Pathways to improving the school stock of England towards net zero

RESEARCH

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ABSTRACT

A disaggregated (school-level) analysis of the retrofit potential of primary and secondary schools of England is presented, using data from a highly detailed database of the energy use and characteristics of the school stock. The overall carbon emissions reduction potential for the stock is explored under different packages of retrofit measures, as well as how the rollout of those measures between the present and 2050 might shape the pathways towards net zero. Even with a fixed set of assumptions about what measures are implemented and at what rate, it is shown that decisions about the deployment process can greatly affect the annual and cumulative emissions of the overall stock over the coming decades. Under certain scenarios, decisions about the criteria used to define the school retrofit order can result in a doubling of cumulative emissions by 2050, or impact whether the interim 2035 target is met.

POLICY RELEVANCE

The performance of England's primary and secondary schools, and how it might improve in the context of long-term carbon emissions reduction targets, is shown. The paper quantifies how decisions about the deployment of retrofits determine the pathways that the stock will take towards net zero. The analysis shows considerable emissions reductions are feasible, through a mix of building envelope improvements, conversion to electric heating, rooftop photovoltaics and aided by projected improvements to the grid. However, the results show that—even with a high deployment rate (650 schools/year to retrofit all schools by 2050)—the approach taken to deploying those retrofits (*i.e.* the policies and guidance that dictate which schools are prioritised for improvement) will determine the long-term performance of the overall stock and whether or not interim emissions targets can be met.

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1. INTRODUCTION

Within the UK, the education sector represents an important part of the building stock. Schools account for 2% of national annual emissions and 15% of the public sector total (BEIS 2020). If the country is to meet its target of net zero emissions by 2050, improving the performance of the school stock will therefore be crucial (HMG 2019). Furthermore, due to its position in society, it has been noted that the sector represents not just an opportunity for emissions reductions but also a chance to engage young people in the topic of sustainability (DECC 2014).

In the context of the national emissions reduction targets, as well as the public sector-specific goals, the Department for Education (DfE) are committed to making considerable improvements to the performance of the school building stock (DfE 2022a). This includes supporting both theoretical research as well as practical pilot study initiatives, including the Energy Pods project, a rollout of prefabricated low-carbon heating plant retrofits (DfE 2022a); GenZero, new building standards for ultra-low carbon new school constructions, considering embodied as well as operational carbon (DfE 2022c); the Priority School Building Programme, which provided funding for refurbishing and rebuilding schools (ESFA 2016); and the School Rebuilding Programme, which will undertake major retrofit/rebuild projects (DfE 2022d). They will also set school carbon emissions reduction targets between 2025 and 2035 in conjunction with the Let's Go Zero campaign (Ashden & GAP 2022).

Over 24,000 school establishments exist (ONS 2022). Retrofitting England's schools will require considerable effort and cost over an extended period of time. Official figures are not readily available, but one simple analysis estimated a cost for converting the current school stock to net zero of £14 billion over and above the £11 billion already needed for general building maintenance and upkeep (Energise 2021). In order for such a large, long-term and costly undertaking to be successful, it is necessary to gain a better understanding of not only the overall improvement potential, but also the impact of the deployment process itself. This is because the cumulative emissions and costs will be determined by the shape of the overall pathway to 2050, even if individual reduction targets are met for specific years (Lowe & Oreszczyn 2020). For example, while the 2035 emissions reduction target could be met at any point between now and then (depending on how quickly building improvements are undertaken), the 'cost' of starting the process later would be higher cumulative emissions overall, as well as possibly higher fuel costs. Several recent documents have highlighted the importance of the deployment process when improving the building stock. Considering different scenarios for retrofitting the national building stock, emissions reductions by 2035 have been estimated to range from 45% to 65% depending on factors including the timings, costs and technical performance (CCC 2020a). Elsewhere, a recent economic analysis to test the 'assumptions about the timing and smoothness of action to deliver the transition [to net zero]' found that delaying action on climate change to 2030 would result in higher national debt and 50% higher costs overall (OBR 2021). Specifically in schools, the need for more information is acknowledged in the recent DfE strategy document that notes that:

> There is still a lot of evidence to gather on new technologies and innovative approaches to sustainable building design, retrofit, ICT [information and communications technology], building management and the surrounding environment. Our focus until 2025 will be piloting—gathering evidence and sharing research to learn from our experience. [...] From 2025 onwards, we will accelerate change once we understand the best value for money approach.
>
> (DfE 2022a)

This paper builds on a significant body of work undertaken to date to explore energy performance in the school stock (Hong *et al.* 2022; Schwartz *et al.* 2021, 2022; Godoy-Shimizu *et al.* 2021). It uses a highly detailed database to examine the potential for reducing emissions, with a focus on primary and secondary schools in England, which account for approximately 85% of schools in England by count (DfE 2017). A simple model was produced that uses this database to quantify the impact of different scenarios for rolling out retrofits between now and 2050. The model evaluates each school individually, allowing retrofit pathways for the stock to be defined and assessed at a disaggregate level (*e.g.* What is the impact of retrofitting school A in 2030 or 2040?). The paper has the following broad aims:

- To examine the overall potential for improving the primary and secondary school stock of England, and how close this gets to achieving net zero,
- To explore how decisions about the way that retrofits are rolled out (in terms of timing, retrofit order and any wider restrictions) impact on the longitudinal performance of the stock.

2. LITERATURE REVIEW

Historically, data on the performance of the school stock has been available through a wide range of sources. During the 1990s, for example, the Building Research Establishment (BRE) and Department of the Environment, Transport and the Regions (DETR) published documents providing guidance on the performance and improvement potential of schools. These included energy consumption benchmarks based on data from several thousand schools in the late 1980s and mid-1990s (BRE 1991, 1998). In the early 2000s, updated benchmarks covered water use as well as energy (DfE 2004). While those documents represent releases of aggregated schools' performance data, the Display Energy Certificate (DEC) scheme, introduced in 2008, involves the collection and publication of annualised electricity and fossil–thermal energy data on large public non-domestic buildings, including schools, on a disaggregate basis (DCLG 2015).

Information on the physical characteristics of school buildings and the systems within have also been available from multiple places. The online database Edubase (recently renamed 'Get Information About Schools'—GIAS), for example, while primarily providing information on students, staffing and exam performance, also includes school status, capacity and location data (DfE 2017), as well as annual expenditure on energy use and building maintenance via the linked School Financial Benchmarking database (DfE 2018). The DEC database meanwhile includes information on heating, ventilation and air-conditioning (HVAC) systems (the presence of air-conditioning or mechanical ventilation, special energy end uses, renewables, and the main heating fuel) alongside the energy use figures mentioned previously. Further details, including occupancy metrics, are also used in the DEC process, but these were excluded from the public data release at the time of writing (DLUHC 2022).

In recent years, national surveys have been commissioned to better understand the make-up and condition of the education estate. The Property Data Survey Programme (PDSP) and Condition Data Collection (CDC) schemes were surveys of the English school stock carried out in 2012–14 and 2017–19, respectively (EFA 2015; ESFA 2017). These gathered detailed information on variables including the building envelopes, internal uses, systems and condition of the stock through visual inspection. A follow-up, CDC2, is currently underway and due to finish in 2026 (DfE 2021b).

Numerous studies have analysed the above data to examine the condition and performance of the education sector of the UK. The data have shown, for example, that almost half of the school stock by area was constructed before the 1970s (DfE 2021a), when building regulations covering the conservation of fuel and power for new non-domestic buildings were introduced (King 2007). As expected, construction age has been shown to be strongly linked to maintenance needs, with average estimated costs per m^2 for remedial works dropping considerably for schools constructed post-1980 (DfE 2021a). Age and condition have been shown to be correlated to differences in energy performance, with higher typical fossil–thermal energy use associated with poorer heating plant and controls conditions (Hong *et al.* 2022). A study of DEC energy use matched to detailed energy audits for 150 English schools also found marked differences in energy use with school construction (Mohamed *et al.* 2021). Electricity use was found to be highest in modern constructions, potentially due to increased ICT use, in line with past findings (GAP *et al.* 2006). Heating use was highest in schools built during the 1945–70 post-war period, which is noted to be associated with lightweight construction and large windows—features linked to increased thermal loss. Statistical analyses have also been used to identify those variables that are strong determinants of school energy use, including ventilation type, occupancy and form factors (Hong *et al.* 2014, 2022). The DEC data have been used to produce the latest school energy benchmarks published by CIBSE (2021) and, since energy data are available for multiple years, some studies have assessed the longitudinal changes in school performance. These have found falling fossil–thermal and rising electricity use between the 1990s and early 2010s (Godoy-Shimizu *et al.* 2011), with fossil–thermal continuing to fall and electricity remaining relatively steady thereafter (Hong *et al.* 2019). Finally, several studies have examined the relationship between building renovations/rebuilds with student attainment, generally finding little long-term correlation (Williams *et al.* 2015; Ive *et al.* 2015).

Numerous studies have explored the retrofit potential of the national school stock, generally using some of the above-mentioned data as inputs to building simulation. A probabilistic model applied to London secondary schools estimated the reduction in gas use from roof insulation and building fabric air tightness measures to be 4% and 11%, respectively (Tian & Choudhary 2012). Elsewhere, information from telephone interviews and surveys was integrated with existing data to model the energy breakdown and retrofit potential for the national non-domestic building stock (BEIS 2016). Considering the education sector as a whole (including colleges and universities), the abatement potential was estimated to be 45% reduction in total energy, with 'building instrumentation & control measures, carbon & energy management and space heating' having the largest predicted impact.

Applying building simulation to four school archetypes, an analysis of different combinations of retrofit measures on life cycle carbon and costs found that replacing the existing heating plant had the largest predicted impact on energy and carbon, ahead of envelope measures such as draughtproofing and additional insulation (Bull *et al.* 2014). An archetype London primary school was also used to test a new exergy-based retrofit model, capable of considering factors such as economic impact and thermal comfort as part of multi-optimisation analyses (Kerdan *et al.* 2016, 2017). More recently, a school stock model was produced using 168 archetypes for the primary school stock of England (Schwartz *et al.* 2021). This was expanded to evaluate overheating risk and indoor environmental quality (IEQ) metrics, and showed that energy retrofits (specifically wall insulation, double-glazing and external shading) could negatively impact IEQ and, conversely, that some IEQ measures will increase heating demand (Grassie *et al.* 2022).

The potential need for increased mechanical ventilation or cooling was also identified in earlier modelling of archetype primary and secondary schools in London and Edinburgh (Jenkins *et al.* 2009). Moving beyond archetype-based approaches, a new model has recently been developed capable of running dynamic simulation for the school stock on a one-by-one basis (Schwartz *et al.* 2022). Using PDSP linked to detailed geographical information system (GIS)-based geometry data from Ordnance Survey, this model can automatically generate and run accurate models for almost half of schools within PDSP, based on the currently available data.[1]

3. METHODS

The methods for this study involved two main parts. First, the production of a large database of the English school stock; and second, modelling the impact of different retrofit pathways using the database.

- *Unified Schools Database*

  An initial iteration of the schools database was created previously (Hong *et al.* 2022); for the present study, data were added from the CDC, the aforementioned national survey of the English school stock (DfE 2021a). Section 3.1 describes the processing and integration of this new dataset, as well as the preparation of the database for the retrofit pathways analyses. Papers are available covering the creation of the original database (Hong *et al.* 2022), as well as its application in energy analyses (Schwartz *et al.* 2021, 2022; Godoy-Shimizu *et al.* 2021).

- *Retrofit pathways*

  Section 3.2 details the retrofit assessment methodology and the modelled scenarios. In line with the overall objectives outlined previously, a simple approach was adopted to enable school-level assessments to be made for the entire stock at a disaggregate level. The modelling and assumptions used are explained, as are the potential impacts of any methodological limitations. As the analysis is part of long-term research into the school stock, future work including potential improvements are discussed in the conclusions.

3.1 SCHOOLS DATABASE

Before the present study, a fully disaggregate database of the English school stock (the Unified Schools Database) was created using data from three key sources introduced previously: Edubase, DECs and PDSP:

- Edubase/Get Information About Schools is the central register of all schools and colleges in England (DfE 2017). From this database, variables including school type, status and capacity were used. Edubase has been used as the spine of the Unified Schools Database.
- From the DEC database, key performance data were gathered in the form of the annualised electricity and fossil–thermal energy consumption figures, alongside key variables such as the main heating fuel, total floor area and internal environment (DCLG 2015).
- The PDSP survey, from 2012 to 2014, covers 86% of schools in England (EFA 2015). From this, variables used included various factors known to influence performance, including construction dates, built form and internal uses.

For the present study, data from the CDC have been incorporated into the Unified Schools Database. A successor to the PDSP, the CDC survey, undertaken during 2017–19, gathered updated and more detailed information about the condition of the English school stock (DfE 2021a). The raw CDC files consist of multiple tables, with millions of rows, covering 22,031 schools[2] as well as building form, envelope, building services systems and internal uses; with a 'condition' grade (rated A–D from visual inspection) for each of these variables. Data are provided at a block level[3] in terms of proportions of totals, enabling characteristics to be assessed in terms of detailed breakdowns. For example, for each school (or school block) the floorspace with different ventilation systems can be calculated, or the breakdown of different wall types, or the proportion of electrical services in need of immediate repair.

The processing steps undertaken for the CDC data were in line with those used for the PDSP (Hong *et al.* 2022): the data were tidied, and aggregated to a school scale, with checks to ensure that totals added up where appropriate. Elements with gaps, inconsistencies or unreasonable values (*e.g.* internal use breakdowns not adding to 100%) were identified and flagged or removed, amounting to 0.4% of schools. The school unique reference number (URN) was used to match the CDC to the Unified Schools Database.

3.1.1. Data coverage

Within the database, data coverage is not complete. This reflects the scale of the original datasets, changes in the stock that may have occurred since their collection, as well as any issues arising from the data-processing and matching steps. For the present study, missing data were estimated using distributions from the available data, split by school type. For example, since 7.2% of the primary schools *with* age data have an overall construction date of 'pre-1900', 7.2% of the primaries *without* a construction date were assumed to be built 'pre-1900'. Variables were randomly assigned across the schools with missing data, as summarised in Table 1.[4] Figure 1, meanwhile, shows the distribution of real and estimated data for each variable. The total counts of each school type across England in 2019 are included in brackets. Where available, 2019 energy data were selected, as the most recent year with energy data before the school closures due to the pandemic in early 2020 (Adams & Stewart 2020). Since the present study focuses on primary and secondary schools only, other school types (*e.g.* nurseries or special educational needs schools) were excluded from the analyses and are not shown. Additionally, 92 primary/secondary schools were excluded for having unlikely data.

VARIABLE		SOURCE	
TYPE	**DETAIL**	**WHERE SCHOOL-SPECIFIC DATA ARE AVAILABLE**	**WHERE SCHOOL DATA ARE UNAVAILABLE**
Area	School total floor area (m^2)	*School-specific data:* Total floor area from CDC data	*Partial schools data:* Where available, school capacity (number of students) from the Edubase is multiplied by the mean student density for the type (m^2/pupil) *Aggregate data:* Where capacity is unavailable, schools are randomly assigned a floor area decile for the type
Age	School construction date (10-year bands, from pre-1900 to post-2010)	*School-specific data:* Age band from CDC data. Where a school has blocks built at different times, the largest age band by floor area is selected	*Aggregate data:* Where age data are unavailable, schools are randomly assigned an age band based on the distribution of known ages for the school type
Roof	Total roof area (m^2)	*School-specific data:* Total roof area from CDC data, excluding skylights	*Aggregate data:* Where roof data are unavailable, the total floor area is multiplied by the mean roof-to-floor area ratio for the type
Heating plant condition	Overall grade (A–D, based on visual inspection)	*School-specific data:* Overall condition grade for the heating plant. Where a school has a multiple plant, an area-weighted grade is produced	*Aggregate data:* Where plant condition is unavailable, schools are randomly assigned a grade based on the distribution for the school type
Fuel type	Main heating fuel (gas, electricity, oil, *etc.*)	*School-specific data:* Main heating fuel from the most recent DEC (excluding 2020)	*Aggregate data:* Where fuel data are unavailable, schools are randomly assigned a fuel type based on the distribution for the school type
FTH and Elec EUI	Annual energy intensity for space and water heating (weather corrected) and (non-thermal) electricity (kWh/m^2)	*School-specific data:* Most recent DEC energy data used (excluding 2020) where available	*Aggregate data:* Where fuel data are unavailable, schools are randomly assigned an EUI decile based on the school type and main heating fuel. For electrically heated schools, the electricity for space and water heating is estimated based on the ratio of FTH to Elec for the school type

Table 1: Summary of the variables used for the retrofit analyses.

Note: CDC = Condition Data Collection; DEC = Display Energy Certificate; EUI = energy-use intensity; FTH = fossil thermal.

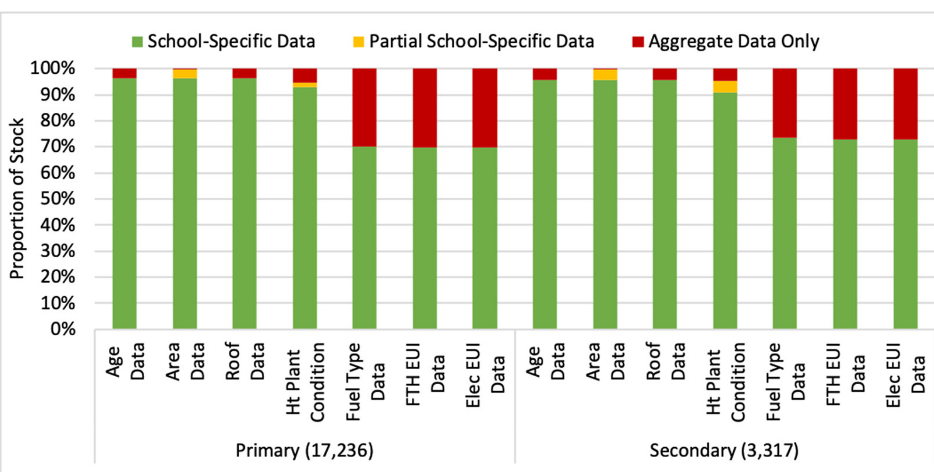

Figure 1: Distribution of data for the current school stock, within the Unified Schools Database.

As shown in Figure 1, the coverage within the Unified Schools Database is high (> 95% of schools have data on age, form and heating plant condition, and approximately 70% have energy data); however, the approach taken for filling in the gaps has some shortcomings. For example, the unknown variables were treated as independent, but school age is linked to small differences in performance (Hong *et al.* 2022). Furthermore, the characteristics of the schools with known data may not be fully representative of those without.

The Unified Schools Database is a large database consisting of multiple tables, with the preparation and all subsequent queries/analyses carried out in PostgreSQL v9.5.24 (PGDG 2022). For the present study, the disaggregate data for the 20,000 primary and secondary schools in England (Figure 1) were exported and the subsequent retrofit pathways calculations were then carried out in a large MS Excel file.

3.2 RETROFITS PATHWAYS

The retrofit pathways were assessed with three types of measures: (1) improving building envelopes, (2) replacing existing heating plant and (3) installing renewable technologies. In line with the paper's aims, these were evaluated for each school using simple assumptions, described with examples below.

- *Envelope improvements*

  The impact of envelope measures has been treated as percentage reductions in annual space heating energy, as summarised in Table 2 (columns 4–6). These figures are adapted from Bull *et al.* (2014), a building simulation-based study on the impact of wall, roof, glazing and infiltration improvements to archetypical schools of different construction eras.[5] Three levels have been defined (A–C), corresponding with increasing thermal performance. It has been assumed that 80% of thermal energy is for space heating and 20% for water heating (Hong *et al.* 2014). Under this approach, a 1950s' school with 100 kWh/m[2] current gas thermal demand would have 79.2 kWh/m[2] gas demand following type B envelope improvements, calculated as:

  $$(100 \times 0.8 \times [1 - 0.26]) + (100 \times 0.2),$$

  using $Q_{tr} = (Q_{tc} \times F_{th} \times [1 - F_{er}]) + (Q_{tc} \times [1 - F_{th}])$,

  where Q_{tc} and Q_{tr} are the current and post-retrofit annual thermal energy intensities, respectively; F_{th} is the fraction of thermal energy associated with space heating; and F_{e} is the expected reduction in space heating following the envelope improvement measures.

- *Heating plant*

  This has been treated as replacing the existing space and water heating plant (assumed to have an average efficiency of 86%, or 100% for electrically heated schools[6]), with a heat pump with an average coefficient of performance (COP) of 2.5 for space heating and electric water heating with an efficiency of 100% (HMG 2014). Therefore, a school with 100 kWh/m[2] current gas thermal demand would have 44.72 kWh/m[2] electricity thermal demand following this measure, calculated as:

  $$([100 \times 0.8 \times 0.86]/2.5) + ([100 \times 0.2 \times 0.86]/1.0),$$

  using $Q_{tr} = ([Q_{tc} \times F_{th} \times \eta_{hc}]/\eta_{hr}) + ([Q_{tc} \times \{1 - F_{th}\} \times \eta_{wc}]/\eta_{wr})$

  where η_{hc} and η_{hr} are the current and post-retrofit space heating efficiencies; and η_{wc} and η_{wr} are the current and post-retrofit water heating efficiencies. Schools currently served by biomass heating were excluded from this measure.

- *Renewables*

  This has been assumed to be the installation of roof-mounted photovoltaics (PV). Table 2 (column 7) shows the assumed proportion of viable roof space, based on an analysis of the solar potential of 802 primary schools in London (Godoy-Shimizu *et al.* 2021). 'Viable' roof space was calculated in terms of the technical potential for PV, without the consideration of practical factors such as finances. Average annual electricity generation was assumed to be 125, 116 and 109 kWh/m[2] for south, mid- and northern England, respectively, scaled

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from Burnett *et al.* (2014). Therefore, a 1950s' school in London with 1000 m^2 of roof would generate 65,000 kWh of electricity per year, calculated as 1000 × 0.52 × 125.

Retrofit pathways for the stock will be determined by school-level factors (*e.g.* the retrofits applied to each school, and the resulting change in energy use), stock-level factors (*e.g.* how and over what period the retrofits are deployed across the stock), and external factors (*e.g.* the future grid improvement). Therefore, the above-described school-level assessments were scaled up in the context of stock-level drivers to calculate the retrofit pathways. For example, for a scenario examining the impact of rolling out a package of retrofits at a rate of 50 schools/year, over a 20-year period: First the current and post-retrofit energy use is calculated for each school. Next, each school is ranked in terms of the rollout drivers in the scenario to determine if/when they are improved (*e.g.* if retrofits are to be rolled out on the basis of construction date, then the 1000 oldest schools within the stock would be identified and ordered over the retrofit period). Finally, the overall performance of the stock is calculated for each year from the pre- or post-retrofit energy for each school as appropriate.

Schools identified within Edubase as being scheduled to close were assumed to be exempt from all retrofits (5.5% of schools). For future projections, the carbon emissions associated with mains electricity were calculated using the commercial, consumption-based projections from the Green Book's supplementary tables (BEIS 2021). It should be noted that this suggests very large reductions in carbon intensity of the grid in the coming decades; reaching 0.05 kgCO_2/kWh in 2030, compared with current values of approximately 0.2 kgCO_2/kWh. The impact of this assumption, especially on the relative benefit of electrification of heating compared with demand-reduction measures, is discussed below.

Table 2: Assumed impacts of envelope improvement measures and photovoltaics (PV).

SCHOOL AGE	DISTRIBUTION OF SCHOOL AGE OVER STOCK (%)		REDUCTION IN SPACE HEATING DEMAND (%)			ROOF AREA SUITABLE
–	PRIMARY	SECONDARY	OPTION A	OPTION B	OPTION C	FOR PV (%)
Pre-1900	0.07	0.00	0.20	0.35	0.50	0.32
1900–10	0.04	0.00	0.19	0.34	0.48	0.32
1911–20	0.04	0.00	0.18	0.32	0.46	0.32
1921–30	0.04	0.01	0.17	0.31	0.44	0.43
1931–40	0.05	0.02	0.16	0.29	0.42	0.43
1941–50	0.05	0.04	0.15	0.28	0.40	0.43
1951–60	0.10	0.08	0.14	0.26	0.38	0.52
1961–70	0.19	0.21	0.13	0.25	0.36	0.52
1971–80	0.17	0.22	0.12	0.23	0.34	0.61
1981–90	0.09	0.11	0.11	0.22	0.32	0.55
1991–00	0.05	0.05	0.10	0.20	0.30	0.55
2001–10	0.05	0.12	0.00	0.00	0.00	0.55
2011–20	0.04	0.13	0.00	0.00	0.00	0.55

Reflecting the simplified method of estimating the impact of each retrofit, several limitations, as well as factors outside the scope of the present analyses, could benefit from a more detailed modelling approach. Assessing annual energy means that temporal factors are not considered which is important for quantifying the proportion of PV-generated electricity that can be used on-site, for example, especially in schools (Clochet *et al.* 2022). Related factors, such as the grid's capacity to cope with increased electricity use or generation (through electric-heating PV, respectively) are outside of the scope of the study. The current approach also effectively assumes that each school's underlying demand is constant. Thus, rebound effects or the impact of climate change, such as a reduction in future space heating needs, are outside of the scope, as are more drastic changes such as an increase in air-conditioning (BEIS 2021c). Non-space/water heating uses of fossil fuel are also not considered, most notably cooking; past studies have estimated that catering accounts for 7.5% of total energy in the education sector (BEIS 2016). While the analyses represent a theoretical potential for the stock, specific building factors may limit how much is achievable in practice. For example, schools with listed buildings and those in conservation areas will have restrictions on the types of improvement measures allowed (Historic England 2018). For a proportion of the stock, some measures may also be 'hard to treat' and financially or practically unviable. Similarly, a proportion of schools have existing PV (or solar hot water) installations. Unfortunately, detailed information on these systems is unavailable, but these cases would represent a reduction in the space available for further rooftop PV. Finally, since this study explores the potential for changes to the existing school stock, new constructions are not considered. For context, best practice targets for new schools are 65 kWh/m^2, with 15 kWh/m^2 for space heating (GPF 2021; LETI 2020), and a recent strategy document suggests that:

> all new school buildings delivered by DfE (not already contracted) will be net zero in operation.
>
> (DfE 2022a)

3.3 RETROFIT SCENARIOS

Several scenarios have been tested to explore the impact of improving the primary and secondary schools of England. To quantify not just the potential of the stock as a whole, but also how decisions on the rollout process impact on the transition period, these scenarios have been defined on the basis of the following three factors:

- *Retrofit measures*

  The measure, or combination of measures, being applied to the schools will determine the overall improvement potential of the stock. For the present paper, packages of retrofits have been defined additively; envelope measures only (step i), envelope measures plus heat pumps (step ii), and envelope measures, heat pumps plus rooftop PV (step iii). Each of the three levels of envelope measures have been tested (Table 2, options A–C). Thus, a total of nine packages have been tested, labelled as Ai-Aiii, Bi-Biii and Ci-Ciii.

- *Rollout rate*

  While the choice of retrofits will define the final (post-improvement) state of the stock, decisions about how those retrofits are rolled out will determine the performance and carbon emissions over the rollout period. For the present study, three different (steady) rollout rates have been tested (250, 500 and 650 schools/year). For context, the School Rebuilding Programme is aiming to achieve 50 major school retrofits per year (DfE 2022b). It should be noted that given the number of schools, rates of 250 and 500 schools/year only result in 36% and 73% of the stock being improved during 2020–50, respectively.[7] Additionally, three different 'full rollout' starts were tested (starting in 2020, 2030 and 2040, with rates scaled up to ensure complete improvement of the stock).

- *Rollout driver*

  In addition to the retrofit measures and rollout rate, choices about the order that schools are selected for improvement will also influence the overall performance of the stock (*e.g.* through policies around when retrofits are required or how funding should be allocated). For example, retrofits could be deployed on the basis of emissions reduction potential (improving schools from largest to lowest predicted improvement), or current performance (improving schools from highest energy users to lowest). Deployment could also be linked to non-energy factors (*e.g.* based on the current condition, or student performance). For the present study, the following drivers have been tested: improving based on predicted emissions reduction, current energy performance and heating plant condition.

4. RESULTS AND DISCUSSION

This section presents the results of the analysis. First, section 4.1 examines the overall impacts of the nine packages of retrofit measures on the school stock, in terms of energy and emissions. Next, the longitudinal impacts of the rollout rate and drivers are explored in section 4.2. Where appropriate, the projected changes in school emissions are compared with national targets for 2035 and 2050: 78% and 100% reductions in emissions compared with 1990 levels, respectively (BEIS 2021d; CCC 2020a).

4.1 RETROFIT MEASURES

Figure 2 presents the predicted impact of the nine retrofit packages on the overall school stock energy use, compared with current performance.

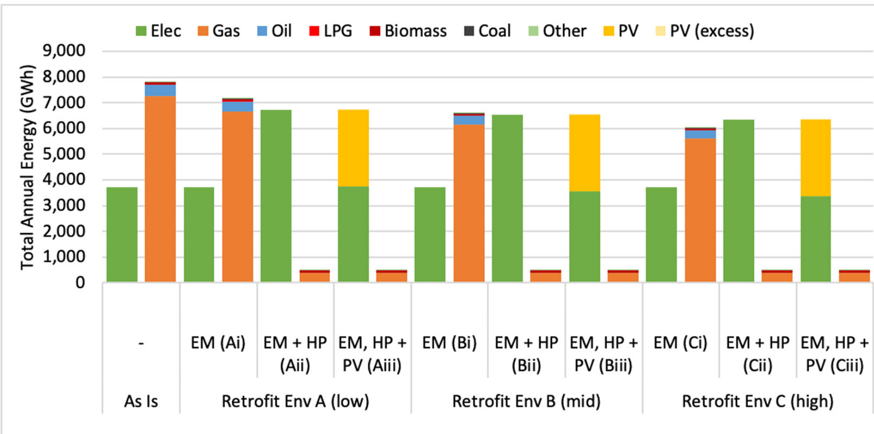

Figure 2: Total energy consumption following each package of retrofit measures.

Note: EM = envelope measures; HP = heat pump; PV = photovoltaics.

The results suggest that, using envelope measures alone, the expected impact on energy use is relatively low. As the dominant space-heating fuel in education buildings, gas consumption might fall by 8–23% (for envelope measures A–C), but this amounts to a drop in total energy use of only 6–16%. The results for envelope A are in line with the Building Energy Efficiency Survey (BEES) project findings, which estimated the abatement potential of fabric measures in primary and secondary schools as 9% and 6% reductions in non-electricity and total energy use, respectively (BEIS 2016). As expected, a transition to heat pumps will result in a considerable rise in electricity use (71–82% compared with current levels), although this is less than the corresponding drop in fossil fuel consumption, reflecting the differences in plant efficiencies. In line with past analyses, the results suggest considerable opportunities for on-site generation (Godoy-Shimizu *et al.* 2021). The results suggest that rooftop PV could generate almost half of electricity demand within the school stock under a conversion to all-electric heating. However, it should be noted that this represents a change in annual net use: for any given school, the proportion of generated electricity that can be used, rather than sold to the grid, will depend on the profiles of electricity generation and demand, as well as factors such as the presence of storage. Despite an overall reduction in energy consumption, the heat pump scenarios without PV may result in a net *increase* in fuel costs, depending on the relative price of gas and electricity: based on 3 and 14 p/kWh, for example, total fuel costs for the stock would rise by 12–18%.[8]

Figure 3 shows the total emissions of the school stock for each package of measures. The post-retrofit figures have been calculated based on the expected carbon intensity of the grid in 2030. Since this will result in a drop in the emissions *even without making any improvements to the buildings at all*, the performance of the current stock is presented in terms of both the current condition and 2030. The carbon intensities for gas, biomass, coal, liquefied petroleum gas (LPG), oil and other, respectively, have been assumed to remain constant at 0.18, 0.04, 0.39, 0.21, 0.27 and 0.21 $kgCO_2/kWh$, while the grid is 0.21 and 0.05 $kgCO_2/kWh$ in 2019 and 2030, respectively (BEIS 2021).

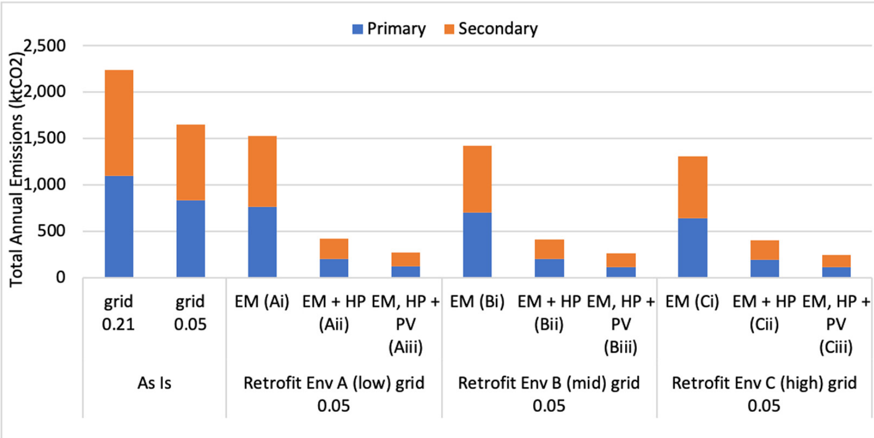

Figure 3: Total emissions of stock following each package of retrofit measures.

Note: EM = envelope measures; HP = heat pump; PV = photovoltaics.

The results suggest that, even leaving the buildings as is, total emissions from schools will fall by a quarter by 2030 if the projected improvement to the grid is achieved. Without a corresponding major reduction in the carbon intensity of gas, the fabric-only scenarios are only expected to result in an additional 6–16% drop. Converting schools to all-electric would enable more of the energy consumption of the stock to benefit from the projected improvements to the grid, with overall emissions reductions of over 80% compared with current levels. While this is largely driven by the future grid carbon intensity, even assuming 0.10 $kgCO_2$/kWh were achieved (projected for around 2026; BEIS 2021) emissions reductions of almost 70% would still be reached under the 'envelope + heat pump' scenarios. Of course, a large-scale transition to heat pumps could also encourage greater use of cooling, especially in the context of a warming climate, which would increase electricity demand and reduce the emissions drop accordingly. It should be noted that the ability of PV to offset any remaining fossil fuel use is greatly reduced as the carbon intensity of the grid falls relative to that of the fossil fuels. Naturally, if mains gas were improved in the same order of magnitude as the projections for the grid (*e.g.* through the injection of biogas or hydrogen), then this would strongly affect the environmental benefits of PV as well as electric heating.

4.2 RETROFIT ROLLOUT

The above results represent the expected total impact of the different retrofit packages on the stock. In practice, however, such large-scale improvements are only likely to be possible over a long timescale. Therefore, along with deciding *which* retrofits are made, decisions about *how* and *when* improvements are deployed will also be crucial.

4.2.1. Rollout drivers

Figure 4 presents the impact of different rollout drivers on the overall annual schools' energy use and emissions between 2020 and 2050 (note that the grid projections include an increase in carbon intensity around 2024, hence the slight bump in emissions in Figure 4b). Key results are summarised in Table 3. In each scenario, package Biii (envelope B, heat pump and PV) has been applied at a constant rate of 650 schools/year. Thus, in all scenarios, all schools have been retrofitted by 2050 and the final performance of the stock is identical; the only difference is the order in which the schools are improved, as explained below:

A1. 'CO_2 impact' scenario: roll out from the schools with the highest predicted total emissions reduction to the schools with the lowest.

A2. 'Current EUI' scenario: roll out from the schools with the highest current total energy-use intensity (EUI) to those with the lowest.

A3. 'Heating plant' scenario: roll out from the schools with heating plant in the worst condition to those with the best condition plant.

A4. 'CO_2% impact' scenario: roll out from the schools with the highest predicted percentage emissions reduction to those with the lowest.

A5. 'CO_2 impact (reversed)' scenario: roll out from the schools with the lowest predicted total emissions reduction to those with the highest.

In each scenario, ties in the ranking process were broken through random draw. Therefore, for example, for scenario A3, the predicted emissions reduction for each school is calculated and ranked to determine the retrofit order. If multiple schools have identical predicted reductions, then their order is randomly assigned.

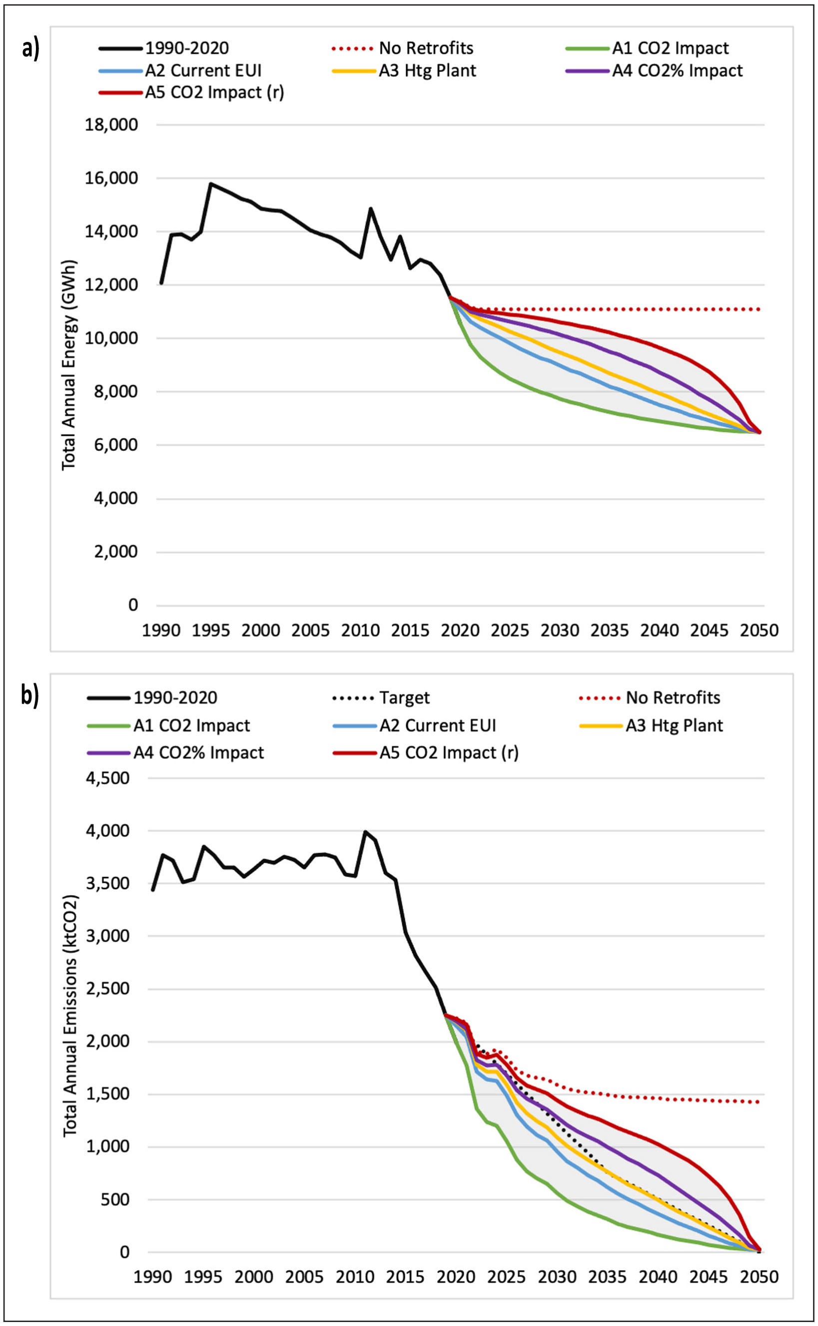

Figure 4. Impact of different retrofit rollout drivers on annual energy use **(a)** and emissions **(b)**.

The individual lines show the results for trajectories A1–A5. A1 and A5 represent the fastest and slowest possible rates of emissions reduction, respectively. Thus, the shaded area bound by these lines represents the full range of possible improvement trajectories for the stock, for the given package of measures and rollout rate. The energy and emissions are shown from 1990[9] for context. Historic performance has been estimated back to 2010 using DEC data, and further back by scaling from aggregate energy data, with linear interpolation used to fill in gaps in the available data (BEIS 2020; Hong *et al.* 2022). Finally, the dotted lines represent the linear trajectory to meet the 2035 and 2050 emissions reduction targets (in black) and leaving the stock as is (in red).

The results highlight the impact that the choice of rollout drivers will have in large-scale long-term building improvement programmes. Considering the individual scenarios, rolling out retrofits to those schools with the highest predicted improvement potential first (scenario A1) or those with the highest current energy use first (A2) result in quicker emissions reductions compared with prioritising those schools with the worst heating plant or the greatest predicted percentage improvement first (A3 and A4, respectively). Significantly, comparison with the target trajectories highlights how difficult the 2035 target may be to achieve, even with the high rate of deployment assumed. The point that any given trajectory will meet the 2035 target can be seen on Figure 4b by tracking horizontally from 2035 on the black dotted line. The shaded area width shows that, for this set of retrofits and rate, a 78% reduction in emissions compared with 1990 levels could be reached between 2028 and 2045, depending on the rollout driver. Amongst the scenarios tested, only A1 and A2 are expected to achieve the 78% target by 2035.

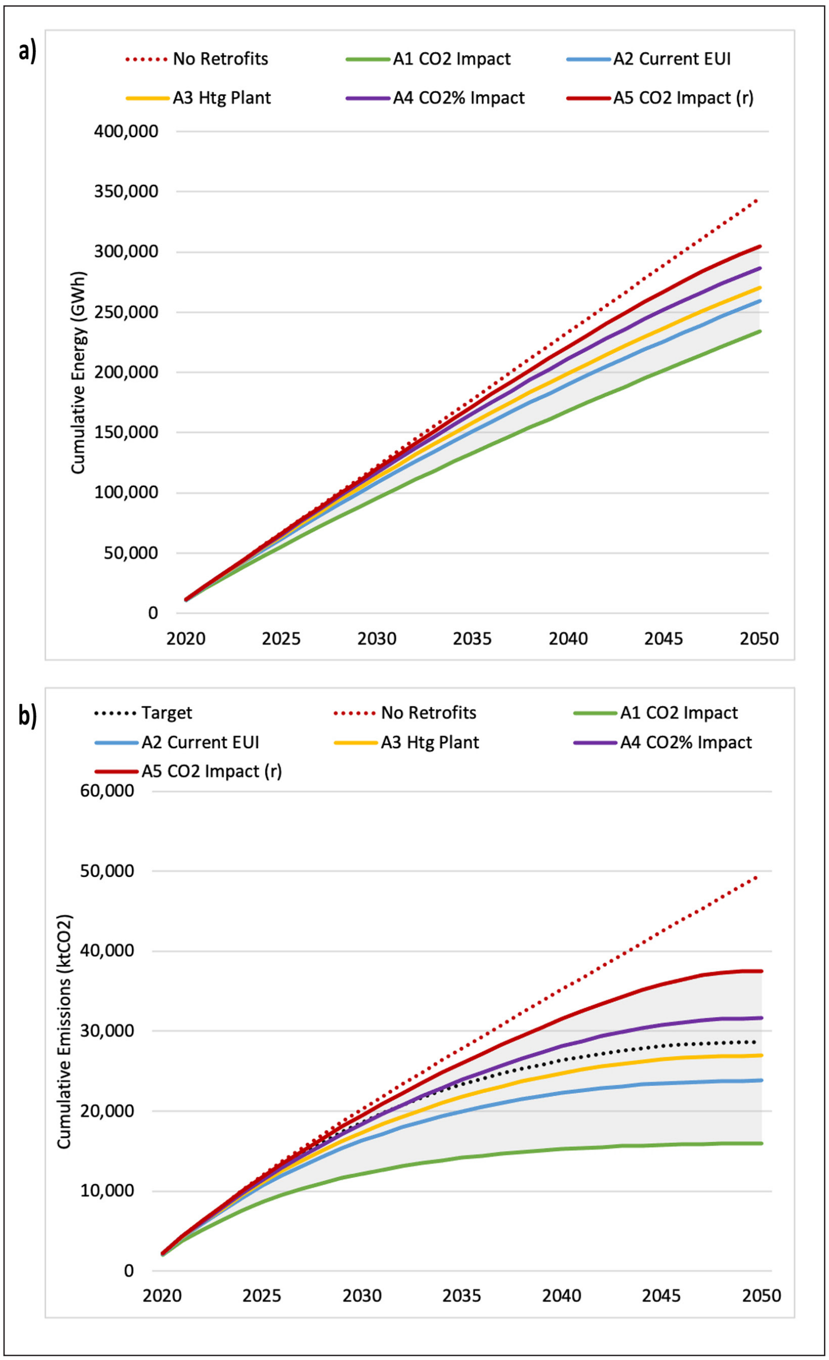

Figure 5: Impact of different retrofit rollout drivers on cumulative energy use **(a)** and emissions **(b)**.

The impact of the drivers is amplified when considering the cumulative results. Figure 5 shows the cumulative energy and emissions associated with the school stock for the same scenarios over the retrofit period. The shaded area again represents the overall range. While all five scenarios result in considerable improvement compared with leaving the stock as is, there is a 135% difference in cumulative emissions by 2050 between the fastest and slowest rollout drivers. This is partly shaped by the predicted trajectory for the grid, which is explored below.

SCENARIO		TOTAL ENERGY USE (GWH)				TOTAL EMISSIONS (KTCO_2)				YEAR 78% CO_2 REDUCTION ACHIEVED
REF	DETAIL	ANNUAL IN 2019	ANNUAL IN 2035	ANNUAL IN 2050	CUMULATIVE TO 2050	ANNUAL IN 2019	ANNUAL IN 2035	ANNUAL IN 2050	CUMULATIVE TO 2050	
A1	CO_2 impact	11,533	7,246	6,503	234,396	2,252	312	26	15,964	2028
A2	Current EUI	11,533	8,211	6,503	259,093	2,252	616	26	23,806	2033
A3	Heating plant	11,533	8,702	6,503	270,402	2,252	762	26	26,932	2036
A4	CO_2% impact	11,533	9,511	6,503	286,695	2,252	998	26	31,606	2040
A5	CO_2 impact (r)	11,533	10,214	6,503	304,612	2,252	1,227	26	37,505	2045

Table 3: Overall impacts of different rollout driver scenarios.

Note: EUI = energy-use intensity.

4.2.2. Retrofit start years, rollout rates and restrictions

While the previous scenarios assumed that building improvements would be undertaken at a rate of 650 schools/year, from 2020, in practice this may not be achievable. It might take time for arranging finances, procurement, *etc.* and there are competing priorities for investment in the school stock. Therefore, the impacts of different starting dates and rollout rates were explored. Figure 6 presents the annual and cumulative emissions for three scenarios, each using the same package of measures (envelope B + heat pump + PV), but with different starts and rates such that the total stock is still complete by 2050: scenarios A (650 schools/year from 2020), B (960 schools/year from 2030) and C (1832 schools/year from 2040). Figure 7 meanwhile presents three further scenarios, assuming rollout rates of 650, 500 and 250 schools/year (scenarios A, D and E, respectively), with the same package of measures and each starting in 2020. Each chart shows the range of possible emissions trajectories. Throughout, scenario A is the same as that presented in section 4.2.1, so the green-shaded areas in Figures 6 and 7 are identical to the grey-shaded areas in Figures 4b and 5b, respectively. The key figures for each scenario are included in Table 4.

Assuming that such high retrofit rates are even achievable, the results illustrate the impact of delays in starting the roll out of improvements across the stock. While the final performance in 2050 is identical across each of the scenarios, starting the works in 2030 or 2040 results in considerably higher cumulative emissions overall. Since large improvements in the carbon intensity of the grid are expected in the short term, this is particularly pronounced for the best trajectories in each case. Starting retrofits in 2030 or 2040, and rolling them out on the worst trajectory (*i.e.* retrofitting the schools with the lowest expected improvement first) results in 10% or 20% higher cumulative emissions respectively compared with the same approach starting in 2020. However, under the best trajectory (*i.e.* retrofitting the schools with the largest predicted emissions reduction potential first) the increases are 66% for 2030 and 133% for 2040. Achieving the 2035 target is technically achievable starting in 2030 (although the fastest improvement trajectory only achieves a 78% reduction by 2033, leaving very little slack) but, naturally, is not if starting in 2040.

The above scenarios all assume that the entire school stock will have been retrofitted by 2050. However, in practice this may not be feasible, so further tests, in Figure 7, were undertaken to explore the impact of reduced retrofit rates, such that a portion of the stock remains unchanged by 2050. As expected, the results show that a reduced rollout rate greatly impacts on the overall improvement potential for the stock. Crucially, unlike at 650 schools/year, under the 250 and 500 schools/year scenarios the rollout driver determines not just *how* the stock changes over time but also *which* schools remain untouched in 2050. Thus, the performance of the stock in 2050 varies considerably, even with a fixed set of retrofit measures being rolled out at a fixed rate. Thus, decisions about how retrofits are rolled out are even more important when the expectation

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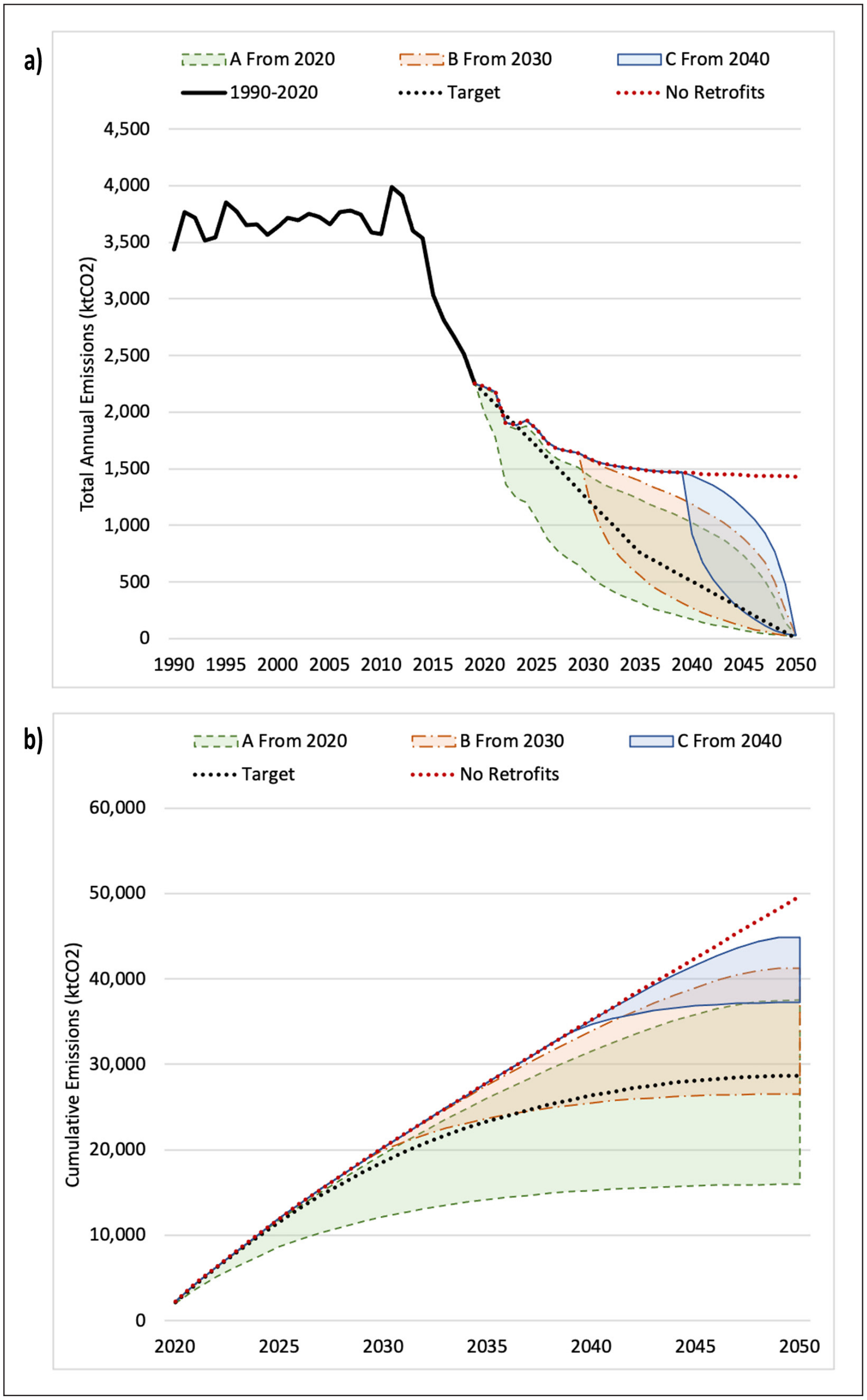

Figure 6: Impact of different retrofit rollout start years on annual **(a)** and cumulative **(b)** emissions.

is that not all the stock may be retrofitted. The slower rates result in annual emissions being four to 33 times higher in 2050 under the 500 schools/year rollout, and 14 to 49 times higher under the 250 schools/year scenarios compared with 650 schools/year, depending on the rollout drivers (Table 4). This is largely driven by the proportion of schools remaining on gas heating.

As may be expected, a key factor determining the selection process is school size. Within each scenario, the fastest emissions reduction trajectories generally improved larger schools before smaller ones. In scenario A, for example, under trajectory A1 the mean floor area of retrofitted schools is 11,660 and 697 m^2 during the first and final five years, respectively, compared with 2282 and 7347 m^2, respectively, under trajectory A4. While this may suggest that larger schools should be prioritised to achieve the fastest improvements to the stock, it is important to note that such an approach would indirectly bias the types of schools retrofitted. This is because the mean

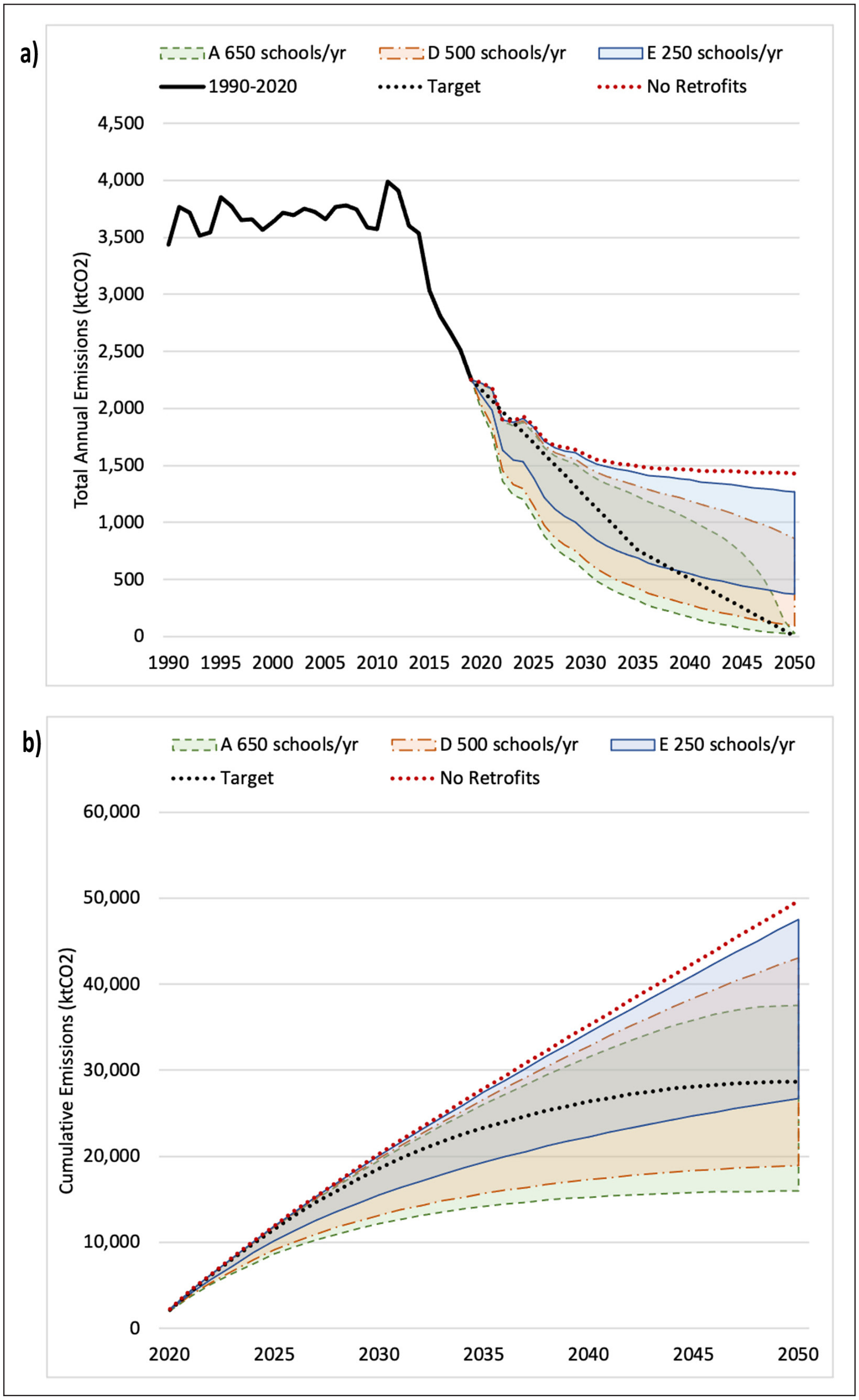

Figure 7: Impact of different retrofit rollout rates on annual **(a)** and cumulative **(b)** emissions.

size of primary schools is significantly smaller than secondaries (Hong *et al.* 2022). Consequently, despite accounting for less than a fifth of the stock by count, secondary schools make up almost 85% of the schools retrofitted in the first five years under trajectory A1. To examine this in further detail, a final set of scenarios was produced assuming 650 schools/year from 2020 with retrofit measures Biii, but applying restrictions to ensure that the make-up of the schools retrofitted each year reflect the make-up of the overall school stock. Under scenario F, each year the proportion of primary schools selected for retrofits equals the total proportion of primaries, while scenario G ensures that the spatial distribution (defined using the local authority in which each school is located) is consistent. The results are shown in Figure 8. As expected, the impact of such a rollout restriction slows the emissions reduction pace for the stock as a whole: under scenario F in particular, the fastest that a 78% reduction in annual emissions can be reached is 2031 instead

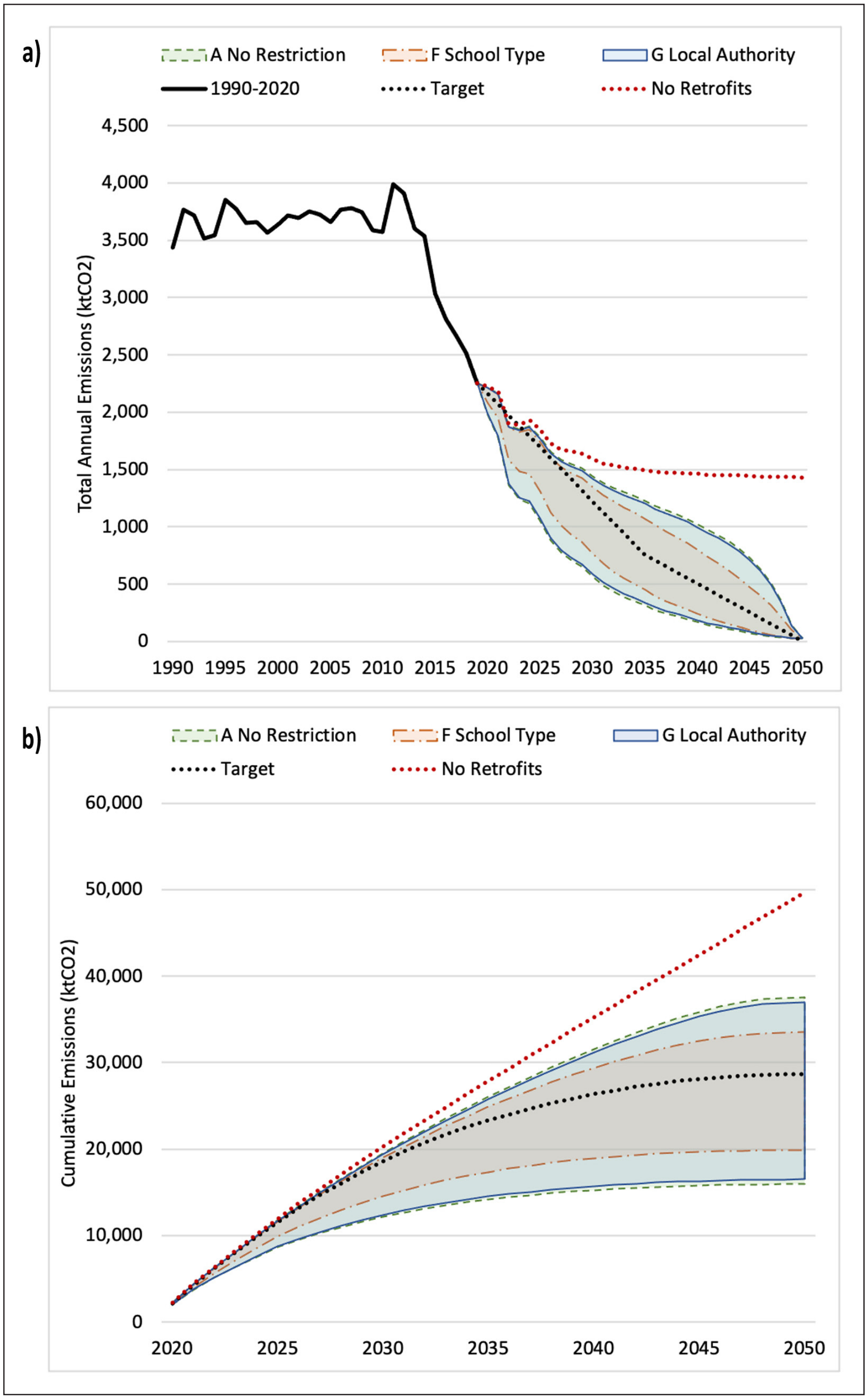

Figure 8: Impact of different retrofit rollout restrictions on annual **(a)** and cumulative **(b)** emissions.

of 2028, and the minimum cumulative emissions by 2050 are increased by 25%. In contrast, the impact of the spatial restriction is limited, with minimum cumulative emissions raised by only 3.4%.

Across the analyses presented so far, an underlying assumption has been that the retrofit process is the only mechanism by which schools are improved. Thus, within each scenario, each school remains as is until it is selected for improvement (envelope, heating plant and PV measures). In reality, it is likely that schools may choose to replace existing fossil fuel-based heating plant with low carbon or electricity-based heating as part of the essential plant replacement/maintenance schedule, especially in the context of a phase out of gas boilers. Therefore, a final set of scenarios was tested whereby, alongside the retrofit process, each year a proportion of the remaining schools with fossil fuel-based heating plant would convert to simple electric heating (assumed to be 100% efficient): scenario A where no electric heating conversion occurs, scenario H where 250 schools/year convert to electric heating from 2040, and scenario I where 250 schools/year convert from 2030. Note that any schools converted to electric heating are still eventually improved as usual, so the final performance of the stock in 2050 is the same across each of the scenarios. The results are shown in Figure 9 and, as before, scenario A is identical to that shown in Figures 4–8 enabling a direct comparison to be made. It should be noted that the introduction of this second set of building changes in scenarios H and I makes the definition of the overall fastest and slowest emissions trajectories more complex than the previous analyses. The true worst case would involve schools being converted to electric heating immediately before being selected for the retrofits. Since the electric heating-conversion process is intended to represent a general maintenance cycle, these have therefore been applied on a random basis, independent of the deployment of retrofits.

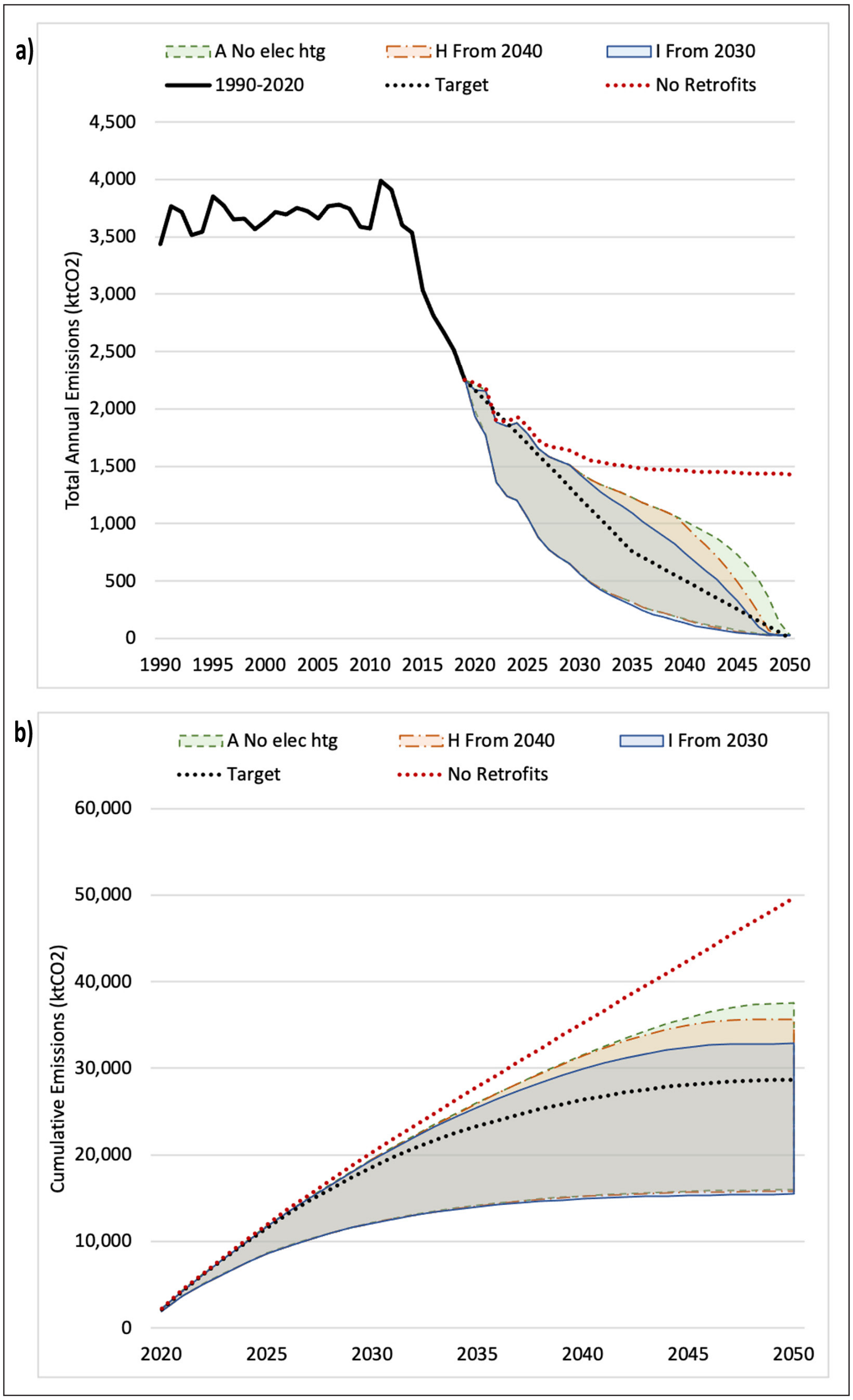

Figure 9: Impact of electric heating conversions on annual **(a)** and cumulative **(b)** emissions.

Table 4: Overall impacts of different retrofit rollouts.

SCENARIO					FASTEST EMISSIONS REDUCTION TRAJECTORY				SLOWEST EMISSIONS REDUCTION TRAJECTORY			
REF.	RETROFIT START YEAR	RETROFIT RATE (SCHOOLS/YEAR)	RETROFIT ROLLOUT RESTRICTION	CONVERSION TO ELECTRIC HEATING, ALONGSIDE RETROFITS	ANNUAL EMISSIONS IN 2035 ($KtCO_2$)	ANNUAL EMISSIONS IN 2050 ($KtCO_2$)	CUMULATIVE EMISSIONS TO 2050 ($KtCO_2$)	YEAR 78% CO_2 REDUCTION ACHIEVED	ANNUAL EMISSIONS IN 2035 ($KtCO_2$)	ANNUAL EMISSIONS IN 2050 ($KtCO_2$)	CUMULATIVE EMISSIONS TO 2050 ($KtCO_2$)	YEAR 78% CO_2 REDUCTION ACHIEVED
Baseline												
A	2020	650	None	None	312	26	15,964	2028	1,227	26	37,505	2045
Different start years												
B	2030	960	None	None	548	26	26,550	2033	1,391	26	41,221	2047
C	2040	1,832	None	None	1,496	26	37,252	2041	1,496	26	44,885	2049
Different rollout rates												
D	2020	500	None	None	420	92	18,922	2029	1,320	862	43,044	> 2050
E	2020	250	None	None	683	368	26,681	2033	1,435	1,267	47,505	> 2050
Applying retrofit restrictions												
F	2020	650	School type	None	447	26	19,907	2031	1,069	26	33,513	2041
G	2020	650	Local authority	None	337	26	16,511	2028	1,200	26	36,936	2045
Added conversion to electric heating												
H	2020	650	None	250/year from 2040	312	26	15,816	2028	1,227	26	35,676	2043
I	2020	650	None	250/year from 2030	286	26	15,459	2028	1,089	26	32,843	2040

The schools (temporarily) converted to electric heating in scenarios H and I do not have reductions in heating demand due to envelope improvements or the benefit of renewable electricity generation through PV, or the high COPs of heat pumps. Nonetheless, the results suggest that this will still have a major impact on the overall emissions of the stock, particularly on the slower trajectories. Without any conversions, the results suggest that an overall emissions reduction of 78% could be achieved by as late as 2045, whereas this upper limit reduces to 2040 where electric heating conversion occurs from 2030, with cumulative emissions over the overall period falling by 12%. Under the fastest emissions reduction rollout of retrofits, the impact of the conversion to electric heating is less pronounced, with no change in the year that 78% emissions reductions are achieved (2028), and only a 3% reduction in cumulative emissions overall.

5. CONCLUSIONS

An analysis of the retrofit potential of the primary and secondary school stock of England was presented, using a highly detailed, disaggregate (school-level) database of energy performance and building characteristics.

The results suggest there is a large potential for emissions reduction across English schools, particularly in switching from gas to electric heating. Such a change is likely to result in an increase in electricity demand, even in conjunction with envelope improvements. Nonetheless, large emissions reductions are possible, driven by the projected changes to the grid, as well as the difference between typical gas boiler efficiency and heat pump coefficient of performance (COP). It should be noted that several practical considerations are outside of the scope of the present analysis, which may reduce the retrofit potential. For example, almost 10% of schools have listed buildings or are in conservation areas, which may restrict the potential for rooftop photovoltaics (PV), or for envelope measures that would affect the external appearance of the buildings.

Crucially, however, the results show that even if all the stock were to be improved by 2050 (requiring approximately 650 schools/year), how quickly emissions reductions are made will be strongly determined by the drivers that define how those retrofits are rolled out. In turn, this impacts the viability of meeting the 2035 emissions reduction target, as well as the total cumulative emissions (and fuel bill) of the stock over the retrofit period. Improving schools expected to have the largest absolute potential first, for instance, results in half of total emissions over the 2020–50 period, compared with rolling out the same measures at the same rate, but improving schools predicted to have the largest percentage impact first. It is important to note, however, that key characteristics are not distributed uniformly across the school stock. Most significantly, since secondary schools are typically larger than primaries, the scenarios that prioritise total emissions reduction potential have a strong bias towards improving secondaries first. The analysis shows the impact that controlling for this bias in the rollout process will have on the projected improvement pathways for the stock. In this way, high (stock-level) decisions about the pathways towards 2050 may need to be made in conjunction with local- and school-level considerations.

While the simplified approach to assessing improvements used here has enabled large-scale analyses to be undertaken quickly at the individual school level, several areas could be improved as part of future work. For example, it may be possible to make use of more detailed data on form and characteristics to estimate the envelope impacts on a per school basis, instead of the construction band assumptions currently used. An integration of retrofit costs would enable retrofit rollouts to be assessed in terms of annual spend rather than the number of schools per year. Since some costs will scale with size (*e.g.* envelope measures based on exposed areas, or heating plant based on duty), such an approach would provide an alternative means of comparing the impact on larger versus smaller schools; and therefore the relative benefits of improving secondaries or primaries. Similarly, embodied carbon is not evaluated within the present analyses, but their consideration in the context of life cycle assessment could allow a better assessment of overall benefits and costs of different improvement measures.

The impact of changes in heating plant are considered, but the calculations could also be improved to include more detail (*e.g.* changes to the heating distribution systems). Finally, while the present analyses has assumed that retrofit measures will be applied to each school all at once, consideration of phasing of improvements may be beneficial. This may impact school performance during the different phases (*e.g.* insulating a school in one year and then installing heat pumps several years later, compared with PV which is a more 'independent' measure), and may better reflect the realities of getting funding for school refurbishment projects (Al-Bunni & Shayesteh 2018).

More generally, however, the integration of detailed building simulation will enable a better understanding of the improvement potential of the stock. To this end, work is currently ongoing to apply the updated schools database into a fully disaggregate, one-by-one digital twin of the school stock (Schwartz *et al.* 2022). This model, which includes detailed data on building form (footprints and heights) enables dynamic thermal simulation to be undertaken for each individual school block, allowing potential retrofit measures to be assessed with a consideration of issues such as temporal factors, changes to occupancy behaviour and climate change. It also enables a detailed breakdown of energy uses to be considered, allowing more nuanced retrofit options to be evaluated, including controls and ventilation system improvements. Evaluating the impact of improvements to ventilation systems, for example, is a key next step given that ventilation can account for a large portion of overall thermal losses and is of increasing importance in the context of Covid-19. In addition to improving the modelling approach, work is also ongoing to make greater use of the information within the schools database. For example, data on the condition of the heating plant could be used as an indicator of current plant efficiency, or school characteristics such as age could be used as indicators of the likelihood of hard-to-treat elements. The former would particularly impact the 'plant condition' trajectories, while the latter might lower the overall emissions reduction potential, as well as affecting the pathways.

The analyses presented within this paper highlight both the potential for emissions reduction for the school stock of England as well as the magnitude of this task. Even assuming sustained high rates of deployment, the results suggest that the pathway towards net zero will require considerable effort.

NOTES

1 For the remaining schools, models can be produced, albeit with poorer reliability quality; reflecting the complexity of matching across the various datasets (Schwartz *et al.* 2022).

2 Accounting for 99.8% of government-funded schools in England (DfE 2021a), the increase in coverage relative to PDSP reflects the scope of the previous survey. For example, schools built or modernised after 2004 were excluded from the PDSP (EFA 2015).

3 In the context of these surveys, a school 'block' can represent a stand-alone, physically isolated structure, or alternatively a part of a building with some distinct element (*e.g.* different construction age).

4 Not all the variables held in the Unified Schools Database are listed, only those used in the present study.

5 In practice, there will be considerable variety in the appropriate measures (and heating demand reduction potential) amongst schools of similar ages. For example, a proportion of the schools in the oldest construction band will have had retrofits/refurbishment, while some of the schools in the newest will be suitable for improvements.

6 Unfortunately, quantitative information on plant performance is not available through the school surveys, or the available large-scale datasets. Plant efficiencies were selected to reflect similar analyses, including assumptions from analyses of non-domestic buildings (CCC 2020b).

7 The highest rate (650 schools/year) results in all schools being retrofitted by 2050, due to schools within the sample already scheduled to close.

8 At the time of writing, fuel costs within the UK are very much higher than these values.

9 The historical energy and emissions estimates for the period 1990–95 are particularly complex owing to a lack of available clear data. The total emissions estimates for 1990 and 2006 in the present study are 16% and 4% higher, respectively, compared with similar figures from DCSF (2010). Equivalent figures for energy use are not available, so a comparison of electricity and fossil fuels cannot be made.

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DGS: analysis/underlying model and author; SH: author; IK: guidance for analyses and author; YS: author; AM: author; DM: author and funding.

COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

At the time of writing, the complete Unified Schools Database was not publicly available. However, several of the underlying datasets used in its creation are freely accessible online, as detailed in the text.

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