

Top-down assessment of the energy performance of the English school stock: National trends and analysis of school rebuilding programmes

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ABSTRACT

To reach the legal target of net zero by 2050, the UK Department for Education (DfE) is responding to this challenge by retrofitting existing buildings and designing new buildings to reduce carbon emissions. Assessing and reporting on the operational energy performance of these rebuilding programs can help to further inform and drive evidence-based decarbonisation initiatives. This study utilises the Display Energy Certificate (DEC) dataset and the Get Information About Schools (GIAS) dataset to create a combined database, aiming to analyse and compare the energy usage of school buildings constructed under two school rebuilding programs: Building Schools for the Future (BSF) and the Priority School Building Program (PSBP). It also investigates the latest energy consumption of English primary and secondary school buildings and trends over the period 2018 to 2023, specifically the impact of COVID-19 pandemic on energy use. Additionally, it explores the energy consumption patterns of school buildings when using different types of heating, ventilation and air conditioning (HVAC) systems and main heating fuels. A total of 13,569 schools are covered, representing approximately 69% of primary schools and 58% of secondary schools in England. This study found that the energy performance of the higher-cost BSF schools is not only inferior to that of lower-cost PSBP schools but also lags behind the remaining school building stock. There are differences in both fossil thermal energy and electricity consumption between primary and secondary school buildings. Furthermore, variations in building characteristics can contribute to differences in energy use patterns. This study can inform the quantification of energy performance in various sectors and guide the development of future energy upgrade measures and emission reduction policies.

1. Introduction

Buildings in the UK produced 89 MtCO₂e of greenhouse gases (GHGs), which accounted for 20 % of the national total and was the second largest source of emissions in the country [1]. Of these, 15 % of public sector carbon emissions were from school buildings [2]. An analysis of annual school financial reports revealed that energy expenditure in 2023/24 was around £1200 million, doubling that of the 2018/19 academic year [3]. The Carbon Trust [4] stated that upgrading UK school buildings has the ability to reduce annual energy bills by £44 million and prevent the production of 625,000 tonnes of CO₂.

The UK DfE has launched three major school rebuilding programmes in a continuous and overlapping cycle over the last 20 years, all of them aiming to construct or refurbish school buildings to improve building performance in line with the newly issued school design guidelines. Building Schools for the Future (BSF) is a programme with a £55 billion total budget, launched in 2004, which expected to refurbish or rebuild

every secondary school in England over the next 15 years [5]. The average budget allocated to school buildings under this programme was £1,850/m² and required a minimum BREEAM 'very good' rating to ensure environmental sustainability [6,7]. However, this programme was stopped in 2010 for a number of reasons, including insufficient progress and cost overruns, and only 559 schools were rebuilt or refurbished, which is around 17 % of all secondary schools in England [8,9]. Then the government allocated £4.4 billion to create the Priority School Building Programme (PSBP) in 2011 to deal quickly and cost-effectively with 537 schools in urgent need of repair [10,11]. The average total capital cost for each PSBP school was £1,113/m² [12]. Compared to BSF schools, PSBP schools reduced overall scale while maintaining the same number and area of teaching spaces, saving an average of £6 million per secondary school [13]. Meanwhile, the baseline design requirements for the programme set operational energy consumption targets of less than 60 kWh/m² and 50 kWh/m² for fossil fuel and electricity use respectively [14]. The School Rebuilding

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Programme (SRP), which began in 2020 with the aim of achieving net-zero carbon emissions from the operation of buildings, intends to rebuild and refurbish 500 schools and sixth form colleges in England to improve the sustainability of building performance [15]. The government provided £2 billion in funding for the first 100 projects [15]. As the programme is scheduled for completion five years later, and most projects are still ongoing, SRP schools were not included in the detailed analysis.

Most previous studies have focused on comparing school rebuilding programmes in terms of capital investment and design specifications [10,13,16]. Meanwhile, case-based evidence has shown that the actual operational performance of school buildings generally did not match the design expectations [17–22]. Therefore, it is necessary to investigate and analyse the actual energy usage at the operational stage of buildings under various rebuilding programmes. The Energy Performance of Buildings Regulations (England and Wales) were first published in the UK in 2007 and introduced Display Energy Certificates (DECs) for the purpose of recording energy consumption and carbon emissions in public buildings [23]. Following subsequent amendments to the regulations, the need to display a DEC for public buildings over 250 m² in England and Wales has been a mandatory requirement since July 2015 [24].

The aim of this study was to utilise the DEC dataset to compare the energy performance of BSF and PSBP schools within the context of the national school building stock and to update the latest energy consumption characteristics of primary and secondary school buildings in England. This is the first time that a systematic energy performance analysis was conducted for the PSBP schools against previous programmes. For this purpose, firstly, three databases containing school information and DEC records were developed for All School Building Stock, the BSF School Building Stock and the PSBP School Building Stock. The current energy use of the school buildings in these three databases were analysed separately and trends in energy consumption patterns over the period 2018–2023 were reviewed. Next, differences in energy use between modern schools under these two school rebuilding programmes and the remaining schools in the databases were compared to evaluate the effectiveness of new building programmes in improving energy efficiency. Lastly, a longitudinal energy analysis was conducted to assess the impact of the COVID-19 pandemic on the energy performance of school buildings by presenting trends in energy use during the pre-pandemic, lockdown, and post-pandemic periods.

Following this introduction, Section 2 provides a literature review highlighting previous related studies. Section 3 describes the research methodology, including data sources and collection, data processing and integration, and methods of analysis. Section 4 presents the results from four aspects, namely: overall school performance, energy use intensity (EUI) comparison by HVAC systems, EUI comparison by main heating fuels, and EUI comparison across three school building clusters. Section 5 discusses the results obtained. Finally, conclusions, limitations and future work are summarised in Section 6.

2. Literature review

The DEC database has been used as a publicly available information in many studies to quantify the trends and characteristics of energy use for various types of public sector building stock in the UK. Godoy-Shimizu et al. [25] analysed energy consumption and CO₂ emissions data from almost 8,500 school DECs (including primary schools, secondary schools and academies) submitted between 2008 and 2009. The results were compared with the 1999–2002 energy data published by the DfE and found that despite a significant reduction in fossil thermal energy consumption, an increase in electricity consumption led to an upward trend in CO₂ emissions. Moreover, secondary schools consumed more electricity than primary schools, but primary schools had the highest fossil thermal energy consumption. The fossil thermal energy consumption showed a correlation with the number of heating degree days in the region where the building is located. Hong et al. [25,26]

investigated trends in DEC lodged energy data from 2010 to 2019 for English primary and secondary schools that used natural gas as their main heating fuel, where fossil thermal energy consumption was weather corrected based on the heating degree days. The results showed that heating and electricity consumption displayed consistent trends with previous studies. The research also identified differences in energy use patterns between primary and secondary schools, suggesting that there is potential for enhancing benchmarking methods. They also highlighted the need to integrate datasets with more building characteristics to further understand the operational energy performance of schools and provide more accurate benchmarking. One limitation is that both studies excluded DEC records for schools newly built or rebuilt after 2004. It is also worth noting that several international studies in Asia [28–33] and Europe [34–39] compared differences in energy consumption between different types of educational buildings. Considering that energy use characteristics are closely related to the climate and fuel structures of each region, this paper focused on relevant research findings in the UK context.

Apart from the study of DEC data for English schools, Armitage et al. [40] used DECs to quantify the energy consumption of the office building stock from 2008 to 2009. The assessment indicated that newer office buildings used less fossil thermal energy but had increased electricity consumption due to the higher number of electrical equipment and air conditioning. Hong et al. [41] categorised public sector buildings into seven types to show their respective energy use between 2010 and 2016. The results revealed an overall decrease in the EUI of public sector buildings, but electricity consumption in schools and hospitals continued to rise. This study did not compare the differences in energy use between primary and secondary school buildings.

The above UK research based on DEC data focused on identifying energy use patterns across building types at the national level. In contrast, research in other countries often rely on more limited building stock for analysis. This comparison highlights the unique advantages of the DEC dataset in terms of coverage and diversity of building types. However, the DEC dataset provides only annual total energy consumption by fuel type for each building, without breakdown by end use or month. This restricts deeper analysis of energy use patterns and their contributions to total consumption. Besides, although some studies have evaluated the relationship between building age and energy performance, the energy use patterns of newly built buildings in the past 15 years have not been separately grouped and investigated due to the lack of age classification information or the absence of timely updates in the research [27,40].

On the other hand, most studies evaluating energy consumption using DEC records have been limited to data up to 2020, with little attention given to more recent years. Considering that since the declaration of COVID-19 as a global pandemic by the World Health Organisation (WHO) in March 2020, the impact of the lockdown measures on the occupancy schedules of buildings led to changes in energy demand. Hence, a comparison of energy use in the pre-pandemic, lockdown and post-pandemic periods is necessary. Many studies have focused on the impact of the COVID-19 pandemic on total electricity and gas demand [42–44], but due to the difficulty of obtaining energy consumption breakdowns for the building sector, relevant research has not been extensive. The analysis of measured data with large sample sizes concentrated on domestic buildings [45–49]. Research on non-domestic buildings, predominantly commercial [50,51] and university buildings [52,53], tended to use case studies or data analysis based on small sample sizes.

3. Methodology

3.1. Data sources and collection

This study created datasets for BSF schools, PSBP schools and all school building stock in England based on data from two sources:

Display Energy Certificates (DECs): The UK Department for Levelling Up, Housing and Communities (DLUHC) has published DEC data issued for public buildings since 2008 through the Open Data Community platform [54]. The dataset contains annual electricity and fossil thermal energy consumption in addition to address, postcode, building type, floor area, occupancy level, main HVAC system type and main heating fuel. DEC records lodged until 20 August 2024 were downloaded to analyse recent energy consumption. DEC records from 2018 to 2023 were used in the longitudinal analysis of energy performance, where 2018–2019 was considered as pre-pandemic, 2020–2021 as the lockdown period, and 2022–2023 as the post-pandemic period.

Get Information About Schools (GIAS): GIAS is a national public dataset provided by the DfE containing the registration records of all educational establishments in England and Wales, which includes the unique reference number (URN), name, address, postcode, status (open or closed), educational phase, and school capacity for each establishment [55]. Information on schools registered before 30 June 2024 was downloaded. The main purpose of introducing this dataset was to identify the educational phase (e.g. primary or secondary) in order to discuss and compare the differences in energy use patterns between primary and secondary schools.

3.2. Data processing and integration

In this study, Python 3.11 was used to preprocess the DEC dataset then integrate it with the GIAS dataset through address matching. Fig. 1 illustrates the data processing and integration procedures.

3.2.1. Preparation of the DEC dataset

The information showed in the BSF and PSBP school lists downloaded from the UK government website was different. The BSF school list, comprising 700 schools, included the name, URN, postcode, and local authority area for each school. The first PSBP school list (261 schools) only showed the name and local authority area of the schools. The second PSBP school list (277 schools) included the name, URN and local authority area of the schools. However, these were the original information for each school when the application for funding was submitted. The names and URNs of the new schools after reconstruction or refurbishment through the BSF and PSBP programmes may change. It can be divided into the following categories: (1) Refurbishment based on the original school building, the school's name and URN remain unchanged. (2) Refurbishment or reconstruction on the original school building site. However, due to changes in the funding body, the school is re-registered with a new URN, and the school's name may change. (3) Reconstruction on the new site, the school is re-registered and a new URN is allocated, and the school's name is typically changed. In addition, there may be cases where schools merge or several schools share a new school building. Therefore, in order to extract the correct DEC record, the information in the school list needed to be updated to show the name, URN and postcode of the new school. Considering that the name and postcode of schools were not unique, the URN of each school was adjusted or added through automatic matching and manual retrieval, and then the school information corresponding to all URNs was extracted from the GIAS dataset.

The first step in automated matching was to extract school information from the GIAS dataset that matched URNs in the BSF and PSBP lists and to check school status. Schools with a status of 'Open' fall under

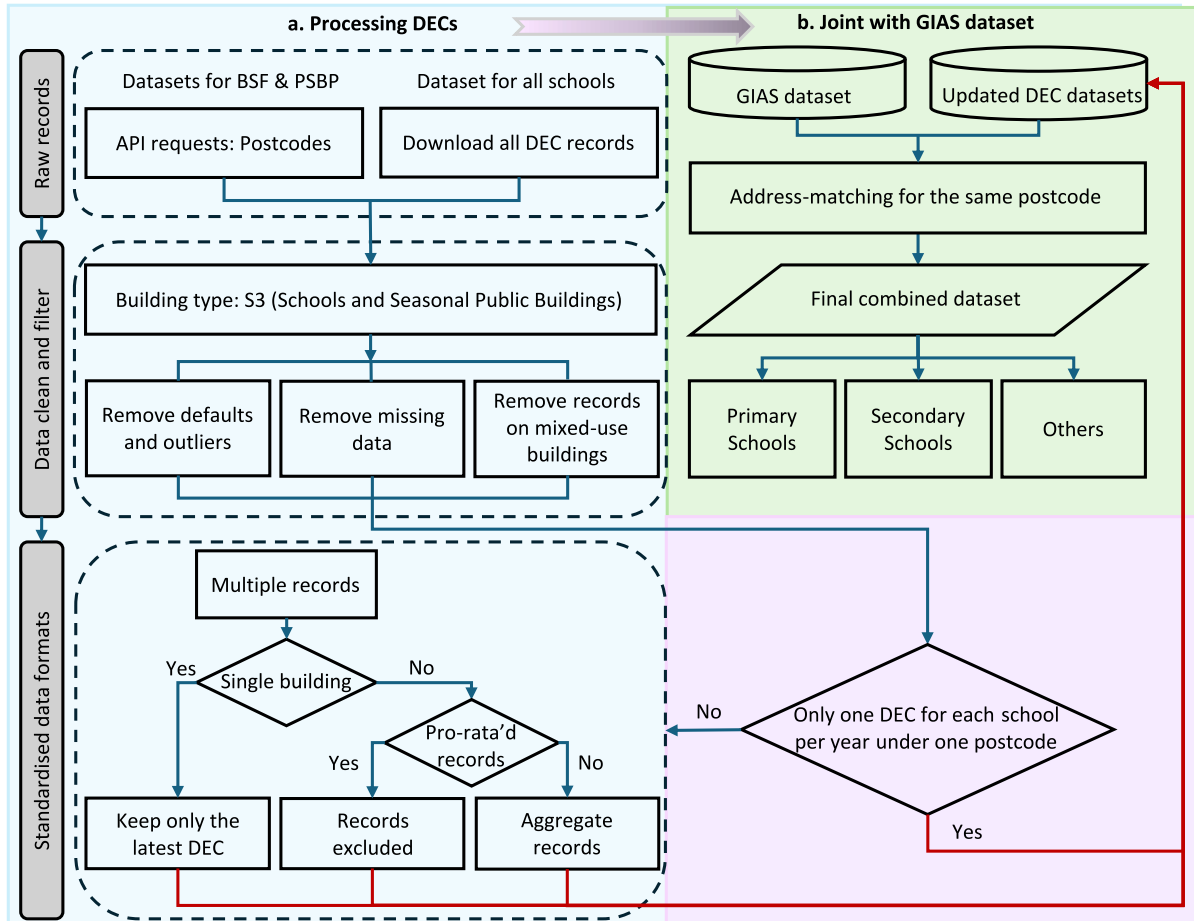


Fig. 1. Data processing and integration procedures.

the first category mentioned above. The second step involved using the postcode of schools with a status of 'Closed' as matching information. All school data under these postcodes was retrieved from the GIAS dataset, and the new URN of each rebuilt or refurbished school was confirmed through manual checks. Schools with updated URNs based on this process fell under the second category. Since the first PSBP school list did not list the URNs or postcodes of the schools, the list can only be processed based on the school names. Both the list and the GIAS dataset were provided by the DfE, thus recording the same school names. By using the school's name for matching along with manual checking, the URN and postcode of each school can be obtained for the above two steps. Schools that still have not confirmed their new URNs after these steps belong to the third category, whose URNs and postcodes have changed. The UK government's GIAS website can be searched for the registration of a school's predecessor or successor institution based on the school's name or URN. Therefore, the remaining schools can use this manual search method to record the newly assigned URN. Finally, because URN is unique, GIAS datasets dedicated to new schools under the BSF and PSBP projects can be proposed based on the updated URN.

There are two ways to extract raw DEC records from the data platform: download directly or query the data through the API. For this study, all DEC records lodged until 20 August 2024 were downloaded as the basis for creating an energy dataset for all school building stock. For BSF and PSBP schools, the postcode information in the GIAS dataset was used as a query parameter to ensure the API returns only the DEC records associated with these specific postcodes. In summary, the above was the initial preparation for creating energy datasets for all schools, BSF schools and PSBP schools respectively.

3.2.2. Processing of DEC dataset

The Display Energy Certificate (DEC) shows building types in 29 benchmark categories based on the main function of the building. Mixed-use buildings may be assigned to more than one building type. DEC records for school buildings are generally under the category 'S3: Schools and seasonal public buildings'. After excluding records that do not belong this category, DEC records were then cleaned and filtered based on data processing guidelines developed in previous studies [41,56]. DEC records containing the following three types of data were mainly excluded:

- Default and outlier values: Default operational ratings (200 or 9999); outlier operational ratings (below 5 or above 1000); outlier building area (less than 50 m²).
- Missing values: missing energy use data; zero electrical energy use; non-electrically heated buildings with zero fossil thermal energy use.
- Mixed-use building records: buildings that do not only fall into the S3 classification and are benchmarked using a composite method. The composite benchmark refers to a result based on the proportional distribution of total useful floor area among different uses [57].

Notably, the operational rating recorded in the DEC represents a numerical indicator of the building's actual annual carbon dioxide emissions [58]. A building with the same level of energy performance as the benchmark building will have an operational rating of 100. Thus, ratings below 5 often indicate nearly unoccupied buildings, while values above 1000 are outside realistic operational ranges for school buildings. Although such outliers account for less than 1 % of the raw dataset, these extreme values likely represent data errors or atypical cases, and their exclusion ensures a more reliable analysis.

After removing the above DEC records, the next step was to standardise the data format of multiple DEC records under the same postcode within a year to ensure that each school has only one DEC record per year under a postcode. First, to identify the address and floor area to determine whether multiple DEC records belong to the same building. For the same building, only the latest DEC record submitted in the year was retained. For schools comprising multiple buildings, the DEC

measurement method was determined by examining the annual electricity and fossil thermal energy consumption of these buildings. Records indicating identical consumption across multiple buildings within the same school were excluded, as such data were likely prorated rather than derived from individual measurements. For multiple DEC records generated by measuring the energy consumption of each building in a school separately, the data was integrated based on the area-weighted method. At the same time, the main heating fuel and building environment of the building with the largest floor area in this group of buildings were output to represent the entire school.

The final step in the DEC data processing was to weather-corrected the fossil thermal energy consumption based on 2021 heating degree days that represent the UK average climate using Eq. (1) [57,59]. This adjustment followed the approach outlined in CIBSE TM41, which forms the basis for the benchmark adjustments presented in CIBSE TM46 [57,60]. The monthly heating degree days from 2018 to 2023 have been publicly released as part of the annual Digest of the UK Energy Statistics [61]. Based on previous research, space heating in school buildings accounts for around 80 % of the total fossil thermal energy consumption, and adjusting for it can avoid differences in space heating demand caused by region and year [26].

$$N_{dd} = \left[N \times \left(1 - \frac{P}{100} \right) \right] + \left[\left(N \times \frac{P}{100} \right) \times \left(\frac{S}{L} \right) \right] \quad (1)$$

Where N_{dd} is the fossil-thermal energy use of a school adjusted for degree-days (kWh/m²/year); N is the unadjusted fossil-thermal energy use (kWh/m²/year); P is the proportion of the fossil-thermal energy use related to space heating (%), taken as 80 % in this study; L is the number of degree days in the assessment period; and S is the standard UK heating degree days, taken as 2021 in this study.

3.2.3. Integration of the DEC dataset with the GIAS dataset

In order to further classify each DEC dataset according to the school type, it is necessary to integrate it with the GIAS dataset into a unified dataset to supplement the school information. The GIAS dataset contained the URN of each school, but the DEC database did not have this information. Also, the sources of the GIAS and DEC datasets were different, leading to inconsistencies in the names of schools recorded. To match the two datasets, the postcode served as the main identifier, and the Levenshtein distance was then used to calculate the similarity between address pairs to determine if they refer to the same building under the postcode. The Levenshtein distance is a metric that measures the difference between two strings and can be calculated using Python [62]. Before calculating the metric, specific abbreviations frequently appearing in school names were replaced with their full forms, such as converting 'CoE Primary School', 'CE Primary School' and 'CofE Primary School' to 'Church of England Primary School', to improve consistency across records. The reliability of the address-matching process was established by using the 2018 All-School dataset as a test set to determine the appropriate similarity score threshold. In this dataset, all matches with similarity scores above 65 were confirmed as correct, while scores below 35 indicated no match. Based on this, a conservative threshold of 65 was applied to ensure high matching accuracy. Across each year of analysis, approximately 8 % of schools (around 800 schools) fell below this threshold. To maximise the sample size, all such cases were manually checked to confirm correct matches. The validity of this threshold was then tested on the 2019 All-School dataset, where the matching accuracy exceeded 99 %, confirming the robustness of the approach.

3.2.4. Creation of unified datasets and their subsets

After the above steps, unified datasets containing DEC records issued since 2018 was finally created for all schools, BSF schools, and PSBP schools. Each dataset was also divided into three subsets based on school type: primary school buildings, secondary school buildings, and other

school buildings. Due to the lack of school type information for Welsh schools (marked as ‘Not Applicable’ in the GIAS dataset), they were also classified as other schools in this study. Consequently, the scope of this research was limited to schools in England. Table 1 shows the change in the number of DEC records per year after each step of DEC data processing. Before the data format was standardised, there could be more than one DEC record for a school in a postcode. Thus, the data in brackets in Table 1 indicate the number of sites. Table 2 shows the number of schools by school type per year in the final unified dataset after integration with the GIAS dataset. It should be noted that the number of all schools in the unified dataset was lower than the number in the final DEC dataset because the address matching between DEC and GIAS data was not highly consistent. Due to the limited number of BSF and PSBP schools, manual adjustments can be made to ensure that the number of schools in the unified dataset was the same as that in the DEC dataset. Moreover, subsets for analysing recent energy use pattern were created based on the records from 2022 to 2024 in the three unified databases.

3.3. Methods of analysis

This study quantified the latest energy use patterns of the building stock in each of the unified datasets and examined the changes over the past six years. The unified database of all school building stock was first analysed to understand current overall school energy performance. As the energy data did not conform to a normal distribution, a non-parametric Mann-Whitney-Wilcoxon test comparing two independent samples was used to assess differences in electricity and fossil thermal energy use between primary and secondary schools [63]. A longitudinal analysis was also conducted to explore year-to-year changes in overall school electricity and fossil thermal energy from 2018 to 2023. Next, differences in energy performance between schools with different HVAC system types and different main heating fuels were assessed. Since the Mann-Whitney-Wilcoxon test was not applicable for multiple comparison correction, the Kruskal-Wallis test was conducted to assess differences in energy consumption among several groups of school buildings [64]. Further pairwise comparisons were conducted using Dunn’s test to identify significant differences between groups, and Bonferroni correction was used to control for the possibility of increased test error rates due to multiple comparisons [65]. Finally, the same latest energy use patterns and longitudinal analyses were performed on the unified dataset of BSF and PSBP schools. Differences in energy consumption between modernised schools under these two rebuilding programmes and other school buildings were also compared.

4. Results

4.1. Overall school performance

Fig. 2 shows the current annual EUI of primary and secondary schools in England using cumulative distribution curves. The DEC dataset includes building occupancy levels, recording hours where annual occupancy exceeds the nominal maximum by 25 % as extended occupancy, otherwise it is shown as standard occupancy [57]. Schools with extended occupancy levels accounted for less than 6 % of the total in both the primary and secondary unified datasets developed for this study. The differences in average fossil thermal energy and electricity consumption between schools with standard and extended occupancy levels were less than 6 %. Therefore, this study did not categorise discussions based on occupancy levels. Commonly, the 25th percentile represents buildings with lower energy use and is referred to as the ‘good practice’ benchmark. The 50th percentile represents the median performance and is referred to as the ‘typical practice’ benchmark [27,66,67]. Thus, typical practice for current electricity EUI in primary and secondary schools was 39 kWh/m² and 43 kWh/m² respectively, and 104 kWh/m² and 90 kWh/m² for fossil thermal energy consumption. Mann-Whitney-Wilcoxon test on the electricity consumption and fossil thermal energy consumption for these two types of schools, respectively, both resulted in $p < 0.001$, which indicated that there was a statistically significant difference in energy consumption by school type. Secondary schools consumed more electricity and less fossil thermal energy than primary schools. Table 3 summarises the statistics for energy use in primary and secondary schools. Total energy consumption may not necessarily match the sum of electricity and fossil thermal energy consumption because schools with high total energy consumption did not necessarily have the worst performance in electricity and fossil thermal energy use at the same time.

Fig. 3 presents the year-on-year variation in fossil thermal energy and electricity use from 2018 to 2023 for both the ‘good practice’ and ‘typical practice’ benchmarks. It demonstrates that primary schools consumed more fossil thermal energy and less electricity than secondary schools. The energy consumption trends for the same fuel type were generally consistent. Energy use was relatively stable in the pre-pandemic period, with electricity consumption dropping sharply during the lockdown, but fossil thermal energy use remained at pre-pandemic levels. The post-pandemic period started with rapid rises in energy use, with data for 2022 showing higher fossil thermal energy consumption than in the pre-pandemic period, but falling back to lower than pre-pandemic levels in 2023. Electricity consumption did not increase beyond pre-pandemic levels, remaining roughly the same in 2023 as it was in 2022.

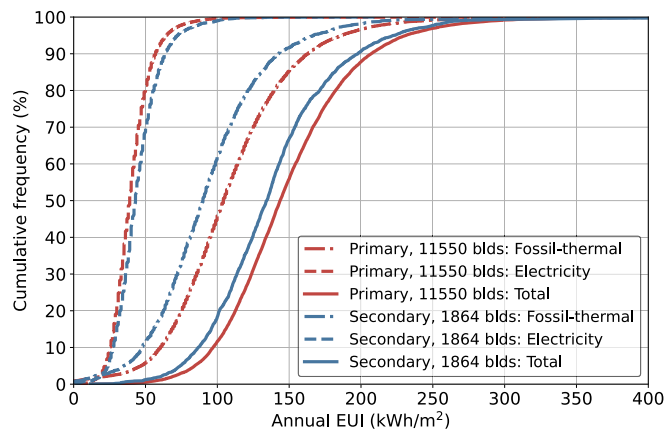
Table 1
Change in number of DEC records after each step of DEC data processing.

Year	Raw data			Data clean and filter			Standardised data formats		
	BSF schools	PSBP schools	All schools	BSF schools	PSBP schools	All schools	BSF schools	PSBP schools	All schools
2018	821 (413)	645 (307)	19,178 (13276)	483 (289)	377 (212)	15,844 (11276)	254	189	10,328
2019	841 (418)	635 (332)	18,893 (13268)	536 (322)	445 (272)	17,308 (12333)	280	239	11,256
2020	820 (416)	592 (305)	18,087 (12861)	554 (335)	414 (257)	16,678 (12072)	280	218	10,578
2021	911 (453)	708 (361)	19,352 (13561)	625 (363)	538 (329)	18,080 (12845)	301	282	11,472
2022	875 (445)	700 (370)	19,175 (13747)	608 (361)	542 (352)	18,056 (13080)	294	309	11,819
2023	882 (453)	680 (362)	19,208 (13837)	638 (386)	536 (350)	18,077 (13213)	321	296	11,922
2024	512 (272)	326 (182)	11,346 (8574)	348 (210)	260 (168)	10,665 (8176)	164	141	7402

Table 2

Number of schools by school type in the final unified dataset.

Year	Primary schools			Secondary schools			Other schools		
	BSF schools	PSBP schools	All schools	BSF schools	PSBP schools	All schools	BSF schools	PSBP schools	All schools
2018	0	88	7551	207	89	1223	47	12	811
2019	0	119	8152	226	102	1343	54	18	976
2020	0	108	7694	235	95	1276	45	15	890
2021	0	155	8480	240	113	1367	61	14	864
2022	0	168	8685	231	121	1349	63	20	1045
2023	0	159	8632	254	114	1355	67	23	1119
2024	0	86	5525	123	46	769	41	9	579
Latest	0	205	11,550	316	156	1864	83	31	1553

**Fig. 2.** Cumulative distribution curves of annual EUI.

4.2. Comparison of EUI by HVAC systems

Table 4 presents the energy usage statistics for primary and secondary schools, categorised by HVAC system type based on DEC records, showing that 95 % of primary schools and 73 % of secondary schools

have heating and natural ventilation systems. The sample size of school buildings using only natural ventilation, only mechanical ventilation, or only air conditioning is very small, representing 0.03 % and 1 % of the total number of primary and secondary schools, respectively. Therefore, the following analysis did not include school buildings with these three HVAC system types. Preliminary tests showed that differences in HVAC system types significantly affected fossil thermal energy and electricity consumption in primary and secondary schools (KW, $p < 0.001$). However, the Kruskal-Wallis test could only demonstrate that energy consumption under at least one type of HVAC system differed from the other groups. To identify the specific HVAC system that led to a significant difference, the pairwise comparison using Dunn's test was performed as a follow-up test. The results of the Dunn's test with Bonferroni correction (p-values) are presented in Table 5.

The difference in energy consumption between schools with H&NV systems and those with H&MV systems was significant ($p < 0.0083$). Typical fossil thermal energy use in primary and secondary schools with H&NV systems was 18 % and 10 % more than in buildings with H&MV systems, respectively. For electricity consumption, it was 9 % and 22 % less, respectively. There was no significant difference ($p < 0.0083$) in energy consumption between buildings with the two HVAC system types in mixed mode (MM&NV and MM&MV). Typical energy consumption data recorded by DEC records for these two systems demonstrated characteristics consistent with H&NV and H&MV systems. Buildings dominated

Table 3

EUI statistics.

Building type (N)	EUI (kWh/m ²)	10 %	25 %	50 %	75 %	90 %	Mean	Standard Deviation
Primary (11550)	Electricity	25	32	39	47	57	41	17
	Fossil-thermal	60	80	104	132	163	109	45
	Total	97	118	144	174	207	149	48
Secondary (1864)	Electricity	27	34	43	53	64	45	16
	Fossil-thermal	47	68	90	114	143	95	64
	Total	87	109	134	161	198	140	67

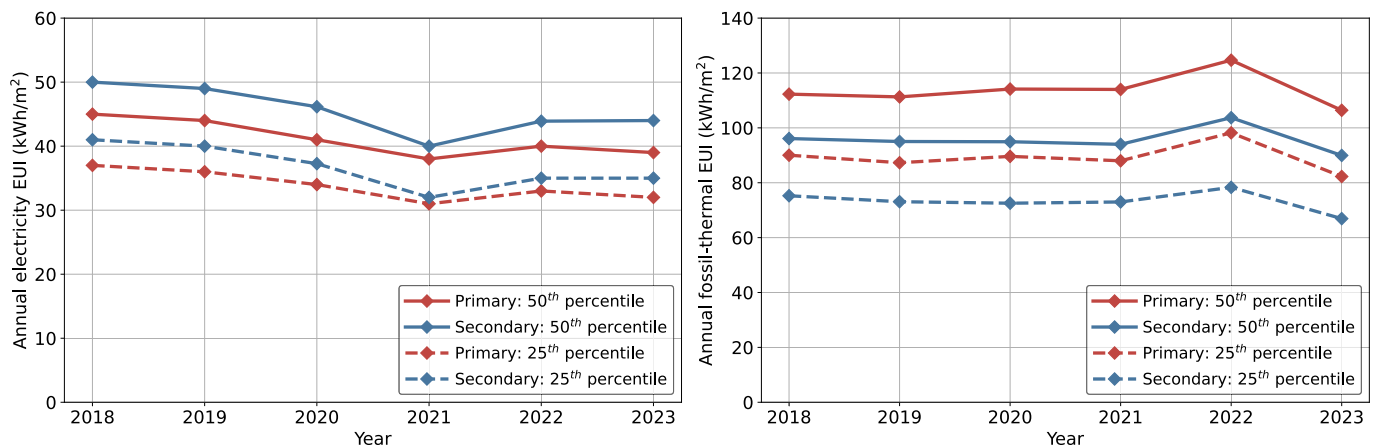
**Fig. 3.** Variation in electricity and fossil thermal energy use over time.

Table 4
EUI statistics by HVAC system type.

HVAC system	School type	Number	Fossil-thermal EUI (kWh/m ²)			Electrical EUI (kWh/m ²)		
			25 %	50 %	75 %	25 %	50 %	75 %
H&NV	Primary	10,985	81	105	132	31	39	47
	Secondary	1353	70	92	116	33	40	49
H&MV	Primary	320	67	89	117	35	43	52
	Secondary	355	61	83	110	43	51	60
MM&NV	Primary	154	74	101	122	34	41	46
	Secondary	80	68	88	104	42	50	56
MM&MV	Primary	45	67	87	118	34	42	51
	Secondary	53	52	78	102	43	53	62
NV	Primary	11	70	99	149	37	45	51
	Secondary	1	24	24	24	49	49	49
MV	Primary	2	46	71	95	54	57	59
	Secondary	2	119	139	160	48	48	48
AC	Primary	33	0	31	71	47	59	71
	Secondary	20	23	67	104	35	59	78

Note: HVAC = Heating, ventilation and air conditioning; H&NV = Heating and natural ventilation; H&MV = Heating and mechanically ventilation; MM&NV = Mixed-mode with Natural Ventilation; MM&MV = Mixed-mode with Mechanical Ventilation; NV = Natural Ventilation Only; MV = Mechanical Ventilation Only; AC = Air Conditioning.

by mechanical ventilation systems consumed more electricity and less fossil thermal energy than buildings relying on natural ventilation. Additionally, a significant difference ($p < 0.0001$) was found in the electricity consumption in secondary school buildings when comparing schools with H&NV to those with the mixed mode. Typical electricity consumption in secondary school buildings with the MM&NV and MM&MV systems was 25 % and 33 % higher, respectively, than that in H&NV schools. In contrast, none of the schools with H&MV systems differed significantly in energy consumption from the schools with the mixed mode ($p > 0.0083$). Hence, the Kruskal-Wallis test was conducted on the energy consumption among these three HVAC system types (H&MV, MM&NV, MM&MV), and the result was $p > 0.05$, indicating that there is no significant difference between them. Fig. 4 shows the cumulative distribution curves of annual EUI by HVAC system.

4.3. Comparison of EUI by main heating fuels

Table 6 shows energy usage statistics for primary and secondary schools, categorised by the main heating fuels in the DEC records. 91 % of primary schools and 92 % of secondary schools use natural gas as the main heating fuel, followed by oil and electricity. Schools using biomass, district heating, liquefied petroleum gas (LPG) or biogas as the main heating fuel were not included in this analysis, as these four fuel types accounted for only 1 % and 2 % of the total in primary and secondary

schools. Preliminary tests showed that differences in main heating fuel significantly affected fossil thermal energy and electricity consumption in primary and secondary schools (KW, $p < 0.001$). The results of the Dunn's test for pairwise comparisons (p -values) with Bonferroni correction are presented in Table 7.

The main finding was that there was a significant difference in energy consumption between buildings using electricity as the main heating fuel and those using natural gas and oil ($p < 0.0167$). Typical electricity consumption in primary and secondary schools using electricity for heating was 84 % and 19 % more than in buildings using natural gas, and 71 % and 28 % more than in buildings using oil. For fossil thermal energy use, some of the schools that use electricity as the main heating fuel did not use any other type of fuels. Thus, as shown in Table 6, the typical fossil thermal energy use for primary school buildings under this category is 0, and for secondary school buildings, it is only 10 kWh/m². Besides, significant differences in energy consumption were found only for primary school buildings when comparing schools using natural gas as the main heating fuel with those using oil ($p < 0.0001$). Typical fossil thermal energy consumption in primary schools using natural gas for heating was 18 % more than in buildings using oil, and typical electricity use was 7 % less. Fig. 5 shows the cumulative distribution curves of annual EUI by main heating fuels, showing that buildings with electricity as the main heating fuel consume the least total energy.

4.4. Comparison of EUI in three school building stock clusters

Fig. 6 shows the distribution and comparison of the energy performance by school type for the BSF school building stock, the PSBP school building stock, and the remaining school building stock in half-violin plots with box plots. Within each cluster of school building stock, electricity use was higher in secondary schools, while primary schools consumed more fossil thermal energy, which is consistent with the results of the overall school energy performance analyses in Section 4.1. By fuel type, for electricity, BSF secondary schools were the cluster with the highest electricity consumption, PSBP schools consumed more electricity than the remaining schools. For fossil thermal energy, remaining primary schools consumed the most, while PSBP secondary schools consumed the least. By school type, for primary schools, the PSBP primary schools had the greatest consumption of electricity, but both fossil thermal energy and total energy consumption were significantly lower than in the remaining schools. For secondary schools, BSF secondary schools had the greatest fossil thermal and electrical EUI, and their fossil thermal energy consumption was also higher than that of PSBP primary school buildings. PSBP secondary schools had a slightly higher electrical EUI than the remaining schools, but had the lowest levels of fossil thermal and total energy consumption. Table 8

Table 5
Results of Bonferroni-corrected Dunn's test by HVAC system type.

HVAC system	School type	Energy	H&NV	H&MV	MM&NV	MM&MV
H&NV	Primary	Fossil-thermal	—	< 0.0001	> 0.0083	> 0.0083
		Electricity	—	< 0.0001	> 0.0083	> 0.0083
	Secondary	Fossil-thermal	—	< 0.0083	> 0.0083	> 0.0083
		Electricity	—	< 0.0001	< 0.0001	< 0.0001
H&MV	Primary	Fossil-thermal	—	—	> 0.0083	> 0.0083
		Electricity	—	—	> 0.0083	> 0.0083
	Secondary	Fossil-thermal	—	—	> 0.0083	> 0.0083
		Electricity	—	—	> 0.0083	> 0.0083
MM&NV	Primary	Fossil-thermal	—	—	—	> 0.0083
		Electricity	—	—	—	> 0.0083
	Secondary	Fossil-thermal	—	—	—	> 0.0083
		Electricity	—	—	—	> 0.0083
MM&MV	Primary	Fossil-thermal	—	—	—	—
		Electricity	—	—	—	—
	Secondary	Fossil-thermal	—	—	—	—
		Electricity	—	—	—	—

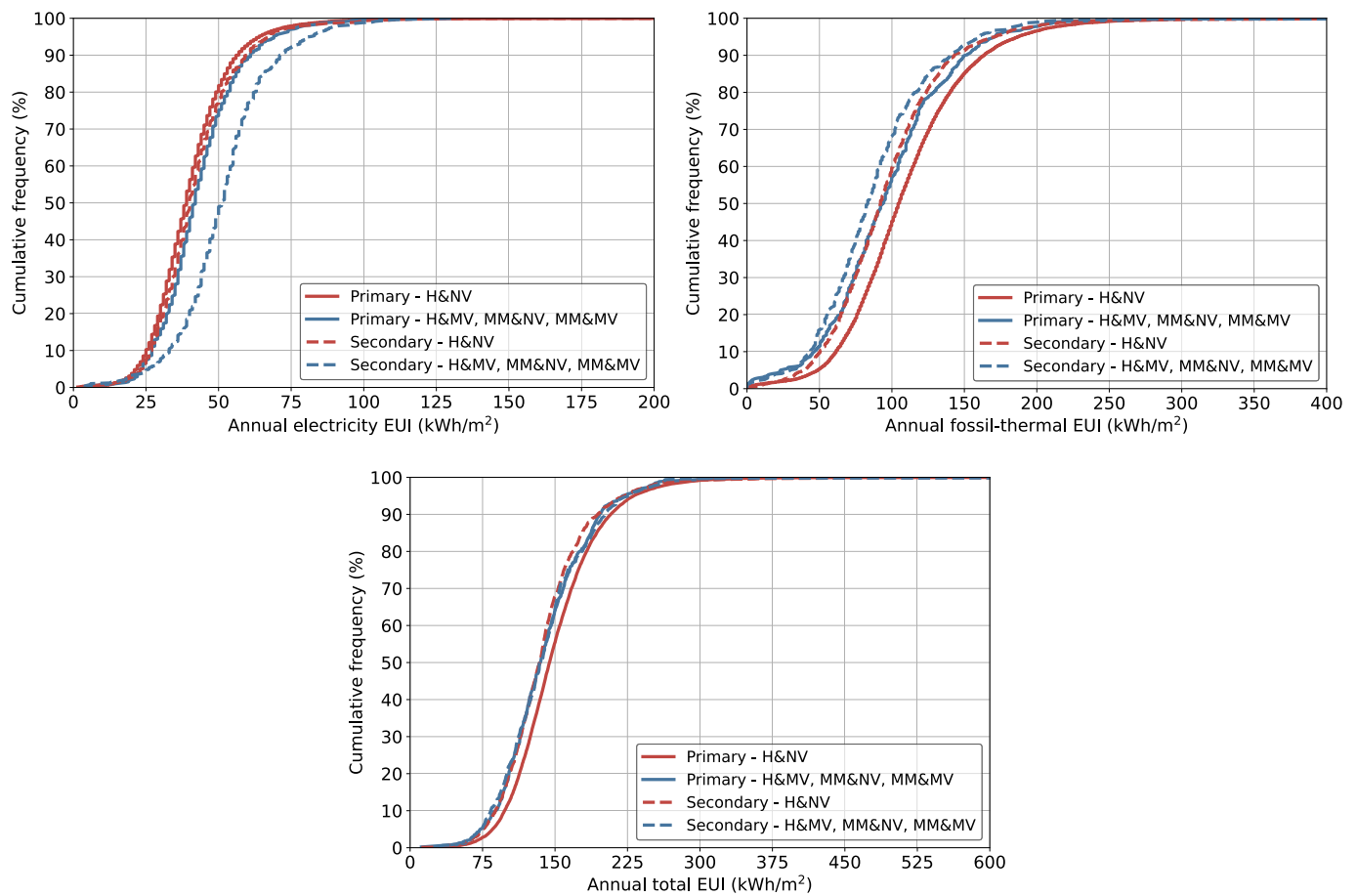


Fig. 4. Cumulative distribution curves of annual EUI by HVAC systems.

Table 6
EUI statistics by main heating fuel type.

Main heating fuel	School type	Number	Fossil-thermal EUI (kWh/m ²)			Electrical EUI (kWh/m ²)		
			25 %	50 %	75 %	25 %	50 %	75 %
Natural gas	Primary	10,527	83	106	133	31	38	47
	Secondary	1712	69	90	114	34	43	53
Oil	Primary	664	67	90	118	33	41	49
	Secondary	77	67	84	114	34	40	46
Electricity	Primary	189	0	0	35	55	70	85
	Secondary	42	0	10	52	38	51	78
Biomass	Primary	88	87	108	137	36	43	52
	Secondary	31	91	106	155	39	50	56
District heating	Primary	16	72	108	137	32	43	49
	Secondary	2	78	86	94	36	37	39
LPG	Primary	65	60	84	120	33	43	52
	Secondary	0	—	—	—	—	—	—
Biogas	Primary	1	495	495	495	30	30	30
	Secondary	0	—	—	—	—	—	—

summarises statistics on energy use by school type and cluster.

Fig. 7 shows the year-to-year changes in the use of fossil thermal energy and electricity for these three school building stock clusters from 2018 to 2023, with both ‘good practice’ and ‘typical practice’ benchmarks. For fossil thermal energy, primary schools in the remaining school building stock have consistently recorded the highest consumption over the past six years. Good practice buildings in this cluster used more fossil thermal energy than typical practice PSBP secondary schools during the lockdown and post-pandemic period. The BSF Schools currently had the highest fossil thermal EUI under typical practice of the three secondary school building clusters. However, in the pre-pandemic period (2018–2019), the BSF Schools had the lowest fossil thermal EUI

under typical practice of all these building clusters. For electricity use, BSF secondary schools consistently had the highest electricity consumption over the past six years. BSF secondary schools at the good practice level consumed even more electricity than PSBP schools and the remaining schools at typical practice.

5. Discussion

5.1. Comparison of primary and secondary school buildings

This study found that electricity consumption was higher in secondary schools than in primary schools, while fossil thermal energy

Table 7

Results of Bonferroni-corrected Dunn's test by main heating fuel type.

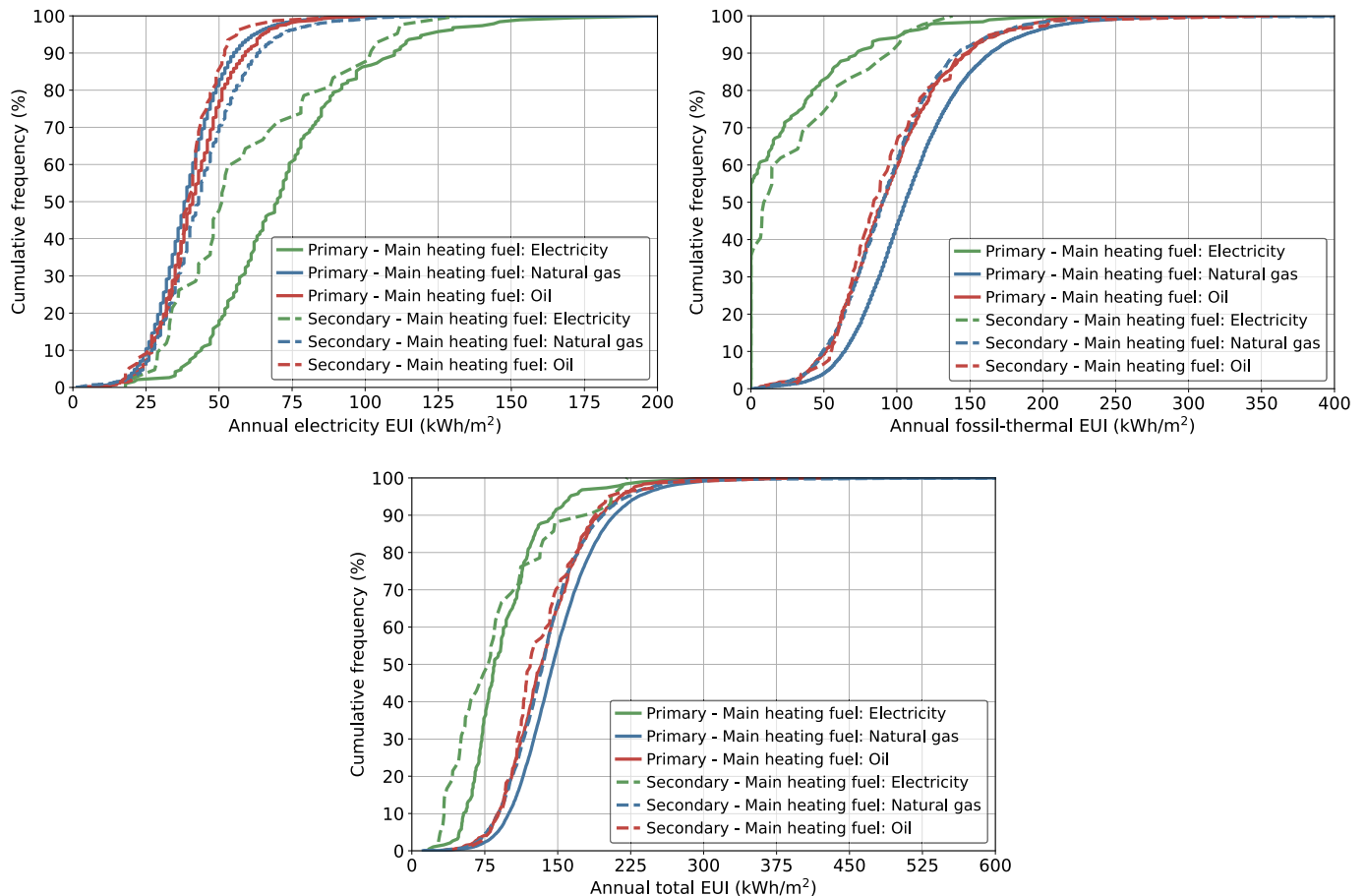
Main heating fuel	School type	Energy	Natural gas	Oil	Electricity
Natural gas	Primary	Fossil-thermal	—	< 0.0001	< 0.0001
		Electricity	—	< 0.0001	< 0.0001
	Secondary	Fossil-thermal	—	> 0.0167	< 0.0001
		Electricity	—	> 0.0167	< 0.0167
Oil	Primary	Fossil-thermal	—	—	< 0.0001
		Electricity	—	—	< 0.0001
	Secondary	Fossil-thermal	—	—	< 0.0001
		Electricity	—	—	< 0.0001
Electricity	Primary	Fossil-thermal	—	—	—
		Electricity	—	—	—
	Secondary	Fossil-thermal	—	—	—
		Electricity	—	—	—

consumption was higher in primary schools than in secondary schools. This is consistent with the findings of two previous studies that analysed DEC data prior to June 2012 [25,26]. However, these two studies demonstrated no statistically significant difference in fossil thermal energy use between primary and secondary schools, which is different from the findings of the current data analysis. Another research on DEC records from 2012 to 2014 obtained the same result as this study, that is, there was a statistically significant difference in both fossil thermal energy and electricity use in primary and secondary schools [27]. The potential reason for the significant difference in electricity consumption is that secondary schools have more ICTs and equipment in school facilities. Data on the condition of school buildings collected in both the Property Data Survey Programme (PDSP) and Building Energy Efficiency Surveys (BEES) indicated that secondary schools have more

energy-intensive activities and energy-consuming equipment than primary schools [68,69]. The increased internal gain caused by this difference in space and equipment utilisation reduces the need for space heating, which could be a likely reason for the gradual difference in fossil thermal energy use between primary and secondary schools.

5.2. HVAC systems

For HVAC systems, heating & natural ventilation systems (H&NV) and heating & mechanical ventilation (H&MV) systems are the main types applied in school buildings and reported on DECs. The test results revealed significant differences in both fossil thermal energy and electricity consumption patterns between fully naturally ventilated (NV) buildings and fully mechanically ventilated (MV) buildings. The

**Fig. 5.** Cumulative distribution curves of annual EUI by main heating fuels.

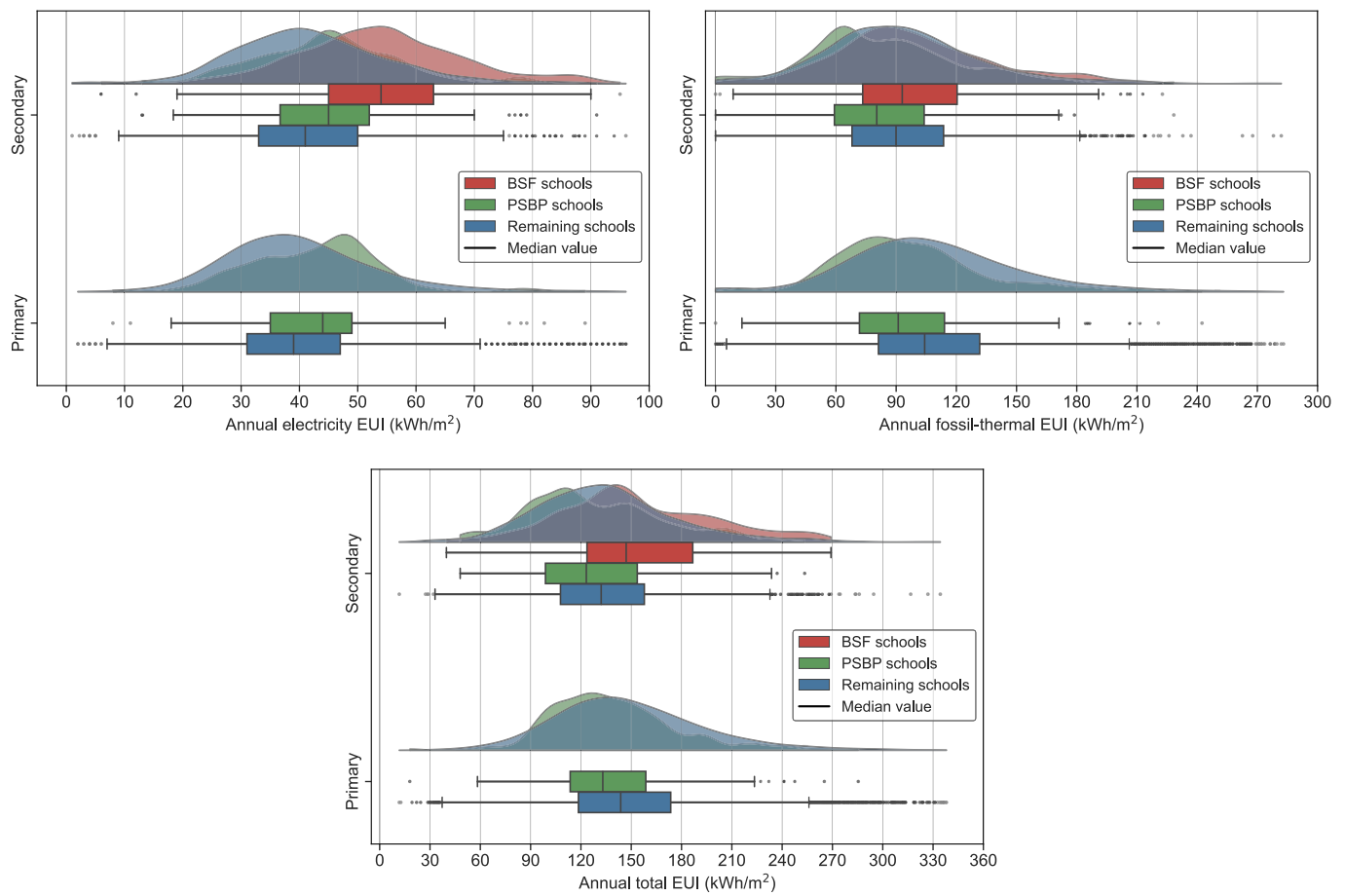


Fig. 6. Comparison of EUI in three school building stock clusters.

Table 8

EUI statistics in three school building stock clusters.

Building type	Clusters (N)	EUI (kWh/m ²)	10 %	25 %	50 %	75 %	90 %	Mean	Standard Deviation
Primary	PSBP (205)	Electricity	28	35	44	49	55	43	12
		Fossil-thermal	57	72	91	114	148	97	38
		Total	99	114	133	159	192	140	38
	Remaining schools (11374)	Electricity	25	31	39	47	57	41	17
		Fossil-thermal	60	81	104	132	163	109	45
		Total	97	119	144	174	207	150	48
	BSF (316)	Electricity	37	45	54	64	76	55	17
		Fossil-thermal	53	73	93	122	159	106	120
		Total	101	124	147	187	223	161	120
Secondary	PSBP (156)	Electricity	30	37	45	52	61	46	15
		Fossil-thermal	43	59	81	105	138	86	48
		Total	85	99	124	155	191	132	51
	Remaining schools (1518)	Electricity	27	33	41	50	60	43	16
		Fossil-thermal	47	68	90	114	143	94	44
		Total	86	108	132	158	193	137	48

statistics showed that buildings with mechanical ventilation consumed more electricity but had relatively lower fossil thermal energy consumption, which is consistent with the findings of previous studies [25–27]. However, the results of the same test on the energy consumption records for 2012 showed negligible differences in fossil thermal energy consumption (KW, $p > 0.05$) [26]. This is inconsistent with the findings of this study and may be due to the fact that both the airtightness of the school building envelope and the efficiency of the mechanical ventilation system with heat recovery have been improved in the last decade, thus the reduction in the unexpected ventilation has contributed to the reduced consumption of fossil thermal energy for heating. In addition, this study found no significant difference in fossil

thermal energy and electricity consumption between the H&MV system and the two mixed-mode systems (MM&NV and MM&MV). This responds to the fact that it is reasonable to classify HVAC systems into NV, MV and AC only in the PDSP dataset. The analysis of the energy use differences between MV and NV systems based on the PDSP dataset [27] aligns with the findings of this study.

5.3. Main heating fuel types

This study analysed energy consumption based on the classification of the main heating fuel types. Natural gas, oil and electricity are the main types of heating fuels used in school buildings. The results of the

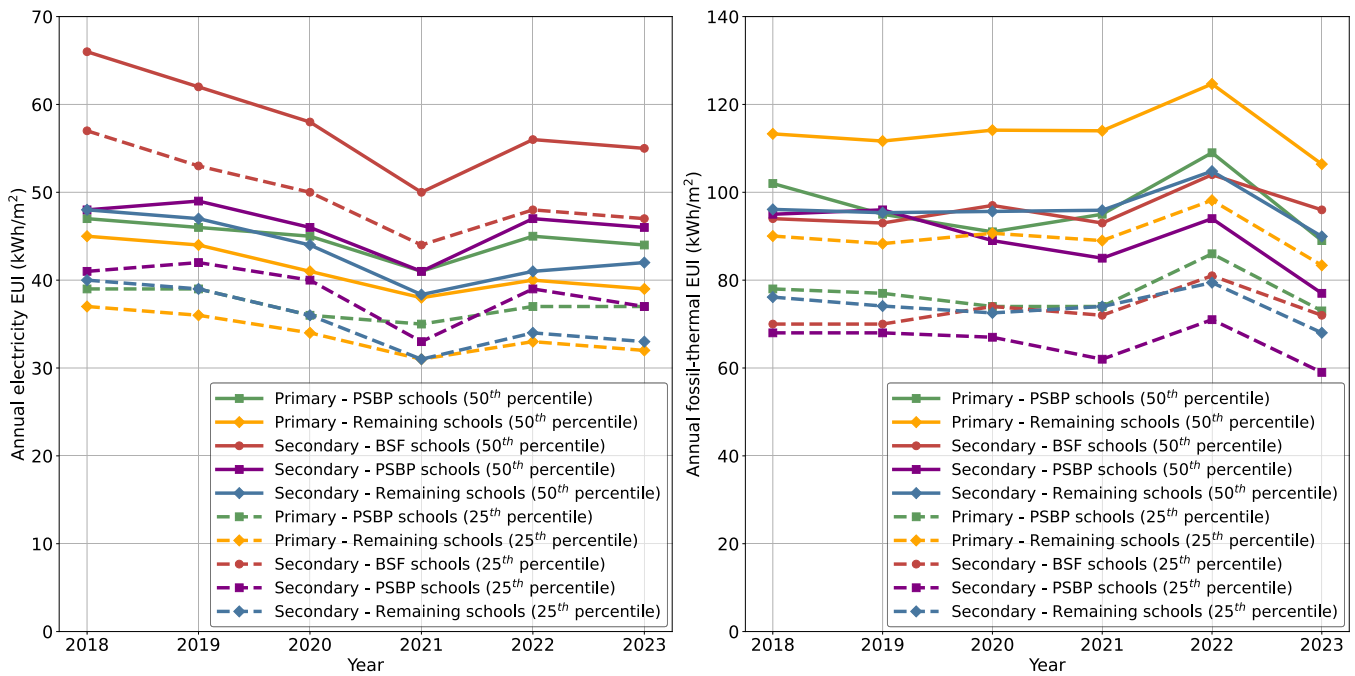


Fig. 7. Variation in electricity and fossil thermal energy use over time for three school building stock clusters.

tests indicated that there was a significant difference in the energy consumption of schools that used electricity for heating compared to the other two types. Buildings with electricity as the main heating fuel showed a much greater reduction in fossil thermal energy use than the increased in electricity consumption, resulting in the lowest total energy consumption among the three types. This could be attributed to the promotion and policy support of heat pump technology. The UK public sector actively encourages the replacement of gas boilers with air-to-water heat pumps or air-to-air heat pumps and supports replacing equipment four years before their expected end of life [70]. Heat pump systems are typically three to four times more efficient than gas boilers or other electric heating equipment, significantly reducing the energy demand of buildings [70,71]. Besides, most heat pump installations are in new or refurbished buildings, which typically have a good thermal envelope and airtightness. The other part of the heat pump market is driven by government initiatives, such as the Non-domestic Renewable Heat Incentive Scheme [72], Clean Growth Strategies [73] or Public Sector Decarbonisation Scheme [74], where the replacement of heating systems is commonly accompanied by upgrades to glazing and other insulation materials. These factors together contribute to the overall energy efficiency of buildings. Thus, as a key measure for heating electrification and achieving net-zero emissions, the application of heat pumps played an important role in reducing the use of fossil fuels [73,75]. Additionally, the results of analysing the DEC records for 2008/2009 showed that electricity consumption accounted for less than a third of total energy consumption [25]. However, since the carbon intensity of electricity at the time (0.49 kg CO₂e per kWh) was nearly three times that of natural gas (0.18 kg CO₂e per kWh), electricity consumption significantly influenced the variation in total CO₂ emissions in primary and secondary schools [76]. In 2024, the UK gas factor remains at 0.18 kg CO₂e per kWh, the oil factor is 0.25 kg CO₂e per kWh, while the electricity CO₂ factor falls by 57 % (0.21 kg CO₂e per kWh) compared to the earlier period due to the increase in renewable energy generation [77]. Therefore, despite the gradual increase in the share of electricity consumption in recent years, overall CO₂ emissions from schools should have been reduced and no longer be dominated by electricity use, given the reduction in total energy consumption and the significant decrease in the carbon intensity of the UK electricity grid.

5.4. Comparison of BSF schools, PSBP schools and the remaining school building stock

For energy use patterns in different clusters of school building stock, the operational energy performance of PSBP schools was relatively better than that of the remaining school building stock, whereas the operational energy performance of BSF schools was worse than that of the remaining school building stock. Both the typical practice level and average of electricity use intensity in PSBP schools met the operational energy target of less than 50 kWh/m². However, fossil fuel consumption exceeded the target of 60 kWh/m², with even good practice PSBP primary schools reaching 72 kWh/m². It is worth noting that the BSF program took more effort to design, which was slow and costly to construct. In contrast, the PSBP schools were based on a specifically proposed baseline design, reducing project costs by 1/3 compared to BSF schools while improving construction efficiency [78]. Besides, under the PSBP program, the space design of primary and secondary schools was reduced by 15 % and 5 %, respectively, compared to BSF schools, avoiding unnecessary space waste while maintaining equivalent teaching spaces [13]. Although influenced by the updated design requirements in the Building Regulations, both the insulation of the building fabric and the equipment efficiency of the building services systems in the PSBP schools have been improved in comparison to the BSF schools. However, considering the financial and time investment in the BSF program, these modern schools built after 2004 are expected to be more energy efficient than the remaining building stock. These buildings may have inherent operational problems or mismanagement of systems due to complex building design, causing the gap between measured performance and design intent [79]. For example, an evidence showed that the contractor for the a BSF school installed both a biomass boiler and a gas boiler for the building in order to achieve the required BREEAM rating, while the operational stage relied solely on the gas boiler [7].

5.5. Impact of the COVID-19 pandemic

The impact of COVID-19 pandemic on building use patterns contributed to fluctuations in energy consumption to some extent. Fossil thermal energy consumption varied slightly between 2018 and 2021,

but fluctuated in the two years following the end of the pandemic. This could be explained by the fact that during the lockdown, the UK government required the dependent children of staff in key positions to attend school as usual. 47 % of key workers in 2019 had dependent children aged 15 or under [80]. As a result, school buildings continued to operate during the lockdown, which prevented the expected reduction in space heating demand. This finding is in line with previous studies showing that energy consumption in the UK non-domestic sector did not significantly decline during the pandemic, and that space heating demand in domestic buildings did not rise substantially [47,49]. Moreover, the impact of the pandemic on occupant behaviour that carries over into the post-pandemic period, such as habitually opening windows to introduce fresh air, could be a potential reason for the apparent rise in fossil thermal intensities in 2022. Electricity consumption in 2021 reached its lowest point between 2018 and 2023, which can be attributed to the application of automated controls and settings in school buildings. The low occupancy of buildings during the lockdown resulted in reduced system and equipment usage intensity, leading to a corresponding decrease in electricity consumption. However, in 2022, it rebounded as activities return to normal. Excluding the period of the COVID-19 pandemic (2020–2021), electricity consumption in schools showed an overall downward trend, driven by school refurbishments, advances in technology such as the lower efficacy of LED lights compared against fluorescent lights previously used, and building energy efficiency upgrades measures in recent years. Notably, annual electricity demand in the UK had already been declining prior to the pandemic, and the trend observed in schools reflects this broader national pattern [43,44].

6. Conclusion

This study utilised publicly available DEC and GIAS datasets to perform a top-down analysis of the latest energy use patterns in school buildings across England and the trends observed between 2018 and 2023. It also categorised and compared the energy consumption of primary and secondary school buildings according to their HVAC systems and main heating fuels. In addition, to the best of the authors' knowledge, this paper is the first to utilise the DEC dataset to compare BSF schools and PSBP schools in terms of energy use against the remaining older schools. The main conclusions drawn from this study are:

- Primary schools consumed more fossil thermal energy and less electricity than secondary school buildings.
- Buildings with mechanical ventilation used more electricity and less fossil thermal energy than buildings with natural ventilation.
- Buildings using electricity as the main heating fuel consumed less total energy than buildings using natural gas and oil as the main heating fuel.
- BSF schools with higher financial investment had poorer total energy performance even compared against older buildings, while PSBP schools with compact and economic designs operated more efficiently. This finding has important implications for school building programmes, although other building and educational performance metrics should also be considered for a holistic assessment of the effectiveness of these schemes.
- The COVID-19 pandemic and the energy crisis increased uncertainty in energy use, which made it more difficult to summarise trends in energy consumption. Although schools were partially open during this period, the level of fossil thermal energy use suggests strategies such as zone control for HVAC systems were not used to isolate the unoccupied zones for energy use.

There are some limitations of this study. For the research methodology, the top-down approach used in this paper can show the comparison of historical energy consumption data and trends at the building

stock level under different classifications. However, the limitation is that it is not possible to identify the energy consumption of each end-use at the level of individual buildings and their relationship with the total energy consumption [81]. Future work will consider introducing bottom-up modelling combined with a case study approach to bridge this knowledge gap. For the processing of the data, this study has weather corrected the fossil thermal energy data using of the UK average heating degree-days to avoid biasing the results due to regional climate differences. Investigating the effects of these regional differences could also be part of a future study. Furthermore, this study was limited by the information available in the DEC dataset, making the exploration of variables potentially affecting energy consumption less extensive. Studies have been conducted to integrate the DEC dataset with the Property Data Survey Program (PDSP) dataset, which contains building conditions, to incorporate additional variables [27]. In the future, attention should be paid to the release of other available datasets and testing the feasibility of integration with the DEC dataset. Further research is also recommended to explore how identified factors such as building size, spatial layout and system complexity contribute to the observed differences in energy performance between BSF and PSBP schools, as well as other possible causes.

In conclusion, this study enhanced the understanding of the energy performance in England's school building stock. It reviewed the energy consumption of buildings under two large school rebuilding programmes that were completed. This on the one hand contributed to updating the energy benchmarks and demonstrated the gap between current school building performance and the ambition to achieve net-zero GHG emissions. It emphasised the need to advance energy technology and efficiency upgrades to further reduce carbon emissions. On the other hand, the essential role of the DEC database as a source of information for retrospective and long-term studies of energy use was underlined, as well as the added value of being able to match with other datasets to introduce more investigable variables. It should be noted that most of the current datasets rely on inconsistently formatted address information for matching, which may result in the final combined dataset being less representative due to insufficient sample sizes, hence further standardisation of the datasets should be required in order to maximise the practical value of the information collection.

CRedit authorship contribution statement

Jingxuan Yang: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Esfand Burman:** Writing – review & editing, Supervision, Conceptualization. **Dejan Mumovic:** Writing – review & editing, Supervision.

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.

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Data availability

Data will be made available on request.

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