Top-down and bottom-up analysis of energy performance trends in schools: Insights for achieving net-zero performance in use

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Abstract
With the goal of transitioning to net zero carbon buildings, school buildings are in urgent need of cost-effective and energy-efficient solutions to improve building performance, for which the UK Department for Education (DfE) has set up different school rebuilding and refurbishment programmes. The aim of this paper is to understand the recent energy use characteristics of primary and secondary school buildings constructed under the Building Schools for the Future (BSF) and Priority School Building Programme (PSBP) and the trends in energy use between 2018 and 2023 by statistically analysing Display Energy Certificate (DEC) data. Subsequently, a school building was selected from a cluster of school stock with relatively higher energy performance as a case study for building performance modelling. Multiple scenario tests were identified to investigate the feasibility of further improving the energy performance of school buildings.

Keywords School stock, Display Energy Certificate (DEC), Energy performance

1.0 Introduction
The UK Department for Education (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), a programme with a total budget of £55 billion, was launched in 2004 with the ambition to refurbish or rebuild all secondary schools in England over the next 15 years (1). However, this programme was stopped in 2010 for a number of reasons, including insufficient progress and cost overruns (2). 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 (3,4). The School Rebuilding 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 (5). The government provided £2 billion in funding for the first 100 projects (5).

Previous case studies have shown that the actual operational performance of school buildings generally did not match the design expectations (6–11). It is therefore 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 (12). Following subsequent amendments to the regulations, the need to display a DEC for public buildings over 250 m^2 in England and Wales has been a mandatory requirement since July 2015 (13). The DEC database has now 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 (14–18).

This study intended to inform further improvements in the energy performance of the school building stock by analysing the characteristics of school energy use from both a top-down and bottom-up analysis. The top-down analysis involved using the DEC database to quantify the latest energy performance of primary and secondary school buildings in the UK and to review trends in energy consumption patterns over the period 2018-2023. Three databases containing basic school information and DEC records were developed, which are for the All School Building Stock, the BSF School Building Stock and the PSBP School Building Stock. Bottom-up analysis referred to a school building selected as a case study for performance modelling and scenario testing. The underlying causes of differences between the model based on design expectations and the calibrated model outputs were investigated and the potential for operational performance of the building was explored.

2.0 Methodology

2.1 Top-down analysis approach

This study used Python 3.11 to first preprocess the DEC dataset and then integrate with the Get Information About Schools (GIAS) dataset through address matching (19,20). The DEC dataset records annual energy consumption data for electricity and fossil thermal energy. The GIAS dataset provides the phase of education (e.g. primary or secondary). Table 1 presents the number of schools by school type for each year in the final unified dataset. Of these, other schools refer to school buildings other than primary and secondary schools, including nurseries, all-through schools and 16-plus schools. Due to inconsistencies in the submission dates of DEC record by schools, the latest subset of energy usage includes records from the unified database for the years 2022–2024. The database of all school building stock was first analysed to understand latest overall school energy performance. As the energy data did not conform to a normal distribution, a non-parametric Mann-Whitney U-test was used to assess differences in electricity and fossil thermal energy use between secondary and primary schools (21). If the p-value is ≤ 0.001, it is considered that there is a significant difference between the two sets of data. Longitudinal analyses were then conducted to explore year-to-year variations in overall school energy performance from 2018 to 2023. Where 2018-2019 was considered as the pre-Covid19 pandemic period, 2020-2021 as the lockdown period and 2022-2023 as the post-pandemic period. The fossil thermal energy consumption data has been weather-corrected to 2021 heating degree-days, which represents the average climate for the UK (22). Next, the same statistical analyses were performed on the unified dataset of BSF and PSBP schools. Finally, the difference in energy consumption between modern schools under these two school rebuilding programmes was compared with the rest of the school building stock. Fossil thermal energy consumption has also been weather-corrected based on heating degree days.

Year	Primary schools			Secondary schools			Other schools		
	BSF	PSBP	All	BSF	PSBP	All	BSF	PSBP	All
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	11550	316	156	1864	83	31	1553

Table 1 – Number of schools by school type in the final unified dataset

2.2 Bottom-up analysis approach

In this study, the case building was modelled in DesignBuilder software using the Simple HVAC modelling approach. This approach is based on the National Calculation Method (NCM) activity dataset and predefined HVAC templates, which is one of the modelling approaches proposed in CIBSE TM54 for individual buildings (23,24). The modelling results, including the effect of equipment loads, were compared with measured data and the models were validated against the monthly calibration criteria defined in ASHRAE Guideline 14 (25). These criteria use two statistical metrics, the normalised mean bias error (NMBE) and the coefficient of variation of the root mean square error (CVRMSE), to validate that the calibrated model meets acceptable standards (NMBE < ±5% and CVRMSE < 15%). Then feasible energy saving and emission reduction measures were identified by analysing changes in input information and simulation results between the baseline and calibrated models. The bottom-up analysis is used to show an example of the ‘potential’ energy performance of the latest cluster of school buildings covered in the study against the ‘actual’ performance represented in the statistical sample.

3.0 Results

3.1 Overall school performance

Figure 1 shows the current annual energy use intensity (EUI) of primary and secondary schools in England using cumulative distribution curves. 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. (15,26,27). Thus, typical practice for current electricity EUI in primary and secondary schools is 39 kWh/m^2 and 43 kWh/m^2 respectively, and 104 kWh/m^2 and 90 kWh/m^2 for fossil thermal energy consumption. Mann-Whitney U-tests 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 heat energy than primary schools. Table 2 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 fuel use at the same time.

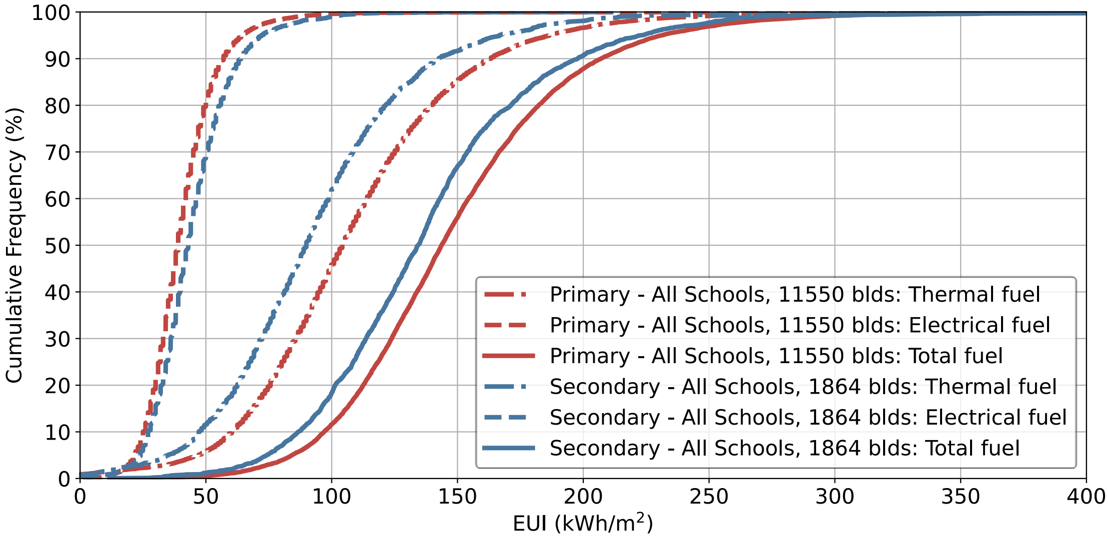

Figure 1 – Cumulative distribution curves of annual EUI

Building type (N)	EUI (kWh/m^2)	10%	25%	50%	75%	90%	Mean	Standard Deviation (SD)
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

Table 2 – EUI statistics

Figure 2 presents the year-on-year variation in thermal fuel and electricity use from 2018-2023, respectively, for both the ‘good practice’ and ‘typical practice’ benchmarks. The figure also 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 thermal fuels remained at pre-pandemic levels. The post-pandemic period started with rapid rises in energy use, with data for 2022 showing higher thermal fuel 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.

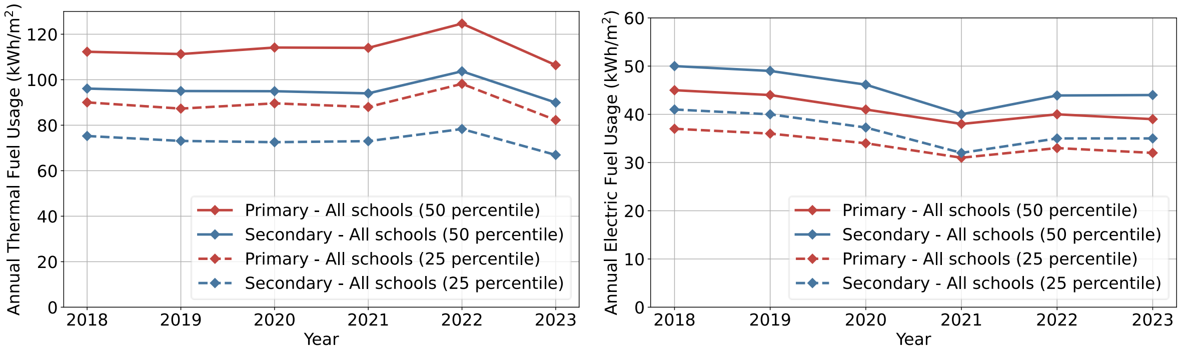

Figure 2 – Variation in thermal fuel (left) and electricity (right) use over time

3.2 Comparison of EUI in three school building stock clusters

Figure 3 shows the annual EUI of the BSF school building stock, the PSBP school building stock, and the remaining school building stock in boxplots for comparison. Within the same building stock clusters, fossil thermal energy use was high in primary schools, while secondary schools consumed more electricity, which is consistent with the results of the overall school energy performance analyses in the previous section. 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, the primary school buildings in the remaining schools consumed the most fossil thermal energy. The secondary school buildings in the PSBP school cluster consumed the least fossil thermal energy. By school type, for primary schools, the PSBP primary buildings 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 school buildings have the greatest fossil thermal and electrical EUI, and their fossil thermal energy consumption is even higher than that of PSBP primary school buildings. PSBP secondary schools have a slightly higher electrical EUI than the remaining schools, but have the lowest levels of fossil thermal and total energy consumption. Table 3 summarises statistics on energy use by school type and cluster.

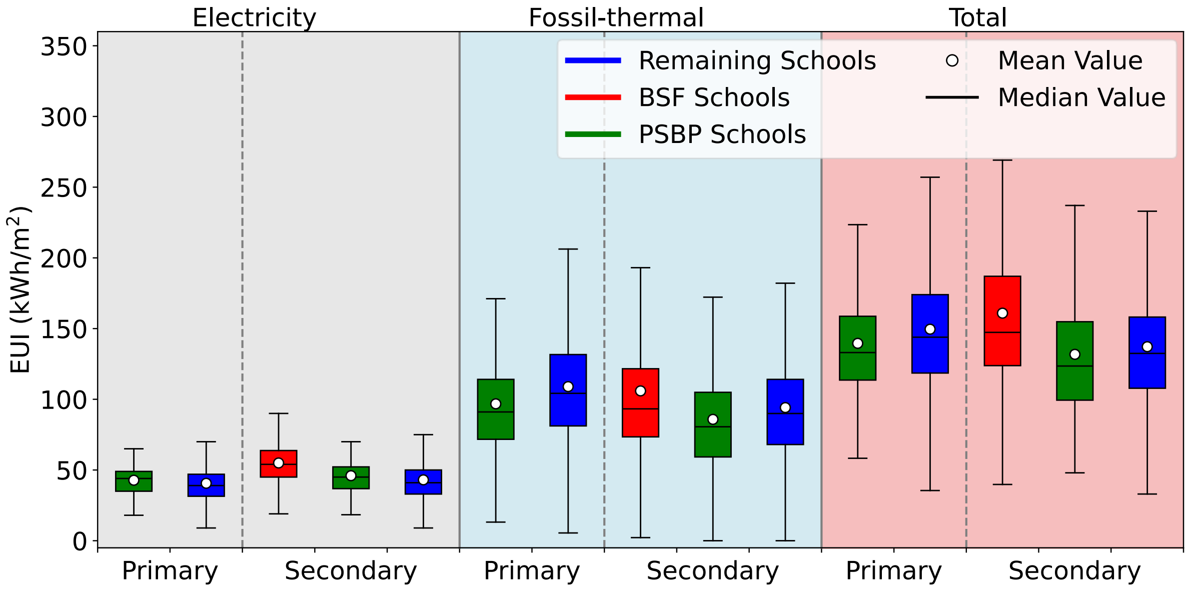

Figure 3 – Comparison of EUI in three school building stock clusters

Building type	Clusters (N)	EUI (kWh/m²)	10%	25%	50%	75%	90%	Mean	SD
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
Secondary	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
	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

Table 3 – EUI statistics in three school building stock clusters

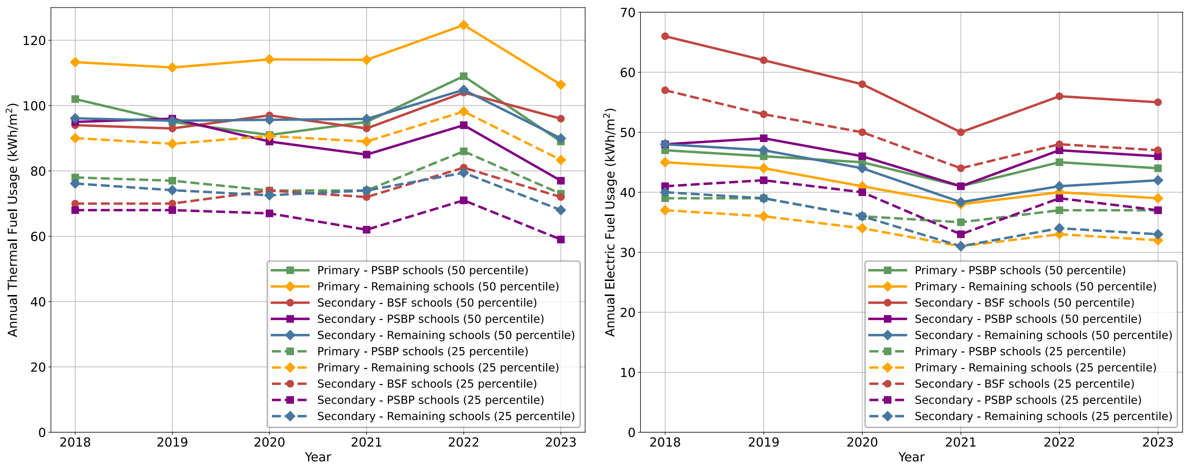

Figure 4 – Variation in thermal fuel (left) and electricity (right) use over time

Figure 4 shows the year-to-year changes in the use of thermal fuels and electricity for these three school building clusters from 2018-2023, with both ‘good practice’ and ‘typical practice’ benchmarks. For thermal fuel use, primary schools in the remaining school building stock have consistently consumed the highest amount of thermal fuel over the past six years. Good practice buildings in this cluster used even more thermal fuel than typical practice PSBP secondary schools during the lockdown and post-pandemic period. The BSF Schools currently has 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 were consistently the cluster with 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.

3.3 Case study: A PSBP Primary School

The above study identified PSBP schools as having relatively better operational energy performance by comparing the DEC records of different school clusters. In the following section, a PSBP primary school building was used as a case study for a bottom-up analysis of the in-use energy performance at an individual building level. The school, located in the North of England and opened in 2019, is a L-shaped two-storey building with about 2400 m^2 of floor area. Figure 5 illustrates the building model developed in DesignBuilder software for this case study. Table 5 shows the input parameters and data sources in the baseline model. The baseline model represents the potential operational performance of the building under the design conditions. The information for the modelling was obtained from as-built architectural drawings, building services and engineering schematics collected through site visits. In the meantime, the building's energy bills for the past year were also collected to get the actual operational energy performance (April 2023 to March 2024). The measured annual natural gas consumption was 81 kWh/m^2 and the annual electricity consumption was 41 kWh/m^2, both of which lie between best practice and typical practice for the PSBP primary schools cluster.

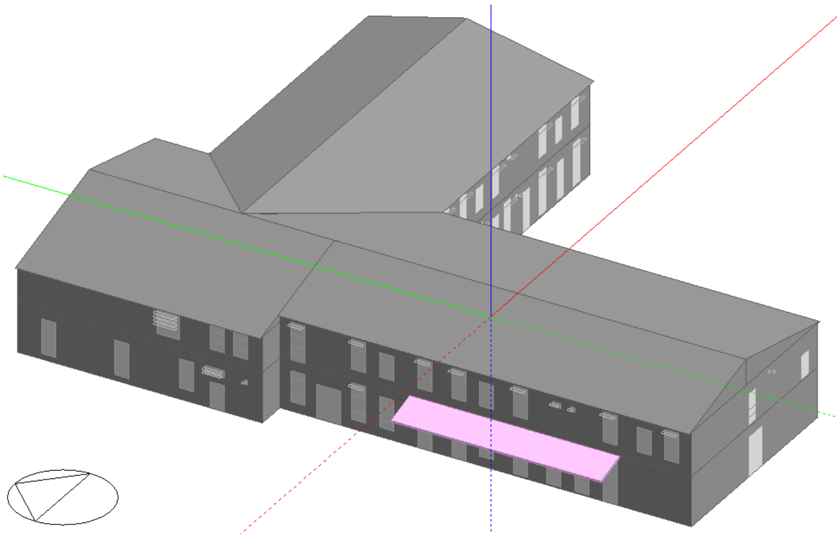

Figure 5 – Building model developed for the case study with DesignBuilder

Categories	Details	Data source
External envelope	U-value (W/m^2K): External wall: 0.26; External floor: 0.20; Roof: 0.18; Window: 1.35; Door: 1.90. Air tightness: 4.85 $m^3/(m^2.hr)$ @ 50 Pa.	Architectural drawings, air pressure test
Occupancy	Nominal capacity: 480 pupils & 20 Staff. Weekdays: 7:30-18:00. Weekends: unoccupied.	Site visit
Heating	Seasonal efficiency for the condensing gas-fired boiler: 96.6%. Weekdays: 6:30-7:30 for preheating and 7:30-18:00.	Engineering schematics, technical specifications, site visit
Cooling	Seasonal energy efficiency ratio for the DX system: 6.94.	

	Same as the occupancy schedule.	
Domestic hot water	Seasonal efficiency for the condensing gas-fired water heater: 97%. Delivery temperature: 65 °C.	
Ventilation	Heat recovery efficiency: 90%. Operational schedule: same as the occupancy schedule.	
Lighting	Installed power density: 2.4 W/m^2/(100lux).	

Table 4 – Input parameters for the baseline model

The baseline model predicted yearly gas and electricity consumption of 21.5 kWh/m^2 and 30.5 kWh/m^2 respectively, both of which were better than the good practice PSBP primary school building and put together would meet the RIBA net-zero operational target for schools if achieved in practice (28). The modelled total energy consumption is in the top 10% of DEC records for this cluster. This, however, presents a significant gap with the in-use energy performance of the building. Figure 6 illustrates the comparison of simulated monthly gas and electricity usage from the baseline model against measured data. In order to calibrate the model and identify potential causes of the gap, reasonable scenario assumptions, based on the site visits and a review of the literature of the performance gap in schools (6–11), were proposed for testing. Figure 7 shows the scenario test results from the baseline model to the calibrated model and the comparison with the measured data.

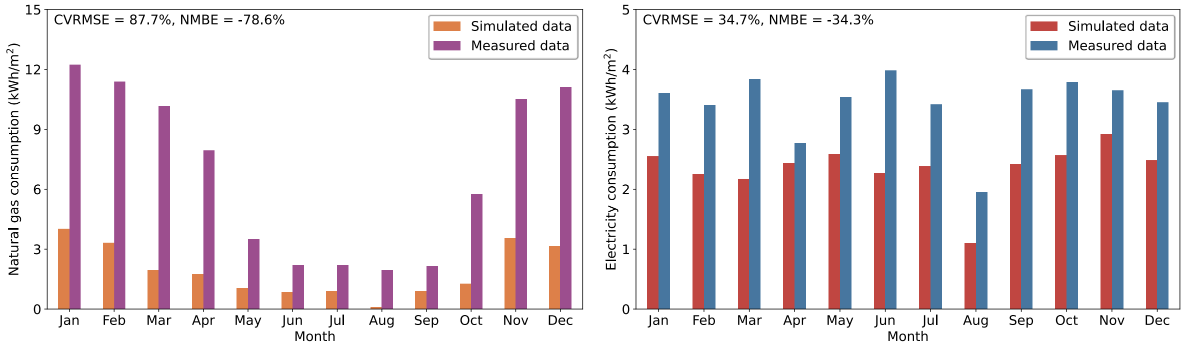

Figure 6. Comparison of simulated monthly natural gas (left) and electricity (right) usage against measured data for the baseline model

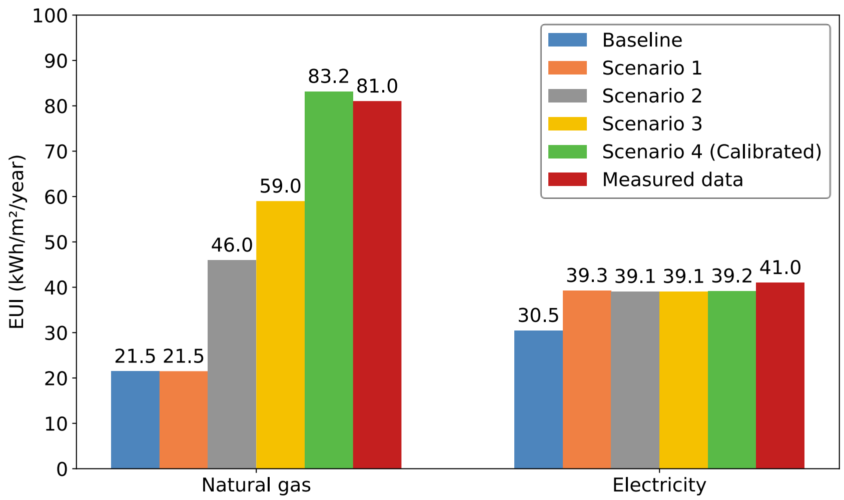

Figure 7 Scenario test results from the baseline model to the calibrated model

Scenario 1 was based on updating the heat gain generated by the equipment in the server room from the NCM value of 50 W/m^2 to the maximum recommended value of 250 W/m^2 as per the latest DfE guidelines for PSBP schools (the systematic bias in measured vs. modelled electricity use indicates an underestimation of electrical equipment load in the baseline model) (29). This reflects the impact of the increase in ICT equipment on the electricity consumption. Scenarios 2 and 3 were developed by changing the building background ventilation rate to 0.5 air change per hour (ACH) and extending the operating hours of the heating system during half-term breaks in the heating season. These two scenarios were proposed based on information gathered during the site visit to incorporate random window opening behaviour by occupants and the fact that the heating system would still operate normally during non-term hours into the modelling considerations. For Scenario 4 the heating set point temperature was adjusted upwards from the NCM value to 22°C. The final simulated natural gas consumption was 83.2 kWh/m^2/year and electricity consumption was 39.2 kWh/m^2/year. This scenario is cumulative of the above scenario assumptions and the calculated NMBN and CVRMSE meet the monthly calibration criteria. The modelling for Scenario 4 is therefore a calibrated model. Figure 8 shows the monthly natural gas and electricity usage simulated by the calibrated model compared to the measured data.

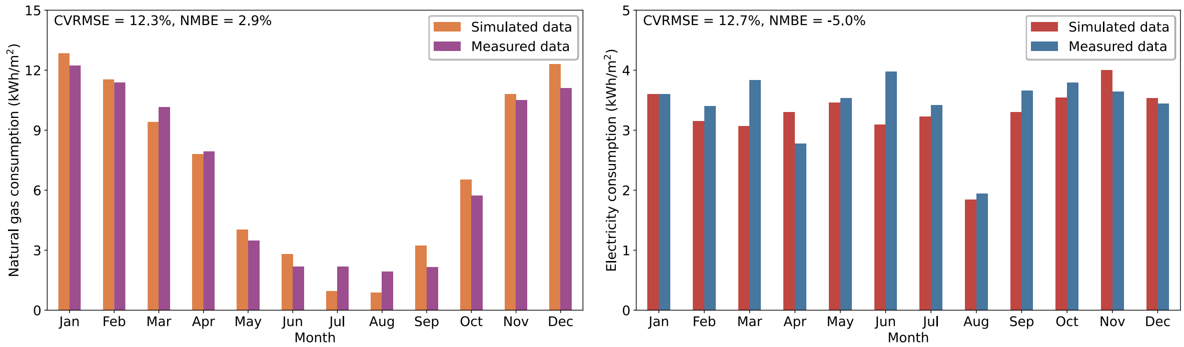

Figure 8. Comparison of simulated monthly natural gas (left) and electricity (right) usage against measured data for the calibrated model

4.0 Discussion

This study found that electricity consumption was higher in secondary schools than in primary schools, while fossil thermal energy 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 (16,17). However, these two studies showed 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 2012-2014 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 (15). 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 (30,31). 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.

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. It is worth noting that each school under the BSF program was designed individually, which was slow and costly to construct. In contrast, PSBP schools adhered to specifically proposed baseline design requirements., reducing project costs by 1/3 compared to BSF schools while improving construction efficiency (32). 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 (33). 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, resulting in the gap between measured performance and design intent.

The impact of Covid-19 pandemic on building use patterns contributed to some extent to fluctuations in energy consumption. Overall, the consumption of thermal fuels varied slightly from 2018-2021, but fluctuated during the two years after the end of the pandemic, which may be due to the impact of the pandemic on occupant behaviour, such as habitually opening windows to introduce fresh air. Electricity consumption, on the other hand, is on a slow downward trend overall, disregarding changes during the pandemic. The dependent children of staff in key positions in the UK during the lockdown would still attend school as usual. 47% of key workers in 2019 had dependent children aged 15 or under (34). As a result, school buildings would have remained operational during the lockdown, which may explain the lack of the expected reduction in space heating demand. Instead, the lower electrical energy consumption could be attributed to the application of automated controls and settings in the school building. Low occupancy leads to a lower density of system and equipment use, which results in significantly lower electrical energy consumption than under normal occupancy. The long-term reduction in electricity use in schools may be driven by the better efficacy offered by the latest LED technology used in new PSBP schools and reductions in power density of electronic equipment.

Bottom-up analyses of the individual building revealed that operational energy performance has a high potential for improvement through enhanced routine maintenance and management of the building services system (e.g. optimum space time utilisation of building services and improving HVAC zoning and schedule arrangements). Thus, a combination of top-down and bottom-up analyses should be used to locate the energy consumption level of the building and to propose feasible energy saving measures. In addition, in order to use building performance modelling for practical purposes, the assumptions for scenario testing need to be based on the actual operation of the building, rather than relying on individually more sensitive input parameters to achieve model calibration.

5.0 Conclusions

This paper used the publicly available DEC dataset to report the energy use patterns of primary and secondary schools in England. It also analysed the latest energy consumption and EUI changes for different clusters of school buildings over the period 2018-2023. The study found that BSF schools with high financial investment had poor energy performance, while PSBP schools with compact designs had more efficient building operations. However, an investigation of a PSBP primary school at the individual building level still identified significant gaps between the actual operation of the building and the design expectations. And the scenario testing revealed even without refurbishing the building, there were a variety of practical measures that could be taken to further reduce the operational energy consumption of the building. The limitation of this study is that only one building in one cluster was used as a case study, and in the future more cases will be introduced for further comparative studies.

References

1. Education and Skills Committee. Sustainable Schools: Are we building schools for the future? Seventh Report of Session 2006–07 [Internet]. London: House of Commons: Education and Skills Select Committee; 2007 Jul [cited 2022 Jan 23]. Available from: https://publications.parliament.uk/pa/cm200607/cmselect/cmeduski/140/140.pdf
2. DfE. Equalities impact assessment: building schools for the future [Internet]. Department for Education; 2012 [cited 2023 Feb 12]. Available from: https://www.gov.uk/government/publications/equalities-impact-assessment-building-schools-for-the-future
3. James S, Brown E. Review of education capital: progress update. Department for Education; 2013 Dec p. 31. Report No.: DFE-00286-2013.
4. ESFA. Priority School Building Programme: overview [Internet]. Education and Skills Funding Agency; 2016 [cited 2022 Jan 23]. Available from: https://www.gov.uk/government/publications/psbp-overview/priority-school-building-programme-overview
5. DfE. GOV.UK. 2021 [cited 2022 Jan 23]. Major rebuilds begin at schools across England. Available from: https://www.gov.uk/government/news/major-rebuilds-begin-at-schools-across-england
6. Bordass B, Cohen R, Standeven M, Leaman A. Assessing building performance in use 3: energy performance of the Probe buildings. Build Res Inf. 2001 Mar;29(2):114–28.
7. Pegg IM, Cripps A, Kolokotroni M. Post-occupancy performance of five low-energy schools in the UK. ASHRAE Trans. 2007 Jul 1;113(2):3–14.
8. Carbon Trust. Closing the gap: Lessons learned on realising the potential of low carbon building design [Internet]. London, UK: Carbon Trust; 2011 [cited 2022 Jul 17]. Available from: https://phai.ie/wp-content/uploads/2017/07/ctg047-closing-the-gap-low-carbon-building-design.pdf
9. Burman E, Kimpian J, Mumovic D. Building Schools for the Future: Lessons Learned From Performance Evaluations of Five Secondary Schools and Academies in England. Front Built Environ. 2018 Apr 19;4:22.
10. Jain N, Burman E, Robertson C, Stamp S, Shrubsole C, Aletta F, et al. Building performance evaluation: Balancing energy and indoor environmental quality in a UK school building. Build Serv Eng Res Technol. 2020 May 1;41(3):343–60.
11. Jradi M. Dynamic Energy Modelling as an Alternative Approach for Reducing Performance Gaps in Retrofitted Schools in Denmark. Appl Sci. 2020;10(21):7862.
12. DCLG. The Energy Performance of Buildings (Certificates and Inspections) (England and Wales) Regulations 2007 [Internet]. The Department for Communities and Local

Government (DCLG); 2007 [cited 2024 Sep 23]. Available from: https://www.legislation.gov.uk/uksi/2007/991/contents
13. DCLG. The Energy Performance of Buildings (England and Wales) Regulations 2012 [Internet]. The Department for Communities and Local Government (DCLG); 2012 [cited 2024 Sep 23]. Available from: https://www.legislation.gov.uk/uksi/2012/3118/contents
14. Hong S, Mylona A, Davies H, Ruyssevelt P, Mumovic D. Assessing the trends of energy use of public non-domestic buildings in England and Wales. Build Serv Eng Res Technol [Internet]. 2018 Oct 18 [cited 2024 Sep 23]; Available from: https://journals.sagepub.com/doi/10.1177/0143624418806135
15. Hong SM, Godoy-Shimizu D, Schwartz Y, Korolija I, Mavrogianni A, Mumovic D. Characterising the English school stock using a unified national on-site survey and energy database. Build Serv Eng Res Technol. 2022 Jan 1;43(1):89–112.
16. Hong SM, Paterson G, Mumovic D, Steadman P. Improved benchmarking comparability for energy consumption in schools. Build Res Inf. 2014 Jan 2;42(1):47–61.
17. Godoy-Shimizu D, Armitage P, Steemers K, Chenvidyakarn T. Using Display Energy Certificates to quantify schools' energy consumption. Build Res Inf. 2011 Dec;39(6):535–52.
18. Armitage P, Godoy-Shimizu D, Steemers K, Chenvidyakarn T. Using Display Energy Certificates to quantify public sector office energy consumption. Build Res Inf. 2015 Nov 2;43(6):691–709.
19. DLUHC. Energy Performance of Buildings Data England and Wales [Internet]. 2024 [cited 2024 Sep 23]. Available from: https://epc.opendatacommunities.org/domestic/search
20. DfE. Get Information about Schools - GOV.UK [Internet]. 2024 [cited 2024 Aug 29]. Available from: https://get-information-schools.service.gov.uk/
21. Mann HB, Whitney DR. On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other. Ann Math Stat. 1947 Mar;18(1):50–60.
22. CIBSE. TM46: Energy benchmarks. London: The Chartered Institution of Building Services Engineers; 2008. (Technical Memoranda).
23. CIBSE. TM54: Evaluating operational energy use at the design stage. London: The Chartered Institution of Building Services Engineers; 2022.
24. BRE. NCM: iSBEM for England [Internet]. [cited 2024 Mar 21]. Available from: https://www.uk-ncm.org.uk/download.jsp?id=35
25. ASHRAE. ASHRAE Guideline 14-2014 Measurement Of Energy, Demand, And Water Savings. ASHRAE; 2014.
26. Hong SM, Paterson G, Burman E, Steadman P, Mumovic D. A comparative study of benchmarking approaches for non-domestic buildings: Part 1 – Top-down approach. Int J Sustain Built Environ. 2013 Dec 1;2(2):119–30.
27. CIBSE. Energy Benchmarking Tool [Internet]. 2021 [cited 2024 Oct 10]. Available from: https://www.cibse.org/knowledge-research/knowledge-resources/knowledge-toolbox/benchmarking-registration
28. RIBA. RIBA 2030 Climate Challenge. Royal Institute of British Architects; 2021.
29. DfE. School Output Specification Technical Annex 2H: Energy [Internet]. Department for Education; 2022 [cited 2023 Oct 1]. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1119606/GDB_Annex_2H-Energy-A-C13.pdf
30. EFA. Property data survey programme [Internet]. London: Education Funding Agency; 2015 Feb [cited 2024 Oct 28]. Available from: https://www.gov.uk/government/publications/property-data-survey-programme
31. BEIS. Building Energy Efficiency Survey (BEES) [Internet]. London: Department for Business, Energy & Industrial Strategy; 2016 [cited 2024 Oct 28]. Available from: https://www.gov.uk/government/publications/building-energy-efficiency-survey-bees

32. Deputy Prime Minister's Office, Department for Education. GOV.UK. 2015 [cited 2025 Jan 14]. £6 billion investment to rebuild and improve schools across England. Available from: https://www.gov.uk/government/news/6-billion-investment-to-rebuild-and-improve-schools-across-england
33. Department for Education, Education Funding Agency. GOV.UK. 2012 [cited 2025 Jan 14]. Innovative new school designs deliver efficiency for every pound spent. Available from: https://www.gov.uk/government/news/innovative-new-school-designs-deliver-efficiency-for-every-pound-spent
34. ONS. Office for National Statistcs. 2020. Coronavirus and key workers in the UK.