more than S2 over the eight-year horizon even though both end at the same annual package reduction. Sequencing changes cumulative delivery, not the final technical endpoint.

3.8. Controlled rebasing to the latest official data and bounded scenarios

The historical calculation is retained as the documented 2022 basis. The controlled audit then substitutes the 2026 UK Government location-based factors, DESNZ Q1 2026 non-domestic tariffs released 30 June 2026 and a May 2026 CPI index while keeping the physical quantities and package scope fixed [23–26]. Table 9 records every changed parameter; Table 10 reports the corresponding outcomes. In the oil-fired case, only electricity is updated; the source-case oil price remains £0.085/kWh and is disclosed separately in Table 9.

The average Q1 2026 electricity and gas prices are 24.14 and 5.17 p/kWh, an electricity-to-gas ratio of 4.67. The small-consumer bands are 28.76 and 4.77 p/kWh, a ratio of 6.03. The 2026 generated-electricity factor is 0.13096 $kgCO_2e$/kWh, compared with 0.23314 $kgCO_2$/kWh in the 2022 source basis. These changes are accounting and market

Table 9
Historical and current exogenous parameters used in the controlled rebasing.

Parameter	2022 source basis	2026 / current scenario	Source / treatment
Electricity tariff	£0.2800/kWh	£0.2414/kWh (Q1 2026 average)	DESNZ QEP incl. CCL [24]
Natural-gas tariff	£0.0350/kWh	£0.05167/kWh (Q1 2026 average)	DESNZ QEP incl. CCL [24]
Electricity:gas ratio	8.00	4.67 average; 6.03 small band	Derived from [24]
Small-consumer tariff bands	n/a	Electricity £0.2876; gas £0.04772/kWh	Dataset stress test, not site tariff [24]
Heating-oil price	£0.085/kWh	£0.085/kWh retained	Source-case central value retained; not a Q1 2026 oil tariff
Grid electricity factor	0.23314 $kgCO_2$/kWh	0.13096 $kgCO_2e$/kWh	2026 generated electricity, Scope 2 [23]
Natural-gas factor	0.18387 $kgCO_2$/kWh	0.18231 $kgCO_2e$/kWh gross CV	2026 Scope 1 [23]
Burning-oil factor	2.75821 $kgCO_2$/l	2.54016 $kgCO_2e$/litre	2026 Scope 1 [23]
Capital uplift	2022 budget estimate	CPI coefficient 142.4/123.2 = 1.156	Illustrative May 2026 rebasing [25]
Future grid scenario	n/a	0.015 (2040); 0.002 (2050) $kgCO_2e$/kWh	Green Book consumption-based appraisal scenario including transmission and distribution losses; not boundary-equivalent to the 2026 Scope 2 reporting factor [43]

Note: Tariffs include the Climate Change Levy. The small-consumer values are dataset bands, not measured site tariffs. CPI is an illustrative accounting uplift rather than a construction tender-price forecast.

updates; they do not imply a new building design. The oil price is not

Table 10
Controlled current-data rebasing of carbon, whole-package utility cost and capital.

Case	2022 reduction (%)	2026-factor reduction (%)	2026 residual (%)	2022 package cost change	Current-scenario package change	Small-band gas change	CPI-rebased capex (£)
School A (oil)	67.8	78.4	21.6	−27.9%	−33.0%	n/a	165,998
School B (gas)	65.4	78.8	21.2	+13.3%	−13.1%	−0.6%	266,399
School C (gas)	56.7	72.5	27.5	+16.4%	−5.1%	+5.4%	401,663
School D (gas)	60.6	75.4	24.6	+14.8%	−8.7%	+2.7%	701,805
Case mean	62.6	76.3	23.7	+4.2%	−15.0%	+2.5%*	–
Portfolio aggregate	61.4	75.7	24.3	+9.2%	−11.5%	+2.8%*	1,535,865

Note: 2026 carbon values apply the current Government factors to the unchanged physical quantities. For gas-fired schools, whole-package utility-cost results use Q1 2026 average or small-consumer electricity and gas tariffs. For School A, Q1 2026 electricity is paired with oil retained at £0.085/kWh. CPI-rebased capital uses 142.4/123.2 = 1.156. School A is excluded from the gas small-band summary.

updated: School A retains £0.085/kWh in the current scenario.

Four findings emerge from the controlled rebasing.

(1) First, the case reductions increase from 56.7 to 67.8% on the 2022 source basis to 72.5–78.8% using the 2026 factors. The case mean rises from 62.6% to 76.3%, and the aggregate reduction from 61.4% to 75.7%. The current-factor residual remains 21.2–27.5 percentage points; it is smaller but not zero.

(2) Second, the CPI coefficient raises combined indicative capital from £1.329 million to £1.536 million but does not alter the case ordering. A ± 20% capital scenario produces a portfolio capital-to-annual-abatement ratio of £6.52–£9.78/($kgCO_2$ yr^{-1}) on the CPI-rebased basis. These are accounting sensitivities, not tender forecasts.

(3) Third, the whole-package tariff conclusion reverses under the current average-tariff scenario for the gas cases, but the small-band result remains mixed. Fig. 6 prevents that reversal from being over-attributed to ASHP: the isolated output-level counterfactual retains positive central incremental costs for the gas cases and spans cost neutrality under the η/SCOP bounds.

(4) Fourth, the proportional COVID/demand stress test leaves percentage reduction unchanged at 61.4% because the same 5–15% multiplier is applied to baseline and post-package quantities, while absolute annual avoided carbon rises from 188.5 to 197.9–216.7 tCO_2/yr. This demonstrates robustness only to uniform scaling; differential occupancy, ventilation or schedule effects require a model rerun.

A separate external scenario applies the official appraisal trajectory values of approximately 0.015 $kgCO_2e$/kWh in 2040 and 0.002 $kgCO_2e$/kWh in 2050 [43]. With the 2026 non-electric fuel factors retained and the same all-electric post-package quantities, the case-mean residual is approximately 3.1% in 2040 and 0.4% in 2050; the aggregate values are approximately 3.2% and 0.4%. The Green Book values are per electricity consumed and include transmission and distribution losses, unlike the 2026 generated-electricity Scope 2 factor used in the current reporting calculation. The future residuals are therefore scenario outputs on a

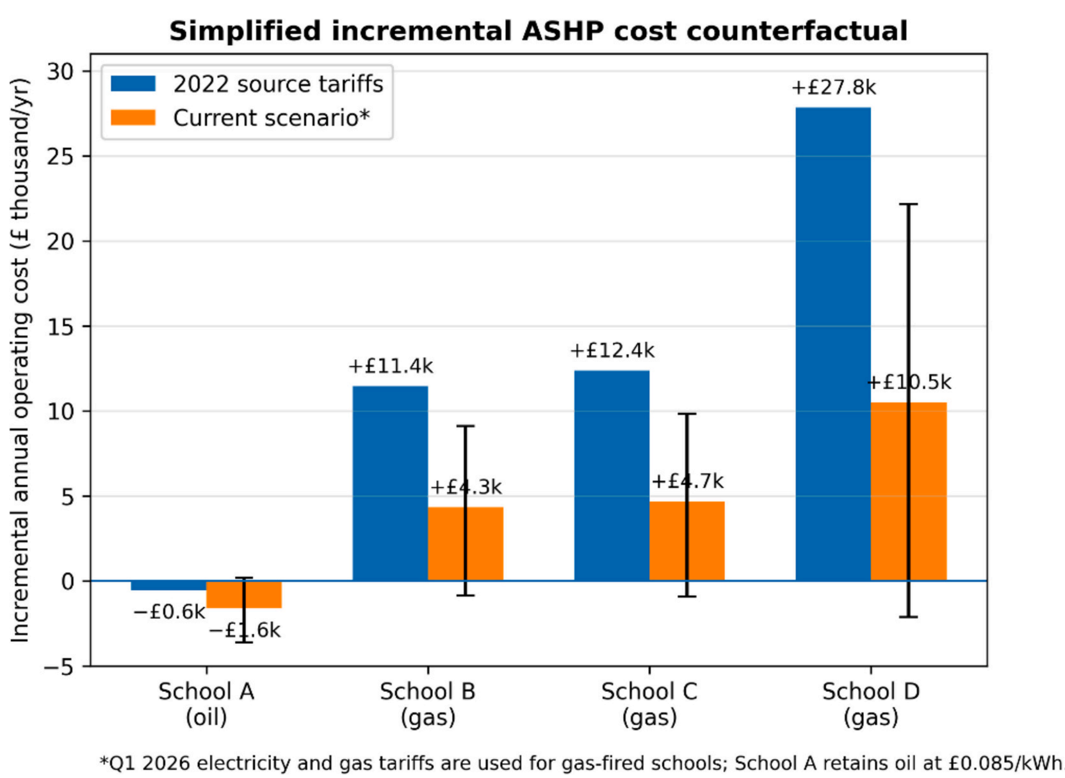

Fig. 6. Simplified incremental ASHP cost counterfactual under the 2022 basis and current tariff scenario. Error bars show the bounded ηb = 0.80–0.90 and SCOP = 2.5–4.0 range. Gas cases use Q1 2026 electricity and gas; School A uses Q1 2026 electricity with oil retained at £0.085/kWh. This is an output-level diagnostic, not a recovered source-model run.

different electricity-accounting basis, not a boundary-equivalent continuation of the 2026 residual.

These projected reductions are not guaranteed building-level outcomes. They depend on external power-sector delivery and on the unchanged physical end state remaining valid. The defensible conclusion is conditional: early electrification exposes the asset's location-based operational emissions to future grid decarbonisation, while tariff, performance, connection capacity and residual accounting still require active management. They should not be read as a continuous like-for-like reporting series with the 2026 Scope 2 result.

4. Discussion

4.1. Durable and contingent conclusions under controlled rebasing

The most durable finding is not a single percentage but the distinction between the physical package and the vintage of its accounting inputs. The same reported energy quantities produce a 61.4% aggregate reduction under the 2022 source basis and 75.7% under the 2026 factor set. The package remains a partial current-factor decarbonisation outcome, but the size of the residual is highly factor-dependent. Reporting both vintages is more informative than silently replacing the historical result.

The controlled protocol also prevents a common category error. Tariffs and factors can be rebased without rerunning the model; schedules, weather, occupancy distribution, fabric performance, plant curves and controls cannot. The method's practical value lies in stating this decision boundary and classifying which conclusions survive it.

4.2. Exploratory capital-intensity observation

The four points show a monotonic increase in £/% with floor area, but the sample cannot determine whether this is caused by scale, scope, plant capacity, baseline carbon, procurement conventions or the denominator itself.

The capital-to-annual-abatement ratio provides a useful complementary denominator because it compresses the case spread, but it is still a one-year screening ratio. It should be used alongside absolute capital, £/m^2, peak electrical demand, lifecycle cost and deliverability rather than promoted as a universal funding metric.

A larger multi-authority and multi-consultancy dataset would be required to test economies of scale or funding design. The present result is best treated as a preliminary hypothesis: proportional indicators can move differently from absolute-abatement indicators across heterogeneous buildings.

4.3. Whole-package economics versus the incremental heat-system effect

The analysis distinguishes the whole-package end state from the incremental heat-system counterfactual. The whole-package end state asks whether the final reported package costs more or less to operate under a tariff set. The incremental counterfactual asks what happens when baseline delivered heat is replaced by ASHP electricity under explicit efficiency assumptions. Because fabric, lighting, controls and PV can offset ASHP electricity, the answers need not have the same sign.

That distinction is visible in the current-price results. The three gas cases show whole-package savings under the average tariff, while the central isolated ASHP counterfactual remains cost-positive. Higher SCOP, lower electricity prices or higher gas prices can cross the threshold; poor performance can widen the penalty. The appropriate conclusion is tariff- and performance-contingency, not universal ASHP bankability or unbankability.

The oil case remains structurally different because the displaced fuel is more expensive. Even so, the output-level counterfactual is not a design substitute: emitter temperatures, defrost, auxiliaries, capacity, DNO constraints and fabric interaction must be resolved at the next project stage.

For practitioners, package economics should therefore be reported in parallel with a technology counterfactual, and both should be recalculated using the actual procurement tariff. This avoids using package-wide PV or lighting savings to mask the operating-cost exposure of heat electrification.

4.4. Cumulative implications of sequencing

Integrating annual savings changes the interpretation of sequencing. S3 and S2 reach the same final annual reduction, yet S3 avoids about 371 tCO_2 more over eight years. The result supports early delivery of high-carbon measures when feasible, but it does not invalidate fabric-first engineering where load reduction is necessary for plant sizing, comfort or electrical capacity.

The sequencing curves remain heuristic because source-report allocations are not independent measure runs. Their valid use is programme timing: they show the carbon opportunity cost of deferral under a common allocation basis. A design-stage sequence should be re-evaluated with coupled simulations, disruption constraints, procurement lead times and post-installation verification.

4.5. Uncertainty, practitioner workflow and limitations

The scenario register distinguishes accounting uncertainty from physical uncertainty. Tariffs, dated factors and index multipliers can be propagated directly. SCOP and boiler efficiency can be explored as a simplified output-level test. U-values, ventilation, occupancy schedules and measure interactions require the original model because their effects are coupled. Treating all variables as equally amenable to spreadsheet sensitivity would create false precision.

The six-step workflow provides a practical gate for carrying old feasibility reports into procurement: reconcile the evidence; freeze or rerun the physical case; define the carbon boundary; update dated external inputs; classify the conclusion; and replace generic assumptions with site tariffs, DNO evidence and tendered costs. This is the principal implementation contribution of the study.

4.6. Transferability and generalisability

The study describes four schools in one estate and one consultancy methodology. It cannot estimate national distributions, economies of scale, typical heat-pump performance or preferred UK funding rules. Accordingly, all numerical conclusions are framed at the case-set level.

Analytical transferability remains possible where another programme uses similar feasibility-stage evidence. The audit questions – what is physical, what is exogenous, what is missing, and which conclusion changes sign – are portable even when the numerical results are not.

Future validation should draw on multiple authorities, consultancies, climate regions, school typologies and procurement routes, and should retain model files plus measure-only and combined runs. Post-retrofit monitoring would then allow the controlled rebasing method to be tested against realised rather than solely modelled performance.

4.7. Robustness register

Table 11 classifies each central conclusion by the evidence supporting it and the condition under which it may be used. The register deliberately distinguishes direct arithmetic from output-level scenarios and from conclusions that require new physical modelling.

5. Conclusion

This four-case study demonstrates a controlled way to audit ageing feasibility conclusions without pretending that a spreadsheet update is a

Table 11
Robustness register for the central case-set findings.

Finding	Evidence classification	Use condition / reason
2022 package reductions of 56.7–67.8%	Robust within case set ((source-report calculations)	Direct arithmetic from baseline and combined package values; not verified post-retrofit performance
2026-factor reductions of 72.5–78.8%	Accounting-contingent	Physical quantities fixed; result changes with dated location-based factors
Whole-package tariff sign	Tariff-contingent	Average and small-consumer bands produce different gas-case signs
Incremental ASHP cost	Conditional-fragile	Output-level η/SCOP counterfactual; measure-only model runs unavailable
Capital intensity rises across four cases	Exploratory	Monotonic observation only; $n = 4$ and common costing method
Capital-to-annual-abatement ordering	Robust as screening arithmetic	Not a lifecycle MAC; based on source-report allocations
Cumulative sequencing ranking S3 > S1 > S2	Conditional	Arithmetic is reproducible; physical measure interactions are unquantified
Future-grid residual decline	External-scenario contingent	Depends on projected consumption-based appraisal factors that include T&D; not guaranteed building delivery and not boundary-equivalent to the 2026 Scope 2 result

new building model. Under the 2022 source basis, the packages reduce reported operational CO_2 by 56.7–67.8% (aggregate 61.4%). Applying the 2026 Government factors to the unchanged physical quantities raises the case reductions to 72.5–78.8% (aggregate 75.7%), leaving a 21.2–27.5% location-based residual. The physical package has not improved; the accounting context has changed.

The economic conclusion is more conditional. Whole-package gas-case costs change from 13.3 to 16.4% increases under the 2022 tariffs to 5.1–13.1% savings under Q1 2026 average electricity and gas tariffs, yet the small-band proxy remains mixed and the central incremental ASHP counterfactual remains cost-positive for the gas cases. The oil result uses Q1 2026 electricity with the source-case oil price retained at £0.085/kWh and must not be read as a Q1 2026 oil-tariff observation. Sequencing also matters cumulatively: the carbon-led scenario avoids 1283 tCO_2 over eight years, compared with 1106 tCO_2 for fabric-first and 912 tCO_2 for cost-led sequencing. These are bounded case-set findings, not national estimates.

For public-estate programme owners, the audit supports six operational actions:

(1) Label baseline-to-final utility comparisons as whole-package outcomes unless non-ASHP and ASHP-only counterfactuals are available.
(2) Carry forward calibrated physical quantities only when the design, schedules, weather treatment and equipment assumptions remain unchanged; otherwise rerun the model [48].
(3) Update location-based factors, actual contract tariffs, DNO constraints and procurement costs at the decision date, retaining the historical result for auditability.
(4) Report cumulative tCO_2 avoided for programme sequences, not only the annual endpoint percentage.
(5) Use the capital-to-annual-abatement ratio only as a feasibility-stage screening metric and accompany it with lifecycle cost, absolute capital, electrical-capacity and deliverability evidence.
(6) State the operational-carbon boundary explicitly and present future grid decarbonisation as a separate appraisal scenario. Where future factors include transmission and distribution losses but the current reporting factor does not, report the boundary shift rather than presenting a single continuous series.

Further work should test the method on larger multi-source portfolios with retained model files, explicit measure-only and combined runs, end-use-resolved occupancy and weather normalisation, and post-retrofit monitoring. Those data would permit physical interaction, lifecycle economics, uncertainty distributions and stock-level scaling to be assessed without the inferential constraints of the present four-case synthesis.

Competing interests

The author contributed to data collection, model development, validation, report writing and quality assurance for the underlying 2022 feasibility studies. This relationship is disclosed because the manuscript is a secondary synthesis of professional project data. The controlled rebasing, counterfactual calculations, cumulative sequencing analysis and journal interpretation were undertaken independently after the consultancy work. No payment or sponsor input was received for this manuscript.

Declaration of generative AI and AI-assisted technologies

During preparation of this manuscript, the author used OpenAI ChatGPT for language editing. All source selection, assumptions, calculations, interpretations and final wording were reviewed by the author, who takes full responsibility for the manuscript.

CRediT authorship contribution statement

Harshul Singhal: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2026.118063.

Appendix B. Evidence-strength and uncertainty register

Data availability

The numerical dataset is derived from four project-specific 2022 decarbonisation feasibility reports prepared by the author for a UK local authority. The reports remain confidential because they contain identifiable school and client information. Supplementary Data S1 provides the anonymised provenance register, exact package calculations, calibration statistics available in the retained evidence, missing-information audit, source-report allocation reconciliation, controlled 2026 rebasing, whole-package tariff tests, simplified ASHP counterfactual, cumulative sequencing calculations and scenario register. It does not reconstruct unavailable source-model inputs.

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