Preprint. This paper has not yet been peer reviewed.

Air change rates in NHS general wards: weighing airborne infection risk against the energy, cost and carbon of ventilation

Naushad Ali

Independent Researcher, Luton, United Kingdom

Corresponding author: Naushad Ali, naushada43@gmail.com

Article type: Original research paper

Word count (main text): approximately 4,500 (excluding abstract, tables, figure captions, declarations and references)

Abstract

Health Technical Memorandum 03-01 sets a design rate of six air changes per hour (ACH) for general wards in England, but the infection-control benefit and the operating cost of that rate are rarely set side by side. This study combines a Wells-Riley airborne infection model with an annual energy, cost and carbon model for a four-bed ward bay of 172.8 m^3, using current UK energy prices and 2026 carbon factors. For a single infectious patient over 24 hours, modelled infection probability for each susceptible patient fell from 8.3% to 5.2% for tuberculosis and from 6.2% to 3.9% for SARS-CoV-2 when ventilation rose from 6 to 10 ACH. Each additional air change cost about £263 and 318 $kgCO_2e$ a year with a run-around coil and gas heating, and the benefit of each extra air change fell steadily as the rate rose. Reaching 10 equivalent air changes with a portable HEPA unit instead of extra outdoor air cut the added running cost by 80–89% and the added emissions by 90–95%. If an existing air handling unit is simply run faster, the added cost rises to about £4,700 a year because fan power grows with the cube of airflow. The results support keeping the HTM baseline for outdoor air and using air cleaning to go beyond it.

Keywords: hospital ventilation; air change rate; Wells-Riley model; airborne infection; energy; carbon emissions; HEPA air cleaner; HTM 03-01

Practical application

Estates and building services engineers are often asked to raise ward ventilation to reduce airborne infection, usually without knowing what it will cost to run. This paper gives a simple method, with worked figures for a standard four-bed NHS bay, for estimating the annual energy, cost and carbon of each extra air change alongside the change in modelled infection risk. It shows that portable HEPA filtration is usually the cheapest and lowest-carbon way to add clean air above the HTM 03-01 baseline, and that running an existing air handling unit faster is the most expensive option.

1. Introduction

Healthcare-associated infection remains common in English hospitals. The most recent national point prevalence survey found that 8.0% of patients in NHS acute trusts had a healthcare-associated infection in 2023, up from 6.6% in 2016, and pneumonia and other lower respiratory tract infections made up 29.6% of the total [1]. Some respiratory infections spread through the air over distances longer than conversational range, and ventilation is one of the few controls that acts on that route without depending on staff or patient behaviour. Interest in ward ventilation rose sharply during the COVID-19 pandemic, and many trusts increased ventilation rates or bought portable air cleaners.

Ventilation also uses a lot of energy. Every cubic metre of outdoor air brought into a ward has to be moved by fans and, for much of the year in the UK, heated. The NHS has committed to reaching net zero for the emissions it controls directly by 2040, with an 80% reduction by 2028–2032, and NHS England has noted that the extra ventilation and air conditioning used to protect patients and staff during the pandemic added to its emissions [2]. Estates teams therefore face a real trade-off: more air should mean lower infection risk, but it also means higher bills and more carbon.

That trade-off is rarely quantified in terms an estates engineer can use. Guidance sets design air change rates, and infection modelling studies show how risk changes with ventilation, but the two are seldom combined with current UK prices and carbon factors. This paper does that for a typical NHS general ward bay. It asks three questions:

(i) How does modelled airborne infection risk in a four-bed bay change as the air change rate rises from 2 to 12 ACH?

(ii) What does each extra air change cost in energy, money and carbon under realistic plant arrangements in England?

(iii) If a ward needs more clean air than the HTM 03-01 baseline, is it cheaper and lower in carbon to supply more outdoor air or to add portable HEPA filtration?

2. Background

2.1 Ventilation requirements for general wards

In England, ventilation of healthcare premises is governed by Health Technical Memorandum (HTM) 03-01 [3]. The guidance prefers natural ventilation where it can be shown to work, but mechanical or mixed-mode systems are needed wherever a minimum rate has to be guaranteed, and most modern multi-bed ward bays fall into that category. HTM 03-01 gives a design rate of 6 ACH for general wards and single rooms, and sets 10 L/s per person as the minimum outdoor air supply in general areas [3]. The Scottish equivalent uses the same 6 ACH figure [4]. For a four-bed bay the air change requirement is far more demanding than the per-person minimum, so in practice it is the air change rate that sets the airflow. HTM 03-01 also expects healthcare systems to be full fresh air with energy recovered from the extract, and limits the supply-to-room temperature difference to 7 K in cooling and 10 K in heating [3].

Other guidance takes different positions. ASHRAE Standard 170 in the United States requires 4 total ACH for patient rooms, of which 2 ACH must be outdoor air, and 12 ACH for airborne infection isolation rooms [5]. The World Health Organization defines an airborne precaution room as one with at least 12 ACH [6]. More recently, the Lancet COVID-19 Commission proposed targets for non-infectious air delivery of 4, 6 and more than 6 equivalent air changes per hour (eACH) for good, better and best performance, which can be met by any mix of outdoor air, filtration and germicidal ultraviolet light [7]. NHS England guidance on portable HEPA devices uses the same idea of equivalent air changes, defined as clean air delivery rate divided by room volume, but makes clear that air cleaning does not remove the need to meet minimum fresh air standards [8].

2.2 Ventilation and airborne infection

The most widely used model linking ventilation to airborne infection is the Wells-Riley equation, introduced in its common form by Riley et al. to describe a measles outbreak in a school [9]. It treats the infectious dose as a number of "quanta" released by an infector and diluted in well-mixed room air, and gives the probability of infection for a susceptible person as a function of the quanta emission rate, breathing rate, exposure time and ventilation rate. Later work extended it to non-steady conditions and to other removal mechanisms such as filtration and ultraviolet disinfection [10], and Rudnick and Milton showed how it can be driven by measured carbon dioxide concentrations [11]. Its limitations are well known: it assumes the air is well mixed, it represents only the long-range airborne route, and the quanta emission rate has to be back-calculated from outbreaks rather than measured directly [12].

Field evidence supports the general relationship even if it cannot fix a precise dose-response. In a study of hospital rooms in Lima, Escombe et al. measured air change rates and used Wells-Riley to show that modelled tuberculosis risk fell sharply as ventilation increased, with diminishing returns at high rates [13]. Beggs et al. reviewed ward ventilation guidance in the UK and the United States and found little evidence on which to base minimum ward air change rates [14]. Noakes and Sleigh showed that in a multi-bay ward, poor mixing between bays can reduce the number of infections compared with a fully mixed prediction, which means a single-zone model should be read as a tool for comparing options rather than for predicting absolute risk [15].

2.3 Previous work combining risk and energy

Many studies have used Wells-Riley to size ventilation for a target infection risk [16–18], but few have put a price on it. Noakes et al. coupled an outbreak model to a ventilation cost evaluation for a hypothetical hospital ward [19], and later modelled upper-room ultraviolet systems in a multi-room ward, concluding that they may be an energy-efficient alternative to higher ventilation rates [20]. Both studies predate the 2021 edition of HTM 03-01, the 2014 ecodesign requirements for ventilation units and the rapid fall in the carbon intensity of UK grid electricity.

Evidence on portable air cleaners in UK hospitals has grown since 2020. On COVID-19 surge wards at Addenbrooke’s Hospital, Conway Morris et al. found airborne SARS-CoV-2 on every sampling day before a HEPA filter and ultraviolet unit was switched on, on none of the days it

was running, and again after it was switched off [21]. Thuresson et al. recovered less airborne SARS-CoV-2 RNA from rooms with higher ventilation or a HEPA unit [22], and laboratory work by Lindsley et al. showed that two portable cleaners adding 5.2 eACH reduced exposure to simulated exhaled aerosol by 49–65% [23]. To the author's knowledge, no published study has compared the running cost and carbon of extra outdoor air with those of portable HEPA filtration for an NHS ward under current UK conditions.

3. Methods

3.1 Reference ward bay

The reference space is a four-bed bay of 64.0 m², the area given in Health Building Note 04-01 [24]. HBN 04-01 does not specify a ceiling height, so a height of 2.7 m was assumed, giving a volume of 172.8 m³. One air change per hour in this bay is therefore 172.8 m³/h, or 48 L/s. The bay is assumed to be ventilated mechanically for 8,760 hours a year, which is normal for in-patient areas. The analysis covers 2 to 12 ACH. The upper end matches the WHO airborne precaution rate [6], and the lower end covers the ASHRAE 170 patient room rate [5] and older wards that do not meet HTM 03-01.

3.2 Infection risk model

Infection probability was estimated with the steady-state Wells-Riley equation, extended to include particle deposition, biological decay and air cleaning as first-order removal terms [10,25]:

$$P = 1 - \exp[\, -Iqpt \,/\, (V\,(\lambda_v + k + \lambda_d + \lambda_c))\,] \qquad (1)$$

where P is the probability that a susceptible person is infected, I is the number of infectors, q is the quanta emission rate (quanta/h), p is the breathing rate of the susceptible person (m³/h), t is the exposure time (h), V is the room volume (m³), λ_v is the outdoor air change rate (h^{-1}), k is the deposition rate, λ_d is the rate of biological decay, and λ_c is the equivalent air change rate from air cleaning. With at least 2 ACH and 24 hours of exposure, the room reaches near-steady conditions within a small fraction of the exposure period, so the steady-state form is reasonable.

Three pathogens were modelled to span a range of infectiousness (Table 1). For tuberculosis, the base quanta rate of 13 quanta/h used by Escombe et al. was adopted [13]. For influenza, 100 quanta/h was used, following Rudnick and Milton [11]. For SARS-CoV-2, 10.5 quanta/h was used, the value estimated by Buonanno et al. for a resting, breathing infector with a high viral load [26]. A deposition rate of 0.24 h^{-1} was applied to all three pathogens [25], and a decay rate of 0.63 h^{-1} was applied to SARS-CoV-2 only, based on the aerosol half-life reported by van Doremalen et al. [25,27]. One infectious patient and three susceptible patients were assumed, with 24 hours of exposure and a breathing rate of 0.30 m³/h, the upper end of the sedentary range in the US EPA Exposure Factors Handbook [28]. A breathing rate of 0.6 m³/h, used in earlier ward studies [13], was tested as a sensitivity case. Because the quanta rates are uncertain by an order of magnitude or more [12,18], the results are best read as relative changes between ventilation rates rather than as absolute risks.

3.3 Energy, cost and carbon model

Annual fan electricity was calculated from the specific fan power (SFP) of the air handling system:

$$E_{\text{fan}} = \text{SFP} \times Q \times h / 1000 \qquad (2)$$

where E_{fan} is in kWh, SFP is in W/(L/s), Q is the supply airflow in L/s and h is the annual operating hours. Because the SFP of a ventilation system depends on its design, three values were tested: 1.5 W/(L/s) for a recent, efficient system, 2.0 W/(L/s) as a central case and 3.0 W/(L/s) for older plant. These are assumptions chosen to span a realistic range, not measured values.

Equation (2) assumes that the system is designed for the airflow in question, so that SFP stays roughly constant. Increasing the airflow through an existing system is different. If the ductwork is unchanged, fan power rises roughly with the cube of airflow, so a separate case was modelled in which an air handling unit designed for 6 ACH at 2.0 W/(L/s) is run faster to deliver more air:

$$W = W_6 \, (\lambda_v / 6)^3 \qquad (3)$$

where W_6 is the fan power at the 6 ACH design flow.

The heat needed to warm outdoor air was estimated from annual heating degree days:

$$E_{\text{heat}} = \rho c_p \times \dot{V} \times \text{HDD} \times 24 \times (1 - \varepsilon) / 3600 \qquad (4)$$

where E_{heat} is in kWh, ρc_p is 1.206 kJ/(m³·K), $\dot{V}$ is the outdoor airflow in m³/h, HDD is the annual heating degree days in K·day, and ε is the heat recovery efficiency. The long-term average of 2,061 heating degree days for Great Britain (1991–2020, base 15.5 °C) was used [29]. Heat recovery efficiencies of 68% for a run-around coil and 73% for a plate heat exchanger were taken from the minimum values in the ecodesign regulation for ventilation units [30]. Run-around coils are common in healthcare because they keep supply and extract airstreams fully separate. A case with no heat recovery was included to represent older plant. Heat was assumed to come from gas boilers with a seasonal efficiency of 0.85, or, as an alternative, from an air source heat pump with a seasonal coefficient of performance of 3.0. Both values are assumptions.

Costs were based on average UK non-domestic prices for the second quarter of 2026, including the Climate Change Levy: 24.51 p/kWh for electricity and 5.28 p/kWh for gas [31]. Emissions were calculated with the UK Government 2026 conversion factors: 0.14396 $kgCO_2e$/kWh for grid electricity, including transmission and distribution losses, and 0.183 $kgCO_2e$/kWh for natural gas on a gross calorific value basis [32]. The 2025 electricity factor of 0.19553 $kgCO_2e$/kWh was used to test the effect of grid decarbonisation [33]. Cooling energy was not included.

3.4 Portable HEPA filtration

Portable air cleaning was modelled as an addition to the 6 ACH outdoor air baseline, in line with NHS England guidance [8]. Raising the bay from 6 to 10 eACH, the example used in that guidance, requires a clean air delivery rate of 691 m³/h. Power use was taken from the data

sheet of a commercially available unit with an H14 HEPA filter, which gives an airflow range of 400–1,200 m³/h and a power draw of 32–170 W across its four speed settings [34]. The highest ratio of power to airflow (170 W at 1,200 m³/h, or 0.14 W per m³/h) was used as the central case and the lowest (32 W at 400 m³/h, or 0.08 W per m³/h) as the low case. The unit was assumed to run continuously. Capital cost, filter replacement and noise were not included in the cost comparison, but are discussed in Section 5.

Table 1. Model inputs.

Parameter	Value	Source
Bay floor area	64.0 m²	HBN 04-01 [24]
Ceiling height	2.7 m	Assumed
Bay volume	172.8 m³ (48 L/s per ACH)	Calculated
Infectors / susceptibles	1 / 3	Assumed
Exposure time	24 h	Assumed
Breathing rate	0.30 m³/h (sensitivity 0.6 m³/h)	[13,28]
Quanta rate: tuberculosis	13 quanta/h	[13]
Quanta rate: influenza	100 quanta/h	[11]
Quanta rate: SARS-CoV-2	10.5 quanta/h	[26]
Deposition rate	0.24 h^{-1}	[25]
SARS-CoV-2 decay rate	0.63 h^{-1}	[25,27]
Specific fan power	1.5, 2.0, 3.0 W/(L/s)	Assumed range
Heat recovery efficiency	0%, 68%, 73%	[30]
Heating degree days	2,061 K·day (base 15.5 °C)	[29]
Boiler efficiency / heat pump SCOP	0.85 / 3.0	Assumed
Electricity / gas price	24.51 / 5.28 p/kWh	[31]
Electricity carbon factor	0.14396 kgCO_2e/kWh (2025 set: 0.19553)	[32,33]
Gas carbon factor	0.183 kgCO_2e/kWh (gross CV)	[32]
HEPA unit power per unit airflow	0.08–0.14 W per m³/h	[34]

4. Results

4.1 Infection risk and air change rate

Figure 1(a) and Table 2 show the modelled probability of infection for one susceptible patient sharing the bay with one infectious patient for 24 hours. At the HTM 03-01 rate of 6 ACH, the probability was 8.3% for tuberculosis, 48.7% for influenza and 6.2% for SARS-CoV-2. Raising the rate to 10 ACH reduced these to 5.2%, 33.4% and 3.9%, relative reductions of 38%, 31% and 36%. Dropping to the ASHRAE 170 patient room rate of 4 ACH increased them to 12.0%, 62.6% and 8.6%.

The benefit of each additional air change fell steadily as the rate increased (Figure 1(b)). For tuberculosis, going from 2 to 3 ACH reduced the 24-hour risk by about 6 percentage points, going from 6 to 7 ACH by about 1.1 points, and going from 11 to 12 ACH by less than 0.4 points. The same pattern held for the other two pathogens. Doubling the rate from 6 to 12 ACH

roughly halved the dose but reduced the risk by only 4.0 percentage points for tuberculosis and 2.8 points for SARS-CoV-2.

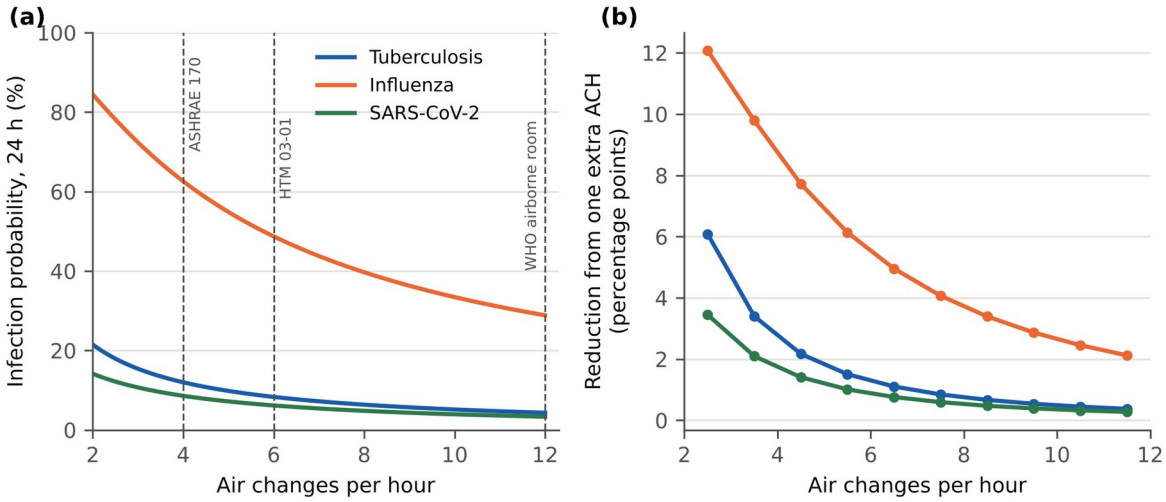


Figure 1. (a) Modelled 24-hour probability of infection for one susceptible patient in a 172.8 m³ four-bed bay with one infectious patient, against air change rate. Dashed lines mark the ASHRAE 170 patient room rate [5], the HTM 03-01 general ward rate [3] and the WHO airborne precaution rate [6]. (b) Reduction in 24-hour infection probability from each additional air change.

Table 2. Modelled 24-hour probability of infection (%) for one susceptible patient, and expected new infections among the three susceptible patients (in brackets), with one infectious patient in the bay.

Pathogen	2 ACH	4 ACH	6 ACH	8 ACH	10 ACH	12 ACH
Tuberculosis	21.5 (0.64)	12.0 (0.36)	8.3 (0.25)	6.4 (0.19)	5.2 (0.15)	4.3 (0.13)
Influenza	84.4 (2.53)	62.6 (1.88)	48.7 (1.46)	39.7 (1.19)	33.4 (1.00)	28.9 (0.87)
SARS-CoV-2	14.1 (0.42)	8.6 (0.26)	6.2 (0.19)	4.8 (0.14)	3.9 (0.12)	3.3 (0.10)

Expected infections = 3 × probability. Values are relative indicators; absolute risk depends strongly on the quanta rate.

4.2 Energy, cost and carbon of ventilation

Table 3 and Figure 2 show the annual energy, cost and carbon of ventilating the bay. In the central case (scenario A: SFP 2.0 W/(L/s), run-around coil heat recovery and gas heating), ventilating the bay at 6 ACH used about 5,050 kWh of fan electricity and 6,470 kWh of gas a year, costing £1,580 and emitting 1.9 tCO_2e. Each additional air change added 841 kWh of electricity and 1,078 kWh of gas, at a cost of £263 and 318 $kgCO_2e$ a year.

Cost and carbon came from different places. Fan electricity accounted for 78% of the added cost of each air change (£206 of £263), because electricity costs more than four times as much as gas per kWh. For carbon the balance was reversed: gas heating accounted for 62% of the added emissions (197 of 318 $kgCO_2e$), because the 2026 electricity factor is now lower than the factor for gas. Measures that cut fan energy therefore save the most money, while measures that cut heating save the most carbon.

Plant arrangement made a large difference. With older plant (scenario B: SFP 3.0 W/(L/s) and no heat recovery), each air change cost £487 and 798 $kgCO_2e$ a year, about two and a half times the carbon of the central case. With an efficient system (scenario C: SFP 1.5 W/(L/s) and a plate heat exchanger), each air change cost £203 and 257 $kgCO_2e$. Replacing gas boilers

with a heat pump (scenario D) left the cost almost unchanged at £281 per air change but cut the carbon to 165 kgCO_2e, about half the central case.

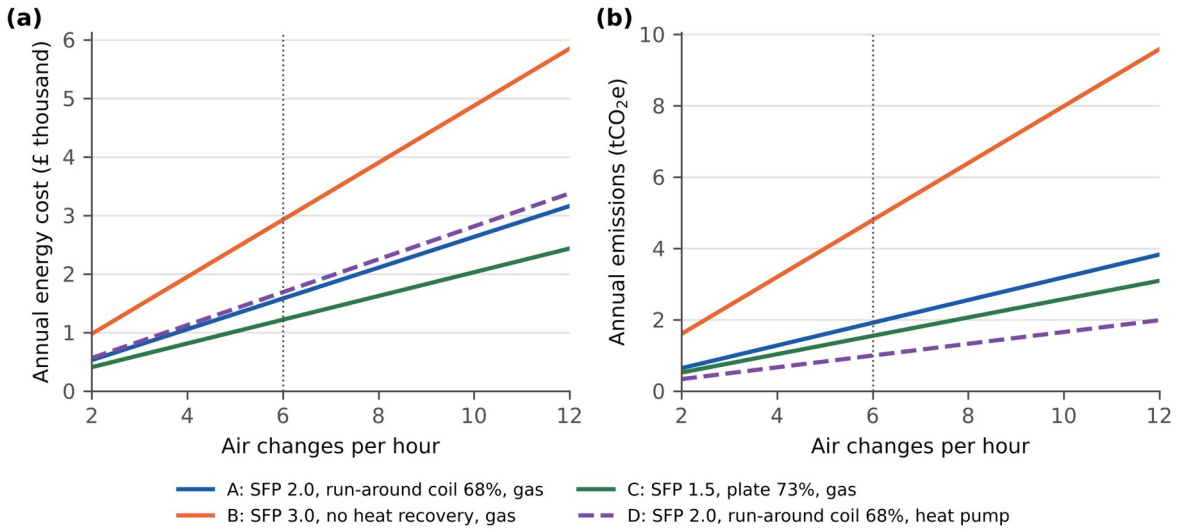


Figure 2. Annual (a) energy cost and (b) emissions of ventilating a 172.8 m³ four-bed bay against air change rate, for four plant scenarios. The dotted line marks 6 ACH.

Table 3. Annual energy, cost and emissions for the bay at 6 ACH, and the marginal values for each additional air change.

Scenario	At 6 ACH: cost (£/yr)	At 6 ACH: emissions (tCO_2e/yr)	Per extra ACH: electricity (kWh/yr)	Per extra ACH: gas (kWh/yr)	Per extra ACH: cost (£/yr)	Per extra ACH: emissions ($kgCO_2e$/yr)
A: SFP 2.0, run-around coil 68%, gas	1,578	1.91	841	1,078	263	318
B: SFP 3.0, no heat recovery, gas	2,922	4.79	1,261	3,369	487	798
C: SFP 1.5, plate 73%, gas	1,216	1.54	631	910	203	257
D: SFP 2.0, run-around coil 68%, heat pump	1,686	0.99	1,146	0	281	165

Electricity at 24.51 p/kWh and 0.14396 kgCO_2e/kWh; gas at 5.28 p/kWh and 0.183 kgCO_2e/kWh. SFP in W/(L/s). Cooling not included.

4.3 Routes from 6 to 10 equivalent air changes

Table 4 and Figure 3 compare four ways of raising the bay from 6 to 10 eACH. In the model, every route gives the same reduction in infection risk, because Equation (1) treats an equivalent air change from a HEPA filter in the same way as an air change of outdoor air. The routes differ only in what they cost to run.

Supplying the extra air through a system designed for 10 ACH added £1,052 and 1.27 tCO_2e a year. Using a heat pump instead of gas for heating cut the added carbon to 0.66 tCO_2e but raised the added cost slightly, to £1,124. Speeding up an existing air handling unit designed for 6 ACH was by far the most expensive route. Because fan power rises with the cube of airflow, the fan load rose by a factor of 4.6, adding £4,716 and 3.43 tCO_2e a year. In practice, many existing units could not deliver this increase at all without new fans and ductwork.

A portable HEPA unit delivering 691 m³/h of clean air, about 58% of the maximum output of the unit modelled, added between £119 and £210 a year in electricity and between 70 and 123

kgCO_2e. Compared with extra outdoor air through a correctly designed system, this is 80–89% less in running cost and 90–95% less in emissions. HEPA filtration needs no heating, and filtering a cubic metre of air takes much less fan power than moving outdoor air through a full air handling system.

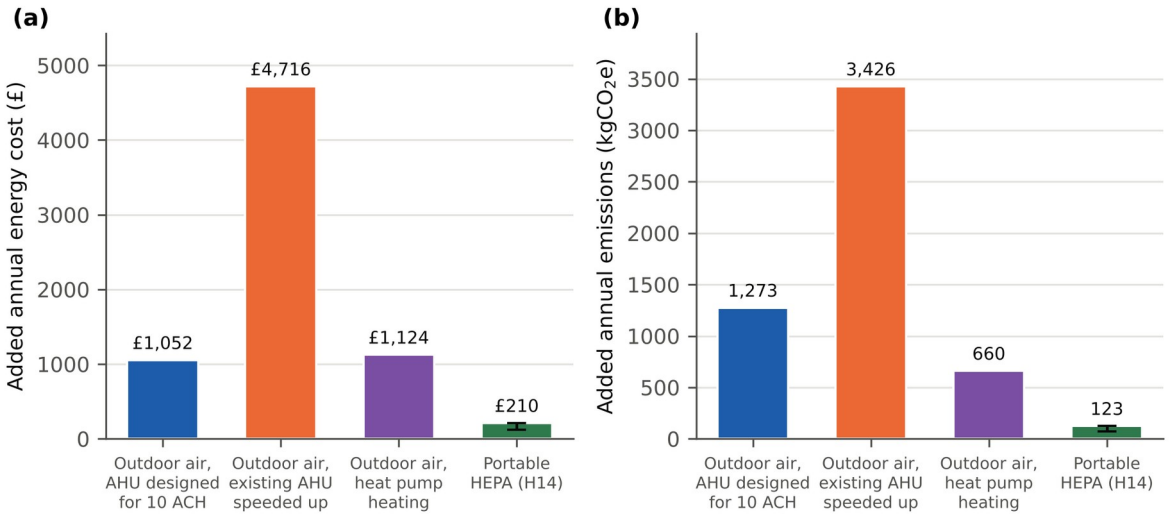


Figure 3. Added annual (a) energy cost and (b) emissions of raising a 172.8 m³ bay from 6 to 10 equivalent air changes per hour by four routes. Outdoor air routes use SFP 2.0 W/(L/s) and a 68% run-around coil. The error bar on the HEPA route shows the range between the lowest and highest power-to-airflow ratio of the unit modelled.

Table 4. Added annual energy, cost and emissions of raising the bay from 6 to 10 eACH.

Route	Added electricity (kWh/yr)	Added gas (kWh/yr)	Added cost (£/yr)	Added emissions (kgCO_2e/yr)
Outdoor air, system designed for 10 ACH, gas heating	3,364	4,312	1,052	1,273
Outdoor air, system designed for 10 ACH, heat pump	4,585	0	1,124	660
Outdoor air, existing 6 ACH unit run faster, gas heating	18,314	4,312	4,716	3,426
Portable HEPA, 691 m³/h clean air	484–858	0	119–210	70–123

The modelled reduction in 24-hour infection probability is the same for every route: from 8.3% to 5.2% for tuberculosis, from 48.7% to 33.4% for influenza and from 6.2% to 3.9% for SARS-CoV-2.

4.4 Sensitivity

Doubling the breathing rate to 0.6 m³/h roughly doubled the modelled risks at low values (tuberculosis 15.9% at 6 ACH and 10.0% at 10 ACH) but did not change the pattern of diminishing returns or the ranking of the routes. With the 2025 electricity carbon factor, the added emissions of going from 6 to 10 ACH with outdoor air rose from 1.27 to 1.45 tCO_2e and those of the HEPA route from 0.12 to 0.17 tCO_2e. The ranking is therefore robust to the recent change in grid carbon intensity. Heating energy scales directly with degree days, so a site with 10% more degree days than the national average would see the heating share of each result rise by 10%. Across a 24-bed ward with the volume of six such bays, each extra air change in the central case would cost about £1,580 and 1.9 tCO_2e a year.

5. Discussion

5.1 Diminishing returns

The infection model shows the classic shape of dilution: large gains when moving away from poor ventilation and steadily smaller gains after that. Running costs, by contrast, rise at least in proportion to airflow, and faster if existing fans are pushed beyond their design point. This mismatch is the core of the trade-off. For the parameters used here, the step from 4 to 6 ACH, which brings a ward up to the HTM 03-01 rate, buys three to four times as much risk reduction per pound as the step from 10 to 12 ACH. The case for making sure every general ward actually achieves its design rate is therefore much stronger than the case for routinely designing above it. In the author's experience as an estates engineer in an NHS acute trust, wards with mechanical ventilation often fall short of their design rate in practice. The usual causes are worn fans, loaded filters, leaking ductwork and air leaks through the casings of older air handling units. None of these is visible to ward staff, and all of them reduce airflow gradually. In older estates the first priority should therefore be to restore and verify the design rate before any increase above it is considered.

5.2 Cost and carbon point in different directions

A practical finding of this study is that the cost and carbon of extra ventilation now come mainly from different sources. Fan electricity drives the cost, while heating drives the carbon wherever gas boilers are still in use. This has changed as UK grid electricity has decarbonised: between the 2025 and 2026 conversion factors, the carbon intensity of grid electricity fell by about 26% [32,33]. For estates teams, this means that energy-saving measures should be judged on both measures. Fan replacements and control improvements give the fastest financial payback. Better heat recovery and the move away from gas heating give the largest carbon savings. A heat pump on its own did not reduce the running cost of ventilation at current prices, but it roughly halved its carbon.

5.3 Air cleaning above the HTM baseline

The comparison in Section 4.3 favours portable HEPA filtration as a way of adding clean air above 6 ACH, by a wide margin on both cost and carbon. This agrees with NHS England guidance, which treats portable air cleaners as a supplement to, not a substitute for, the minimum outdoor air supply [8], and with the Lancet Commission's framing of clean air in equivalent air changes [7]. It also agrees with the earlier finding of Noakes et al. that air disinfection can be an energy-efficient alternative to higher ventilation rates in wards [20]. The field evidence from Addenbrooke's shows that a correctly sized unit can remove detectable airborne SARS-CoV-2 from a ward bay [21]. Portable units are also the only practical option for many older wards. In the author's trust, as in many NHS estates, some wards are naturally ventilated and have no air handling unit at all. Their ventilation rate depends on window opening and the weather, and cannot be raised on demand. For these wards, air cleaning is the one way to add a controllable amount of clean air without major building work.

The running-cost comparison leaves out several things that matter in practice. Portable units have a capital cost, need regular filter changes and safe disposal of used filters, take up floor space and can be noisy. NHS England guidance says units should normally not exceed 50 dB

at 3 m [8], and the unit modelled here would need to deliver about 58% of its maximum airflow to provide 4 eACH in this bay; its data sheet gives sound pressure levels of 32–44 dB at 1 m across its speed settings [34]. Units can be switched off or unplugged by staff, and they only work if positioned so that air reaches the whole bay. Their performance should be checked when installed and at intervals afterwards, and linking them to the building management system, as the NHS England guidance recommends, would help. Even allowing for these factors, the running-cost difference of around £840–930 a year per bay leaves considerable room for maintenance and replacement costs.

5.4 Implications for estates practice

Five practical points follow from the results. First, the design rate of 6 ACH in general wards should be treated as a floor that is verified, not just designed for, because the largest gains in modelled risk come from bringing poorly ventilated spaces up to it. Second, where more clean air is wanted, for example during the winter respiratory season or in bays housing vulnerable patients, portable HEPA filtration is likely to be the cheapest and lowest-carbon option. Third, increasing the speed of existing air handling units beyond their design flow should be avoided as a way of raising ventilation, because the cube law makes it very expensive and it may also cause noise, draughts and pressure problems. Older units are also poorly placed to take extra load. The problems the author sees most often in ageing ward plant are obsolete components, frequent belt failures, excessive noise and vibration, reduced airflow, deteriorating casings, moisture build-up and slow pneumatic controls, usually against a backlog of deferred maintenance. Pushing such units harder adds to the risk of unplanned downtime. Fourth, ventilation needs to be made more visible to clinical staff. In the author’s experience, requests from wards to the estates team are almost always about temperature, and requests to increase ventilation are rare. That is understandable, because ward staff cannot see or feel an air change rate. Simple measures such as carbon dioxide displays in ward bays, which can also be used to estimate risk [11], and regular reporting of measured airflow to infection prevention and control teams would help ventilation to be managed as an infection control measure and not only as a comfort issue. Fifth, when ward ventilation plant is replaced, specifying low SFP, high-efficiency heat recovery and low-carbon heat will cut the running cost and carbon of every air change for the life of the plant.

6. Limitations

This is a modelling study and has several limitations. The model assumes a mechanically ventilated bay with a constant airflow, so it does not represent naturally ventilated wards, whose ventilation rate varies with the weather and with window opening. The Wells-Riley model also assumes well-mixed air and represents only long-range airborne transmission, not close-range or contact routes. The quanta emission rates are uncertain by more than an order of magnitude, so absolute risks should not be quoted from this work. Only the relative changes between ventilation rates are meaningful. The ceiling height, SFP values, boiler efficiency and heat pump performance are assumptions. The heating calculation uses national degree days with a 15.5 °C base, which probably understates the heating needed to supply air at typical ward temperatures, and cooling energy was not included. Energy prices are national averages, and individual trusts may pay more or less. The HEPA comparison covers running

energy only, and the power data come from a single manufacturer's data sheet. Finally, the model does not include the clinical or economic cost of the infections themselves, so it cannot say whether a given increase in ventilation is cost-effective in health terms. Measured data from NHS ward air handling units, including actual airflow, fan power and heat recovery performance, would make the energy side of the analysis more robust.

7. Conclusions

For a typical four-bed NHS ward bay, each additional air change of outdoor air above the HTM 03-01 rate of 6 ACH costs about £260 and 320 kgCO_2e a year with current plant and prices, and buys a steadily smaller reduction in modelled airborne infection risk. Fan electricity now drives the cost of ventilation and gas heating drives the carbon. Where more clean air is needed, portable HEPA filtration can deliver the same equivalent air changes for 80–89% less running cost and 90–95% less carbon than extra outdoor air, while speeding up existing air handling units is the most expensive option. The practical message for estates teams is to verify that wards achieve their design rate, use air cleaning to go above it or where wards have no mechanical ventilation, make ventilation visible to ward staff, and invest in efficient fans, heat recovery and low-carbon heat when plant is replaced.

Acknowledgements

None.

Declaration of generative AI use

During the preparation of this work the author used Google (Gemini 3), a generative AI tool, to assist with literature searching, writing the model code and editing the text. The tool was not used to generate data. All input values are taken from the cited sources or are stated as assumptions. The author reviewed and edited all content and takes full responsibility for the article.

Author contributions

Naushad Ali: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

Statements and declarations

Ethical considerations

This study used published literature, official guidance, published statistics and manufacturer data only. It involved no human participants and no patient or staff data, so ethical approval was not required.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Declaration of conflicting interest

The author is employed in estates engineering by an NHS trust in England. The study was carried out independently of that employment and uses no data from the trust. The author has no financial or other relationship with any manufacturer of ventilation or air cleaning equipment.

Funding statement

The author received no financial support for the research, authorship and/or publication of this article.

Data availability

All input values are given in Table 1 with their sources. The Python code used for the model and figures is provided as Supplementary Material S1.

References

1. UK Health Security Agency. Point prevalence survey of healthcare-associated infections, antimicrobial use and antimicrobial stewardship in England, 2023. Report, UKHSA, London, UK, 2025.
2. NHS England. Delivering a net zero NHS. Board paper BM/21/25(Pu), https://www.england.nhs.uk/wp-content/uploads/2021/09/item4-delivering-net-zero-nhs-updated.pdf (30 September 2021, accessed 2 November 2026).
3. NHS England. Health Technical Memorandum 03-01: specialised ventilation for healthcare premises. Part A: the concept, design, specification, installation and acceptance testing of healthcare ventilation systems. Report, NHS England, London, UK, 2021.
4. NHS National Services Scotland. Scottish Health Technical Memorandum 03-01: ventilation for healthcare premises. Part A: design and validation, version 3.0. Report, NHS NSS, Edinburgh, UK, 2022.
5. ANSI/ASHRAE/ASHE. Standard 170-2017: ventilation of health care facilities. Atlanta, GA: ASHRAE, 2017.
6. Atkinson J, Chartier Y, Pessoa-Silva CL, et al. (eds). Natural ventilation for infection control in health-care settings. Geneva: World Health Organization, 2009.
7. The Lancet COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel. Proposed non-infectious air delivery rates (NADR) for reducing exposure to airborne respiratory infectious diseases. Report, The Lancet COVID-19 Commission, November 2022.
8. NHS England. Application of HEPA filter devices for air cleaning in healthcare spaces: guidance and standards. Estates Technical Bulletin NETB 2023/01A, NHS England, London, UK, 2023.
9. Riley EC, Murphy G and Riley RL. Airborne spread of measles in a suburban elementary school. Am J Epidemiol 1978; 107(5): 421–432. DOI: 10.1093/oxfordjournals.aje.a112560.
10. Gammaitoni L and Nucci MC. Using a mathematical model to evaluate the efficacy of TB control measures. Emerg Infect Dis 1997; 3(3): 335–342. DOI: 10.3201/eid0303.970310.
11. Rudnick SN and Milton DK. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor Air 2003; 13(3): 237–245. DOI: 10.1034/j.1600-0668.2003.00189.x.
12. Sze To GN and Chao CYH. Review and comparison between the Wells-Riley and dose-response approaches to risk assessment of infectious respiratory diseases. Indoor Air 2010; 20(1): 2–16. DOI: 10.1111/j.1600-0668.2009.00621.x.

13. Escombe AR, Oeser CC, Gilman RH, et al. Natural ventilation for the prevention of airborne contagion. PLoS Med 2007; 4(2): e68. DOI: 10.1371/journal.pmed.0040068.

14. Beggs CB, Kerr KG, Noakes CJ, et al. The ventilation of multiple-bed hospital wards: review and analysis. Am J Infect Control 2008; 36(4): 250–259.

15. Noakes CJ and Sleigh PA. Applying the Wells-Riley equation to the risk of airborne infection in hospital environments: the importance of stochastic and proximity effects. In: Indoor Air 2008: 11th international conference on indoor air quality and climate, Copenhagen, Denmark, 17–22 August 2008, paper 42.

16. Kurnitski J, Kiil M, Wargocki P, et al. Respiratory infection risk-based ventilation design method. Build Environ 2021; 206: 108387. DOI: 10.1016/j.buildenv.2021.108387.

17. Aganovic A, Bi Y, Cao G, et al. Estimating the impact of indoor relative humidity on SARS-CoV-2 airborne transmission risk using a new modification of the Wells-Riley model. Build Environ 2021; 205: 108278. DOI: 10.1016/j.buildenv.2021.108278.

18. Dai H and Zhao B. Association of the infection probability of COVID-19 with ventilation rates in confined spaces. Build Simul 2020; 13(6): 1321–1327. DOI: 10.1007/s12273-020-0703-5.

19. Noakes CJ, Sleigh PA and Khan MAI. Appraising healthcare ventilation design from combined infection control and energy perspective. HVAC&R Res 2012; 18(4): 658–670. DOI: 10.1080/10789669.2011.592054.

20. Noakes CJ, Khan MAI and Gilkeson CA. Modeling infection risk and energy use of upper-room ultraviolet germicidal irradiation systems in multi-room environments. Sci Technol Built Environ 2015; 21(1): 99–111. DOI: 10.1080/10789669.2014.983035.

21. Conway Morris A, Sharrocks K, Bousfield R, et al. The removal of airborne severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and other microbial bioaerosols by air filtration on coronavirus disease 2019 (COVID-19) surge units. Clin Infect Dis 2022. DOI: 10.1093/cid/ciab933.

22. Thuresson S, Fraenkel CJ, Sasinovich S, et al. Airborne severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in hospitals: effects of aerosol-generating procedures, HEPA-filtration units, patient viral load, and physical distance. Clin Infect Dis 2022. DOI: 10.1093/cid/ciac161.

23. Lindsley WG, Derk RC, Coyle JP, et al. Efficacy of portable air cleaners and masking for reducing indoor exposure to simulated exhaled SARS-CoV-2 aerosols – United States, 2021. MMWR Morb Mortal Wkly Rep 2021; 70(27): 972–976. DOI: 10.15585/mmwr.mm7027e1.

24. Department of Health. Health Building Note 04-01: adult in-patient facilities. Report, The Stationery Office, London, UK, 2009.

25. Buonanno G, Morawska L and Stabile L. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications. Environ Int 2020; 145: 106112. DOI: 10.1016/j.envint.2020.106112.

26. Buonanno G, Stabile L and Morawska L. Estimation of airborne viral emission: quanta emission rate of SARS-CoV-2 for infection risk assessment. Environ Int 2020; 141: 105794. DOI: 10.1016/j.envint.2020.105794.

27. van Doremalen N, Bushmaker T, Morris DH, et al. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N Engl J Med 2020; 382(16): 1564–1567. DOI: 10.1056/NEJMc2004973.

28. US Environmental Protection Agency. Exposure factors handbook: 2011 edition. Report EPA/600/R-09/052F, US EPA, Washington, DC, 2011.

29. Department for Business, Energy and Industrial Strategy. Long term mean temperatures 1991 to 2020. Energy Trends special article, BEIS, London, UK, March 2022.

30. Commission Regulation (EU) No 1253/2014 of 7 July 2014 implementing Directive 2009/125/EC with regard to ecodesign requirements for ventilation units. Off J Eur Union 2014; L337: 8–26.

31. Department for Energy Security and Net Zero. Quarterly energy prices: September 2026. Statistical release, DESNZ, London, UK, 2026.

32. Department for Energy Security and Net Zero. Greenhouse gas reporting: conversion factors 2026 (methodology report and full set). DESNZ, London, UK, 2026.

33. Department for Energy Security and Net Zero. Greenhouse gas reporting: conversion factors 2025. DESNZ, London, UK, 2025.

34. Maico Elektroapparate-Fabrik GmbH. CleanBox 1200 mobile air purifier (0095.0650): product data sheet. Villingen-Schwenningen, Germany, n.d.

Figure legends

Figure 1. (a) Modelled 24-hour probability of infection for one susceptible patient in a 172.8 m³ four-bed bay with one infectious patient, against air change rate. Dashed lines mark the ASHRAE 170 patient room rate, the HTM 03-01 general ward rate and the WHO airborne precaution rate. (b) Reduction in 24-hour infection probability from each additional air change.

Figure 2. Annual (a) energy cost and (b) emissions of ventilating a 172.8 m³ four-bed bay against air change rate, for four plant scenarios. The dotted line marks 6 ACH.

Figure 3. Added annual (a) energy cost and (b) emissions of raising a 172.8 m³ bay from 6 to 10 equivalent air changes per hour by four routes. Outdoor air routes use SFP 2.0 W/(L/s) and a 68% run-around coil. The error bar on the HEPA route shows the range between the lowest and highest power-to-airflow ratio of the unit modelled.

Supplementary Material S1: model and figure code

Air change rates in NHS general wards: weighing airborne infection risk against the energy, cost and carbon of ventilation. Python 3 with NumPy and Matplotlib. Run model.py to reproduce the results and figs.py to reproduce Figures 1–3.

model.py

```
"""Infection risk vs ventilation energy, cost and carbon for an NHS four-bed ward bay.

Steady-state Wells-Riley with additional first-order removal terms
(Riley et al. 1978; Gammaitoni & Nucci 1997; Buonanno et al. 2020):

    P = 1 - exp( -I q p t / (V (ACH + k + lam + eACH_hepa)) )

Energy: fan electricity at a specific fan power (SFP), and heating of outdoor
air from annual heating degree days with heat recovery.
"""
import json
import numpy as np

# ---------------- Room ----------------
AREA = 64.0          # m2, four-bed room, HBN 04-01
HEIGHT = 2.7         # m, assumed
V = AREA * HEIGHT    # m3
LPS_PER_ACH = V / 3.6  # l/s per air change per hour

# ---------------- Infection ----------------
I = 1                # infectors
N_SUS = 3            # susceptible patients in the bay
p = 0.30             # m3/h, sedentary breathing (US EPA EFH 2011)
t = 24.0             # h
k_dep = 0.24         # 1/h deposition (Buonanno et al. 2020)
PATHOGENS = {
    'Tuberculosis':      dict(q=13.0,  lam=0.0),   # Escombe et al. 2007
    'Influenza':         dict(q=100.0, lam=0.0),   # Rudnick & Milton 2003
    'SARS-CoV-2':        dict(q=10.5,  lam=0.63),  # Buonanno, Stabile & Morawska 2020; decay Buonanno 2020
}

def risk(ach, q, lam, ehepa=0.0, p=p, t=t, k=k_dep):
    removal = ach + k + lam + ehepa
    return 1 - np.exp(-I * q * p * t / (V * removal))

# ---------------- Energy, cost, carbon ----------------
HOURS = 8760
RHO_CP = 1.2 * 1.005          # kJ/(m3 K)
HDD = 2061                    # K day, base 15.5 C, GB 1991-2020 (DESNZ Energy Trends)
P_ELEC = 0.2451               # GBP/kWh, DESNZ QEP Q2 2026 non-domestic incl. CCL
P_GAS = 0.0528                # GBP/kWh
CF_ELEC_2026 = 0.14396        # kgCO2e/kWh consumed (DESNZ 2026)
CF_ELEC_2025 = 0.19553        # kgCO2e/kWh consumed (DESNZ 2025)
CF_GAS = 0.183                # kgCO2e/kWh gross CV (DESNZ) -- check against 2026 full set
ETA_BOILER = 0.85             # assumed
SCOP_HP = 3.0                 # assumed

def heat_kwh_per_ach(eff_hr, hdd=HDD):
    """Annual heat to warm outdoor air for one ACH in the bay, after heat recovery (kWh)."""
    m3h = V                    # m3/h for 1 ACH
    kwh = RHO_CP * m3h * hdd * 24 / 3600   # kJ/(m3K)*m3/h*K*h -> kJ ... /3600 -> kWh
    return kwh * (1 - eff_hr)

def fan_kwh(ach, sfp):
    return sfp * LPS_PER_ACH * ach * HOURS / 1000

def fan_kwh_cubic(ach, sfp_design, ach_design=6.0):
    """Existing AHU sped up/down from its design point: power ~ flow^3."""
    p_design_w = sfp_design * LPS_PER_ACH * ach_design
    return p_design_w * (ach / ach_design) ** 3 * HOURS / 1000

def annual(ach, sfp=2.0, eff_hr=0.68, heat='gas', cf_elec=CF_ELEC_2026, cubic=False, hdd=HDD):
    fan = fan_kwh_cubic(ach, sfp) if cubic else fan_kwh(ach, sfp)
    q_heat = heat_kwh_per_ach(eff_hr, hdd) * ach
    if heat == 'gas':
        gas = q_heat / ETA_BOILER; elec_h = 0.0
    else:
        gas = 0.0; elec_h = q_heat / SCOP_HP
    elec = fan + elec_h
    cost = elec * P_ELEC + gas * P_GAS
    co2 = elec * cf_elec + gas * CF_GAS
    return dict(fan_kwh=fan, heat_kwh=q_heat, gas_kwh=gas, elec_kwh=elec, cost=cost, co2=co2)

# HEPA: Maico CleanBox 1200 datasheet: 400-1200 m3/h, 32-170 W, H14
HEPA_W_PER_M3H = 170 / 1200      # W per m3/h at top speed (conservative)
```

```
HEPA_W_PER_M3H_LOW = 32 / 400
def hepa_annual(each, w_per_m3h=HEPA_W_PER_M3H, cf_elec=CF_ELEC_2026, hours=HOURS):
    m3h = each * V
    kwh = m3h * w_per_m3h * hours / 1000
    return dict(m3h=m3h, units_1200=m3h / 1200, elec_kwh=kwh, cost=kwh * P_ELEC, co2=kwh * cf_elec)

if __name__ == '__main__':
    out = {}
    out['geometry'] = dict(V=V, lps_per_ach=LPS_PER_ACH)
    achs = np.arange(2, 12.01, 0.5)
    out['risk_curve'] = {n: [float(risk(a, **d)) for a in achs] for n, d in PATHOGENS.items()}
    out['achs'] = achs.tolist()
    # risk table at selected ACH
    sel = [2, 4, 6, 8, 10, 12]
    out['risk_table'] = {n: {a: float(risk(a, **d)) for a in sel} for n, d in PATHOGENS.items()}
    out['exp_inf_table'] = {n: {a: float(N_SUS * risk(a, **d)) for a in sel} for n, d in PATHOGENS.items()}
    # Marginal annual per extra ACH (linear design case)
    base = annual(6); plus = annual(7)
    out['marginal_per_ach'] = {k: plus[k] - base[k] for k in base}
    # Scenario table: annual at 6 ACH and marginal per ACH for several configurations
    scen = {
        'A: SFP 2.0, RAC 68%, gas':   dict(sfp=2.0, eff_hr=0.68, heat='gas'),
        'B: SFP 3.0, no HR, gas':     dict(sfp=3.0, eff_hr=0.0, heat='gas'),
        'C: SFP 1.5, plate 73%, gas': dict(sfp=1.5, eff_hr=0.73, heat='gas'),
        'D: SFP 2.0, RAC 68%, ASHP':  dict(sfp=2.0, eff_hr=0.68, heat='hp'),
    }
    out['scenarios'] = {}
    for name, kw in scen.items():
        a6 = annual(6, **kw); a7 = annual(7, **kw)
        out['scenarios'][name] = dict(at6=a6, per_ach={k: a7[k] - a6[k] for k in a6})
    # Raising 6 -> 10 eACH: outdoor air vs HEPA top-up
    target = 10
    oa_lin = {k: annual(target)[k] - annual(6)[k] for k in annual(6)}
    oa_cub = {k: annual(target, cubic=True)[k] - annual(6, cubic=True)[k] for k in annual(6)}
    hp = hepa_annual(target - 6)
    hp_low = hepa_annual(target - 6, w_per_m3h=HEPA_W_PER_M3H_LOW)
    out['route_6_to_10'] = dict(outdoor_linear=oa_lin, outdoor_cubic=oa_cub, hepa=hp, hepa_low=hp_low)
    # risk at 10 equivalent: both routes give same removal in the model
    out['risk_6_10'] = {n: dict(r6=float(risk(6, **d)), r10_oa=float(risk(10, **d)), r10_hepa=float(risk(6, ehepa=4, **d))) for n,
    # grid factor sensitivity for route comparison
    out['route_2025_factor'] = dict(outdoor=annual(target, cf_elec=CF_ELEC_2025)['co2'] - annual(6, cf_elec=CF_ELEC_2025)['co2'],
                                    hepa=hepa_annual(4, cf_elec=CF_ELEC_2025)['co2'])
    # 24-bed ward scale-up (6 four-bed bays equivalent volume)
    out['ward_scale'] = dict(bays=6, per_ach={k: v * 6 for k, v in out['marginal_per_ach'].items()})
    # breathing-rate sensitivity
    out['risk_p06'] = {n: dict(r6=float(risk(6, p=0.6, **d)), r10=float(risk(10, p=0.6, **d))) for n, d in PATHOGENS.items()}
    # heat per ACH per 1000 degree days
    out['heat_per_ach_per_1000hdd_noHR'] = heat_kwh_per_ach(0.0, 1000)
    json.dump(out, open('results.json', 'w'), indent=2, default=float)
    print(json.dumps({k: out[k] for k in ['geometry', 'risk_table', 'marginal_per_ach', 'route_6_to_10', 'risk_6_10', 'route_2025_f
    for n, s in out['scenarios'].items():
        print(n, {k: round(v) for k, v in s['at6'].items()}, {k: round(v) for k, v in s['per_ach'].items()})
```

figs.py

```
import json, numpy as np
import matplotlib
matplotlib.use('Agg')
import matplotlib.pyplot as plt
from model import risk, PATHOGENS, annual, hepa_annual, HEPA_W_PER_M3H_LOW, CF_ELEC_2025

BLUE, ORANGE, GREEN, PURPLE = '#1c5cab', '#eb6834', '#2f7a4d', '#7a4ea3'
INK, INK2, GRID = '#0b0b0b', '#52514e', '#e4e3df'
plt.rcParams.update({'font.family': 'DejaVu Sans', 'font.size': 9, 'axes.edgecolor': INK2,
                     'axes.labelcolor': INK, 'xtick.color': INK2, 'ytick.color': INK2,
                     'axes.spines.top': False, 'axes.spines.right': False})
COLS = {'Tuberculosis': BLUE, 'Influenza': ORANGE, 'SARS-CoV-2': GREEN}
a = np.linspace(2, 12, 101)

# ---- Figure 1: risk vs ACH (a) and marginal reduction per extra ACH (b) ----
fig, ax = plt.subplots(1, 2, figsize=(7.2, 3.2))
for n, d in PATHOGENS.items():
    r = risk(a, **d) * 100
    ax[0].plot(a, r, color=COLS[n], lw=1.8, label=n)
    ai = np.arange(2, 12)
    dr = (risk(ai, **d) - risk(ai + 1, **d)) * 100
    ax[1].plot(ai + 0.5, dr, color=COLS[n], lw=1.8, marker='o', ms=3.5)
for x, lab, y0, dx, ha in [(4, 'ASHRAE 170', 70, 0.12, 'left'), (6, 'HTM 03-01', 58, 0.12, 'left'), (12, 'WHO airborne room', 40, -
    ax[0].axvline(x, color=INK2, lw=0.8, ls='--')
    ax[0].text(x + dx, y0, lab, ha=ha, va='bottom', fontsize=6.5, color=INK2, rotation=90)
ax[0].set_xlabel('Air changes per hour'); ax[0].set_ylabel('Infection probability, 24 h (%)')
ax[0].set_ylim(0, 100); ax[0].set_xlim(2, 12.3); ax[0].grid(axis='y', color=GRID, lw=0.8); ax[0].set_axisbelow(True)
ax[0].legend(frameon=False, fontsize=8, loc='upper center', bbox_to_anchor=(0.66, 1.0))
ax[1].set_xlabel('Air changes per hour'); ax[1].set_ylabel('Reduction from one extra ACH\n(percentage points)')
ax[1].grid(axis='y', color=GRID, lw=0.8); ax[1].set_axisbelow(True); ax[1].set_xlim(2, 12)
for i, t in enumerate('ab'):
```

```
    ax[i].text(-0.18, 1.02, f'({t})', transform=ax[i].transAxes, fontsize=10, weight='bold')
fig.tight_layout(); fig.savefig('fig1.png', dpi=300); plt.close(fig)

# ---- Figure 2: annual cost and carbon vs ACH, scenarios ----
scen = [('A: SFP 2.0, run-around coil 68%, gas', dict(sfp=2.0, eff_hr=0.68, heat='gas'), BLUE, '-'),
        ('B: SFP 3.0, no heat recovery, gas', dict(sfp=3.0, eff_hr=0.0, heat='gas'), ORANGE, '-'),
        ('C: SFP 1.5, plate 73%, gas', dict(sfp=1.5, eff_hr=0.73, heat='gas'), GREEN, '-'),
        ('D: SFP 2.0, run-around coil 68%, heat pump', dict(sfp=2.0, eff_hr=0.68, heat='hp'), PURPLE, '--')]
fig, ax = plt.subplots(1, 2, figsize=(7.2, 3.3))
for name, kw, c, ls in scen:
    cost = [annual(x, **kw)['cost'] / 1000 for x in a]
    co2 = [annual(x, **kw)['co2'] / 1000 for x in a]
    ax[0].plot(a, cost, color=c, ls=ls, lw=1.8, label=name)
    ax[1].plot(a, co2, color=c, ls=ls, lw=1.8)
ax[0].set_ylabel('Annual energy cost (£ thousand)'); ax[1].set_ylabel('Annual emissions (tCO$_2$e)')
for i, t in enumerate('ab'):
    ax[i].set_xlabel('Air changes per hour'); ax[i].grid(axis='y', color=GRID, lw=0.8); ax[i].set_axisbelow(True)
    ax[i].axvline(6, color=INK2, lw=0.8, ls=':'); ax[i].set_xlim(2, 12); ax[i].set_ylim(bottom=0)
    ax[i].text(-0.18, 1.02, f'({t})', transform=ax[i].transAxes, fontsize=10, weight='bold')
fig.legend(*ax[0].get_legend_handles_labels(), loc='lower center', ncol=2, frameon=False, fontsize=7.5, bbox_to_anchor=(0.5, -0.01)
fig.tight_layout(rect=(0, 0.1, 1, 1)); fig.savefig('fig2.png', dpi=300); plt.close(fig)

# ---- Figure 3: routes from 6 to 10 eACH ----
oa_lin = {k: annual(10)[k] - annual(6)[k] for k in ('cost', 'co2')}
oa_cub = {k: annual(10, cubic=True)[k] - annual(6, cubic=True)[k] for k in ('cost', 'co2')}
oa_hp = {k: annual(10, heat='hp')[k] - annual(6, heat='hp')[k] for k in ('cost', 'co2')}
h_hi = hepa_annual(4); h_lo = hepa_annual(4, w_per_m3h=HEPA_W_PER_M3H_LOW)
labels = ['Outdoor air,\nAHU designed\nfor 10 ACH', 'Outdoor air,\nexisting AHU\nspeeded up', 'Outdoor air,\nheat pump\nheating', '
cost = [oa_lin['cost'], oa_cub['cost'], oa_hp['cost'], h_hi['cost']]
co2 = [oa_lin['co2'], oa_cub['co2'], oa_hp['co2'], h_hi['co2']]
cols = [BLUE, ORANGE, PURPLE, GREEN]
fig, ax = plt.subplots(1, 2, figsize=(7.2, 3.3))
for i, (vals, ylab, fmt) in enumerate([(cost, 'Added annual energy cost (£)', '£{:,.0f}'), (co2, 'Added annual emissions (kgCO$_2$e
    b = ax[i].bar(range(4), vals, color=cols, width=0.6, edgecolor='white')
    lo = h_lo['cost'] if i == 0 else h_lo['co2']
    ax[i].errorbar(3, vals[3], yerr=[[vals[3] - lo], [0]], fmt='none', ecolor=INK, capsize=4, lw=1.2)
    for j, v in enumerate(vals):
        ax[i].text(j, v + max(vals) * 0.02, fmt.format(v), ha='center', va='bottom', fontsize=7.5, color=INK)
    ax[i].set_xticks(range(4), labels, fontsize=7); ax[i].set_ylabel(ylab)
    ax[i].grid(axis='y', color=GRID, lw=0.8); ax[i].set_axisbelow(True); ax[i].set_ylim(0, max(vals) * 1.15)
    ax[i].text(-0.2, 1.02, f'({"ab"[i]})', transform=ax[i].transAxes, fontsize=10, weight='bold')
fig.tight_layout(); fig.savefig('fig3.png', dpi=300); plt.close(fig)
print('ok', oa_lin, oa_cub, oa_hp, h_hi['cost'], h_lo['cost'], h_hi['co2'], h_lo['co2'])
```