

The COVID-19 Legacy: Indoor Air Quality, Thermal Comfort and Energy Use in English Classrooms

Abstract

Good air quality is essential for public health. This study of English school classrooms investigates the interplay between indoor air quality (IAQ), energy-related constraints, and stakeholder practices. Using a mixed-methods approach, we combined semi-structured interviews with teachers and senior leaders and an IAQ measurement campaign (CO₂, PM_{2.5}, temperature, and relative humidity) across *twelve* classrooms to explore how the post-pandemic context shifted stakeholder priorities. We analyse the tensions between providing healthy indoor environments and maintaining thermal comfort against a backdrop of rising energy costs, constrained school budgets, and Net Zero targets. Our findings reveal how these pressures result in reactive compromises that often prioritise thermal comfort and cost over consistent ventilation and air quality.

Keywords: Indoor Air Quality, Thermal Comfort, Schools, Net Zero, Climate Change, Stakeholders

1. Introduction

2 The quality of indoor environments in the UK is attracting increasing
3 attention, shaped by several interconnected crises and policy commitments.
4 These include: the airborne transmission of COVID-19 [1] and the wider
5 long-term impacts of poor indoor air quality (IAQ); substantial increases in
6 wholesale energy prices owing to geopolitical factors, including the Russian
7 invasion of Ukraine [3]; and Net Zero targets for energy use and greenhouse
8 gas emissions [4].

9 Although the effects of the above are felt throughout the built environ-
10 ment, including homes, workplaces, and public buildings, schools face distinct
11 challenges. In particular, children and young people (CYP) are at greater risk
12 from poor air quality [5], compounded by substantial constraints on funding
13 for necessary upgrades to the school estate. It is estimated that approxi-

14 mately 90% of our time is spent indoors [6, 7, 8], and for CYP much of this
15 is spent in classrooms [9].

16 These crises highlight the challenges of **good indoor air quality in schools**,
17 where shifting priorities require constant compromise. Schools are tasked
18 with balancing the creation of safe, comfortable learning spaces against com-
19 mitments to improve energy efficiency and reduce carbon emissions. This
20 tension is often dictated by the occupants’ evolving understanding of their
21 environment [10], rigid pedagogical constraints (e.g., lesson routines, noise ex-
22 pectations, and safeguarding), and the shifting socio-political challenges [11].
23 This was acutely highlighted during the COVID-19 pandemic, when the con-
24 ventional notion of increasing airtightness to reduce heat loss was directly
25 challenged by the need to ventilate to reduce airborne transmission [12]. For
26 many schools, the requirement to keep windows and doors open proved “un-
27 workable” and unsustainable [13, 14], particularly during winter.

28 In this paper, we examine the interconnected and sometimes conflicting
29 nature of aligning health and environmental co-benefits in English school
30 classrooms, through a focus on managing indoor air quality (IAQ) and en-
31 ergy. We combine in-classroom IAQ, temperature, and humidity data with
32 semi-structured interviews with staff at six schools in the North West of
33 England to analyse the relationship between air quality, energy consump-
34 tion, and building characteristics. **This study is situated in the immediate
35 post-lockdown period, but the tensions between thermal comfort and ven-
36 tilation extend beyond that crisis.** Our work uncovers how these compet-
37 ing pressures produce ‘responsibilisation’ (the shifting of operational burden
38 from institutions onto individuals), where structural deficits in the build-
39 ing stock and strategic advice are offloaded onto teachers. We demonstrate
40 how ‘infrastructural invisibility’—where controls are hidden, inaccessible, or
41 ineffective—forces staff into a zero-sum choice between health and warmth,
42 a choice they are structurally unable to win.

43 **2. Background**

44 *2.1. The Health and Policy Context of School IAQ*

45 Poor IAQ is associated with a range of acute and chronic health effects [2].
46 While evidence is primarily linked to outdoor air pollution exposure [15],
47 IAQ is gaining importance [16], especially as most personal exposure occurs
48 indoors [17], and some pollutant concentrations can be greater indoors [18,
49 19]. Furthermore, while many pollutants are not directly perceivable, social

50 science research suggests that occupants can develop ‘bodily reasoning’ to
51 perceive otherwise ‘invisible’ chemical exposures [23, 24], creating a complex
52 relationship between actual and felt safety.

53 Early studies by Dockery et al. [25], Andersen et al. [26], and Alzona et
54 al. [27] demonstrated the significant harms of poor IAQ. Large measurement
55 campaigns in schools have documented significant spikes in $PM_{2.5}$, PM_{10} , and
56 CO_2 during occupied hours, driven by inadequate ventilation [28]. Adoles-
57 cents have a higher respiration rate than younger children, likely resulting in
58 more CO_2 in classrooms [29]. Elevated classroom CO_2 has also been associ-
59 ated with reduced cognitive function and decision-making [20], with impli-
60 cations for CYP’s capacity to learn [21]. Younger occupants are particularly
61 vulnerable due to their physical development and typically lack agency to
62 mitigate exposure [30, 22].

63 Indoor pollutants originate from a complex mix of internal and exter-
64 nal sources. Internally, occupant respiration is the primary driver of CO_2
65 levels, while specific classroom activities—such as art, science practicals, or
66 woodworking—generate particulate matter ($PM_{2.5}$) [31]. However, indoor air
67 is also significantly influenced by the ingress of outdoor pollutants, such as
68 particulates from local traffic or industry. This creates a ventilation paradox:
69 while replacing indoor air is vital to remove occupant-generated CO_2 , natural
70 ventilation can inadvertently degrade IAQ by introducing outdoor $PM_{2.5}$ if
71 external pollution levels exceed those indoors [32]. Thus, the effectiveness of
72 opening windows is contingent upon the quality of the ambient outdoor air.

73 The current state of IAQ in UK school classrooms was explored as part
74 of the Schools’ Air Quality Monitoring for Health and Education (SAMHE)
75 project, which monitored IAQ in more than 1000 schools. Wood et al. [33]
76 found that adherence to CO_2 guidelines often depended on average outdoor
77 temperature, indicating the importance of natural ventilation—the process of
78 supplying air to an indoor space through pressure-driven airflow from natural
79 forces such as wind and temperature differences, typically through operable
80 windows and doors [34]—for reducing CO_2 concentrations. The same study
81 also noted that airtightness increased the likelihood of measured CO_2 con-
82 centrations exceeding recommended Department for Education guidelines in
83 both mechanically and naturally ventilated classrooms [35].

84 Baloch et al. [36] observed similar patterns, with CO_2 guidelines con-
85 sistently exceeded and concentrations tending to be greater in schools with
86 more pupils than their target number. This highlights the challenge that
87 growing class sizes [37] pose for achieving good IAQ. Hama et al. [38] found

88 similar trends in London schools, noting that within their diverse sample of
89 30 buildings, challenges in meeting comfort and IAQ targets simultaneously
90 persisted across both legacy and modern infrastructure.

91 These works trace an evolution from material-focused risk to a systemic
92 understanding of air quality shaped by space usage, architecture, and ven-
93 tilation design. IAQ was for a long time figuratively and literally invis-
94 ible to occupants; however, the pandemic brought it into public prominence.
95 COVID-19 acted as a catalyst that altered perceptions and practices regard-
96 ing IAQ in schools [39]. The heightened awareness of airborne transmission
97 risks led to significant advice for schools to increase ventilation by opening
98 windows and doors, even in cold weather [1]. Over 300,000 CO₂ sensors were
99 distributed to schools across the UK with the aim of equipping all schools
100 with them [40].

101 *2.2. The Air-Energy Nexus and the Trilemma*

102 We frame the school environment as a system of sociotechnical provision-
103 ing. In this context, IAQ emerges from the interaction between physical in-
104 frastructure (e.g. windows, sensors, and heating systems) and social practices
105 (e.g. timetabling, classroom management, and behavioural norms). However,
106 IAQ represents only one part of this system. It is a component of Indoor
107 Environmental Quality (IEQ)—the overall condition of a building’s interior
108 environment encompassing air quality, thermal comfort, lighting, and acous-
109 tics. This integrated framework, first articulated by Loftness and Hartkopf
110 in 1989 [41], has since been extensively validated [42] and is distinct from,
111 but interacts with, IAQ. These IEQ dimensions are fundamental to assessing
112 comfort and health and are important indicators for both mould potential [43]
113 and overheating, which is a growing problem across UK building stock [44].

114 Alongside good IAQ, total energy use, and thermal comfort are central
115 concerns—described as a satisfactory temperature of one’s surroundings [45],
116 or by ASHRAE [46] as “that condition of mind that expresses satisfaction
117 with the thermal environment”.

118 The balance of thermal comfort versus energy usage was discussed by
119 Atthajariyakul et al. [47], noting that achieving optimal temperature may
120 require energy-intensive heating, ventilation, and air conditioning (HVAC)
121 systems to cool spaces or to compensate for heat loss from ventilation.
122 Bouzarovski and Robinson [48] describe this balance as the ‘air-energy
123 nexus’, defined as the interconnected relationship between air circulation
124 and energy use in society. Their concept highlights how energy systems

125 influence air quality and movement, emphasising the need to consider air and
126 energy together in both research and policy. Hussain et al. [49] extended this
127 to stakeholder needs—guidelines that must be met—framing the interplay
128 of air quality, energy, and stakeholder requirements as a ‘trilemma’.

129 This “trilemma” is acute in UK schools, which face the compounding crises
130 of post-COVID recovery, financial stringency, and rising energy prices, con-
131 straining their ability to create safer learning spaces. The long-term drive
132 towards reducing energy consumption was complicated when UK Govern-
133 ment advice during the COVID-19 pandemic was to ventilate indoor spaces
134 as much as reasonably possible [50], resulting in increased heat loss and an
135 “energy penalty” as “fresh” outdoor air must be heated to maintain ther-
136 mal comfort. This requires more energy, increasing the carbon emissions
137 associated with schools, the majority of which use fossil-fuel-based heating
138 systems [51].

139 This guidance temporarily put school ventilation management into con-
140 flict with building standards that prioritise energy efficiency, such as Building
141 Bulletin 101 (BB101), which outlines the heating and ventilation policies for
142 schools [35]. This regulatory conflict between ventilation advice and energy-
143 focused building standards shapes how schools manage indoor environments
144 in practice.

145 Building fabric reinforces this tension: 81% of UK school stock predates
146 1976 and largely depends on natural rather than mechanical (fan-driven)
147 ventilation [52], so regulatory and behavioural fixes still run up against legacy
148 estates shaped by earlier guidance (e.g. BB73 [53]).

149 *2.3. Sociotechnical Challenges in Knowing the Air*

150 Recent IAQ monitor deployments have revealed significant barriers to ef-
151 fective IAQ management; sustaining an effective balance between air quality
152 and thermal comfort requires ongoing monitoring of both [12]. Evaluations of
153 the Department for Education’s monitor rollout [55] suggest that providing
154 hardware alone is insufficient to drive behavioural change without formalised
155 training, often leaving teachers with only simplistic advice. Broader environ-
156 mental assessments by Jain et al. [56] point to issues relating to the physi-
157 cal design, use, and occupancy of school classrooms. The expectation that
158 teachers interpret CO₂ data and act on it in real time—while managing a
159 classroom—places an unrealistic sociotechnical demand on already-stretched
160 staff.

161 Effective IAQ requires engaging stakeholders as active participants. How-
162 ever, the ventilation strategy heavily mediates this engagement. Chatzidi-
163 akou et al. [57] argue that while mechanical systems automate control, nat-
164 ural ventilation forces occupants to manage the trade-off between thermal
165 comfort and air quality. Consequently, their work on the SAMHE initiative
166 emphasises co-design and feedback mechanisms over top-down policy. This
167 aligns with Finnegan’s study of UK secondary schools, which demonstrated
168 that sustainability practices are best embedded within the cultural routines
169 of schools [58]. **Low-cost monitoring paired with user-facing interfaces can**
170 **similarly support engagement and self-regulation when combined with train-**
171 **ing [59].**

172 This conflict between adequate ventilation for good IAQ and maintaining
173 thermal comfort is challenging due to the diverse needs and expectations
174 of occupants. In the UK, the average classroom houses between 18 and 32
175 children and one or two adults [37]. These adults may not reach consensus
176 on a comfortable temperature, and **pupils**, who are typically more active and
177 have different metabolic rates, may perceive it differently [29]. In schools,
178 the control of **active** ventilation methods, is typically centralised at a school-
179 wide or classroom level [60]. **This discrepancy between control and agency**
180 **has direct consequences for thermal comfort, IAQ, and energy.**

181 We treat IAQ as a socially constructed outcome [61], negotiated within
182 a complex sociotechnical context where stakeholder practices are central.
183 To interpret these competing priorities, our analysis moves beyond a purely
184 technical assessment to examine how everyday social practices shape class-
185 room environments [62]. The school’s institutional schedule structures this
186 context, creating ‘hidden rhythms’ of occupancy and activity that govern
187 the environment [63]. **This temporal pressure—constraining when staff can**
188 **adopt adaptive practices such as ventilation [64]—intersects with the em-**
189 **bodied experience of thermal comfort and the material limits of the building,**
190 **revealing the ‘air-energy nexus’ or trilemma where health, cost, and learning**
191 **are in constant tension.**

192 **3. Methodology**

193 We employed a mixed-methods approach across twelve classrooms in the
194 North West of England to investigate the interplay between IAQ, energy, and
195 stakeholder practices. The study design consisted of three phases:

196 **Phase 1: Pre-deployment Interviews.** Semi-structured interviews with
197 classroom teachers and the senior leadership team (SLT; e.g., head-
198 teachers and senior leaders responsible for strategic policy) established
199 a baseline of current understanding, institutional constraints, and daily
200 routines.

201 **Phase 2: Measurement Campaign.** A longitudinal IAQ monitoring pe-
202 riod captured physical environmental traces (detailed in Section 3.2),
203 providing the quantitative basis for the study.

204 **Phase 3: Post-deployment Interviews.** Classroom-specific data visual-
205 isations were used as probes to elicit deeper reflective insights into the
206 everyday behaviours, decisions, and institutional constraints producing
207 the observed conditions.

208 *3.1. Study Design and Participants*

209 We recruited six schools using a mix of opportunity and snowball sampling
210 via established contacts in Lancashire and Greater Manchester. Participating
211 schools were situated in catchment areas ranging from Decile 2 (representing
212 the 10–20% most deprived neighbourhoods nationally) to Decile 7 (**represent-**
213 **ing the 30–40th percentile from the least deprived end, i.e. moderately low**
214 **deprivation**) on the English Index of Multiple Deprivation (IMD) [66], and
215 captured a mix of governance structures (Academies, Maintained schools,
216 Grammar schools, and Faith schools). Within participating schools, we pur-
217 posively selected twelve classrooms (Standard classrooms, $n = 8$; Practi-
218 cal classrooms, $n = 4$) to capture variation in ventilation provision and
219 use. Practical classrooms comprised Laboratory and Woodwork spaces. We
220 conducted site visits with participants to confirm suitability and incorpo-
221 rate teacher recommendations regarding classrooms with known or unre-
222 solved thermal comfort experiences, **while also selecting additional classrooms**
223 **within the same schools to capture variation in conditions across context and**
224 **use. Teacher recommendations may mean our sample skews towards class-**
225 **rooms with above-average IAQ or thermal comfort challenges; our sampling**
226 **is therefore intended to explain how these tensions are negotiated in practice,**
227 **rather than to estimate their prevalence across all classrooms.**

228 For each classroom, we recorded classroom type, location, typical occu-
229 pancy, and building services relevant to ventilation and air cleaning (Table 1).
230 **Ventilation is categorised as Natural (operable openings), Mechanical (fan-**
231 **driven), AC (active cooling), LEV Fume/Dust (local exhaust), or integrated**

232 filtration (embedded in HVAC/LEV); PAC (HEPA) units are recorded as in-
 233 room mitigation rather than ventilation, as they do not guarantee outdoor
 234 air exchange. We also grouped classrooms by an indicative construction pe-
 235 riod (Pre-1990 vs Post-1990), reflecting shifts in school design guidance in
 236 the early 1990s (e.g., BB73) [53].

237 Table 1: **Characteristics of participating classrooms.** IDs denote Pri-
 mary (P) or Secondary (S) schools. Occupancy is reported as pupils
 + adults. Classrooms are coded as Standard or Practical (Labora-
 tory/Woodwork). HVAC systems (table coding): Natural = op-
 erable openings; Mechanical = fan-driven whole-room ventilation;
 AC = active mechanical cooling; LEV (Fume) = local exhaust for
 gases; LEV (Dust) = local exhaust for particulates; PAC (HEPA)
 = portable air cleaner (in-room mitigation); integrated filtration =
 filtration embedded within HVAC/LEV (not a standalone PAC).

Classroom ID	Class & School Information	Occupancy	HVAC Systems
P1_C1	Standard; Primary; Lancashire; Post-1990.	33 + 3	Mechanical; AC
P1_C2	Standard; Primary; Lancashire; Post-1990.	30 + 1	Mechanical; AC
P2_C1	Standard; Primary; Lancashire; Post-1990.	16 + 2	Natural
P3_C1	Standard; Primary; Lancashire; Post-1990.	26 + 1	Natural
P3_C2	Standard; Primary; Lancashire; Post-1990.	34 + 1	Natural
P4_C1	Standard; Primary; Lancashire; Pre-1990.	26 + 1	Natural

238

Classroom ID	Class & School Information	Occupancy	HVAC Systems
P4_C2	Standard; Primary; Lancashire; Pre-1990.	23 + 2	Mechanical; AC; integrated filtration (HVAC)
S1_L1	Practical (Laboratory); Secondary; Manchester; Pre-1990.	28 + 1	Natural; LEV (Fume)
S2_DP	Practical (Woodwork); Secondary; Lancaster; Pre-1990.	30 + 2	Mechanical; AC; LEV (Dust); integrated filtration (LEV)
S2_DT	Practical (Woodwork); Secondary; Lancaster; Pre-1990.	24 + 1	Mechanical; AC; LEV (Dust); integrated filtration (LEV)
S2_L1	Practical (Laboratory); Secondary; Lancaster; Pre-1990.	30 + 2	Natural; LEV (Fume)
S2_C1	Standard; Secondary; Lancaster; Pre-1990.	25 + 1	Natural; PAC (HEPA) × 2

239

240 To ensure anonymity, we applied a hierarchical identifier scheme: class-
 241 room teachers by Classroom ID (e.g. $P1_C1$), SLT by School ID (e.g. $P1$),
 242 and interview timing by subscript (e.g. $P4_C2_{Pre}$, $S1_{Post}$).

243 We conducted 28 interviews: primary teachers ($n = 12$, paired pre- and
 244 post-deployment) and SLT ($n = 4$, single post-deployment).

245 Table 2 summarises interview participants and interview timing.

246 Table 2: **Breakdown of interview participants and interview timing.** Role definitions: Classroom Teachers = Micro scale ($n = 12$), paired interviews connecting daily experience to sensor traces; SLT = Macro scale ($n = 4$), strategic context regarding budgets and infrastructure.

Participant Role	Count	Pre-Deployment	Post-Deployment
Classroom Teachers	12	12	12
Senior Leadership Team (SLT)	4	–	4
Total Interviews	28	12	16

247

248 3.2. Measurement Campaign

249 Measurements of CO₂, PM_{2.5}, temperature, and relative humidity were
250 made at a 1-minute time resolution using the NAQTS V2000 [67]. CO₂
251 was monitored both as a potential air pollutant [20] and as an indicator of
252 ventilation air change rates [68]. PM_{2.5} was measured to assess combustion-
253 related pollution and ingress from natural and anthropogenic sources, while
254 temperature and humidity were recorded as key determinants of occupant
255 comfort [69].

256 Prior to deployment, all V2000 sensor units were co-located in a con-
257 trolled environment for two weeks to assess variability against a reference
258 baseline. Calculated correction coefficients were subsequently applied to the
259 experimental dataset.

260 Data collection followed the schedule illustrated in Figure 1. For
261 each classroom, monitoring was conducted in two seasonal periods;
262 Spring/Summer (1st of March – 30th of September, Orange) and Au-
263 tumn/Winter (1st of October – 28th of February, Blue). Data were averaged
264 to characterise typical diurnal rhythms, while specific peaks and troughs
265 were analysed to identify distinct behavioural traces. The duration of
266 individual classroom campaigns (minimum 3 weeks) was determined by
267 practical constraints including school holidays and site access, but averaging
268 across these periods ensured comparability of the resulting profiles.

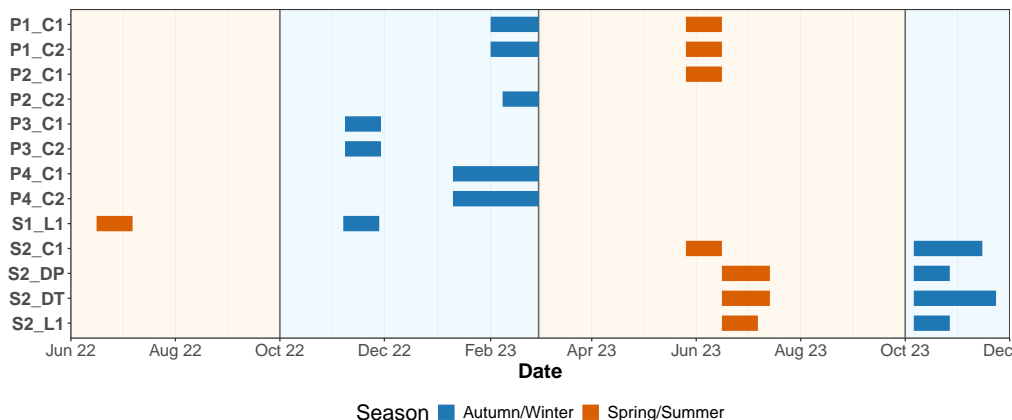


Figure 1: **Data collection schedule.** Gantt chart illustrating the monitoring periods for each classroom, grouped by School ID and sorted by Classroom ID. Solid bars represent the monitoring duration (minimum 3 weeks) for each seasonal period. Shaded backgrounds denote the Spring/Summer (1st of March – 30th of September, Orange) and Autumn/Winter (1st of October – 28th of February, Blue) campaign windows.

269 We measured, photographed, and recorded the floor plan of each class-
 270 room, and decided where to place the air quality monitors. Teachers were
 271 briefed to advise students not to interfere with the units during deployment;
 272 the absence of abrupt, anomalous spikes in the time-series record suggests
 273 this was effective.

274 The V2000 units were placed unobtrusively in the “breathing zone” to
 275 measure the air as close to pupil experience as possible. **Consistent place-**
 276 **ment in the breathing zone across all classrooms follows established guidance**
 277 **to ensure data reliability [70].** The purpose of data collection was to deter-
 278 mine overall trends rather than impacts of specific variables such as occupant
 279 density or classroom volume.

280 Data analysis was conducted using R (v4.4.1) and the *openair* library
 281 (2.18) [71]. We utilise CO₂ concentration as a proxy for ventilation adequacy.
 282 We refer to BB101 [35], which establishes that levels exceeding 1000 ppm indi-
 283 cate insufficient ventilation. **Quantitative trends are contextualised through-**
 284 **out through qualitative insights from the stakeholder interviews.**

285 3.3. Resource Trace Interviews

286 Pre-deployment interviews established a baseline of routines and per-
 287 ceived comfort without the influence of sensor feedback. Post-deployment,

288 we utilised the ‘resource trace’ method [65] to ground our interview questions
289 in physical data. We presented participants with printed time-series visuali-
290 sations of their specific classroom’s CO₂ and temperature profiles. We asked
291 them to identify specific peaks and troughs (e.g., a sharp drop in temperature
292 or rise in CO₂) and recall the specific activities, decisions, or constraints (such
293 as closing a window due to noise or cold) that occurred at those moments.
294 This approach allowed teachers to interpret how their interactions influenced
295 IAQ while discussions with SLT focused on strategic implications for en-
296 ergy budgets and policy. To mitigate social desirability bias, the lead author
297 emphasised their positionality as an independent academic throughout. Fi-
298 nally, interviews were **audio-recorded**, transcribed, and subjected to a hybrid
299 thematic analysis [72]; this blended deductive coding from the quantitative
300 traces with inductive coding of emergent social practices [73] to form “data
301 stories” where quantitative anomalies were triangulated against stakeholder
302 accounts.

303 4. Findings

304 We present our findings as short ‘data stories’, each illustrating how stake-
305 holders navigate the competing pressures of IAQ, thermal comfort, and en-
306 ergy in practice. Three tensions—thermal comfort versus ventilation, barri-
307 ers to agency exposed by the pandemic, and shifting economic priorities—are
308 expanded in the Discussion.

309 4.1. Conflicts Between Thermal Comfort and Ventilation

310 Existing research suggests that 40% of school hours experience periods of
311 overheating and 60% feature PM_{2.5} levels above the recommended maximum
312 threshold [57], primarily due to insufficient ventilation causing a build-up of
313 particulates and heat. Consequently, teachers in naturally ventilated class-
314 rooms faced a constant challenge in balancing pupil thermal comfort against
315 other professional priorities. **In practice, thermal discomfort shaped ventila-**
316 **tion practices, particularly in naturally ventilated classrooms where opening**
317 **windows risked heat loss**, as the class teacher (*P1_C1_Pre*) noted: “*Yeah,*
318 *they can feel the draught...*”, describing pupil reactions to wind chill from
319 open windows.

320 Figure 2 compares CO₂ profiles by season, aggregated across all monitored
321 classrooms.

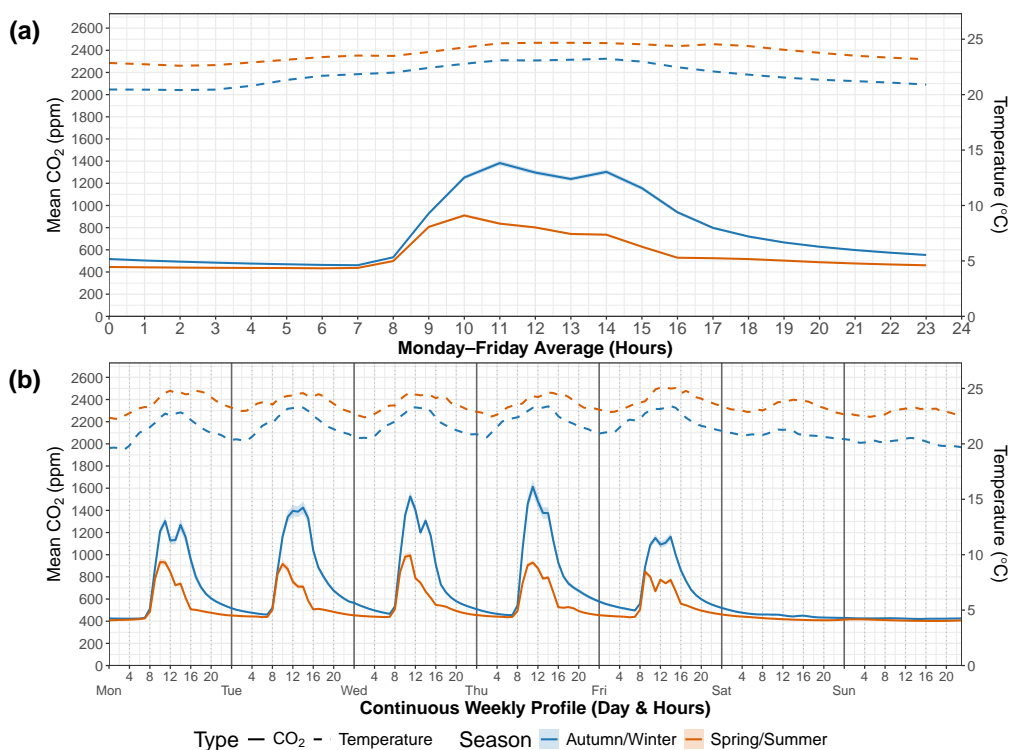


Figure 2: **Seasonal variation of CO₂ and temperature.** (a) Diurnal profile: hourly mean CO₂ (ppm) for occupied weekdays (Mon–Fri, 0–24 hours) with ribbons showing 95% confidence intervals (CI); dashed lines show mean temperature (°C) on a secondary y-axis. (b) Full-week profile: hourly mean CO₂ across all 7 days (Mon–Sun) displayed as a continuous 168-hour timeline with lines and error ribbons. Vertical grid lines mark daily (solid) and 4-hourly (dotted) intervals. Colours indicate season (Spring/Summer, Autumn/Winter).

322 Figure 2 shows lower CO₂ during warmer months (May to July), consistent with CO₂ serving as a proxy for ventilation shaped by occupancy and
 323
 324 window-opening practices.

325 CO₂ levels rise as expected during occupied (teaching) hours across class-
 326 rooms.

327 In Standard classrooms, this accumulation is driven by occupant density
 328 rather than material use, as *P3_C1_Post* noted: “We can feel the air getting
 329 thicker as the day goes on, especially when we’ve got 30 kids packed into the
 330 room”.

331 The tangibility and visibility of air quality issues in Practical classrooms—

332 reinforced by risk assessments for dust and fumes—led to more investment
333 and active management, whereas in Standard classrooms, poor air quality
334 was less obvious and therefore less urgently addressed. **These activity-related**
335 **particulate risks were more immediate in Practical classrooms than in Stan-**
336 **dard classrooms, making targeted ventilation or filtration more clearly justi-**
337 **fied in those spaces.**

338 Of the 12 classrooms studied, only four had a thermostat with a visi-
339 ble thermometer. All interviewees noted that they regulated temperature
340 using their own judgement or their pupils' perception of comfort. For ex-
341 ample, *P2_C1_Pre* expressed how personal judgement and the verbalised ex-
342 perience of children were the main factors—*“they start moaning, so we’ll*
343 *change the temperature”*. Even where controls existed, they were often ob-
344 structed; *P4_C1_Pre* noted that although a thermostat was present, it was
345 difficult to operate—*“There is a thermostat, but it’s behind the cupboards”*.
346 Consequently, keeping pupils warm, rather than considerations of absolute
347 air quality, emerged as the priority. Stakeholders found it easier to adjust
348 ventilation based on thermal comfort needs rather than on IAQ metrics, as
349 *P3_C1_Pre* stated: *“I still think that maybe comfort still overrides some of*
350 *our decisions on whether you have the windows open or closed.”*

351 *S1_L1_Post* stated: *“it got too cold”* when referring to the trade-offs in
352 increasing ventilation over prioritising thermal comfort. This contrast helps
353 explain why quantitative patterns differ by pollutant: **CO₂ reflects general**
354 **ventilation conditions shaped by occupancy and window-opening practices,**
355 whereas PM_{2.5} is shaped by specific activities requiring distinct mitigation
356 strategies.

357 For example, PM_{2.5} concentrations within Practical classrooms (Labora-
358 tory and Woodwork) (Figure 3(a)) had consistently higher background levels,
359 consistent with activities such as combustion from Bunsen burners and dust
360 from wood-based fabrication.

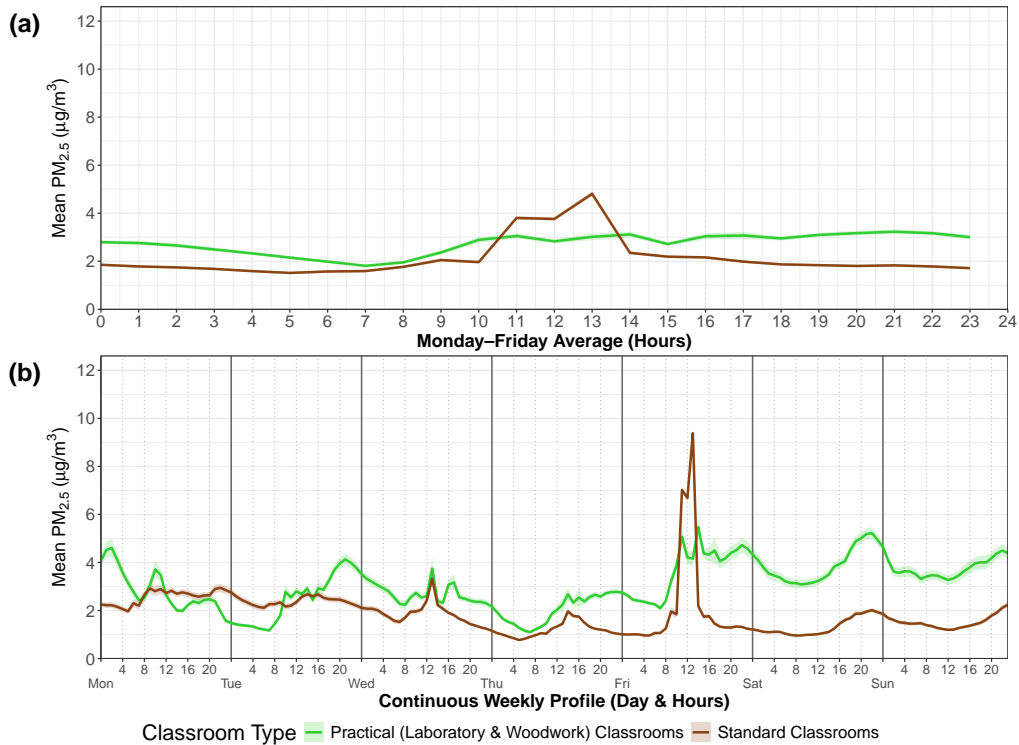


Figure 3: **Mean PM_{2.5} concentrations by classroom type.** (a) Diurnal profile: hourly mean PM_{2.5} ($\mu\text{g}/\text{m}^3$) for occupied weekdays (Mon–Fri, 0–24 hours) with 95% CI ribbons. (b) Full-week profile: hourly mean PM_{2.5} ($\mu\text{g}/\text{m}^3$) across all 7 days (Mon–Sun) displayed as a continuous timeline with lines and error ribbons. Vertical grid lines mark daily (solid) and 4-hourly (dotted) intervals. Colours indicate classroom type (Practical, Standard).

361 Figure 3(b) reveals that PM_{2.5} levels in Practical classrooms remain ele-
 362 vated during weekends. This reflects a reliance on active mitigation: when
 363 local exhaust ventilation (LEV)/extractors are powered down and buildings
 364 sealed for security, residual particulates are trapped. As $S2_DP_{Post}$ ob-
 365 served, even during use “*you can still see dust on surfaces*”, a process that
 366 continues unmitigated in the stagnant, unoccupied air.

367 Activities conducted in Practical classrooms directly drive PM_{2.5}
 368 exposure—“*When we’re doing heavy woodworking, it’s impossible to keep*
 369 *the air completely clean, even with the LEV on*” ($S2_DT_{Pre}$)—while older
 370 naturally ventilated classrooms show dramatic rises in CO₂ during colder
 371 months: “*We just can’t leave the windows open when it’s freezing—it’s*
 372 *not realistic*” ($P3_C1_{Pre}$). Such activities are governed by the national

373 curriculum [74]: the practical requirement for fabrication-based learning
374 generates elevated PM_{2.5} that Standard classrooms do not face.

375 However, practical concerns, building constraints, and rising class
376 sizes [37] often limit the implementation of good IAQ practices. The air
377 quality and thermal comfort needs in the classroom did not specifically
378 align with the goals of site managers and school leadership to reduce energy
379 usage. Together, these pressures reinforced warmth-first decision-making in
380 colder periods, with window opening reduced even when monitoring was
381 available.

382 4.2. Exposing the Barriers to Maintaining Good IAQ

383 A recurring theme throughout the stakeholder interviews was the in-
384 creased attention brought to IAQ by the pandemic; however, this aware-
385 ness was often undermined by a reported lack of training and an unrealistic
386 expectation for staff to act as air quality managers. Although research cor-
387 relates low ventilation rates with increased viral load and COVID-19 trans-
388 mission [75], the subsequent issuance of CO₂ monitors by the Department
389 for Education frequently highlighted poor ventilation without providing the
390 agency required to address it. This limited agency was exemplified by teacher
391 P1_C1_{Pre}, who stated: “We do have a CO₂ monitor somewhere that’s hid-
392 den behind the board—it just sits there and tells us if the air quality is bad
393 or good, but we’re not always able to open the windows”. This disconnection
394 illustrates how monitors often functioned as passive indicators of poor air
395 quality rather than tools for active environmental management.

396 We found the level of IAQ understanding ranged from “*absolutely nothing*”
397 (S2_C1_{Pre}) to knowing that stuffier conditions require opening windows:
398 “we know about carbon dioxide and oxygen, particulate matter and opening
399 windows” (P3_C1_{Pre}). While 18 of the 28 interviews indicated knowledge of
400 ventilation and insulation, this knowledge was often overridden by immediate
401 efforts to maintain a comfortable teaching environment. Even in classrooms
402 where both temperature and CO₂ are actively monitored, teachers still used
403 their own subjective judgement and ‘feel’ when making ventilation decisions.
404 Balancing good IAQ and thermal comfort while teaching was recognised as
405 challenging: “I still try and ventilate. I think fresh air is good for the children,
406 it’s just difficult to stay on top of” (P4_C1_{Pre}).

407 Experiences such as P4_C1_{Pre} noting “it’s difficult to tell with our own
408 sensors—it’s either green, orange or red” highlight the binary presentation
409 of IAQ (good or bad).

410 When we presented specific classroom data profiles (e.g. time-series and
411 diurnal patterns) to teachers during interviews, participants attempted to
412 “trace” peaks and troughs back to concrete drivers such as lesson activities,
413 occupancy changes, and ventilation behaviours (e.g. window opening, door
414 propping, and extractor use). This “resource trace” response moved discus-
415 sion beyond a binary (green/orange/red) judgement towards situated inter-
416 pretation of what the data meant in context, including whether any plausible
417 action existed given constraints such as restricted window opening, comfort
418 priorities, and workload.

419 In some cases, the reaction to poor air quality, either felt or displayed
420 on monitors, was to ventilate: *“I can just open windows and right now I feel*
421 *quite okay.”* ($P2_C1_{Pre}$).

422 However, opening windows was not always possible. One teacher noted
423 their window did not open sufficiently: *“a tiny crack, so they don’t open.*
424 *You can’t open them wide”* ($P3_C1_{Pre}$). Windows were also obstructed by
425 cabinets and cupboards in 4 classrooms and left permanently closed due to
426 space limitations and layout changes, with $S2_DT_{Pre}$ commenting *“reaching*
427 *them can be tricky, and we’ve got a lot of equipment in here as is”*.

428 **Seven of the twelve classrooms studied relied on natural ventilation (open-**
429 **ing windows/doors; Table 1).** Here, the tension was not that airtightness and
430 ventilation are opposites, but that intended ventilation was limited to win-
431 dow opening. Consequently, COVID-19 ventilation advice implied increased
432 window opening, exacerbating heat loss, cost, and comfort pressures. Older
433 Pre-1990 buildings (e.g. the Woodwork classrooms $S2_DP$ and $S2_DT$) have
434 smaller windows due to historical architectural limitations.

435 Relying on natural ventilation was particularly challenging in winter as
436 it reduced indoor temperature. Thermal comfort is often more immediately
437 perceptible than air quality, shifting priorities towards comfort (closing win-
438 dows) and away from good IAQ: *“if it’s cold then yeah, the windows are usu-*
439 *ally shut anyway”* ($S2_C1_{Pre}$); $S1_L1_{Post}$ felt similarly constrained: *“you*
440 *can’t have the fans on, and windows open in this weather [in winter]”*.

441 To show how this seasonal shift differed by ventilation strategy, Figure 4
442 compares CO₂ profiles by season and ventilation type across panels (a)–(d).

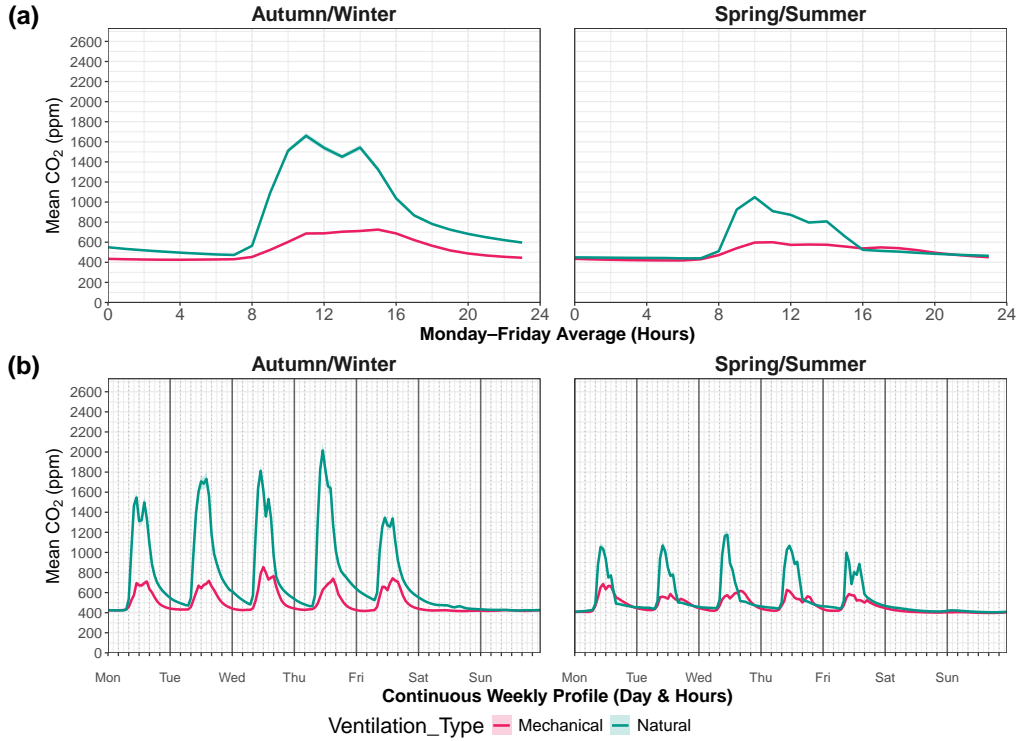


Figure 4: **CO₂ profiles by season and ventilation type.** A 2×2 grid: the top row shows diurnal (hourly Mon–Fri) profiles for (a) Spring/Summer and (b) Autumn/Winter; the bottom row shows the corresponding full-week hourly CO₂ (ppm) profiles (Mon–Sun) for (c) Spring/Summer and (d) Autumn/Winter as continuous timelines with daily (solid) and 4-hourly (dotted) vertical grid lines. Ribbons indicate 95% CI. Colours indicate ventilation type (Natural, Mechanical).

443 We found CO₂ levels increased substantially during winter as thermal
 444 comfort took priority over IAQ. From Figure 2(a), mean CO₂ during
 445 occupied hours in Autumn/Winter is approximately 600 ppm higher than
 446 in Spring/Summer. Teachers reported juggling competing priorities—
 447 ventilation, comfort, and limited provision—particularly when windows
 448 stayed closed in winter to retain heat.

449 Relying on natural ventilation and following guidance to open windows
 450 contrasts with health and safety regulations to maintain a minimum class-
 451 room temperature. These competing constraints are most visible during the
 452 heating season.

453 Focusing on the heating season, Figure 5 isolates Autumn/Winter CO₂

454 levels by ventilation type.

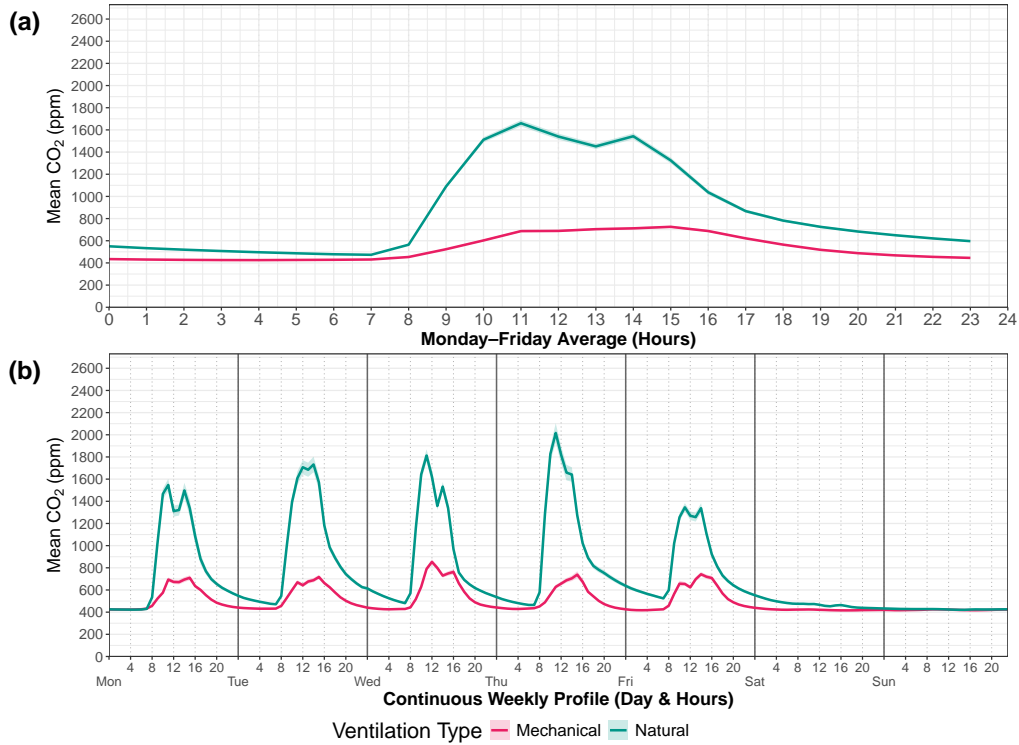


Figure 5: **Winter CO₂ levels by ventilation type.** (a) Diurnal profile: hourly mean CO₂ (ppm) for occupied weekdays (Mon–Fri, 0–24 hours) during Autumn/Winter with 95% CI ribbons. (b) Full-week profile: hourly mean CO₂ across all 7 days (Mon–Sun) displayed as a continuous timeline with lines and error ribbons. Vertical grid lines mark daily (solid) and 4-hourly (dotted) intervals. Colours indicate ventilation type (Natural, Mechanical).

455 Figure 5(a) shows greater diurnal CO₂ variation and higher peaks in naturally ventilated classrooms during Autumn/Winter. Windows were often
456 closed during winter, whereas in mechanically ventilated classrooms air continues to circulate year-round. This uses more energy but maintains consistently lower CO₂ levels.
457
458
459

460 Even where ventilation provision was adequate, thermal comfort consistently shaped ventilation behaviour in winter: reduced window-opening
461 contributed to elevated CO₂ and poorer air quality.
462

463 *4.3. Shifting Priorities Within Schools*

464 These constraints were further intensified as energy prices rose and
465 pandemic-era ventilation practices became harder to sustain.

466 Schools face a difficult balance between Net Zero targets, financial pres-
467 sure (rising energy costs), and achieving good IAQ. The UK’s Net Zero 2050
468 target requires schools to significantly reduce their carbon footprint [76], yet
469 increased ventilation to address COVID-19 health priorities conflicts with
470 this. While ventilation requirements are prominent in UK regulations (e.g.
471 BB101 [35]), gaps exist between intended performance and real-world deliv-
472 ery, constrained by retrofit budgets, maintenance, and building form. Dif-
473 ferences in classroom construction within our sample reflect this. Figure 6
474 illustrates CO₂ levels by building construction period.

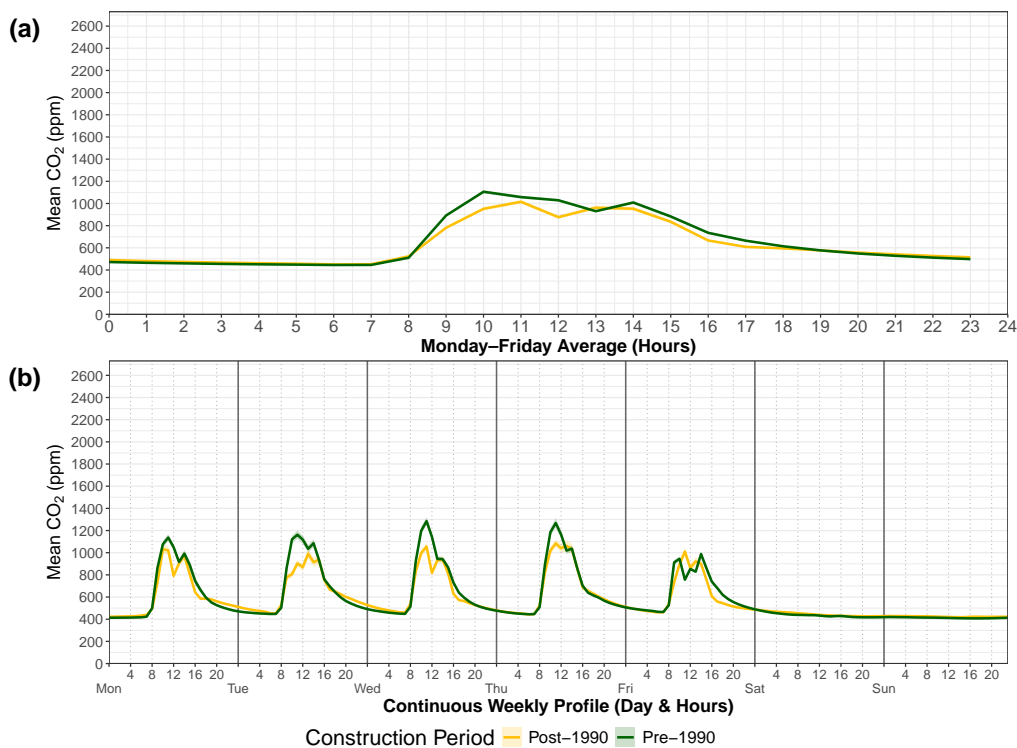


Figure 6: **CO₂ levels by building construction period.** (a) Diurnal profile: hourly mean CO₂ (ppm) for occupied weekdays (Mon–Fri, 0–24 hours) by construction period with 95% CI ribbons. (b) Full-week profile: hourly mean CO₂ across all 7 days (Mon–Sun) displayed as a continuous timeline with lines and error ribbons. Vertical grid lines mark daily (solid) and 4-hourly (dotted) intervals. Colours indicate building construction period. *Note:* Construction-period differences are uncorrected for potential confounders such as occupancy and classroom size.

475 Figure 6 suggests Pre-1990 classrooms exhibit higher CO₂ overall, con-
 476 sistent with their greater reliance on natural ventilation; construction period
 477 reflects broader shifts in school design standards (e.g. BB73 [53]). Post-1990
 478 buildings typically feature mechanical interventions and stricter airtightness,
 479 whereas Pre-1990 stock predominantly relies on natural ventilation. These
 480 patterns are indicative of broader shifts in design standards and are not a
 481 controlled comparison; differences in classroom size, occupancy, and ventila-
 482 tion strategy were not corrected for.

483 Stakeholders in older buildings like $S2_DT_{Pre}$ voiced concerns: “we’ve
 484 been approached to have a heat pump and AC fitted—but the cost would have

485 to be spread out over the next decade”. Newer classrooms like $P4_C2$ provide
 486 a clear example of pandemic adaptation: equipped with **integrated filtration**
 487 (HVAC) (and described by staff as ‘air purifiers’), **it maintained lower CO₂**
 488 **peaks (Figure 7(a)).**

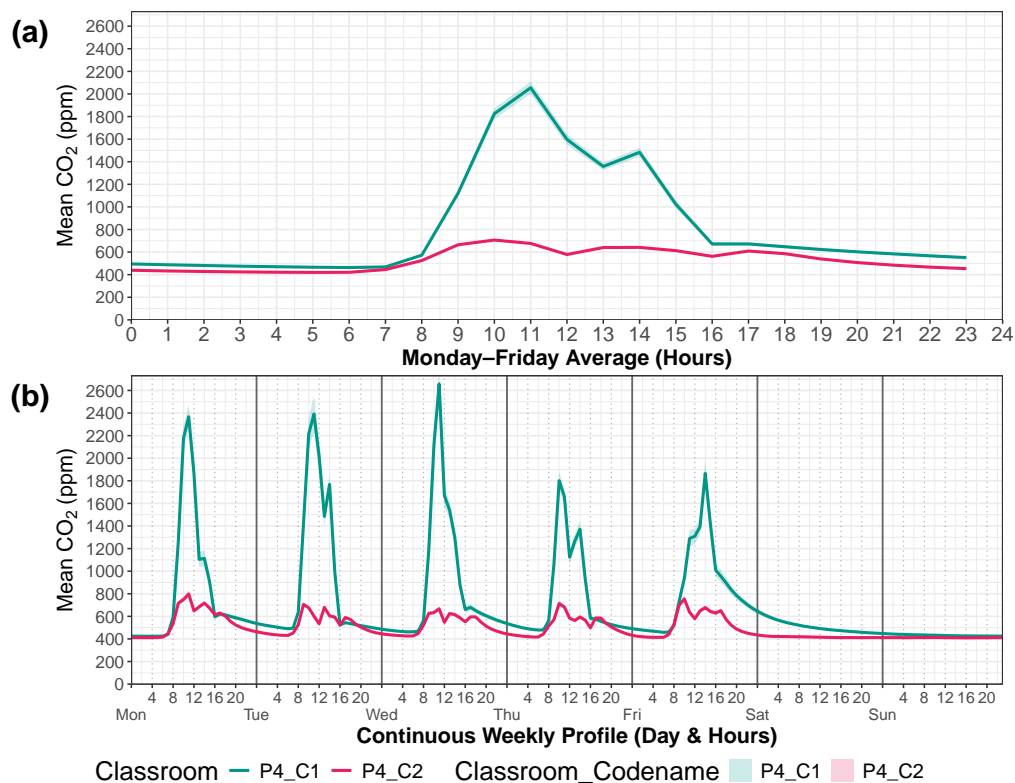


Figure 7: **Within-school CO₂ ventilation comparison (P4).** (a) Diurnal profile: hourly mean CO₂ (ppm) for occupied weekdays (Mon–Fri, 0–24 hours) by classroom (P4_C1, Natural ventilation; P4_C2, Mechanical/HVAC with integrated filtration) with 95% CI ribbons. (b) Full-week profile: hourly mean CO₂ across all 7 days (Mon–Sun) displayed as continuous timelines with lines and error ribbons. Vertical grid lines mark daily (solid) and 4-hourly (dotted) intervals. Colours indicate classroom. The mechanically ventilated classroom (P4_C2) maintains consistently lower CO₂ levels compared to the naturally ventilated classroom (P4_C1) in the same school.

489 Teacher $P4_C2_{Post}$ noted: “the air purifiers that we got during the pan-
 490 demic seem to help with the stuffiness and CO₂ levels”.

491 However, lacking funds for additional filtration (e.g., portable air clean-
 492 ers (PACs) with HEPA filters), other schools resorted to behavioural adap-

493 tations. The pandemic markedly increased awareness of IAQ issues among
494 stakeholders: “we’re in these rooms for 6 odd hours a day, it’s quite se-
495 rious, isn’t it?” (*S2_L1_Pre*). Ventilation practices changed rapidly and
496 were prioritised over thermal comfort as part of viral mitigation strate-
497 gies: “We had to ventilate and that was the message, windows open always”
498 (*P3_C1_Pre*). Across both seasons, Figure 4 shows mechanically ventilated
499 classrooms maintained lower CO₂ than naturally ventilated ones, though
500 warmth–air-quality trade-offs persisted where provision was limited. To mit-
501 igate thermal discomfort, school leaders modified uniform policies, relaxing
502 rules to accommodate lower indoor temperatures [54]. *P3_C1_Pre* described
503 this shift: “we’re a little more relaxed in summer with the ties, and in winter
504 we’ve started to let them wear their coats—especially just after lockdown”.

505 Some participants made their own adaptations to improve air quality; for
506 example, the stakeholder in *S2_DT* installed extra PM_{2.5} sensors. Figure 8
507 illustrates the contrast between two Practical (Woodwork) classrooms in the
508 same school, showing sustained elevated PM_{2.5} linked to material-intensive
509 activities and differences in mitigation practices.

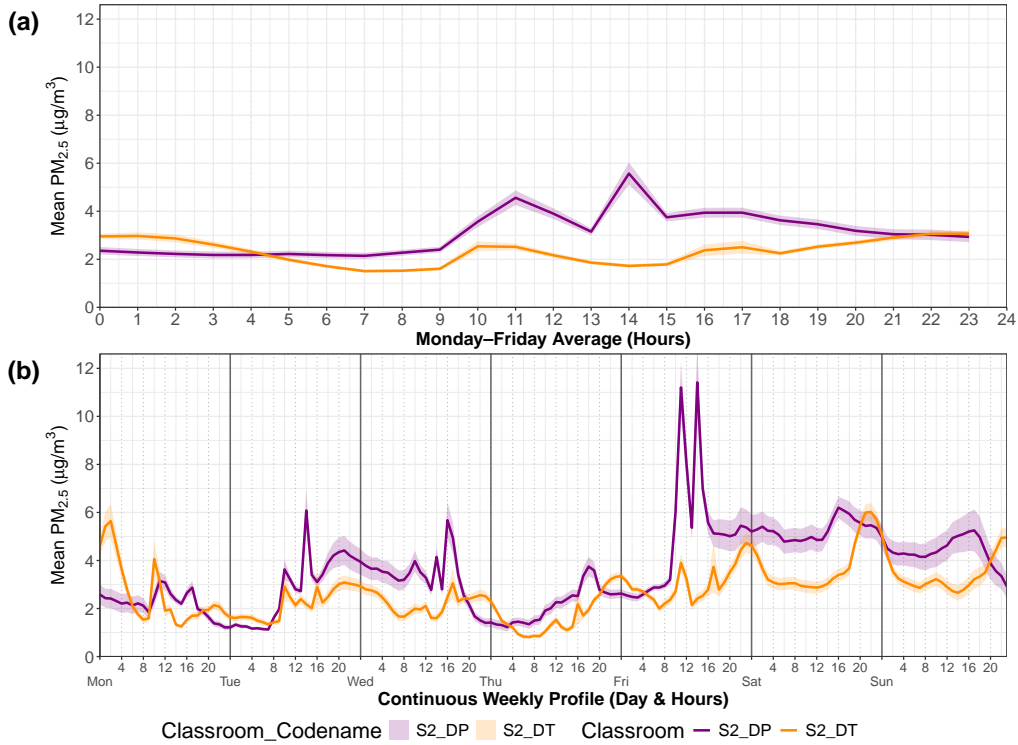


Figure 8: **Comparison of PM_{2.5} in two Practical (Woodwork) classrooms.** (a) Diurnal profile: hourly mean PM_{2.5} ($\mu\text{g}/\text{m}^3$) for occupied weekdays (Mon–Fri, 0–24 hours) by classroom (S2_DP, S2_DT) with 95% CI ribbons. (b) Full-week profile: hourly mean PM_{2.5} ($\mu\text{g}/\text{m}^3$) across all 7 days (Mon–Sun) displayed as continuous timelines with lines and error ribbons. Vertical grid lines mark daily (solid) and 4-hourly (dotted) intervals. Colours indicate classroom.

510 *S2_DT* was actively monitored by the teacher in charge, ensuring regu-
 511 lar use of LEV (Dust) and associated **integrated filtration** (LEV). Interviews
 512 with *S2_DP_{Pre}* confirmed the importance of this proactive management:
 513 “*There are extra fans which start to run during practicals, we’ve got some*
 514 *new extractors*”. While *S2* had the resources to purchase additional filtration
 515 systems, many schools lack this flexibility due to budget constraints, infras-
 516 tructure limitations, and practical feasibility. **Some stakeholders discussed**
 517 **additions to control heating and ventilation better.** For example, installing
 518 **a sensor network to enable a more adaptive ventilation system capable of**
 519 **dynamically balancing air quality and energy consumption.**

520 Reflecting on the limitations of their classrooms, *P1_C1_{Pre}* stated: “*if*

521 *we had thermostats in every room, it'd be easier than just valves on the*
522 *radiators [...] it's hard to reach the valves and it's difficult to keep on top*
523 *of". Since the pandemic, rising energy prices have forced schools to reconsider*
524 *ventilation practices. Maintaining thermal comfort has become a renewed*
525 *priority, often at the expense of IAQ. Teachers like P3_C2_{Pre} described this*
526 *reversal: "We tried to keep the windows open at the start of winter, but it*
527 *didn't last. We were cold".*

528 This reversal was most acute in older, naturally ventilated rooms, where
529 winter ventilation already depended on uncomfortable trade-offs between
530 warmth and fresh air (Figures 4 and 5). *Newer classrooms like P4_C2, with*
531 *mechanical ventilation and integrated filtration (HVAC), sustained IAQ more*
532 *consistently than older rooms such as S2_C1, where limited airflow persisted:*
533 *"we just keep the windows open, but they only open a crack, so all we feel is*
534 *a cool breeze" (S2_C1_{Pre}).*

535 Despite some improvements to IAQ during the pandemic, there are
536 times when teachers are unable to substantially affect the air quality.
537 Several teachers believed that briefly opening windows between lessons
538 or during lunch breaks would be sufficient. *Short, periodic 'shock venti-*
539 *lation' (Stoßlüften) [77] is sometimes effective, though quantitative CO₂*
540 *profiles alone cannot attribute changes to specific airing events without the*
541 *accompanying interview accounts.*

542 Although some ventilation practices continued post-pandemic—*"Even*
543 *now, we keep the doors open between lessons" (P4_C1_{Post})—their effec-*
544 *tiveness was inconsistent and heavily dependent on seasonal conditions.*
545 *As P4_C1_{Pre} described: "We've always had the windows open in summer*
546 *and closed in winter anyway, it's just natural". In Practical (Woodwork)*
547 *classrooms, effectiveness varied; ultimately, enhanced systems in S2_DP led*
548 *to faster PM_{2.5} dilution, yet limitations remained: "We use the extractors*
549 *during lessons, but you can still see dust settling by the end of the day."*
550 *(S2_DP_{Post}).*

551 *Three cross-cutting patterns emerge from these stories: thermal comfort*
552 *priorities drove seasonal window closure and elevated winter CO₂ in naturally*
553 *ventilated classrooms; activity-specific PM_{2.5} in Practical classrooms required*
554 *ongoing active mitigation; and pandemic-era monitoring raised awareness*
555 *without consistently enabling the capability to act.*

556 5. Discussion

557 This study draws on a purposive sample of twelve classrooms across six
558 schools in the North West of England; the findings are not intended to be
559 statistically generalisable but rather to explain how these tensions operate in
560 practice. No quantitative energy data—such as metered consumption or util-
561 ity records—were collected; references to energy use and cost are grounded
562 in stakeholder accounts and should be read as reported experience rather
563 than measured outcomes. Cross-classroom comparisons, including those by
564 construction period (Figure 6) and ventilation type, are presented as raw,
565 unnormalised profiles; whilst classroom characteristics including occupancy,
566 size, and curriculum activity are documented in Table 1, the figures are
567 not corrected for these. Building construction period in particular reflects
568 correlated shifts in design standards (BB73 to BB101) rather than an inde-
569 pendently controlled variable.

570 Taken together, the data stories trace how IAQ, energy use, and stake-
571 holder priorities are negotiated through everyday decisions in English class-
572 rooms. Our findings suggest that the ‘IAQ trilemma’ is not merely a technical
573 balancing act, but a product of systemic ‘responsibilisation’, where struc-
574 tural deficits are offloaded onto teaching staff. *Through the IAQ trilemma*
575 *lens [49], these accounts show how* seasonal behaviour (e.g. shutting windows
576 in winter), infrastructural limitations (e.g. lack of mechanical ventilation in
577 *S2_C1*, restricted window opening, blocked and hard-to-reach thermostats
578 and air quality monitors), and behavioural patterns (e.g. reliance on thermal
579 perception) interact, mutually constituting school classroom indoor air. *The*
580 *overarching pattern is one of ‘institutional paralysis’: stakeholders are given*
581 *data (via CO₂ monitors) without the infrastructure or budget to act.*

582 The subsections below develop these patterns in relation to thermal com-
583 fort constraints, infrastructural barriers, and shifting institutional priorities.

584 5.1. *Managing IAQ Under Thermal Comfort Constraints*

585 *Stakeholder agency shapes how effectively IAQ technologies are used.*
586 IAQ monitors, though present in many classrooms, were often neglected due
587 to poor placement or rendered ineffective by infrastructural limitations, such
588 as hard-to-reach windows limiting the potential to increase ventilation. Even
589 when visible, stakeholders found the feedback too simplistic for nuanced ac-
590 tion, echoing findings on the limitations of ‘traffic light’ signals in complex
591 environments [78]. *Sensors can raise awareness of conditions the human body*

592 cannot easily perceive, but their utility is constrained by the *capability* to act
593 upon IAQ data [79]. Providing data without usable controls represents a fail-
594 ure of design that renders the teacher’s ‘responsibility’ impossible to fulfil.

595 Decisions frequently relied on thermal comfort perception or response to
596 specific complaints rather than specific data. This reliance on verbalised dis-
597 comfort constitutes ‘complaint-driven ventilation’—a reactive model where
598 thermal comfort overrides IAQ. The human body perceives air pollution in
599 diverse ways, often below the threshold of immediate cognisance [24, 23], un-
600 like the historical ‘pea-souper’ smogs [80]. Nonetheless, while such practices
601 based on thermal comfort reflect responsive care, they risk missing underlying
602 IAQ problems that are not as easily or immediately perceptible, especially if
603 they build up slowly over the day.

604 *S2_DT*, by contrast, demonstrated high stakeholder agency. In Practical
605 (Woodwork) classrooms, the tangible nature of pollutants (dust, fumes) le-
606 gitimised mitigation. Staff proactively managed LEV systems, aligning with
607 safety norms for visible risks. Staff may be sensitised by ‘hands-on’ learning
608 with craft materials, where the health and air quality impacts are both known
609 and well covered by health and safety regulations. In Standard classrooms,
610 where such visible cues and dedicated infrastructure are absent, teachers had
611 fewer obvious levers to pull—leaving individual judgement as the primary
612 intervention. Without context-specific training, stakeholders default to im-
613 mediate sensory cues (temperature, draught, and comfort) over long-term
614 IAQ goals. Focusing solely on individual IAQ management, rather than the
615 infrastructures that precede practice in indoor environments, runs the risk
616 of ‘lifestyle drift’ [81]. This avoids dealing with the structural reasons for
617 poor IAQ, focusing instead on actions perceived as easier to achieve, such as
618 nudging behaviour change [82]. This has clear consequences for inequalities,
619 particularly for overcrowded classrooms or schools with fewer resources to
620 mitigate poor IAQ.

621 5.2. Overcoming Barriers to Maintaining Good IAQ Despite Constraints

622 Ventilation is a sociotechnical phenomenon [82] strongly influenced by
623 the interface of physical infrastructure and social practice. Naturally ven-
624 tilated classrooms, such as *P3_C2* and *S2_C1*, rely on opening windows
625 and doors, which during colder months leads to tension between maintaining
626 IAQ and preserving warmth. Our data illustrate how draughts create a ‘sen-
627 sory conflict’. As temperatures dropped, windows remained closed to retain
628 heat, resulting in a ‘winter retreat’ where ventilation was abandoned due to

629 cold. This pattern was consistent across our naturally ventilated sample.
630 This suggests that without systemic support (e.g., automation or appropriate
631 heating and ventilation provision), good IAQ becomes harder to prioritise
632 when thermal comfort pressures are immediate.

633 This challenge is not unique to the UK; studies on non-renovated schools
634 in Portugal have shown similar issues [83], leaving students vulnerable to dis-
635 comfort. This disparity points to the need for IAQ management approaches
636 that can be tailored to different school contexts and building types.

637 Classrooms with mechanical ventilation and integrated filtration (e.g.
638 $P4_C2$) achieved a ‘technological decoupling’ of air quality from thermal
639 comfort, maintaining lower CO₂ without relying on continual window opening
640 during cold periods. Where such systems are present, they absorb the day-
641 to-day ventilation burden that would otherwise fall on individual teachers.
642 Many schools, however, faced equipment and layout limitations. Physical
643 obstruction emerged as a significant barrier; blocked thermostats prevented
644 teachers from enacting thermal control.

645 Opening windows was further restricted by government health and safety
646 regulations [84]. While some classrooms could benefit from portable air clean-
647 ers (PACs; HEPA) or by retrofitting mechanical ventilation to reduce PM_{2.5}
648 and CO₂, this remains out of reach for many schools with constrained bud-
649 gets [85]. The Department for Education has no data on the number of
650 schools with mechanical ventilation [86]. Most school classrooms were not
651 designed for mechanical ventilation, and the Department has estimated £11.4
652 billion is needed to restore schools to adequate air quality and thermal com-
653 fort conditions [87].

654 Technological solutions alone are insufficient; behavioural adaptations
655 and shifts in teaching practice are equally necessary. External factors be-
656 yond occupants’ direct control compound these challenges: outdoor-sourced
657 pollution from vehicle traffic, local industry (e.g. mines and shipping affect-
658 ing $P2$ and $P4$), limited classroom size, and growing pupil numbers. These
659 pressures disproportionately affect schools in lower socioeconomic areas, re-
660 inforcing systemic inequities in air quality—a phenomenon described as air
661 quality poverty, or air (in)quality [88, 89]. . Retrofit technologies—including
662 mechanical ventilation and portable air cleaners (PACs)—are not only costly
663 to install; they also increase energy consumption and carry ongoing mainte-
664 nance and consumables costs.

665 *5.3. Infrastructural Limitations on School Priorities and Rhythms*

666 Since the initial pandemic period, priorities within the classroom appear
667 to have shifted away from constant ventilation towards more pragmatic forms
668 of conservation. While initial COVID-19 responses emphasised keeping win-
669 dows open, participants described this as difficult to sustain in colder periods.
670 Rather than evidencing a direct financial calculation in every case, our data
671 show how health advice, thermal comfort, and resource constraints were ne-
672 gotiated together.

673 In classrooms without mechanical ventilation, and with only limited nat-
674 ural ventilation options, often restricted by safety catches or maintenance
675 issues, classrooms in older buildings experienced significant CO₂ accumu-
676 lation throughout the day. This results partly from valid non-IAQ safety
677 concerns. Conflicting regulations further constrain ventilation: specifically,
678 regulation 1.39 from Approved Document K restricts window openings to *en-*
679 *sure that a 100 mm sphere cannot pass through* [84]. While critical for safety,
680 this limits natural ventilation capacity, preventing the ‘purge’ needed to clear
681 pollutants. Mechanical systems remain rare in English classrooms [90], yet
682 government mandates (e.g. BB101 [35]) demand improved IAQ. Without in-
683 vestment, these targets will remain aspirational.

684 The tension is further complicated by the curriculum and the structure
685 of the school day, which is not designed around the air quality experienced
686 in the classroom. Drawing on rhythm analysis [92, 91], the same temporal
687 structuring applies to IAQ: unoccupied periods allow air exchange, yet short
688 breaks seldom provide low-energy purge ventilation [93].

689 Curriculum activity is also implicated in poor IAQ. Practical classrooms
690 (Laboratory and Woodwork) exhibited lower occupancy but higher levels of
691 PM_{2.5} and CO₂, requiring purpose-driven LEV rather than natural ventila-
692 tion alone.

693 Across several classrooms, staff developed ‘adaptive social norms’—
694 relaxing uniform rules in winter, adjusting class schedules, or repurposing
695 equipment—some with sanction from school leadership. While tolerating
696 thermal discomfort to facilitate ventilation, these are compromises, not
697 sustainable solutions. We use the term “unintended air quality managers”
698 to describe classroom staff expected to monitor ventilation and balance
699 comfort and IAQ—tasks outside their core professional role and, in our data,
700 often undertaken without training, timetable space, or control over building
701 systems. Placing this burden on staff risks “responsibilising” individuals [94]
702 for structural deficits, a tension in public service literature [95]. This

703 risks placing disproportionate pressure on teachers and school staff. This
704 exemplifies the failure of the ‘information deficit model’; providing data
705 without the agency to act simply increases anxiety without improving air
706 quality.

707 While technological solutions (such as mechanical ventilation, filtration
708 in HVAC/LEV, or PACs) are appealing, such technologies require finan-
709 cial resourcing and may be difficult to retrofit without major changes to
710 schools. Given existing financial inequity, this may further the divide be-
711 tween “well-resourced” and “under-resourced” schools. Research from the US
712 demonstrates that building performance disparities disproportionately affect
713 lower-income areas, where pupils from low-income families are more likely to
714 attend school in facilities with poor conditions—including inadequate venti-
715 lation, overcrowding, and deferred maintenance [96]. Such disparities echo
716 the broader social gradient in health and opportunity documented in major
717 public health reviews [97], potentially exacerbating educational inequalities
718 between privileged and disadvantaged communities.

719 The changes in priorities reflect a patchwork of adaptation constrained by
720 ageing infrastructure and limited budgets. Technological interventions alone
721 will not resolve this emergent trilemma.

722 6. Conclusions

723 Through the lens of the IAQ trilemma, this study examined how in-
724 door air quality, energy, and stakeholder practice interact in English schools.
725 Our findings suggest that external pressures—specifically the COVID-19 pan-
726 demic and the subsequent energy crisis—have reshaped these dynamics, ex-
727 posing systemic limitations in effective IAQ management within schools.

728 First, we conclude that thermal pressures and resource constraints can
729 limit air quality improvements. While the pandemic temporarily prioritised
730 ventilation, our data show that this was difficult to sustain once colder condi-
731 tions returned. This oscillation between open-window mandates and closed-
732 window reality demands long-term strategies that genuinely balance health,
733 comfort, and sustainability.

734 Second, structural disparities mediate the trilemma, creating a landscape
735 of inequality. Older, naturally ventilated buildings struggled to maintain
736 adequate CO₂ levels in colder months without significant heat loss, in contrast
737 to classrooms with mechanical ventilation and integrated filtration. The age
738 and design of the school estate are thus key drivers of pupil health outcomes.

739 Third, we contend that the current policy of ‘responsibilisation’—placing
740 the operational burden of the ‘air-energy nexus’ on teachers and casting them
741 as **unintended air quality managers**—is unsustainable. Our study revealed
742 that without automated systems, staff are forced to make impossible trade-
743 offs under significant time pressure. **The mere provision of CO₂ monitors**
744 **highlighted the limits of the ‘information deficit model’ [82]: supplying data**
745 **did not, on its own, empower stakeholders who lacked the agency to alter**
746 **building physics or the budget to heat ventilated rooms.** Technological in-
747 terventions often fail without social integration, as argued by Hughes and
748 Strachan [98], calling for a shift from relying on individual teacher resilience
749 to providing resilient infrastructure.

750 Balancing the IAQ trilemma demands a systemic response to the **struc-**
751 **tural and resource** challenges that force schools into reactive, short-term mea-
752 sures. This requires targeted national funding to address the £11.4 billion
753 repair backlog [87] and a review of regulations like BB101 [35] to resolve
754 inherent conflicts between safety, health, and energy efficiency. Ultimately,
755 we argue that future policy must move beyond **passive monitoring** towards
756 solutions that decouple health from individual action, ensuring that good
757 IAQ is a built-in standard rather than a daily negotiation.

758 References

- 759 [1] L. Morawska, J. W. Tang, W. Bahnfleth, P. M. Bluysen, A. Boerstra,
760 G. Buonanno, J. Cao, S. Dancer, A. Floto, F. Franchimon, C. Haworth,
761 J. Hogeling, C. Isaxon, J. L. Jimenez, J. Kurnitski, Y. Li, M. Loomans,
762 G. Marks, L. C. Marr, L. Mazzarella, A. K. Melikov, S. Miller, D. K.
763 Milton, W. Nazaroff, P. V. Nielsen, C. Noakes, J. Peccia, X. Querol,
764 C. Sekhar, O. Seppänen, S.-i. Tanabe, R. Tellier, K. W. Tham, P. War-
765 gocki, A. Wierzbicka, M. Yao, How can airborne transmission of COVID-
766 19 indoors be minimised?, *Environment International* 142 (2020) 105832.
767 doi:10.1016/j.envint.2020.105832.
768 URL [https://www.sciencedirect.com/science/article/pii/S016](https://www.sciencedirect.com/science/article/pii/S0160412020317876)
769 [0412020317876](https://www.sciencedirect.com/science/article/pii/S0160412020317876)
- 770 [2] B. H. Foundation, Air pollution (Mar. 2025).
771 URL [https://www.bhf.org.uk/information-support/risk-factors](https://www.bhf.org.uk/information-support/risk-factors/air-pollution)
772 [/air-pollution](https://www.bhf.org.uk/information-support/risk-factors/air-pollution)

- 773 [3] G. Keegan, D. for Education, Investment to shield schools from high
774 energy bills and boost to budgets, Tech. rep., Department for Education
775 (Dec. 2022).
776 URL [https://www.gov.uk/government/news/investment-to-shiel](https://www.gov.uk/government/news/investment-to-shield-s-schools-from-high-energy-bills-and-boost-to-budgets)
777 [d-schools-from-high-energy-bills-and-boost-to-budgets](https://www.gov.uk/government/news/investment-to-shield-s-schools-from-high-energy-bills-and-boost-to-budgets)
- 778 [4] D. for Education, Sustainability and climate change: a strategy for the
779 education and children’s services systems (Dec. 2023).
780 URL [https://www.gov.uk/government/publications/sustainabil](https://www.gov.uk/government/publications/sustainability-and-climate-change-strategy/sustainability-and-climate-change-a-strategy-for-the-education-and-childrens-services-systems)
781 [ity-and-climate-change-strategy/sustainability-and-climate](https://www.gov.uk/government/publications/sustainability-and-climate-change-a-strategy-for-the-education-and-childrens-services-systems)
782 [-change-a-strategy-for-the-education-and-childrens-service](https://www.gov.uk/government/publications/sustainability-and-climate-change-a-strategy-for-the-education-and-childrens-services-systems)
783 [s-systems](https://www.gov.uk/government/publications/sustainability-and-climate-change-a-strategy-for-the-education-and-childrens-services-systems)
- 784 [5] S. Holgate, S. Bartington, G. Fuller, J. Barnes, S. Beevers, K. Bhui,
785 B. Castellani, K. Exley, D. Fecht, M. Fisher, C. Griffiths, J. Grigg,
786 R. Harrison, M. Hayden, M. Holland, D. Jenkins, A. Lewis, P. Lewis,
787 R. McEachan, M. Miller, J. Mitchell, S. Moller, N. Nelson, M. Nieuwen-
788 huijsen, C. Noakes, H. Price, N. Rowland, Thornton, A. Whitehouse, A
789 Breath of Fresh Air: Responding to the Health Challenges of Modern
790 Air Pollution, Tech. rep., Royal College of Physicians (Jun. 2025).
791 URL [https://www.rcp.ac.uk/policy-and-campaigns/policy-doc](https://www.rcp.ac.uk/policy-and-campaigns/policy-documents/a-breath-of-fresh-air-responding-to-the-health-challenges-of-modern-air-pollution/)
792 [uments/a-breath-of-fresh-air-responding-to-the-health-cha](https://www.rcp.ac.uk/policy-and-campaigns/policy-documents/a-breath-of-fresh-air-responding-to-the-health-challenges-of-modern-air-pollution/)
793 [llenges-of-modern-air-pollution/](https://www.rcp.ac.uk/policy-and-campaigns/policy-documents/a-breath-of-fresh-air-responding-to-the-health-challenges-of-modern-air-pollution/)
- 794 [6] N. E. Klepeis, W. C. Nelson, W. R. Ott, J. P. Robinson, A. M.
795 Tsang, P. Switzer, J. V. Behar, S. C. Hern, W. H. Engelmann, The
796 National Human Activity Pattern Survey (NHAPS): a resource for as-
797 sessing exposure to environmental pollutants, *Journal of Exposure Sci-*
798 *ence & Environmental Epidemiology* 11 (3) (2001) 231–252. doi:
799 10.1038/sj.jea.7500165.
800 URL <https://www.nature.com/articles/7500165>
- 801 [7] C. Schweizer, R. D. Edwards, L. Bayer-Oglesby, W. J. Gauderman,
802 V. Ilacqua, M. J. Jantunen, H. K. Lai, M. Nieuwenhuijsen, N. Kün-
803 zli, Indoor time-microenvironment-activity patterns in seven regions of
804 Europe, *Journal of Exposure Science & Environmental Epidemiology*
805 17 (2) (2007) 170–181. doi:10.1038/sj.jes.7500490.
- 806 [8] C. Dimitroulopoulou, M. R. Ashmore, A. C. Terry, Use of population
807 exposure frequency distributions to simulate effects of policy interven-

- 808 tions on NO₂ exposure, *Atmospheric Environment* 150 (2017) 1–14.
809 doi:10.1016/j.atmosenv.2016.11.028.
810 URL <https://www.sciencedirect.com/science/article/pii/S1352231016309013>
811
- 812 [9] R. Long, The School Day and Year (Sep. 2024).
813 URL <https://commonslibrary.parliament.uk/research-briefings/sn07148/>
814
- 815 [10] C. A. Faulkner, J. E. Castellini, Y. Lou, W. Zuo, D. M. Lorenzetti,
816 M. D. Sohn, Tradeoffs among indoor air quality, financial costs, and
817 CO₂ emissions for HVAC operation strategies to mitigate indoor virus
818 in U.S. office buildings, *Building and Environment* 221 (2022) 109282.
819 doi:10.1016/j.buildenv.2022.109282.
820 URL <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9358780/>
- 821 [11] S. J. Ball, The education debate, Policy and politics in the twenty-first
822 century, Policy Press, Bristol, 2008.
- 823 [12] H. C. Burridge, R. K. Bhagat, M. E. J. Stettler, P. Kumar, I. De Mel,
824 P. Demis, A. Hart, Y. Johnson-Llambias, M.-F. King, O. Klymenko,
825 A. McMillan, P. Morawiecki, T. Pennington, M. Short, D. Sykes,
826 P. H. Trinh, S. K. Wilson, C. Wong, H. Wragg, M. S. Davies Wykes,
827 C. Iddon, A. W. Woods, N. Mingotti, N. Bhamidipati, H. Woodward,
828 C. Beggs, H. Davies, S. Fitzgerald, C. Pain, P. F. Linden, The ven-
829 tilation of buildings and other mitigating measures for COVID-19: a
830 focus on wintertime, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 477 (2247) (2021) 20200855.
831 doi:10.1098/rspa.2020.0855.
832 URL <https://royalsocietypublishing.org/doi/full/10.1098/rspa.2020.0855>
833
834
- 835 [13] I. News, Teachers say government’s ‘open window policy’ is unworkable
836 in winter (Jan. 2022).
837 URL <https://www.itv.com/news/anglia/2022-01-06/teachers-say-governments-open-window-policy-is-unworkable-in-winter>
838
- 839 [14] L. E. Kim, K. Asbury, ‘Like a rug had been pulled from under
840 you’: The impact of COVID-19 on teachers in England

- 841 during the first six weeks of the UK lockdown, *British Journal of Educational Psychology* 90 (4) (2020) 1062–1083, `_eprint:`
842 `https://bpspsychub.onlinelibrary.wiley.com/doi/pdf/10.1111/bjep.12381`.
843 `doi:10.1111/bjep.12381`.
844 URL `https://onlinelibrary.wiley.com/doi/abs/10.1111/bjep.1`
845 `2381`
846
- 847 [15] J. C. Uzoigwe, T. Prum, E. Bresnahan, M. Garelnabi, The Emerging
848 Role of Outdoor and Indoor Air Pollution in Cardiovascular Disease,
849 *North American Journal of Medical Sciences* 5 (8) (2013) 445–453. `doi:`
850 `10.4103/1947-2714.117290`.
851 URL `https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3784920/`
- 852 [16] G. Duffield, S. Bunn, Indoor Air Quality, POSTbrief 54, Parliamentary
853 Office of Science and Technology, UK Parliament (Sep. 2023). `doi:`
854 `10.58248/PB54`.
855 URL `https://post.parliament.uk/research-briefings/post-p`
856 `b-0054/`
- 857 [17] A. P. Jones, Indoor air quality and health, *Atmospheric Environment*
858 33 (28) (1999) 4535–4564. `doi:10.1016/S1352-2310(99)00272-1`.
859 URL `https://www.sciencedirect.com/science/article/pii/S135`
860 `2231099002721`
- 861 [18] S. Nandasena, A. R. Wickremasinghe, N. Sathiakumar, Indoor air pol-
862 lution and respiratory health of children in the developing world, *World*
863 *Journal of Clinical Pediatrics* 2 (2) (2013) 6–15. `doi:10.5409/wjcp.v`
864 `2.i2.6`.
865 URL `https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4145638/`
- 866 [19] A. C. Lewis, J. Allan, D. Carslaw, D. Carruthers, G. Fuller, R. Harri-
867 son, M. Heal, E. Nemitz, C. Reeves, N. Carslaw, A. Dengel, S. Dim-
868 itroulopoulou, R. Gupta, M. Fisher, D. Fowler, M. Loh, S. Moller,
869 R. Maggs, T. Murrells, P. Quincey, P. Willis, Indoor Air Quality, Tech.
870 rep., Zenodo, version Number: Public version, mirrored from `www.UK-`
871 `Air.gov.uk` (2022). `doi:10.5281/ZENODO.6523605`.
872 URL `https://zenodo.org/record/6523605`
- 873 [20] S. D. Lowther, S. Dimitroulopoulou, K. Foxall, C. Shrubsole, E. Cheek,
874 B. Gadeberg, O. Sepai, Low Level Carbon Dioxide Indoors—A Pollution

- 875 Indicator or a Pollutant? A Health-Based Perspective, *Environments*
876 8 (11) (2021) 125, number: 11. doi:10.3390/environments8110125.
877 URL <https://www.mdpi.com/2076-3298/8/11/125>
- 878 [21] C. Wang, F. Zhang, J. Wang, J. K. Doyle, P. A. Hancock, C. M. Mak,
879 S. Liu, How indoor environmental quality affects occupants' cognitive
880 functions: A systematic review, *Building and Environment* 193 (2021)
881 107647. doi:10.1016/j.buildenv.2021.107647.
882 URL <https://www.sciencedirect.com/science/article/pii/S0360132321000597>
883
- 884 [22] S. Holgate, J. Grigg, H. Arshad, N. Carslaw, P. Cullinan, S. Dim-
885 itroulopoulou, A. Greenough, M. Holland, B. Jones, P. Linden,
886 T. Sharpe, A. Short, B. Turner, M. Ucci, S. Vardoulakis, H. Stacey,
887 L. Hunter, Health Effects of Indoor Air Quality on Children and Young
888 People, in: *Issues in Environmental Science and Technology*, Issues in
889 Environmental Science and Technology, Royal Society of Chemistry,
890 2020, pp. 151–188.
891 URL [https://books.rsc.org/books/edited-volume/891/chapter/
892 676437/Health-Effects-of-Indoor-Air-Quality-on-Children](https://books.rsc.org/books/edited-volume/891/chapter/676437/Health-Effects-of-Indoor-Air-Quality-on-Children)
- 893 [23] N. Shapiro, Attuning to the Chemosphere: Domestic Formaldehyde,
894 Bodily Reasoning, and the Chemical Sublime, *Cultural Anthropology*
895 30 (3) (2015) 368–393. doi:10.14506/ca30.3.02.
896 URL [https://journal.culanth.org/index.php/ca/article/view/
897 ca30.3.02](https://journal.culanth.org/index.php/ca/article/view/ca30.3.02)
- 898 [24] R. G. Altman, R. Morello-Frosch, J. G. Brody, R. Rudel, P. Brown,
899 M. Averick, Pollution comes home and gets personal: women's expe-
900 rience of household chemical exposure, *Journal of Health and Social
901 Behavior* 49 (4) (2008) 417–435. doi:10.1177/002214650804900404.
- 902 [25] D. W. Dockery, C. A. Pope, X. Xu, J. D. Spengler, J. H. Ware, M. E.
903 Fay, B. G. Ferris, F. E. Speizer, An association between air pollution
904 and mortality in six U.S. cities, *The New England Journal of Medicine*
905 329 (24) (1993) 1753–1759. doi:10.1056/NEJM199312093292401.
- 906 [26] I. Andersen, G. R. Lundqvist, L. Mølhave, Indoor air pollution due to
907 chipboard used as a construction material, *Atmospheric Environment*
908 (1967) 9 (12) (1975) 1121–1127. doi:10.1016/0004-6981(75)90188-2.

- 909 URL <https://www.sciencedirect.com/science/article/pii/0004>
910 [698175901882](https://www.sciencedirect.com/science/article/pii/0004698175901882)
- 911 [27] J. Alzona, B. L. Cohen, H. Rudolph, H. N. Jow, J. O. Frohlinger, Indoor-
912 outdoor relationships for airborne particulate matter of outdoor origin,
913 Atmospheric Environment (1967) 13 (1) (1979) 55–60. doi:10.1016/
914 0004-6981(79)90244-0.
915 URL <https://www.sciencedirect.com/science/article/pii/0004>
916 [698179902440](https://www.sciencedirect.com/science/article/pii/0004698179902440)
- 917 [28] P. Kumar, S. Hama, R. A. Abbass, K. V. Abhijith, A. Tiwari, D. Grassie,
918 C. Mitsakou, Environmental quality in sixty primary and secondary
919 school classrooms in London, Journal of Building Engineering 91 (2024)
920 109549. doi:10.1016/j.jobe.2024.109549.
921 URL <https://www.sciencedirect.com/science/article/pii/S235>
922 [2710224011173](https://www.sciencedirect.com/science/article/pii/S2352710224011173)
- 923 [29] D. Molnár, Y. Schutz, The effect of obesity, age, puberty and gender on
924 resting metabolic rate in children and adolescents, European Journal of
925 Pediatrics 156 (5) (1997) 376–381. doi:10.1007/s004310050618.
926 URL <https://doi.org/10.1007/s004310050618>
- 927 [30] M. Oliveira, K. Slezakova, C. Delerue-Matos, M. C. Pereira, S. Morais,
928 Children environmental exposure to particulate matter and polycyclic
929 aromatic hydrocarbons and biomonitoring in school environments: A
930 review on indoor and outdoor exposure levels, major sources and health
931 impacts, Environment International 124 (2019) 180–204. doi:10.101
932 6/j.envint.2018.12.052.
933 URL <https://www.sciencedirect.com/science/article/pii/S016>
934 [041201832186X](https://www.sciencedirect.com/science/article/pii/S016041201832186X)
- 935 [31] Air Quality Expert Group, A. C. Lewis, J. Allan, D. Carslaw, D. Car-
936 ruthers, G. Fuller, R. Harrison, M. Heal, E. Nemitz, C. Reeves,
937 N. Carslaw, A. Dengel, S. Dimitroulopoulou, R. Gupta, M. Fisher,
938 D. Fowler, M. Loh, S. Moller, R. Maggs, T. Murrells, P. Quincey,
939 P. Willis, Indoor Air Quality: Report of the Air Quality Expert
940 Group, Tech. rep., Department for Environment, Food and Rural Af-
941 fairs (Defra), version Number: Public version, mirrored from [www.UK-](http://www.UK-Air.gov.uk)
942 [Air.gov.uk](http://www.UK-Air.gov.uk) (2022). doi:10.5281/ZENODO.6523605.

- 943 URL [https://uk-air.defra.gov.uk/library/reports.php?report](https://uk-air.defra.gov.uk/library/reports.php?report_id=1101)
944 [_id=1101](https://uk-air.defra.gov.uk/library/reports.php?report_id=1101)
- 945 [32] C. Whitty, Chief Medical Officer’s Annual Report 2022: Air Pollution,
946 Tech. rep., Department of Health and Social Care (2022).
947 URL <https://www.gov.uk/government/publications/chief-medical-officers-annual-report-2022-air-pollution>
948
- 949 [33] S. G. A. Wood, A. E. E. Handy, K. Roberts, H. C. Burridge, Assessing classroom ventilation rates using CO2 data from a nationwide study of UK schools and identifying school-wide correlation factors, *Developments in the Built Environment* 19 (2024) 100520. doi: 10.1016/j.dibe.2024.100520.
950
951
952
953 URL <https://www.sciencedirect.com/science/article/pii/S2666165924002011>
954
955
- 956 [34] ASHRAE, Interpretation IC 62.2-2016-1 of ANSI/ASHRAE Standard 62.2-2016 (2016).
957
958 URL <https://www.ashrae.org/File%20Library/Technical%20Resources/Standards%20and%20Guidelines/Standards%20Intepretations/IC-62-2-2016-1.pdf>
959
960
- 961 [35] D. for Education, BB 101: Ventilation, thermal comfort and indoor air quality 2018 (Aug. 2018).
962
963 URL <https://www.gov.uk/government/publications/building-bulletin-101-ventilation-for-school-buildings>
964
- 965 [36] R. M. Baloch, C. N. Maesano, J. Christoffersen, S. Banerjee, M. Gabriel, E. Csobod, E. de Oliveira Fernandes, I. Annesi-Maesano, . Csobod, P. Szuppinger, R. Prokai, P. Farkas, C. Fuzi, E. Cani, J. Draganic, E. R. Mogyorosy, Z. Korac, E. de Oliveira Fernandes, G. Ventura, J. Madureira, I. Paciência, A. Martins, R. Pereira, E. Ramos, P. Rudnai, A. Páldy, G. Dura, T. Beregszászi, . Vaskövi, D. Magyar, T. Pándics, Z. Remény-Nagy, R. Szentmihályi, O. Udvardy, M. J. Varró, S. Kephelopoulos, D. Kotzias, J. Barrero-Moreno, R. Mehmeti, A. Vilic, D. Maestro, H. Moshammer, G. Strasser, P. Brigitte, P. Hohenblum, E. Goelen, M. Stranger, M. Spruy, M. Sidjimov, A. Hadjipanayis, A. Katsonouri-Sazeides, E. Demetriou, R. Kubinova, H. Kazmarová, B. Dlouha, B. Kotlík, H. Vabar, J. Ruut, M. Metus, K. Rand,

- 977 A. Järviste, A. Nevalainen, A. Hyvarinen, M. Täubel, K. Järvi,
978 I. Annesi-Maesano, C. Mandin, B. Berthineau, H.-J. Moriske, M. Giaco-
979 mini, A. Neumann, J. Bartzis, K. Kalimeri, D. Saraga, M. Santamouris,
980 M. N. Assimakopoulos, V. Asimakopoulos, P. Carrer, A. Cattaneo,
981 S. Pulvirenti, F. Vercelli, F. Strangi, E. Omeri, S. Piazza, A. D'Alcamo,
982 A. C. Fanetti, P. Sestini, M. Kouri, G. Viegi, G. Sarno, S. Baldacci,
983 S. Maio, S. Cerrai, V. Franzitta, S. Bucchieri, F. Cibella, M. Simoni,
984 M. Neri, D. Martuzevičius, E. Krugly, S. Montefort, P. Fsadni, P. Z.
985 Brewczyński, E. Krakowiak, J. Kurek, E. Kubarek, A. Wlazło, C. Bor-
986 rego, C. Alves, J. Valente, E. Gurzau, C. Rosu, G. Popita, I. Neamtiu,
987 C. Neagu, D. Norback, P. Bluysen, M. Bohms, P. Van Den Hazel,
988 F. Cassee, Y. B. de Bruin, A. Bartonova, A. Yang, K. Halzlová, M. Jaj-
989 caj, M. Kániková, O. Miklankova, M. Vítková, M. Jovasević-Stojanovic,
990 M. Zivkovic, Z. Stevanovic, I. Lazovic, Z. Stevanovic, Z. Zivkovic,
991 S. Cerovic, J. Jovic-Stojanovic, D. Mumovic, P. Tarttelin, L. Chatzidi-
992 akou, E. Chatzidiakou, M.-C. Dewolf, Indoor air pollution, physical and
993 comfort parameters related to schoolchildren's health: Data from the
994 European SINPHONIE study, *Science of The Total Environment* 739
995 (2020) 139870. doi:10.1016/j.scitotenv.2020.139870.
996 URL [https://www.sciencedirect.com/science/article/pii/S004](https://www.sciencedirect.com/science/article/pii/S0048969720333908)
997 [8969720333908](https://www.sciencedirect.com/science/article/pii/S0048969720333908)
- 998 [37] D. for Education, Schools, pupils and their characteristics, Academic
999 year 2023/24, Tech. rep., Department for Education (Jun. 2024).
1000 URL [https://explore-education-statistics.service.gov.uk/f](https://explore-education-statistics.service.gov.uk/find-statistics/school-pupils-and-their-characteristics)
1001 [ind-statistics/school-pupils-and-their-characteristics](https://explore-education-statistics.service.gov.uk/find-statistics/school-pupils-and-their-characteristics)
- 1002 [38] S. Hama, P. Kumar, A. Tiwari, Y. Wang, P. F. Linden, The under-
1003 pinning factors affecting the classroom air quality, thermal comfort and
1004 ventilation in 30 classrooms of primary schools in London, *Environmental*
1005 *Research* 236 (2023) 116863. doi:10.1016/j.envres.2023.116863.
1006 URL [https://www.sciencedirect.com/science/article/pii/S001](https://www.sciencedirect.com/science/article/pii/S0013935123016675)
1007 [3935123016675](https://www.sciencedirect.com/science/article/pii/S0013935123016675)
- 1008 [39] D. Booker, G. Walker, P. J. Young, Unstable air: How COVID-19 re-
1009 made knowing air quality in school classrooms, *Ephemera Journal* (Jan.
1010 2024).
- 1011 [40] D. for Education, All schools to receive carbon dioxide monitors (Aug.

1012 2021).

1013 URL [https://www.gov.uk/government/news/all-schools-to-rec](https://www.gov.uk/government/news/all-schools-to-receive-carbon-dioxide-monitors)

1014 [eive-carbon-dioxide-monitors](https://www.gov.uk/government/news/all-schools-to-receive-carbon-dioxide-monitors)

1015 [41] V. Loftness, V. Hartkopf, The effects of building design and use on air

1016 quality, *Occupational Medicine* 4 (4) (1989) 643–665.

1017 [42] Y. Al horr, M. Arif, M. Katafygiotou, A. Mazroei, A. Kaushik, E. Elsar-

1018 rag, Impact of indoor environmental quality on occupant well-being and

1019 comfort: A review of the literature, *International Journal of Sustainable*

1020 *Built Environment* 5 (1) (2016) 1–11. doi:10.1016/j.ijbsbe.2016.0

1021 3.006.

1022 URL [https://www.sciencedirect.com/science/article/pii/S221](https://www.sciencedirect.com/science/article/pii/S2212609016300140)

1023 [2609016300140](https://www.sciencedirect.com/science/article/pii/S2212609016300140)

1024 [43] A. V. Arundel, E. M. Sterling, J. H. Biggin, T. D. Sterling, Indirect

1025 health effects of relative humidity in indoor environments, *Environmental*

1026 *Health Perspectives* 65 (1986) 351–361. doi:10.1289/ehp.8665351.

1027 [44] M. Kolokotroni, X. Ren, M. Davies, A. Mavrogianni, London’s urban

1028 heat island: Impact on current and future energy consumption in office

1029 buildings, *Energy and Buildings* 47 (2012) 302–311. doi:10.1016/j.

1030 [enbuild.2011.12.019](https://www.sciencedirect.com/science/article/pii/S0378778811006293).

1031 URL [https://www.sciencedirect.com/science/article/pii/S037](https://www.sciencedirect.com/science/article/pii/S0378778811006293)

1032 [8778811006293](https://www.sciencedirect.com/science/article/pii/S0378778811006293)

1033 [45] Z. S. Zomorodian, M. Tahsildoost, M. Hafezi, Thermal comfort in edu-

1034 cational buildings: A review article, *Renewable and Sustainable Energy*

1035 *Reviews* 59 (2016) 895–906. doi:10.1016/j.rser.2016.01.033.

1036 URL [https://www.sciencedirect.com/science/article/pii/S136](https://www.sciencedirect.com/science/article/pii/S1364032116000630)

1037 [4032116000630](https://www.sciencedirect.com/science/article/pii/S1364032116000630)

1038 [46] R. a. A.-C. E. American Society of Heating, ANSI/ASHRAE Standard

1039 55-2020: Thermal Environmental Conditions for Human Occupancy

1040 (2020).

1041 URL [https://www.ashrae.org/technical-resources/bookstore/s](https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy)

1042 [tandard-55-thermal-environmental-conditions-for-human-occ](https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy)

1043 [upancy](https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy)

- 1044 [47] S. Atthajariyakul, T. Leephakpreeda, Real-time determination of op-
1045 timal indoor-air condition for thermal comfort, air quality and ef-
1046 ficient energy usage, *Energy and Buildings* 36 (7) (2004) 720–733.
1047 doi:10.1016/j.enbuild.2004.01.017.
1048 URL [https://www.sciencedirect.com/science/article/pii/S037](https://www.sciencedirect.com/science/article/pii/S0378778804000258)
1049 [8778804000258](https://www.sciencedirect.com/science/article/pii/S0378778804000258)
- 1050 [48] S. Bouzarovski, C. Robinson, Injustices at the air–energy nexus - Stefan
1051 Bouzarovski, Caitlin Robinson, 2022, *Environment and Planning F* 1 (2-
1052 4) (2022) 168–186. doi:[https://doi.org/10.1177/26349825221123](https://doi.org/10.1177/26349825221123574)
1053 [574](https://doi.org/10.1177/26349825221123574).
1054 URL [https://journals.sagepub.com/doi/10.1177/2634982522112](https://journals.sagepub.com/doi/10.1177/26349825221123574)
1055 [3574](https://journals.sagepub.com/doi/10.1177/26349825221123574)
- 1056 [49] I. Hussain, A. Friday, D. Booker, The Indoor Air Quality Trilemma:
1057 Improving Air Quality, Using Less Energy, and Meeting Stakeholder
1058 Requirements, in: *Extended Abstracts of the 2023 CHI Conference on*
1059 *Human Factors in Computing Systems, CHI EA '23*, Association for
1060 *Computing Machinery*, New York, NY, USA, 2023, pp. 1–6. doi:10.1
1061 [145/3544549.3585898](https://doi.org/10.1145/3544549.3585898).
1062 URL <https://dl.acm.org/doi/10.1145/3544549.3585898>
- 1063 [50] D. for Education, Ventilating classrooms to reduce the spread of Covid
1064 19 doesn't mean pupils need to be cold – here's why – The Education
1065 Hub (Jan. 2022).
1066 URL [https://educationhub.blog.gov.uk/2022/01/ventilating-c](https://educationhub.blog.gov.uk/2022/01/ventilating-classrooms-to-reduce-the-spread-of-covid-19-doesnt-mean-pupils-need-to-be-cold-heres-why/)
1067 [lassrooms-to-reduce-the-spread-of-covid-19-doesnt-mean-pup](https://educationhub.blog.gov.uk/2022/01/ventilating-classrooms-to-reduce-the-spread-of-covid-19-doesnt-mean-pupils-need-to-be-cold-heres-why/)
1068 [ils-need-to-be-cold-heres-why/](https://educationhub.blog.gov.uk/2022/01/ventilating-classrooms-to-reduce-the-spread-of-covid-19-doesnt-mean-pupils-need-to-be-cold-heres-why/)
- 1069 [51] E. A. Committee, MPs warn Government progress is lacking as only
1070 20% of the England's schools estate will be net zero compliant by 2050
1071 - Committees - UK Parliament (Nov. 2023).
1072 URL [https://committees.parliament.uk/work/7925/the-enviro](https://committees.parliament.uk/work/7925/the-environmental-sustainability-of-the-department-for-education/news/198615/mps-warn-government-progress-is-lacking-as-only-20-of-the-englands-schools-estate-will-be-net-zero-compliant-by-2050/)
1073 [nmental-sustainability-of-the-department-for-education/new](https://committees.parliament.uk/work/7925/the-environmental-sustainability-of-the-department-for-education/news/198615/mps-warn-government-progress-is-lacking-as-only-20-of-the-englands-schools-estate-will-be-net-zero-compliant-by-2050/)
1074 [s/198615/mps-warn-government-progress-is-lacking-as-only-2](https://committees.parliament.uk/work/7925/the-environmental-sustainability-of-the-department-for-education/news/198615/mps-warn-government-progress-is-lacking-as-only-20-of-the-englands-schools-estate-will-be-net-zero-compliant-by-2050/)
1075 [0-of-the-englands-schools-estate-will-be-net-zero-complia](https://committees.parliament.uk/work/7925/the-environmental-sustainability-of-the-department-for-education/news/198615/mps-warn-government-progress-is-lacking-as-only-20-of-the-englands-schools-estate-will-be-net-zero-compliant-by-2050/)
1076 [nt-by-2050/](https://committees.parliament.uk/work/7925/the-environmental-sustainability-of-the-department-for-education/news/198615/mps-warn-government-progress-is-lacking-as-only-20-of-the-englands-schools-estate-will-be-net-zero-compliant-by-2050/)
- 1077 [52] Y. Schwartz, D. Godoy-Shimizu, I. Korolija, J. Dong, S. M. Hong,
1078 A. Mavrogianni, D. Mumovic, Developing a Data-driven school building

- 1079 stock energy and indoor environmental quality modelling method, *En-*
1080 *ergy and Buildings* 249 (2021) 111249. doi:10.1016/j.enbuild.2021
1081 .111249.
1082 URL [https://www.sciencedirect.com/science/article/pii/S037](https://www.sciencedirect.com/science/article/pii/S0378778821005338)
1083 [8778821005338](https://www.sciencedirect.com/science/article/pii/S0378778821005338)
- 1084 [53] Department for Education and Employment, *Building Bulletin 73: A*
1085 *guide to energy efficient refurbishment: maintenance and renewal in*
1086 *educational buildings*, Tech. Rep. Building Bulletin 73, HMSO (1991).
1087 URL [https://www.thenbs.com/PublicationIndex/Documents/Deta](https://www.thenbs.com/PublicationIndex/Documents/Details?Pub=DfEE&DocId=249697)
1088 [ils?Pub=DfEE&DocId=249697](https://www.thenbs.com/PublicationIndex/Documents/Details?Pub=DfEE&DocId=249697)
- 1089 [54] D. for Education, *Schools' costs 2022 to 2024* (Feb. 2023).
1090 URL [https://assets.publishing.service.gov.uk/media/63f4e5c](https://assets.publishing.service.gov.uk/media/63f4e5cce90e077bb13a6592/Schools__costs_2022_to_2024.pdf)
1091 [ce90e077bb13a6592/Schools__costs_2022_to_2024.pdf](https://assets.publishing.service.gov.uk/media/63f4e5cce90e077bb13a6592/Schools__costs_2022_to_2024.pdf)
- 1092 [55] D. for Education, *Using CO₂ monitors and air cleaning units in educa-*
1093 *tion and care settings - GOV.UK* (Mar. 2023).
1094 URL [https://www.gov.uk/guidance/using-co-monitors-and-air](https://www.gov.uk/guidance/using-co-monitors-and-air-cleaning-units-in-education-and-care-settings)
1095 [-cleaning-units-in-education-and-care-settings](https://www.gov.uk/guidance/using-co-monitors-and-air-cleaning-units-in-education-and-care-settings)
- 1096 [56] N. Jain, E. Burman, C. Robertson, S. Stamp, C. Shrubsole, F. Aletta,
1097 E. Barrett, T. Oberman, J. Kang, P. Raynham, D. Mumovic, M. Davies,
1098 *Building performance evaluation: Balancing energy and indoor environ-*
1099 *mental quality in a UK school building*, Building Services Engineering
1100 *Research and Technology* Publisher: SAGE Publications Sage UK: Lon-
1101 *don, England* (Dec. 2019). doi:10.1177/0143624419897397.
1102 URL [https://journals.sagepub.com/doi/abs/10.1177/014362441](https://journals.sagepub.com/doi/abs/10.1177/0143624419897397)
1103 [9897397](https://journals.sagepub.com/doi/abs/10.1177/0143624419897397)
- 1104 [57] L. Chatzidiakou, R. Archer, V. Beale, S. Bland, H. Carter, C. Castro-
1105 *Faccetti, H. Edwards, J. Finneran, S. Hama, R. L. Jones, P. Kumar,*
1106 *P. F. Linden, N. Rawat, K. Roberts, C. Symons, C. Vouriot, D. Wang,*
1107 *L. Way, S. West, D. Weston, N. Williams, S. Wood, H. C. Burridge,*
1108 *Schools' air quality monitoring for health and education: Methods and*
1109 *protocols of the SAMHE initiative and project*, *Developments in the*
1110 *Built Environment* 16 (2023) 100266. doi:10.1016/j.dibe.2023.10
1111 0266.
1112 URL [https://www.sciencedirect.com/science/article/pii/S266](https://www.sciencedirect.com/science/article/pii/S2666165923001485)
1113 [6165923001485](https://www.sciencedirect.com/science/article/pii/S2666165923001485)

- 1114 [58] W. Finnegan, Beyond whole-school approaches to sustainability: social
1115 practices and practice architectures at secondary schools in England,
1116 Energy Research and Social Science 102 (2023).
1117 URL [https://ora.ox.ac.uk/objects/uuid:35024004-ca89-4b40-9](https://ora.ox.ac.uk/objects/uuid:35024004-ca89-4b40-9352-40f6cb10a2c3)
1118 [352-40f6cb10a2c3](https://ora.ox.ac.uk/objects/uuid:35024004-ca89-4b40-9352-40f6cb10a2c3)
- 1119 [59] P. K. Sharma, D. Chatterjee, D. Das, S. Saha, Can I take class in that
1120 classroom now? In the perspective of Air Quality, in: Proceedings of
1121 the 24th International Conference on Distributed Computing and Net-
1122 working, ICDCN '23, Association for Computing Machinery, New York,
1123 NY, USA, 2023, pp. 396–401. doi:10.1145/3571306.3571442.
1124 URL <https://dl.acm.org/doi/10.1145/3571306.3571442>
- 1125 [60] S. Mohamed, L. Rodrigues, S. Omer, J. Calautit, Overheating and in-
1126 door air quality in primary schools in the UK, Energy and Buildings 250
1127 (2021) 111291. doi:10.1016/j.enbuild.2021.111291.
1128 URL [https://www.sciencedirect.com/science/article/pii/S037](https://www.sciencedirect.com/science/article/pii/S0378778821005752)
1129 [8778821005752](https://www.sciencedirect.com/science/article/pii/S0378778821005752)
- 1130 [61] H. Bulkeley, The Social Construction of Climate Change: Power, Knowl-
1131 edge, Norms, Discourses - Edited by Pettenger M, Singapore Journal of
1132 Tropical Geography 30 (1) (2009) 141–143, place: Melbourne, Australia.
1133 doi:10.1111/j.1467-9493.2008.00355_2.x.
- 1134 [62] E. Shove, The dynamics of social practice everyday life and how it
1135 changes, SAGE, Los Angeles, 2012.
- 1136 [63] E. Zerubavel, Hidden rhythms: schedules and calendars in social life,
1137 1st Edition, University of California Press, Berkeley, 1985.
- 1138 [64] J. Wajcman, Pressed for time: the acceleration of life in digital capital-
1139 ism, The University of Chicago Press, Chicago, 2015.
- 1140 [65] A. Friday, M. Hazas, O. Bates, J. Morley, C. Lord, K. Wid-
1141 dicks, A. Gormally-Sutton, A. Clear, Unpacking the resource im-
1142 pacts of digitally-mediated domestic practices using resource trace
1143 interviewing, Digital Creativity 33 (3) (2022) 250–275, _eprint:
1144 <https://doi.org/10.1080/14626268.2022.2127773>. doi:10.1080/1462
1145 [6268.2022.2127773](https://doi.org/10.1080/14626268.2022.2127773).
1146 URL <https://doi.org/10.1080/14626268.2022.2127773>

- 1147 [66] Ministry of Housing, Communities & Local Government, English indices
1148 of deprivation 2019 (Sep. 2019).
1149 URL <https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019>
1150
- 1151 [67] D. Gounaris, S. Bezantakos, D. Booker, D. R. Booker, G. Biskos, Performance evaluation of the national air quality testing services V2000
1152 Condensation Particle Counter, Aerosol Science and Technology (Dec.
1153 2024).
1154 URL <https://www.tandfonline.com/doi/abs/10.1080/02786826.2024.2386109>
1155
1156
- 1157 [68] S. Cui, M. Cohen, P. Stabat, D. Marchio, CO2 tracer gas concentration
1158 decay method for measuring air change rate, Building and Environment
1159 84 (2015) 162–169. doi:10.1016/j.buildenv.2014.11.007.
1160 URL <https://www.sciencedirect.com/science/article/pii/S0360132314003606>
1161
- 1162 [69] R. F. Rupp, N. G. Vásquez, R. Lamberts, A review of human thermal
1163 comfort in the built environment, Energy and Buildings 105 (2015) 178–
1164 205. doi:10.1016/j.enbuild.2015.07.047.
1165 URL <https://www.sciencedirect.com/science/article/pii/S0378778815301638>
1166
- 1167 [70] J. P. Temprano, P. Eichholtz, M. Willeboordse, N. Kok, Indoor environmental
1168 quality and learning outcomes: protocol on large-scale sensor
1169 deployment in schools, BMJ Open 10 (3) (2020) e031233. doi:
1170 10.1136/bmjopen-2019-031233.
1171 URL <https://bmjopen.bmj.com/content/10/3/e031233>
- 1172 [71] D. C. Carslaw, K. Ropkins, *openair* — An R package for air quality
1173 data analysis, Environmental Modelling & Software 27-28 (2012) 52–61.
1174 doi:10.1016/j.envsoft.2011.09.008.
1175 URL <https://www.sciencedirect.com/science/article/pii/S1364815211002064>
1176
- 1177 [72] V. Braun, V. Clarke, Using thematic analysis in psychology, Qualitative
1178 Research in Psychology 3 (2) (2006) 77–101. doi:10.1191/14780887
1179 06qp063oa.

- 1180 URL <https://www.tandfonline.com/doi/abs/10.1191/1478088706>
1181 qp063oa
- 1182 [73] J. Saldaña, The coding manual for qualitative researchers, 2nd Edition,
1183 SAGE Publ, Los Angeles, Calif., 2013.
- 1184 [74] D. for Education, National curriculum in England: science programmes
1185 of study, Tech. rep., Department for Education (May 2015).
1186 URL [https://www.gov.uk/government/publications/national-c](https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study/national-curriculum-in-england-science-programmes-of-study)
1187 [urriculum-in-england-science-programmes-of-study/nationa](https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study/national-curriculum-in-england-science-programmes-of-study)
1188 [l-curriculum-in-england-science-programmes-of-study](https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study/national-curriculum-in-england-science-programmes-of-study)
- 1189 [75] H. Dai, B. Zhao, Association of the infection probability of COVID-19
1190 with ventilation rates in confined spaces, Building Simulation 13 (6)
1191 (2020) 1321–1327. doi:10.1007/s12273-020-0703-5.
1192 URL <https://doi.org/10.1007/s12273-020-0703-5>
- 1193 [76] D. for Energy Security & Net-Zero, E. . I. S. Department for Business,
1194 Net Zero Strategy: Build Back Greener (Apr. 2022).
1195 URL [https://www.gov.uk/government/publications/net-zero-s](https://www.gov.uk/government/publications/net-zero-strategy)
1196 [trategy](https://www.gov.uk/government/publications/net-zero-strategy)
- 1197 [77] W. Birmili, H.-C. Selinka, H.-J. Moriske, A. Daniels, W. Straff, Lüf-
1198 tungskonzepte in Schulen zur Prävention einer Übertragung hochinfek-
1199 tiöser Viren (SARS-CoV-2) über Aerosole in der Raumluft, Bundes-
1200 gesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz 64 (12)
1201 (2021) 1570–1580. doi:10.1007/s00103-021-03452-4.
1202 URL <https://doi.org/10.1007/s00103-021-03452-4>
- 1203 [78] S. Kim, E. Paulos, InAir: sharing indoor air quality measurements and
1204 visualizations, in: Proceedings of the SIGCHI Conference on Human
1205 Factors in Computing Systems, CHI '10, Association for Computing
1206 Machinery, New York, NY, USA, 2010, pp. 1861–1870. doi:10.1145/
1207 1753326.1753605.
1208 URL <https://dl.acm.org/doi/10.1145/1753326.1753605>
- 1209 [79] D. Booker, G. Petrou, L. Chatzidiakou, D. Das, F. Farooq, L. Fer-
1210 guson, O. I. Jutila, K. Milczewska, M. Modlich, A. Moreno-Rangel,
1211 S. K. Thakrar, A. M. Yeoman, M. Davies, M. I. Mead, M. R. Miller,

- 1212 O. Wild, Z. Shi, A. Mavrogianni, R. M. Doherty, Ten questions con-
1213 cerning the future of residential indoor air quality and its environmen-
1214 tal justice implications, *Building and Environment* 278 (2025) 112957.
1215 doi:10.1016/j.buildenv.2025.112957.
1216 URL [https://www.sciencedirect.com/science/article/pii/S036](https://www.sciencedirect.com/science/article/pii/S0360132325004391)
1217 [0132325004391](https://www.sciencedirect.com/science/article/pii/S0360132325004391)
- 1218 [80] G. Fuller, *The Invisible Killer: The Rising Global Threat of Air Pollution*
1219 *- and how We Can Fight Back*, Melville House UK, 2019, google-Books-
1220 ID: ORdVxAEACAAJ.
- 1221 [81] J. Popay, M. Whitehead, D. J. Hunter, Injustice is killing people on a
1222 large scale—but what is to be done about it?, *Journal of Public Health*
1223 32 (2) (2010) 148–149. doi:10.1093/pubmed/fdq029.
1224 URL <https://doi.org/10.1093/pubmed/fdq029>
- 1225 [82] J. Few, M. Shipworth, C. Elwell, Ventilation regulations and occupant
1226 practices: undetectable pollution and invisible extraction, *Buildings &*
1227 *Cities* 5 (1) (Feb. 2024). doi:10.5334/bc.389.
1228 URL [https://journal-buildingscities.org/articles/10.5334/](https://journal-buildingscities.org/articles/10.5334/bc.389)
1229 [bc.389](https://journal-buildingscities.org/articles/10.5334/bc.389)
- 1230 [83] I. Valente, J. P. Gouveia, Growing up in discomfort: Exploring energy
1231 poverty and thermal comfort among students in Portugal, *Energy Re-*
1232 *search & Social Science* 113 (2024) 103550. doi:10.1016/j.erss.202
1233 4.103550.
1234 URL [https://www.sciencedirect.com/science/article/pii/S221](https://www.sciencedirect.com/science/article/pii/S2214629624001415)
1235 [4629624001415](https://www.sciencedirect.com/science/article/pii/S2214629624001415)
- 1236 [84] C. . L. G. Ministry of Housing, Protection from falling, collision and
1237 impact: Approved Document K, Tech. rep., GOV.UK (Mar. 2013).
1238 URL [https://www.gov.uk/government/publications/protection](https://www.gov.uk/government/publications/protection-from-falling-collision-and-impact-approved-document-k)
1239 [n-from-falling-collision-and-impact-approved-document-k](https://www.gov.uk/government/publications/protection-from-falling-collision-and-impact-approved-document-k)
- 1240 [85] L. Lightfoot, Schools in England say government not providing enough
1241 air purifiers, *The Guardian* (Jan. 2022).
1242 URL [https://www.theguardian.com/education/2022/jan/14/scho](https://www.theguardian.com/education/2022/jan/14/schools-england-demand-air-purifiers-being-underestimated)
1243 [ols-england-demand-air-purifiers-being-underestimated](https://www.theguardian.com/education/2022/jan/14/schools-england-demand-air-purifiers-being-underestimated)

- 1244 [86] N. Bennett, D. Barran, Schools: Air Conditioning - Question for De-
1245 partment for Education (Jan. 2022).
1246 URL [https://questions-statements.parliament.uk/written-que-](https://questions-statements.parliament.uk/written-questions/detail/2022-01-17/h15415)
1247 [stions/detail/2022-01-17/h15415](https://questions-statements.parliament.uk/written-questions/detail/2022-01-17/h15415)
- 1248 [87] G. Davies, Condition of school buildings, Tech. rep., National Audit
1249 Office (Jun. 2023).
1250 URL [https://www.nao.org.uk/wp-content/uploads/2023/06/con-](https://www.nao.org.uk/wp-content/uploads/2023/06/condition-of-school-buildings.pdf)
1251 [dition-of-school-buildings.pdf](https://www.nao.org.uk/wp-content/uploads/2023/06/condition-of-school-buildings.pdf)
- 1252 [88] L. Gadenne, M. Leroutier, R. Tonito, B. Upton, Air pollution in England
1253 reaches 20-year low but inequalities persist (Dec. 2024).
1254 URL [https://ifs.org.uk/news/air-pollution-england-reaches](https://ifs.org.uk/news/air-pollution-england-reaches-20-year-low-inequalities-persist)
1255 [-20-year-low-inequalities-persist](https://ifs.org.uk/news/air-pollution-england-reaches-20-year-low-inequalities-persist)
- 1256 [89] . Laurent, Air (ine)quality in the European Union, Current Environ-
1257 mental Health Reports 9 (2) (2022) 123–129. doi:10.1007/s40572-0
1258 22-00348-6.
1259 URL <https://doi.org/10.1007/s40572-022-00348-6>
- 1260 [90] D. Grassie, Y. Schwartz, P. Symonds, I. Korolija, A. Mavrogianni,
1261 D. Mumovic, Energy retrofit and passive cooling: overheating and air
1262 quality in primary schools, Buildings and Cities 3 (1) (2022) 204–225.
1263 URL <http://doi.org/10.5334/bc.159>
- 1264 [91] G. Walker, Energy and Rhythm: Rhythmanalysis for a Low Carbon
1265 Future, 1st Edition, Bloomsbury Publishing, New York, 2021.
- 1266 [92] H. Lefebvre, Rhythmanalysis space, time, and everyday life, Continuum,
1267 London ;, 2004.
- 1268 [93] D. Southerton, Time Scarcity: Work, Home and Personal Lives, in:
1269 D. Southerton (Ed.), Time, Consumption and the Coordination of Ev-
1270 eryday Life, Palgrave Macmillan UK, London, 2020, pp. 43–67. doi:
1271 10.1057/978-1-349-60117-2_3.
1272 URL https://doi.org/10.1057/978-1-349-60117-2_3
- 1273 [94] N. Rose, Powers of Freedom: Reframing Political Thought, Cambridge
1274 University Press, Cambridge, 1999. doi:10.1017/CB09780511488856.
1275 URL [https://www.cambridge.org/core/books/powers-of-freedom](https://www.cambridge.org/core/books/powers-of-freedom/EFC621C8C4162825145A582072B635C8)
1276 [/EFC621C8C4162825145A582072B635C8](https://www.cambridge.org/core/books/powers-of-freedom/EFC621C8C4162825145A582072B635C8)

- 1277 [95] E. J. Done, M. Murphy, The responsabilisation of teachers: a ne-
1278 oliberal solution to the problem of inclusion, *Discourse: Studies in*
1279 *the Cultural Politics of Education* 39 (1) (2018) 142–155, `_eprint:`
1280 `https://doi.org/10.1080/01596306.2016.1243517`. `doi:10.1080/0159`
1281 `6306.2016.1243517`.
1282 URL `https://doi.org/10.1080/01596306.2016.1243517`
- 1283 [96] M. Filardo, J. M Vincent, J. S. Kevin, How crumbling school facilities
1284 perpetuate inequality (Apr. 2019).
1285 URL `https://kappanonline.org/how-crumbling-school-facilit`
1286 `ies-perpetuate-inequality-filardo-vincent-sullivan/`
- 1287 [97] M. Marmot, R. Bell, Fair society, healthy lives, *Public Health* 126 Suppl
1288 1 (2012) S4–S10. `doi:10.1016/j.puhe.2012.05.014`.
- 1289 [98] N. Hughes, N. Strachan, Methodological review of UK and international
1290 low carbon scenarios, *Energy Policy* 38 (10) (2010) 6056–6065. `doi:`
1291 `10.1016/j.enpol.2010.05.061`.
1292 URL `https://www.sciencedirect.com/science/article/pii/S030`
1293 `1421510004325`