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Research article

Cleaner air, healthier hospitals: Implementing the UK's Clean Air Hospital Framework

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ABSTRACT

National healthcare services significantly contribute to ambient air pollution and greenhouse gases, particularly through transport and energy generation. Hospitals bring together vulnerable patients in high-traffic settings often in urban areas where there are significant baseline concentrations of ambient pollutants. Therefore, there is a requirement for hospitals to look at ways of reducing their emissions of airborne pollutants, ideally within the framework of achieving net zero goals. This study details the initial implementation of the UK's Clean Air Hospital Framework (CAHF) at two major UK hospitals. CAHF is a proactive self-assessment tool designed to reduce the generation of air pollution from hospital activities. It comprises 215 compliance actions across seven key categories: travel, procurement, design & construction, energy generation, communication & training, outreach & leadership and local air quality. CAHF implementation has focused on sustainable travel options, parking policy, energy efficiency improvements, staff training, education, the adoption of green procurement policies and the incorporation of sustainable travel considerations into new infrastructure designs. Currently, the hospitals are more than half-way towards achieving their implementation goal. To monitor the future overall effectiveness of CAHF, a network of 32 NO_2 diffusion tubes was set up across the hospital sites, together with continuous monitors for NO_2, PM_{10} and $PM_{2.5}$ measurement, and four indoor particulate matter monitors at each hospital. The monitoring programme was supplemented with the development of an ADMS-Urban dispersion model for the site, focussing on emissions from significant adjacent road networks. This study provides an evidence-based exemplar for the CAHF approach and provides a blueprint to support other hospitals to engage in this process.

1. Introduction

Air pollution has emerged as a pressing public health crisis, linked to a range of short- and long-term health effects, both of which can contribute to increased mortality rates (Kampa and Castanas, 2008). In England alone, it is estimated that outdoor air pollution contributed up to 38,000 deaths in 2019 (Jenkins, 2022). Short-term exposure to ambient air pollutants, specifically particulate matter (PM_{10} and $PM_{2.5}$: particulate matter with aerodynamic diameters less than 10 and 2.5 μm respectively), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) can lead to increased all-cause mortality (Orellano et al., 2020; WHO, 2021) and all-cause hospital admissions (Chen et al., 2010). Short-term exposure is also associated with hospital admissions due to stroke (Niu et al., 2021), and respiratory and cardio-vascular diseases (Peel et al., 2005; Phosri et al., 2019; Atkinson et al., 1999). Long-term exposure to ambient air pollution is associated with increased all-cause mortality, as well as with increased incidences of cardiovascular disease, chronic obstructive pulmonary disease (COPD), lung cancer, diabetes, adverse reproductive outcomes and effects on neurological development and cognitive function (WHO, 2021). There is also evidence that long-term exposure to air pollution can increase incidences of dementia (Chen et al., 2017; Carey et al., 2018). Children are particularly vulnerable to the effects of ambient air pollutants because of their under-developed immune system and lungs (WHO, 2005; Schwartz, 2004), as was tragically highlighted

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by the death of 9 year old Ella Adoo Kissi-Debrah in London, the first time that a UK coroner has recorded exposure to air pollution as a cause of death (Dyer, 2020). The elderly are also more vulnerable to the effects of air pollution because of a greater prevalence of underlying health conditions compared to the general population (Simoni et al., 2015).

Nowhere are the potential consequences of poor air quality more acute than in hospitals. These settings host some of the most vulnerable individuals, experience significant traffic and pollution-generating activities, and are often located in urban areas with high baseline levels of air pollutants. In this regard, it is estimated that about 3.5 % of road traffic in England is attributed to the UK's National Health Service (NHS) (NHS England, 2023) and that healthcare systems worldwide are accountable for approximately 4.6 % of global greenhouse gas emissions, much of which will have associated emissions of PM and NO_2 (Watts et al., 2019). Therefore, the NHS has recognised the urgency of reducing air pollution and carbon emissions from hospitals and other health care facilities, understanding that improving air quality aligns with and supports broader net-zero goals (Pinho-Gomes et al., 2023, The Royal Society, 2021, Wang et al., 2020). In this context, the Clean Air Hospital Framework (CAHF), as described in this paper, is embedded within broader NHS policies and strategies on net zero (NHS England, 2023), as well as adhering to legal requirements stipulated in the Health and Care Act 2022 (UK Government, 2022). CAHF originated from a collaboration between the Great Ormond Street Hospital and the Global Action Plan, an environmental charity in the UK (Great Ormond Street Hospital and Plan, 2021). The Framework was conceived as a free-to-access self-assessment tool, designed to aid hospitals in addressing air pollution issues within their premises and surrounding areas. It is built on compliance actions that are evaluated according to the ease of implementation and overall effectiveness. Newcastle upon Tyne NHS Foundation Trust (the Trust) has a target of achieving 'Excellent' status under CAHF by 2025, and to achieve net-zero carbon emissions by 2040 (Newcastle upon Tyne Hospitals NHS Foundation Trust, 2024). The Trust declared a Climate Emergency in 2019, becoming the first healthcare institution globally to make such a commitment (Newcastle upon Tyne Hospitals NHS Foundation Trust, 2020).

In addition to CAHF, in the UK, there is a related NHS Integrated Care System Clean Air Framework' (ICS CAF). The key differences between the two frameworks are the target institution boundaries and the scope of compliance requirements. The ICS CAF is targeted at the Integrated Care System which extends beyond hospitals to include community and mental health services, primary care, local authorities and other healthcare services. In contrast, CAHF, the focus of this paper, aims to help individual hospitals achieve their clean air goals (Global Action Plan, 2022). The paper demonstrates the application of CAHF by integrating comprehensive baseline data across various metrics alongside the highest-resolution ambient and indoor air quality measurements yet reported for hospital settings.

2. Methodology

2.1. Overview of CAHF

CAHF focuses on seven categories: (i) Travel, (ii) Procurement & Supply Management, (iii) Design and Construction, (iv) Energy Generation, (v) Local Air Quality, (vi) Communication & Training, and (vii) Outreach & Leadership (Fig. 1). CAHF offers a structured pathway for hospitals to achieve cleaner air environments, with progress monitored through a points-based approach.

The CAHF package comprises a guidance document and spreadsheet (Great Ormond Street Hospital and Plan, 2021). There are 215 compliance actions that are required to achieve a 100 % rating within CAHF, with these actions spread across the seven categories (Figs. 1) and 28 sub-categories, as detailed in Table 1.

For each sub-category, there are a number of compliance

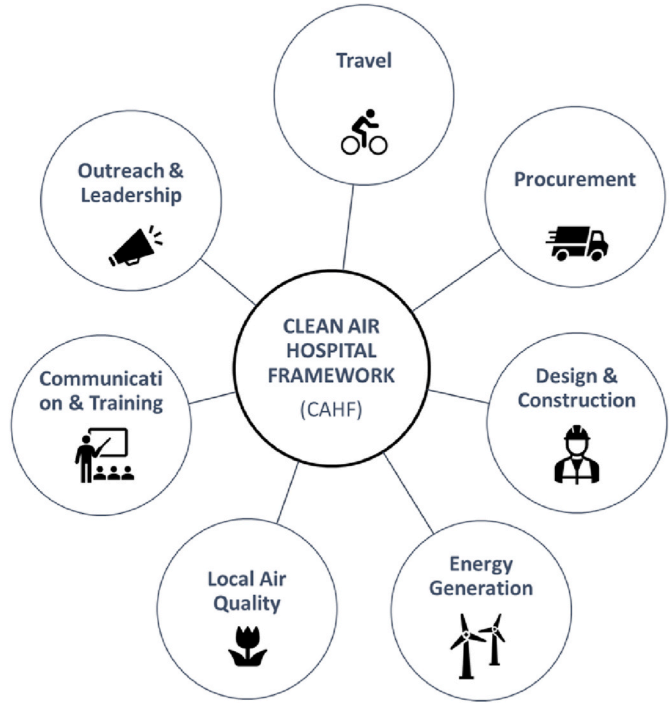

Fig. 1. Clean Air Hospital Framework (CAHF) categories.

Table 1
Main and sub-categories assessed in CAHF, together with respective percentage weightings.

CAHF Focus areas	Category weighting	Subcategories
Travel	28 %	Hospital travel planning (providing information and encouraging lower pollution travel) Walking and cycling infrastructure/ facilities Zero emission vehicle infrastructure Parking for all vehicles Travel to and from the hospital (patient transport & ambulances) Routes to minimise travel Reporting on progress
Procurement	14 %	Procurement and supply chain management Internal ordering Items purchased Couriers
Design and Construction	18 %	Design Layout Building Materials Construction/demolition site
Energy generation	6 %	CHP and onsite boilers Electricity
Local air quality	6 %	Ventilation Air Quality Monitoring Plant life Smoking
Communication & Training	18 %	Clinical advice Engaging patients Board level commitment Training Communication within the hospital
Hospital Outreach & Leadership	10 %	Wider communication and community engagement Influencing for change

requirements that are weighted according to the ease of implementation and overall effectiveness: 1 point (Basic), 5 points (Getting There) and 10 points (Excellent). Two separate examples of the weighting structure are given in Table 2 for the subcategories 'Air Quality Monitoring' (under the Local Air Quality main category); and 'Hospital travel planning' (under the Travel main category). Whilst the overall maximum score achievable is 100 %, there are various stages of achievement that are available under CAHF, as shown in Table 3. The Trust target is to achieve 'Excellent', i.e. over 70 %, by the end of 2025.

2.2. The hospital settings

The Royal Victoria Infirmary (RVI) and Freeman Hospitals are integral parts of the Trust, providing specialised services such as the Great North Trauma & Emergency Centre and the Great North Children's Hospital at the RVI, and the Cardiothoracic Centre and the Northern Centre for Cancer Care at the Freeman Hospital.

The RVI is situated in the city centre on a 13.4-ha site, while the Freeman Hospital occupies a 14-ha suburban site northeast of the city centre. Combined, they offer 1680 beds across 74 wards. Notably, the RVI Trauma Centre alone receives approximately 138,000 new patients annually. Overall, the Trust records approximately 1.8 million patient contacts every year (UK Health Data Research Alliance, 2025).

The locations of the hospitals allow us to study CAHF implementation in two different air quality environments.

Table 2
CAHF compliance requirements for two sub-categories: (a) Local Air Quality and (b) Travel.

Local Air Quality: Air Quality Monitoring		
Basic (1 Point)	Getting There (5 points)	Excellent (10 points)
You monitor air pollution levels on site at hospital entrances, drop-off zones and pick-up points.	You monitor air pollution levels inside as well as outside and showcase results. Monitoring should use the UK Environment Agency's Monitoring Certification Scheme (MCERTS) approved devices or equivalent.	You monitor air pollution levels across the hospital, showcase the results and use the information to improve air quality on site and set targets for improvement.
An indoor air quality audit has been carried out to identify sources of indoor air pollution.	Indoor air quality audits are carried out at regular intervals.	You regularly monitor your progress on indoor air pollution.
	You work with local air quality teams, such as with your local authority to understand the local pollution levels.	
Travel: Hospital travel planning (providing information and encouraging lower pollution travel)		
Basic (1 Point)	**Getting There (5 points)**	**Excellent (10 points)**
You provide staff, patients and visitors information that shows public transport routes in the local area.	You provide staff, patients and visitors clear and accessible maps of public transport, walking and cycling routes to/from the hospital in the local area.	Taxis booked by the hospital are zero tailpipe emission vehicles.
The hospital site is safe, pleasant and easy to get around for cyclists, pedestrians and people with disabilities.	You have campaigns to promote active travel and public transport to visitors and staff.	You work in partnership with the local authority to ensure planning and development decisions minimise air pollution.
Taxis are not allowed to leave their engines running (idling) when waiting near the hospital.	You encourage and facilitate car sharing for colleagues that live close to one another.	
You create a travel hierarchy for travel to and from the hospital for staff, and patient travel.	There are incentives for staff to use lower pollution travel choices. For example, bike loans and allowing staff to opt into a cycle to work scheme.	

Table 3
CAHF assessment outcome rating scale showing the required percentage score for achievement of ranked outcomes within the framework.

Range	Outcome
0–10 %	Basic
10–30 %	Starting out
30–50 %	Getting There
50–70 %	Good
70 % +	Excellent

2.3. Conceptual approach to CAHF implementation

The CAHF implementation methodology used in this project draws upon the Plan Do Check Act cycle, as depicted in Fig. 2 (Seiffert, 2008), with 'Status Assessment' being the starting point. The sequence of implementing the project is iterative, with the review loop constantly active within every phase. A mixed methods approach to collection and analysis of data was adopted to allow for a broader and more grounded study across the multidisciplinary policy focus areas of CAHF (Almeida, 2018). The project is currently within the 'Status Assessment' phase of the cycle for the majority of actions under the framework. Projects of this nature require careful consideration of available financial and human resources to avoid overextending efforts to achieve compliance that may ultimately lead to ineffective implementation (Seiffert, 2008), therefore requiring an alignment of scope and timeframe with available resources.

A minimum of two CAHF implementation and improvement cycles are anticipated to be required to progress the hospital towards achieving the desired goal of 'Excellent' status under CAHF by 2025.

2.4. Baseline status and data requirements

For the first run-through of the implementation cycle, the Status Assessment stage involved the establishment of the baseline status of compliance with CAHF requirements, and the availability of supporting evidence and data. This process was approached in a systematic way through internal document review, site inspections and interviews with key Trust staff. This allowed the assessment of those requirements that were already in compliance with CAHF criteria at the beginning of the project, likely to be as a result of the pre-existing Climate Emergency Strategy or as part of other sustainable practices and active travel promotion (Newcastle upon Tyne Hospitals NHS Foundation Trust, 2020).

If the evidence of compliance was sufficient to meet CAHF requirements, a score was assigned, as per the system outlined in Section 2.1.

For those CAHF requirements that were not found to be compliant, the first Status Assessment iteration also allowed the estimation of the resources and timeframe required to achieve compliance, as well as identifying any gaps in the baseline data. This enabled prioritisation of compliance actions, based on the potential impact of the planned action, and ease of implementation. These prioritisation metrics were assessed by semi-structured interviews with the Trust sustainability team, relevant departmental managers and other stakeholders, with questions drawn directly from the Framework. Each CAHF requirement was qualitatively assessed on a Likert Scale of 1–5 for both impact and ease of implementation, where 1 was low impact/achievability and 5 was high impact/achievability.

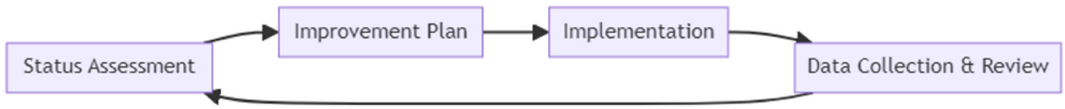

Fig. 2. Feedback approach adopted for monitoring CAHF implementation.

2.5. Identification of required data sources

Implementation of CAHF is data-driven, requiring ready access to key data for evidence and progress monitoring. Table 4 lists, by category, the data sources identified from the activities described in Section 2.4 as necessary for CAHF implementation.

2.6. Air quality monitoring

The ultimate metric for gauging the success of CAHF implementation is the measured concentrations of the most significant atmospheric pollutants, including PM_{10} and $PM_{2.5}$ and NO_2. Such measurements allow an evaluation of CAHF's impact on the local hospital environment and provide a basis for assessing the contribution of the city-wide factors to local concentrations, including the effect of clean air policies such as the Clean Air Zone (Class C, all vehicles, excluding private cars and motorcycles) in Newcastle and Gateshead (DEFRA, 2023a) that borders, but does not include, the RVI.

Prior to the CAHF implementation project, air quality monitoring occurred at only one location at the RVI hospital and none at the Freeman hospital, making it a clear priority to install a network of indoor and outdoor monitors across the two sites. The RVI monitoring was carried out at a Newcastle Urban Observatory (James et al., 2022; Newcastle University, 2023) automatic station located at the main entrance to the RVI (NO, NO_2, NO_x PM_{10}, PM_4, $PM_{2.5}$, PM_1, and meteorological parameters). The Urban Observatory site employs a Thermo Scientific 42i Chemiluminescence NO-NO_2-NO_x Analyzer and an EN 16450 approved Fidas 200 monitor for $PM_{2.5}$ and PM_{10} measurements.

In designing an air quality monitoring strategy for evaluating CAHF implementation, our main objective was to achieve a high spatial resolution of air pollution measurements across the RVI and Freeman hospital sites. Diffusion tubes provide a cost-effective method of gathering such NO_2 data, which is primarily a traffic-derived pollutant in urban areas (Rowell et al., 2021). Thus, we used NO_2 diffusion tubes positioned at 36 locations across the two sites (20 at the RVI and 16 at the Freeman), including at nearby parkland locations so that the effect of green spaces could be evaluated. The locations were chosen to reflect the areas with a high throughput of patients, staff, and visitors, as well as where particularly vulnerable patients are likely to be present, such as the Great North Children's hospital at the RVI and the dialysis unit at the Freeman. The diffusion tubes were mounted using 5 cm spacers to lampposts or other suitable hospital infrastructure, at a height of 2.5 m (locations in Fig. 3). The tubes were left *in situ* for 28 days and changed on specific dates as defined by the UK Department of Environment Food and Rural Affairs (DEFRA) diffusion tube calendar. Exposed diffusion tubes were sent for laboratory analysis at SOCOTEC UK Ltd as previously discussed in Rowell et al. (2021). Newcastle City Council use the same diffusion tube supplier, allowing us to make direct comparisons with surveys carried out under their Local Air Quality Management (LAQM) programme, and the application of co-location bias adjustment factors. We also installed a solar powered AQMesh monitoring pod (NO_2, PM_{10} and $PM_{2.5}$) (Wahlborg et al., 2021) outside the main reception of the Freeman hospital (see Fig. 3b), allowing continuous air quality monitoring, as with the RVI.

Indoor air quality monitoring focussed on particulate matter (PM_{10} and $PM_{2.5}$) because of the availability of low-cost unobtrusive monitors based on laser light scattering technology. Eight (4 at each hospital) PurpleAir PA-I-Indoor monitors were placed at indoor locations across the RVI and Freeman hospitals, typically reception areas and other

Table 4
Key data sources and weighting of each policy focus area according to CAHF.

CAHF Focus areas	Category weighting	Key data available for monitoring
Travel	28 %	• Mobilityways (modal commuting data for all hospital staff, including cycling and walking) • Hospital travel planning • Metrics on zero emission vehicle infrastructure (charging points) • % Trust business journeys by sustainable transport means • Automatic Number Plate Recognition (ANPR) data for on-site transport • Parking data • Taxi booking system (% taxi journeys in electric vehicles) • Patient transport metrics, including private journeys • Traffic survey data on adjacent roads (for dispersion modelling) • Vehicle idling statistics (details of enforcement)
Procurement	14 %	• Details of contracts/future leverage on contract extensions (e.g. contract extension based on achieving a specified EV percentage in the vehicle fleet). • % deliveries by electric and low emission vehicles
Design and Construction	18 %	• Evidence of EV/cycling/walking designed into all new projects • Evidence of sustainability built into material selection • Construction protocols to minimise air pollution (particulates), and related monitoring methods
Energy generation	6 %	• Energy data: combined heat and power (CHP) units and onsite boiler usage • Energy data: electricity usage, including % renewable. • Stand-alone boiler units: maintenance records
Local air quality	6 %	• NO_2, PM_{10}, $PM_{2.5}$ monitoring data from ambient monitoring stations at the RVI, Freeman and the city background site at St Mary's. • Indoor air quality (PurpleAir particulate monitors) • Ventilation performance (e.g. in anaesthetics) • Anaesthetic gas usage
Communication & Training	18 %	• Clinical advice to patients on air quality • Training records: incorporation of air quality and net zero • Air quality awareness raising events for patients and staff • Metrics on monitoring/enforcement of the no-smoking policy
Hospital Outreach & Leadership	10 %	• Data on stakeholder meetings (local authority, universities, other major employers, public transport). • Number of external awareness raising events • Metrics on social media communications

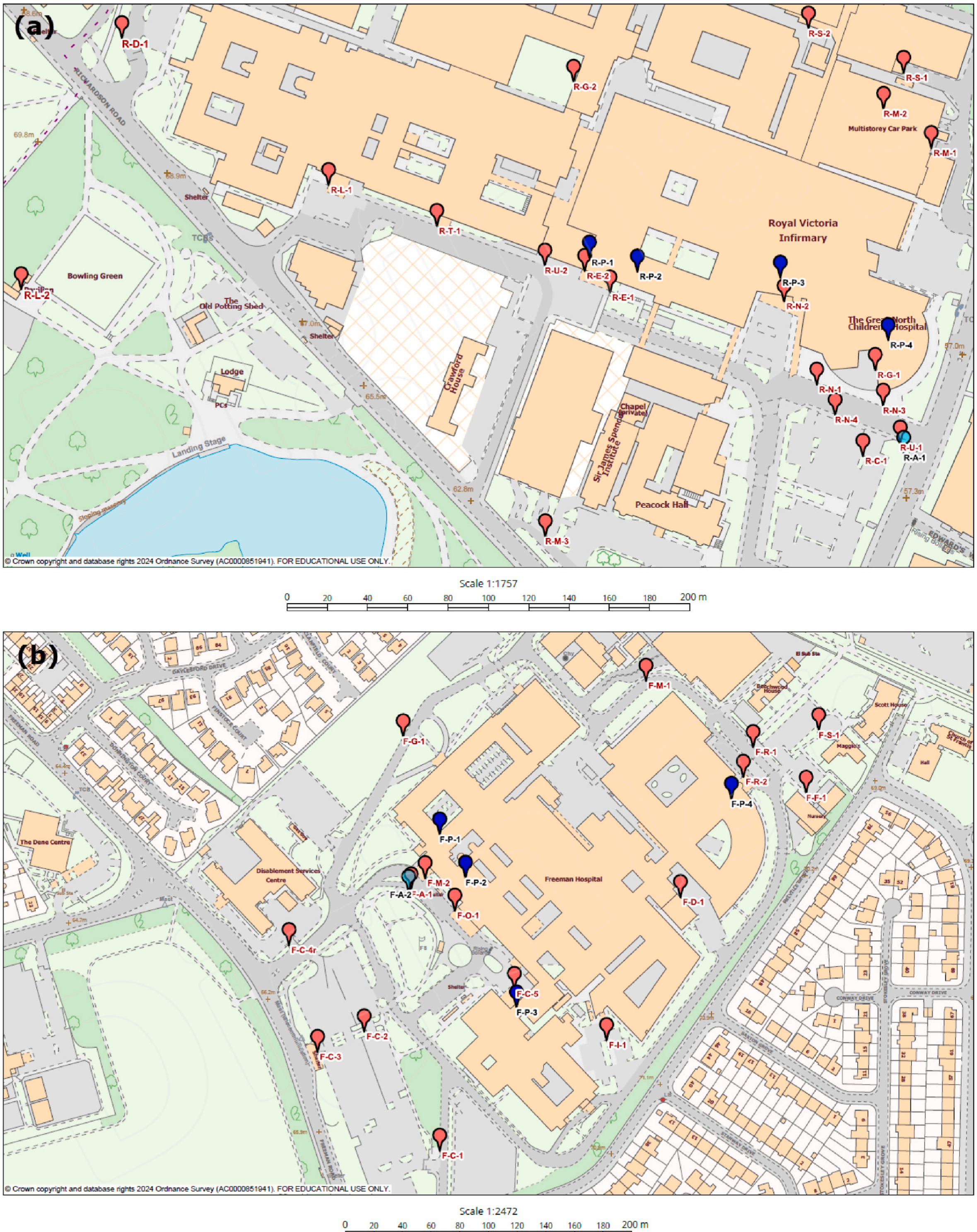

Fig. 3. Locations and designations of air quality monitors at the (a) RVI and (b) Freeman hospitals in Newcastle upon Tyne. Location indicators are colour-coded as follows: red, ambient diffusion tubes (NO_2 only); cyan, ambient continuous monitoring instrument (NO_2, PM_{10} and $PM_{2.5}$); and blue, PurpleAir indoor particulate monitors (PM_{10} and $PM_{2.5}$). The designations refer to the entries in Table 7.

locations where there is high public throughput, as detailed in Fig. 3. PurpleAir monitors have performed well when compared to gravimetric standard methods in indoor calibration exercises (Koehler et al., 2023).

2.7. Air quality modelling

Air quality dispersion models allow the comparison and prioritisation of proposed air quality improvement measures. In this study, we used ADMS-Urban version 5.01 to construct baseline air quality models for the RVI and Freeman hospitals. ADMS-Urban is a modified Gaussian model that is widely used for regulatory purposes by municipal authorities in the UK and internationally. The model requires the input of meteorological data (wind speed, wind direction, temperature, relative humidity, precipitation and cloud cover (Meteorological

Office, 2019), road networks, traffic volumes and other structural aspects, such as the presence of junctions and street canyons.

Meteorological data for the year 2023 was obtained for the closest station to the study sites (Newcastle Airport). Atmospheric chemistry was calculated by selecting the chemistry option module, which incorporates a set of eight reactions (the 'Generic Reaction Set') governing the photochemical reactions involving NO, NO_2, VOC and O_3 (Venkatram et al., 1994). Road network shape file data was imported into ADMS-Urban from the UK Ordnance Survey Open Roads dataset (UK Ordnance Survey, 2023), as per the procedure outlined in the Supplementary Material. Traffic data for roads adjacent to the hospitals was obtained from the UK Department of Transport (Department of Transport, 2023), and The Traffic and Accident Data Unit (TADU) (Gateshead Council, 2023). For roads on the hospital sites, traffic data (patient transport, ambulances, staff vehicles and visitors) was obtained from onsite Automatic Number Plate Recognition (ANPR) systems and from automatic barrier data as well as a taxi booking database. Emission rates were taken from the Emission Factors Toolkit (EFT) version 11.0, supplied with ADMS-Urban. Baseline concentrations for NO_2, PM_{10}, $PM_{2.5}$, NO_X and NO were obtained from the DEFRA background data site (DEFRA 2023b). Traffic speeds were determined from the TADU database and also onsite traffic speed restriction information. Street canyons (one and two-sided) were placed along road lengths using the advanced street canyon modelling option of ADMS-Urban.

3. Results and discussion

3.1. Summary of overall progress across the seven CAHF categories

The CAHF assessment of the RVI and Freeman hospitals established a baseline score of 37.8 % in 2023 indicating a 'Getting There' status, according to the framework's outcome rating scale (see Table 3); this was up from a score of 17 % the previous year. Fig. 4 shows a breakdown of CAHF achievement across the main categories. 'CAHF Max' is the maximum achievable percentage of the overall CAHF score attributed to each of the main categories, with travel, communication & training and design & construction having the greatest weightings, as previously discussed. The 'Initial Assessment' columns show the relative percentages of attainment compared to the maximum, with local air quality (60.5 % of the maximum), design & construction (48.7 %), outreach & leadership (45.2 %) and travel (41.4 %) being the highest performing categories. Procurement (13.9 % of the maximum) and energy generation (16.4 %) are the two areas where least progress has been made. Baseline scores and progress for each of the categories are discussed in Section 3.2.

3.2. Baseline data for individual CAHF categories

3.2.1. Local air quality

3.2.1.1. Air quality statistics for continuous monitoring. Table 5 summarises the air quality statistics for the continuous monitors at each hospital (see locations in Fig. 3), and Table 6 details compliance against UK limit values (UK Government, 2010; UK Government, 2023), or WHO guidelines (WHO, 2021).

Neither hospital breached UK limit values for 24-h or annual

Table 5
Air quality statistics for NO_2, PM_{10} and $PM_{2.5}$ at the RVI (all of 2023) and Freeman (29/09/23–12/11/23) continuous monitoring sites.

Concentrations ($\mu g\ m^{-3}$)	RVI			Freeman		
	NO_2	PM_{10}	$PM_{2.5}$	NO_2	PM_{10}	$PM_{2.5}$
Annual mean	16.6	10.0	6.4	-[a]	7.4	3.5
24 h maximum	39.8	46.5	39.5	-[a]	25.2	17.4
24 h 99th percentile	36.5	35.8	28.6	-[a]	–	–
1 h maximum	85.0	118	73.2		113	45.4
1hr 99th percentile	54.6	37.7	30.2		34.5	29.4

[a] The AQMesh at the Freeman hospital was operational for only 46 days due to a late installation, limiting comparison to annual guidelines. Additionally, due to errors with the NO_2 sensor, this pollutant was omitted from the comparisons for the Freeman.

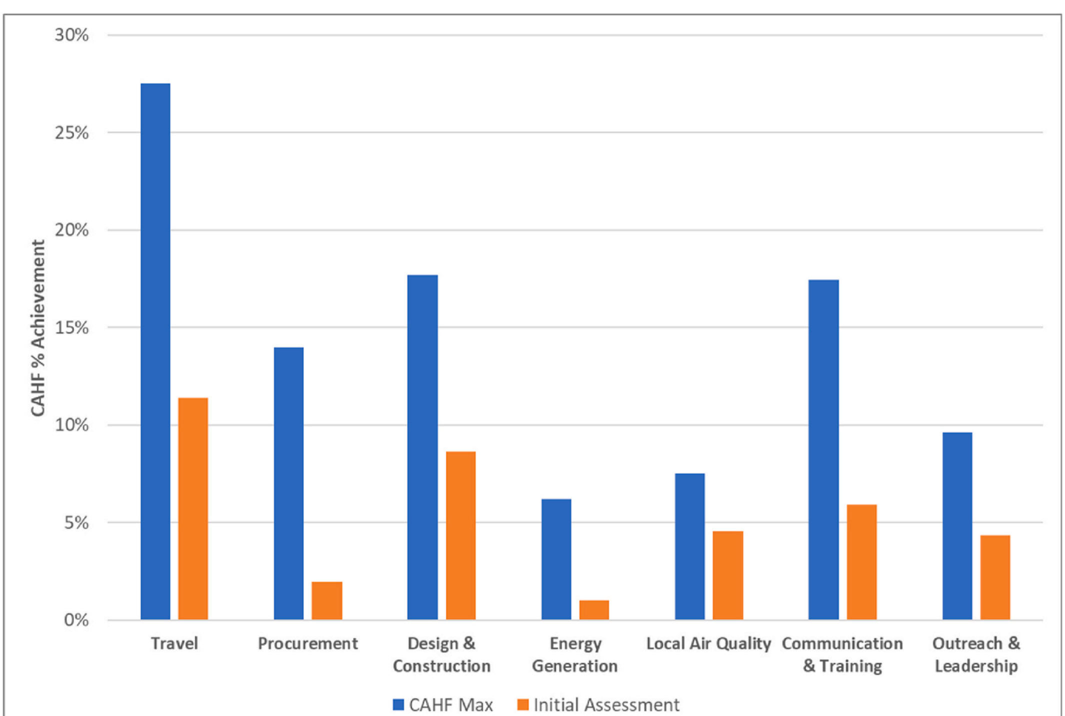

Fig. 4. Relative percentages of total points available for each element under CAHF (CAHF Maximum) compared to the actual percentage achieved at Trust hospitals from the Initial assessment.

Table 6
Exceedances of UK and WHO guideline values for NO_2, PM_{10} and $PM_{2.5}$ at the RVI (all of 2023) and Freeman (29/09/23–12/11/23) continuous monitoring sites.

Pollutant and Limit value/guideline	Exceedance status for RVI (2023)	Exceedance status for Freeman (monitoring period)
NO_2		
UK annual (40 μg m^{-3})	Not exceeded	No data[a]
UK 1 h (200 μg m^{-3})	Not exceeded	No data[a]
WHO 24 h (25 μg m^{-3})	Exceeded (57 times)	No data[a]
WHO annual (10 μg m^{-3})	Exceeded	No data[a]
$PM_{2.5}$		
UK annual, current (20 μg m^{-3})	Not exceeded	Not exceeded (period mean)
England annual, 2040 (10 μg m^{-3})	Not exceeded	Not exceeded (period mean)
WHO 24 h (15 μg m^{-3})	Exceeded (16 times)	Exceeded (3 times)
WHO annual (5 μg m^{-3})	Exceeded	Exceeded (period mean)
PM_{10}		
UK annual (40 μg m^{-3})	Not exceeded	Not exceeded (period mean)
WHO 24 h (45 μg m^{-3})	Not exceeded (1 exceedance, whereas 3 allowed)	Not exceeded (for period)
WHO annual (15 μg m^{-3})	Not exceeded	Not exceeded

[a] See footnote to Table 5.

averages. However, the stricter 2021 WHO annual NO_2 (10 μg m^{-3}), and both the annual (5 μg m^{-3}) and 24-h (15 μg m^{-3}) $PM_{2.5}$ guidelines, were exceeded at both hospitals. Meeting the WHO guidelines, particularly for $PM_{2.5}$, remains challenging for most urban locations. In 2018, only Porto and Stockholm, from those locations monitored, complied in Europe (Carvalho, 2021). Such non-compliance presents a health challenge for sensitive receptors in inner city locations, such as hospitals (current study) care homes (Bentayeb et al., 2015) and schools (Keast et al., 2022). For example, a recent study in Newcastle upon Tyne, UK, showed that ten schools, out of twelve monitored, exceeded the 2021 WHO $PM_{2.5}$ annual average (Keast et al., 2022).

3.2.1.2. Diffusion tube monitoring of NO_2. Table 7 shows the mean diffusion tube-measured concentrations of NO_2 at locations shown in Fig. 3 during September–November 2023 (uncorrected for any co-location biases). The NO_2 mean concentration of tubes at the RVI (25.1 μg m^{-3}) exceeded that at the Freeman (20.2 μg m^{-3}). All monitored locations, were below UK limits (40 μg m^{-3}) but exceeded WHO Guidelines. However, these comparisons require caution, as a full year of diffusion tube data is recommended, and the current monitoring period coincides with yearly NO_2 maxima (Hazenkamp-von Arx et al., 2004). A bias-adjustment factor from the Newcastle City Council co-location exercise at the St Mary's Automatic and Rural Network (AURN) site will be applied once the annual data are complete (DEFRA, 2022).

The current data was important in revealing key relative differences and identifying air pollution hotspots. Initially, ambulance waiting areas were expected to register the highest NO_2, however, at the RVI, the highest concentrations were observed at taxi waiting areas (despite a no-idling policy), the multistorey car park and approaches, and near the main roads. Previous high spatial-resolution diffusion tube monitoring has similarly found high variability of NO_2 concentrations over short distances (Amato et al., 2019; Beckwith et al., 2019; Vardoulakis et al., 2011), for example around roads where concentration gradients of 2 μg m^{-3} m^{-1} have been determined (Amato et al., 2019; Beckwith et al., 2019). Vertical distribution of NO_2 concentrations has also been investigated using diffusion tubes, with higher concentrations measured at child breathing height compared to the standard diffusion tube placement height (Kenagy et al., 2016; Rowell et al., 2021). This important aspect could be investigated further at the RVI children's hospital.

The lowest concentration (13.1 μg m^{-3}) recorded at the RVI was at a pavilion in the adjacent Leazes Park. This may reflect a mitigating effect of dense mature park woodland on traffic-derived NO_2, consistent with studies showing significant pollutant reduction by green infrastructure (Pugh et al., 2012; Yli-Pelkonen et al., 2017). At the Freeman hospital, the highest concentrations were located near car parks and at the Disability Centre at the main entrance.

3.2.1.3. Relationship between air pollutant concentrations at the RVI and Freeman hospitals and the city background. The correlation of hourly air pollutant concentrations at the Freeman and RVI continuous monitoring sites with those at the St Mary's AURN background provides insights into city-wide background influences and local pollutant sources.

Fig. 5 shows that concentrations of NO_2, $PM_{2.5}$ and PM_{10} at the RVI

Table 7
Concentrations of NO_2 (μg m^{-3}) measured at diffusion tube locations across the RVI and Freeman hospitals. ADMS-Urban predicted concentrations are also shown (see section 3.3). Tube IDs with an asterisk have only one or two results due to moisture ingress or because the tube was moved to a higher priority location as part of a re-evaluation of coverage.

RVI hospital				Freeman hospital			
Site location	ID	Meas.	ADMS	Site location	ID	Meas.	ADMS
Multistorey Entrance	R-M-1	32.0	31.7	Multistorey Carpark	F-M-1	19.0	18.7
Multistorey Carpark Level 5	R-M-2	31.4	30.9	Renal Care 1	F-R-1	19.3	17.7
Hospital Supplies Centre	R-S-1	24.0	31.1	Renal Care Entrance Door	F-R-2	16.1	17.8
Great North Children	R-G-1	21.5	30.0	Daft as a Brush parking area	F-D-1	14.9	17.9
Car Park 1	R-C-1	21.9	30.4	IOT	F-I-1	13.1	17.9
New Victoria Wing Taxi Park	R-N-1	22.8	29.6	Car Park 1 (Day Treatment Centre)	F-C-1	19.4	18.1
New Victoria Wing Reception Entrance	R-N-2	21.5	27.2	Car Park 2 (Pay machine)	F-C-2	20.7	18.5
New Victoria Wing Taxi Park by Gate	R-N-3	31.9	30.2	Car Park 3 (Bus stop)	F-C-3*	22.6	19.2
Emergency Steps	R-E−1	21.5	27.1	Car Park 4	F-C-4	18.2	
Emergency Triage Entrance	R-E−2*	23.0	27.1	Disability Centre	F-C-4r	29.2	20.1
Day Treatment Entrance	R-T-1	21.4	26.9	Cardio	F-C-5	17.8	18.1
Leases Wing Entrance	R-L-1	22.9	26.8	Outpatients entrance	F-O-1	21.2	18.5
Leases Park Community Centre	R-L-2	13.1	25.6	Main Entrance	F-M-2	21.6	18.6
Urban Observatory	R-U-1	31.0	31.5	AQMesh	F-A-1	23.8	18.8
New Victoria Wing Taxi beside Fruit store	R-N-4	29.8	29.7	Freespirit	F-F-1	23.0	17.7
New multistorey Entrance	R-M-3	31.9	27.1	Scotts Building	F-S-1	20.8	17.7
Dental Clinic	R-D-1	27.6	26.7	Greenery1	F-G-1	23.2	18.8
Green courtyard	R-G-2	23.0	27.5				
Catering Supplies	R-S-2	25.4	27.9				
Underpass	R-U-2		27.0				

are positively correlated with those at St Mary's (correlation coefficients of 0.736, 0.784 and 0.715 respectively). The slopes on Fig. 5 indicate that pollutant concentrations at the RVI rise by less than one unit for every unit increase observed at St Mary's—that is, the RVI responds more weakly to the same ambient changes. Methodological differences, such as the Tapered Element Oscillating Microbalance - Filter Dynamics Measurement System (TEOM-FDMS) used at St Mary's verses laser scattering at the RVI may explain these relationships, particularly in PM measurements due to the differing moisture removal approaches (Deary et al., 2016; Griffiths et al., 2018). Other explanations include variations in primary and secondary pollutant mixtures, attenuation of the background concentration by urban infrastructure between the two sites (approximately 470 m apart), and differences in wind patterns due to local building orientations.

Whilst these correlations suggest limited scope for reducing air pollution at the RVI due to the city-wide background influence, it must be recognised that the RVI itself contributes significantly to the background concentrations, primarily through vehicular traffic (patient transport, deliveries and hospital visits). Thus, there is an opportunity for the Trust, alongside other Newcastle 'anchor institutions' such as the two universities and Newcastle City Council to collectively improve air quality (Reed et al., 2019; Dragicevic, 2015; Birch et al., 2013).

For the Freeman hospital, data from a shorter monitoring period also showed significant correlations with St Mary's PM measurements (correlation coefficients of 0.256, and 0.255 for $PM_{2.5}$ and PM_{10}, respectively, Fig. 5). However, lower slopes and higher intercepts compared to the RVI, indicate a reduced background influence and greater impact of local sources, consistent with the Freeman's semi-urban location, 2.9 km from St Mary's. NO_2 continuous data from the Freeman were omitted due to instrument issues.

3.2.1.4. Indoor air quality (PM_{10} and $PM_{2.5}$). Continuous indoor monitoring data for PM_{10} and $PM_{2.5}$ concentrations at reception and other public areas in the RVI and Freeman hospitals were analysed for the period October 2023 to January 2024. At the RVI, average $PM_{2.5}$ ranged from 0.62 to 3.04 μg m^{-3} and PM_{10} from 0.75 to 3.68 μg $m^{-3.}$ At the Freeman, $PM_{2.5}$ ranged from 2.04–3.60 μg $m^{-3}$and PM_{10} from 2.30 to 4.16 μg m^{-3}. These concentrations are below the 2021 WHO $PM_{2.5}$ annual guideline value of 5 μg m^{-3} and also lower than concentrations recorded in previous literature studies, for example at hospitals in Bari, Italy (hourly mean baseline of 5 μg m^{-3}, rising to 25 μg m^{-3} during daytime), and Barcelona, Spain (5 μg m^{-3}, rising to 20 μg m^{-3}) in a comparable study employing low cost sensors (Palmisani et al., 2021).

The monitoring revealed clear diurnal patterns in $PM_{2.5}$ concentrations at both hospitals, rising throughout the day and peaking at the end of evening visiting hours (Fig. 6). Similar diurnal patterns were observed

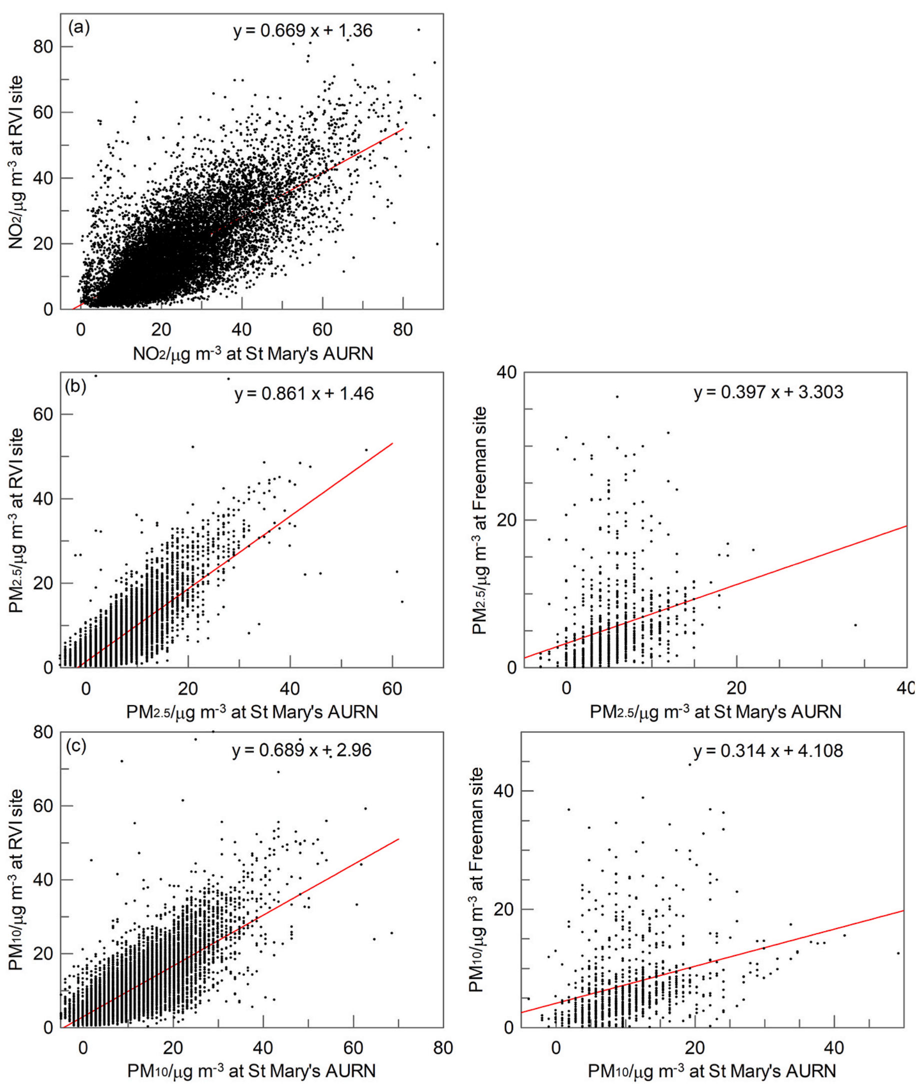

Fig. 5. Correlations between airborne pollutant concentrations at the RVI (04/22 to 01/24) and Freeman (09/23 to 11/23) hospitals with those at the St Mary's background monitoring station.

at hospitals in Bari and Barcelona, though peak concentrations occurred earlier in the day (Palmisani et al., 2021). The current study also observed weekly patterns in PM concentrations, with the highest $PM_{2.5}$ concentrations observed on Sundays. These patterns are likely linked to particulate resuspension from human activity during visits (Qian et al., 2014; Palmisani et al., 2021).

3.2.1.5. Air quality modelling results. Fig. 7 shows a contour plot for NO_2 around the RVI, highlighting hotspots near main roads. The corresponding plot for the Freeman hospital is shown in the supplementary material, Fig. S1. Predicted concentrations at diffusion tube locations are compared to monitored values in Table 7, although caution is needed because the comparison is of a predicted annual concentration with monitoring data for three months or less (DEFRA, 2022). Table 7 shows that at several RVI locations, modelled predictions exceed measured values. The biggest difference was at Leazes Park, where measured NO_2 was over 10 μg m^{-3} lower than predicted, and significantly below the DEFRA background concentration (21.09 μg m^{-3}), consistent with the positive benefits of green spaces and infrastructure, as previously noted (Pugh et al., 2012; Yli-Pelkonen et al., 2017).

At the Freeman hospital, measured concentrations were significantly higher than predicted at several locations, possibly indicating incomplete consideration of actual traffic flows, vehicle composition and speeds. This will be investigated further to enhance the model accuracy, but it highlights the usefulness of ADMS in identifying potential discrepancies in model input data.

ADMS-Urban also enables source apportionment analysis at specified locations (Fig. 8 RVI; Fig. S2 for the Freeman). For the RVI, the results suggest that prioritisation might focus on measures that address traffic on adjacent roads. Although public traffic management is primarily the responsibility of local authorities, the Trust can influence ‘pull factors’ to reduce traffic. For example, the hospital’s multistorey car park previously had lower fees than nearby city centre parking, attracting non-hospital traffic. Such insights from ADMS-Urban can help prioritise hospital-specific air quality improvements. Future work will examine intervention impacts from the Trust and the City Council’s broader improvement initiatives. Additionally, alternative modelling tools, such as CFD-based dispersion models (Sellamuthu and Jeyadharmarajan, 2022) will be considered to better predict pollutant dispersion around hospital buildings, and the effect of green infrastructure (Moradpour and Hosseini, 2020).

3.2.2. Travel and transport

Progress for this section of CAHF is at 41 % of the maximum, with key areas requiring attention including walking and cycling infrastructure and facilities, provision for zero-emission vehicles, and policies on parking and patient transport, as reflected in some of the current initiatives examined below.

3.2.2.1. Staff travel. The Trust has invested in the Mobilityways platform to analyse staff commuting patterns (Mobilityways, 2024). Postcode data indicate 97 % of staff have access to sustainable transport modes (Fig. 9): specifically, lift sharing (97 %), public transport (83 %), cycling (56 %), park and ride (59 %) and walking (6 %).

Using this accessibility data, the ‘Average Commuter Emissions Level Opportunity’ (ACELO) - an optimal sustainable commuting benchmark – was calculated and compared with actual commuting preferences, based on CO_2 equivalent emissions (CO_2e, the optimising metric used by Mobilityways). Fig. 10 compares pre- and post-Covid commuting patterns, highlighting increased car usage post-Covid, but also that the reduction of car commuting through increased lift sharing and active travel presents the greatest potential for lowering emissions. Moreover,

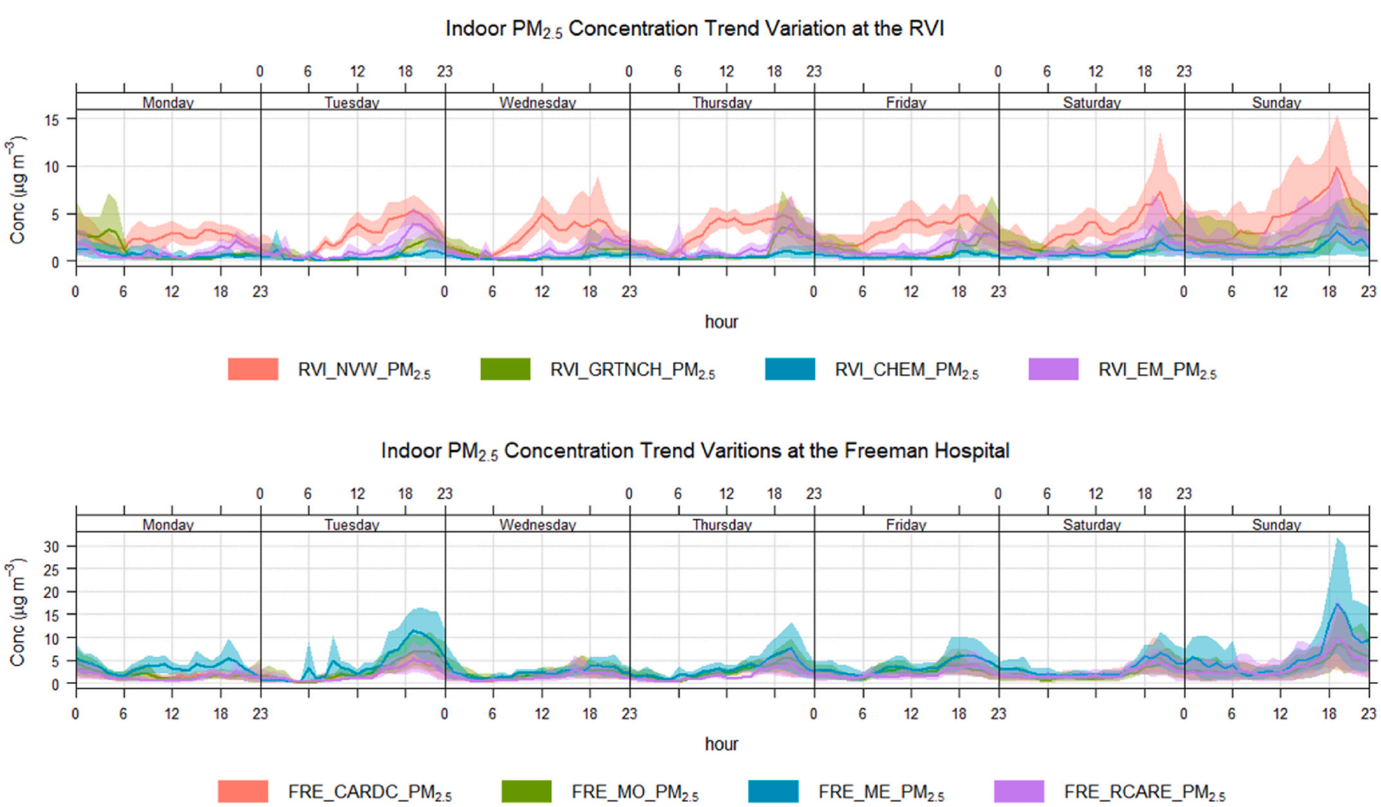

Fig. 6. Diurnal patterns of $PM_{2.5}$ concentrations (±1 SD) at reception areas across the RVI and Freeman hospitals. Abbreviations for RVI sites are as follows: NVW, New Victoria Wing reception; GRTNCH, Great North Children’s Hospital Reception; CHEM, Children’s Emergency Triage; EM, Emergency Triage Reception. Abbreviations for Freeman sites are as follows: CARDC, Cardiothoracic Centre Reception; MO, Main Outpatients Reception; ME, Main Entrance Reception; RCARE, Renal Care Reception.

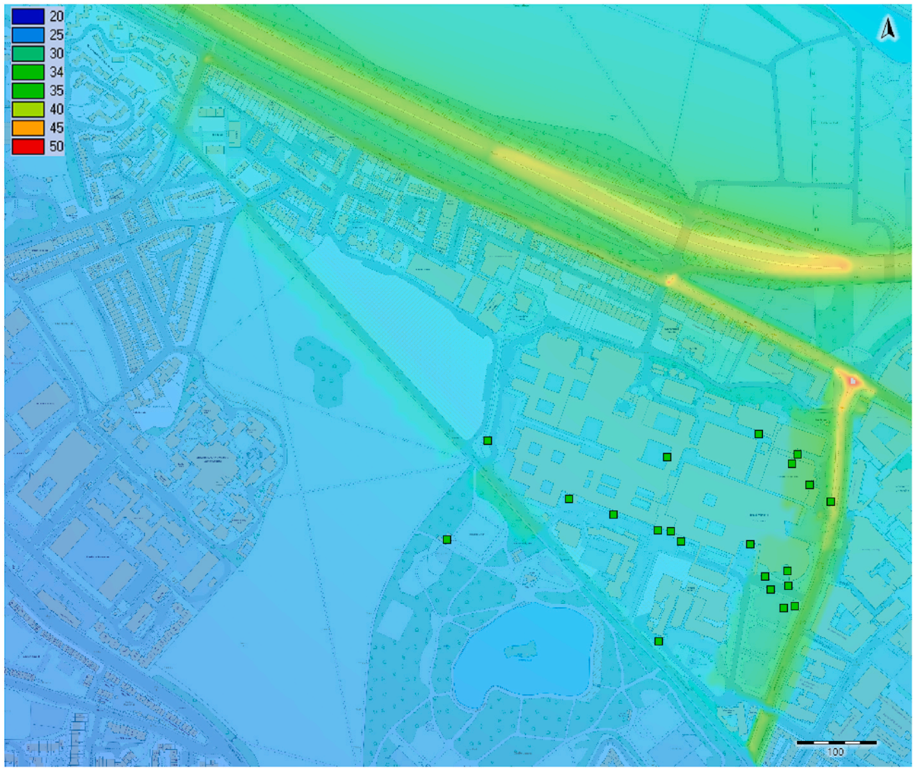

Fig. 7. Contour plot from an ADMS-Urban dispersion model, showing NO_2 concentrations (μg m^{-3}) at the RVI and surrounding areas, with squares indicating diffusion tube locations.

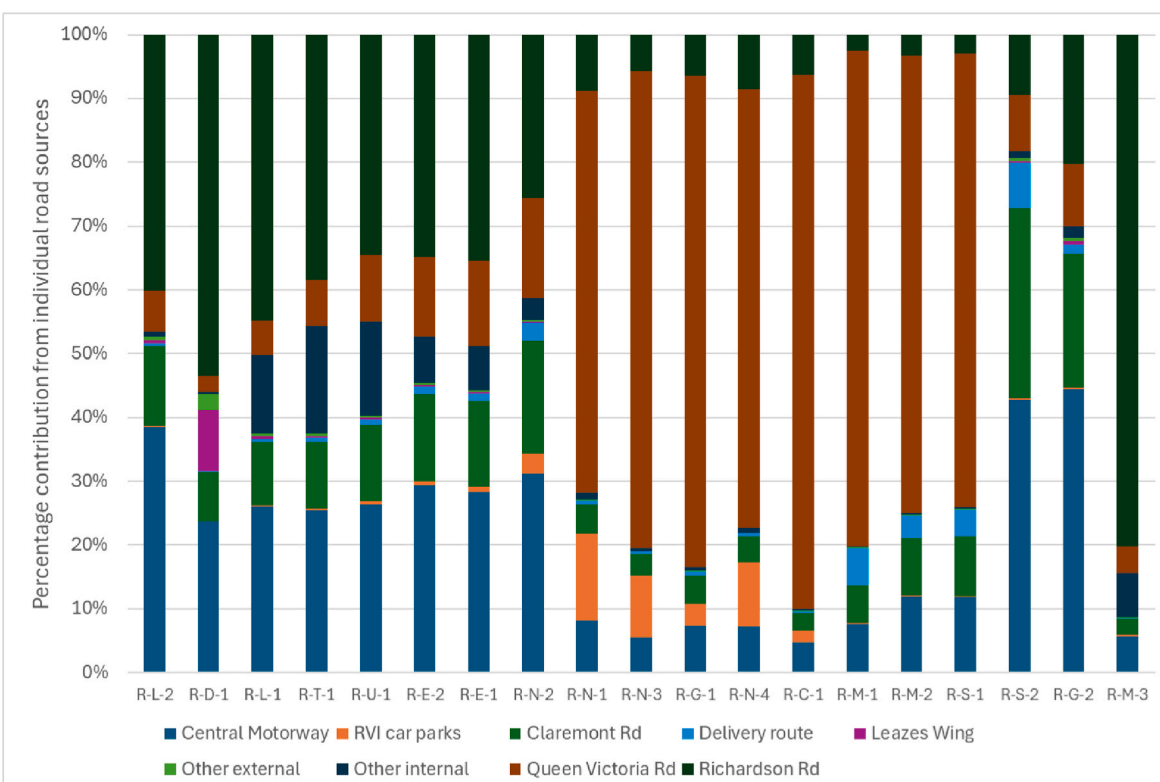

Fig. 8. Source apportionment of contributions from road sources at different receptor points for (a) the RVI and (b) the Freeman hospitals.

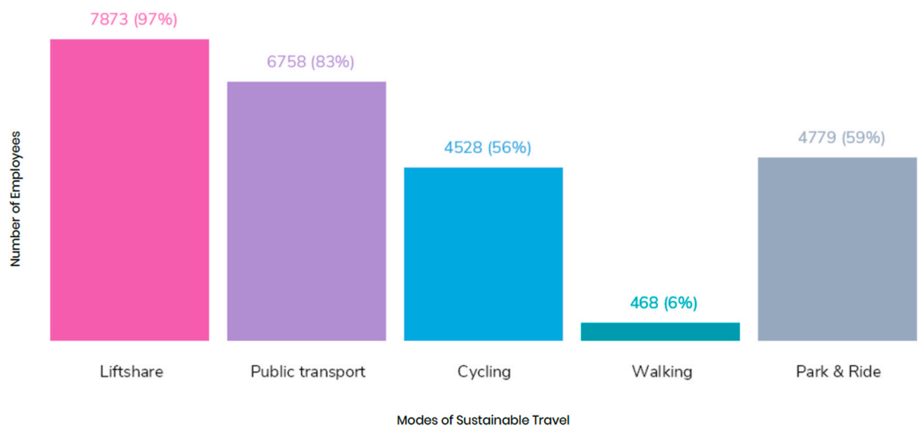

Fig. 9. Access of Trust staff to sustainable travel options based on postcode analysis through the Mobilityways commuting analysis software.

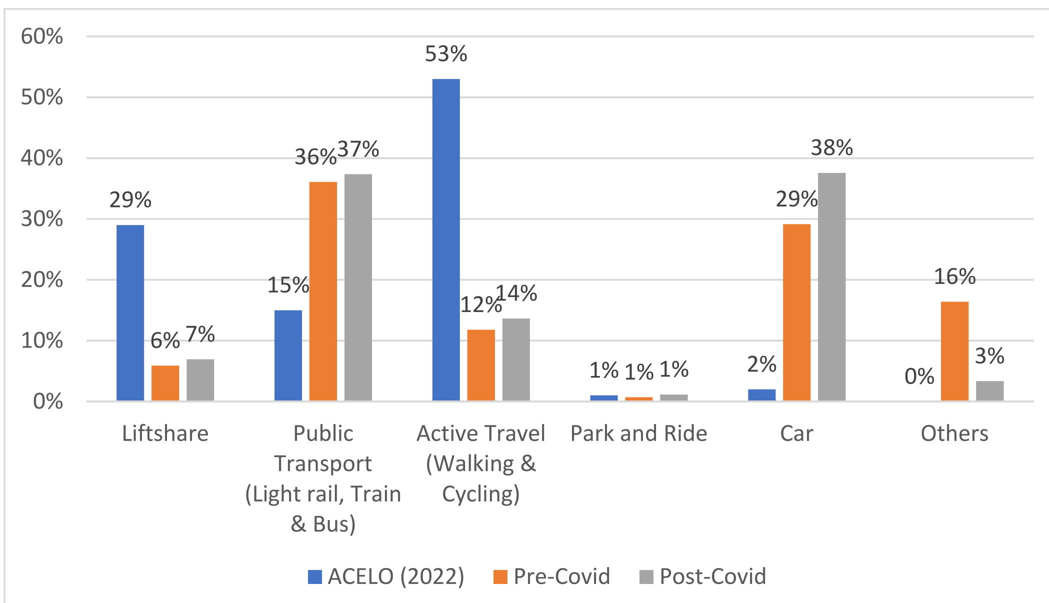

Fig. 10. Best-case travel hierarchy utilisation scenario (ACELO) at the Trust and the pre-covid and 2023 scenario.

active travel contributes to having a more physically active population, which is estimated to save far more lives than achieved through the corresponding reductions in air pollution (NHS England, 2023). Achieving the full ACELO profile could reduce emissions by approximately 425 kg CO_2e per employee, with corresponding reductions in NO_2 and PM emissions. Mobilityways also supports personalised travel plans for staff, assisting the modal shift that is required across the Trust.

3.2.2.2. Patient transport. There are approximately 24,000 patient transport journeys involving taxis, ambulances and minibuses annually within the Trust, some of which are provided by charities connected with the hospital. Patients, such as those undergoing dialysis, may require multiple weekly visits. Current activities to reduce the impact of hospital-administered patient travel include negotiating contracts with taxi companies to incentivise their use of zero emission vehicles (see also section 3.2.3) and co-ordinating pick-ups and drop-offs to minimise individual trips, and aligning transport from different geographical areas for scheduled appointments.

3.2.2.3. Overall hospital traffic, including visits to patients. ANPR cameras at hospital locations monitor overall traffic, including hospital visits. Current data, indicate 4,068,365 annual vehicle visits to the RVI annually and 730,817 to the Freeman. ANPR data, show that electric vehicles account for 15 and 4 % of traffic at the RVI and Freeman respectively, while hybrid vehicles represent 8 and 10 % respectively. The higher number of electric vehicle visits to the RVI may be a consequence of Newcastle's Clean Air Zone (CAZ), which extends to all vehicles except private cars. This baseline data will support ongoing assessments of traffic reduction measures.

3.2.3. Procurement

There is a synergy between air pollution reduction and the net zero objectives that are already integrated into the Trust's procurement procedures. NHS procurement policies have focussed extensively on achieving net zero targets for Scope 1 and 2 emissions by 2040, and Scope 3 by 2045 (NHS England, 2023). The Trust has set more ambitious targets: net zero by 2030 for Scopes 1 and 2, and by 2040 for Scope 3 (Newcastle upon Tyne Hospitals NHS Foundation Trust, 2020). Whilst the target dates of the net zero objectives and the ambition to achieve 'Excellent' under CAHF are not aligned (2030 vs. 2025, respectively), there is a great deal of groundwork that has been undertaken which may facilitate progress under CAHF. Specifically, the Trust has a mandatory 5-step sustainable procurement process, supported via a dedicated sustainability supplier webpage: (1) supplier engagement through an online survey; (2) participation in a dedicated support network, including webinars; (3) carbon footprint reporting; (4) adoption of a net zero target aligned with the Trust's 2040 goal; and (5) publication of a carbon reduction plan. As of April 2024, over 750 suppliers (25 % of the total) responded to the initial survey, with 98 % supporting the Trust's net zero ambition. The commitment to sustainability targets and the five-step process is formalised as a question in the tender document that asks respondents how they propose to help the Trust achieve their net-zero targets. Additionally, a recent question (weighted as 10 % of the whole bidding process) has been added specifically on-air pollution.

Long-term contracts extending beyond the time period of CAHF target for 'Excellent' status (end of 2025) may affect the ability to meet that deadline. Nevertheless, the Trust is proactively exploring ways to incentivise zero-emission vehicles in future courier and patient transport contracts - for example by offering contract extensions conditional on achieving electric vehicle fleet targets. The Newcastle City Council CAZ further incentivises adoption of low emission and electric vehicles by taxis and couriers. Additionally, initiatives to establish delivery hubs serviced by electric vehicles for hospital supplies are ongoing.

3.2.4. Design and construction

There is a significant overlap between the Procurement and the Design and Construction CAHF categories due to the use of contractors. Projects under this category range from minor works such as replacement of air handling units, to the construction of new buildings. Alongside the 5-step sustainable procurement approach outlined in section 3.2.3, the Trust requires onsite contractors to commit to social responsibility and sustainability practices including local labour sourcing. For example, larger construction projects often use diesel-powered equipment and backup generators, creating opportunities to reduce air pollution through controlled usage. The inclusion of metrics for air quality and equipment maintenance as key performance indicators during contract awards should improve emissions control.

Additionally, current procurement guidelines ensure that environmental impacts are considered when sourcing construction materials, such as using Forestry Stewardship-approved timber sources, and water-based paints. Contractors also face restrictions on vehicle numbers onsite.

For construction projects, sustainability measures are best designed into the project at an early stage, based on consultation with staff and patients. An example at the RVI is the design of a proposed new Cardio Unit which included green spaces, drying rooms for cyclist's clothes, covered secured cycle storage (with CCTV) and charging points for electric vehicles. These features replaced an original plan for simple bike stands, directly responding to user feedback, and encouraging cycling as a regular commuting option.

3.2.5. Energy generation

The primary electricity and heat sources for both hospitals are on-site combined heat and power (CHP) plants supplemented by diesel generators and grid electricity (approximately 8.6 %). Energy generation is, therefore, a direct contributor to local air pollution, although emissions are dispersed using 80m and 46m stacks for the RVI and Freeman respectively. Reliable emission rates from the CHP operators have not yet been provided, preventing inclusion in the ADMS-Urban dispersion models.

To achieve excellent status under CAHF for energy generation there is a requirement to cease onsite combustion of fossil fuels or biomass and source 100 % renewable energy from onsite or offsite generation (Great Ormond Street Hospital and Plan, 2021). However, the current CHP operating contract extends to 2027, beyond the 'Excellent' target date (the current CAHF energy score is 16.6 % of the maximum). Post-2027 options for sustainable grid electricity sourcing will be explored, though significant supply infrastructure investment will likely be required, particularly for the RVI. Nevertheless long-term energy generation contracts, often linked to NHS Private Finance Initiative (PFI) schemes, pose significant barriers to achieving net zero and CAHF targets (Simpson et al., 2022).

Overall, building energy use in the Trust showed a 7 % reduction in CO_2e emissions in 2023/24 compared to the previous year (Fig. 11), although total energy consumption has remained relatively constant.

Current measures to reduce building energy use include: (i) adjusting CHP operational strategy to match demand without necessitating export to the grid; (ii); detailed monitoring and analysis of energy usage; (iii) securing £1.7m from the Public Sector Decarbonisation Scheme to fully decarbonise one Trust centre (installation of air source heat pumps, solar panels, LED lighting, and upgrades to the Building Management System); (iv) continuing improvements to energy and water metering (v) investigating city-wide heat network opportunities and techno-economic feasibility of low and zero carbon heating solutions.

Additionally, the Trust is developing a 5-year EV charging strategy. Currently there are twelve 7Kw chargers and four 22 kW chargers installed across Trust sites.

3.2.6. Communication & training

Currently this CAHF category scores 35 % of the maximum, with notable progress in board level commitment to clean air strategies, hosting of 'Clean Air Day' activities, informing visitors and patients about air quality, staff volunteering in clean air activities, training, and communication initiatives.

The Trust Sustainability Team delivers targeted training programmes (Table 8) covering sustainable healthcare (including air quality) to hospital and clinical staff. As of April 2024, sustainability training has helped establish 544 'Green Champions', who disseminate information and motivate colleagues, and 16 Sustainability Ambassadors, equipped to advocate for and implement sustainability in their work areas. Additional focused training is provided to Trust board members and estates department staff.

Internal training and communication are impactful, as evidenced by an 80 % staff awareness level of current sustainability activities. Additionally, whilst over 90 % of staff agreed on the importance of sustainability, 30 % felt the Trust does not make adopting sustainable practices easy (Newcastle upon Tyne Hospitals NHS Foundation Trust, 2024).

Communication with patients about health impacts of poor air quality is a requirement in CAHF, especially when consulting with vulnerable patients in respiratory or cardiac care units. However, as Tan et al. (2023) note, clinicians and health care workers need to be empowered to provide such advice, such as through training and the availability of appropriate resources, including accessible air quality data. One such approach being considered by the Trust, is a system developed by Great Ormond Street Hospital for Children (GOSH) which embeds air quality data into patients' electronic medical records (Hayden et al., 2023). The system issues tailored alerts and suggested actions that are included on the patients' record if NO_2 or $PM_{2.5}$ concentrations at their home postcode exceed the 2021 WHO guidelines,

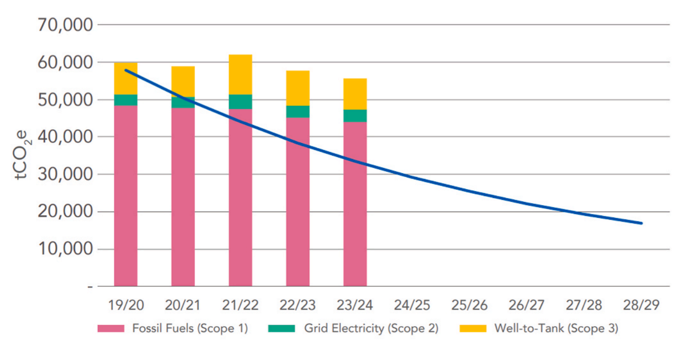

Fig. 11. Total carbon footprint from building energy use (Newcastle upon Tyne Hospitals NHS Foundation Trust, 2024).

Table 8
Sustainability training programs for trust staff.

Training session	Frequency	Delivery Mechanism
Leading in the Transition to Net Zero	Bi-monthly	Online
Sustainability Induction	Weekly	Hybrid
Sustainability E-Learning Platform	All year round	Online
IEMA Foundation Course in Environmental Management	Annually	Online

overcoming clinicians' reluctance to offer advice to patients: in a recent survey, only 15 % of GOSH staff felt comfortable discussing air quality issues with patients (Hayden et al., 2023). Such targeted information facilitates informed decisions on mitigation strategies like mask wearing, reducing outdoor activity, or altering travel plans on poor air quality days (Laumbach et al., 2021). Encouraging patient use of real-time air quality apps could further support informed decisions (Delmas and Kohli, 2020).

Additional communication initiatives explored by other trusts, consistent with CAHF requirements, include: behavioural change messaging, delivered via staff payslips; collating patient testimonies about poor air quality; new staff induction training; creating medical training materials; utilising posters and electronic displays; encouraging staff to use social media to raise public awareness of health effects of poor air quality; and developing clinical guidelines for discussing air pollution with patients (Simpson et al., 2022).

3.2.7. Hospital outreach & leadership

The Trust has already demonstrated national leadership when in 2019 they were the first NHS trust to declare a Climate Emergency (Newcastle upon Tyne Hospitals NHS Foundation Trust, 2020). This was supported by executive backing, a dedicated sustainability team and a detailed climate emergency strategy, with clear goals, targets and an action plan (Newcastle upon Tyne Hospitals NHS Foundation Trust, 2020).

Similar ambition is evident in targeting 'Excellent' CAHF status by 2025, and currently the Trust achieves 40 % compliance in CAHF's Outreach and Leadership category, performing strongly in communication, community engagement, and influencing local change. Collaboration with other Trusts and the wider healthcare sector occurs through the Academic Health Science Network. Research partnerships include local universities and the City Council, for example, in hosting Newcastle University's Urban Observatory air quality monitoring unit on the premises of the RVI (James et al., 2022; Newcastle University, 2023). The CAHF project is itself a collaborative PhD programme through Northumbria University's ReNU Centre for Doctoral Training and is part funded by the Trust. Collaboration with Newcastle City Council includes involvement in their 'Net Zero Newcastle' heat network initiative, that is essential for city-wide decarbonisation. Moreover, given the influence of the city-wide background NO_2 and PM concentrations on hospital air quality, particularly at the RVI, it is clear that partnership working with the City Council and other large employers is essential in facilitating a modal shift to sustainable transport and active travel (Newcastle City Council, 2020).

Recent successful outreach has engaged suppliers and secured commitments aligned with the Trust's Climate Emergency Strategy. Other initiatives include Clean Air Day events, and clean air breakfast groups. The Trust also maintains green spaces and gardens accessible to staff, patients, and visitors, with plans to expand these with the creation of ponds under a 30-year biodiversity management plan. The benefits of such initiatives are wide ranging, in terms of both improved air quality and patient health. An example is the development of 'healing gardens' to support physical, social and emotional wellbeing, and to enhance biodiversity Din et al. (2023).

3.3. Prioritisation

A quadrant plot for prioritisation of Trust actions under CAHF is shown in Fig. 12. Actions in the top-right quadrant are prioritised because they are the easiest to achieve and will significantly impact on hospital air pollution. For example, under 'Design and Construction: Building materials', Life Cycle Assessment (LCA) can guide the selection of building materials to minimise environmental impacts and offer the greatest potential for recycling.

Transport-related actions prioritised include 'hospital travel planning', 'parking for all vehicles' and 'routes to minimise travel'. 'Hospital travel planning' involves procuring zero-emission taxis under new contracts (see Section 3.2.3); providing clear public transport information; active travel campaigns; and facilitating car sharing. The 'Parking for all vehicles' actions include monitoring hospital parking; setting parking fees that incentivise sustainable transport options; and working with local authorities to encourage the use of existing park and ride facilities, e.g. at transport hubs and stations. The 'routes to minimise travel' involves actions such as the development of technologies that reduce some of the need to travel to hospital such as through telemedicine, which is the utilisation of telecommunications technology to provide medical services at distance. Advances in this field occurred following the Covid pandemic (Huang et al., 2023; Rosen et al., 2023), and there is evidence to show that remote consultations, at least in the primary care system, can be as effective as face to face (Carrillo de Albornoz et al., 2022), and may also reduce barriers for the elderly to receive consultations and diagnoses, particularly if they live in remote areas (Andonova and Todorova, 2021). Lastly for the top-right quadrant, under 'Air Quality: smoking' there is a current research project that aims to assess the scale of the problem of patients and visitors smoking in hospital grounds, despite an existing ban (Roycroft et al., 2025).

4. Conclusions

This study reports on the initial phase of implementation of the Clean Air Hospital Framework (CAHF) at two hospitals in the Newcastle upon Tyne Hospitals NHS Foundation Trust. It highlights the importance of establishing baseline data across CAHF categories, and the need to have good spatial and temporal resolution ambient and indoor air quality data.

The air quality monitoring data has highlighted the very significant influence of the city-wide background concentrations of NO_2, PM_{10} and $PM_{2.5}$ on levels observed at the hospital sites, though the effect was less pronounced for the Freeman Hospital which is located further away from the city centre. Whilst this may suggest a limited potential for the hospitals to contribute to significant local air quality improvements in the short-term, it also underscores the need for large employers within the city to work together to improve air quality. Air quality monitoring data showed compliance for both hospitals with UK limit values for PM_{10}, $PM_{2.5}$ and NO_2, though the WHO (2021) guidelines for $PM_{2.5}$ (24hr and annual mean) were exceeded at both hospitals and WHO (2021) guidelines for NO_2 (24hr and annual mean) were exceeded at the RVI (no data was available for the Freeman). Diffusion tube data revealed hotspots of NO_2 concentrations at taxi waiting areas, car parks, delivery routes and areas next to adjacent roads. Furthermore, the study shows that supplementing air quality monitoring data with an ADMS-dispersion model allows (i) source apportionment to be undertaken, which aids in the targeting and prioritisation of CAHF measures; (ii) the identification of discrepancies between monitored and modelled air pollutant concentrations, which may suggest data inaccuracies; and (iii) the evaluation of proposed air quality improvement strategies. Nevertheless, as in all air quality monitoring programmes there are practicalities and compromises that will impact on the quality of the data collected. Diffusion tubes are a cost-effective option for high spatial resolution data, but they have a low temporal resolution (28 days), are prone to moisture contamination and have an uncertainty of $\pm$10–20 %.

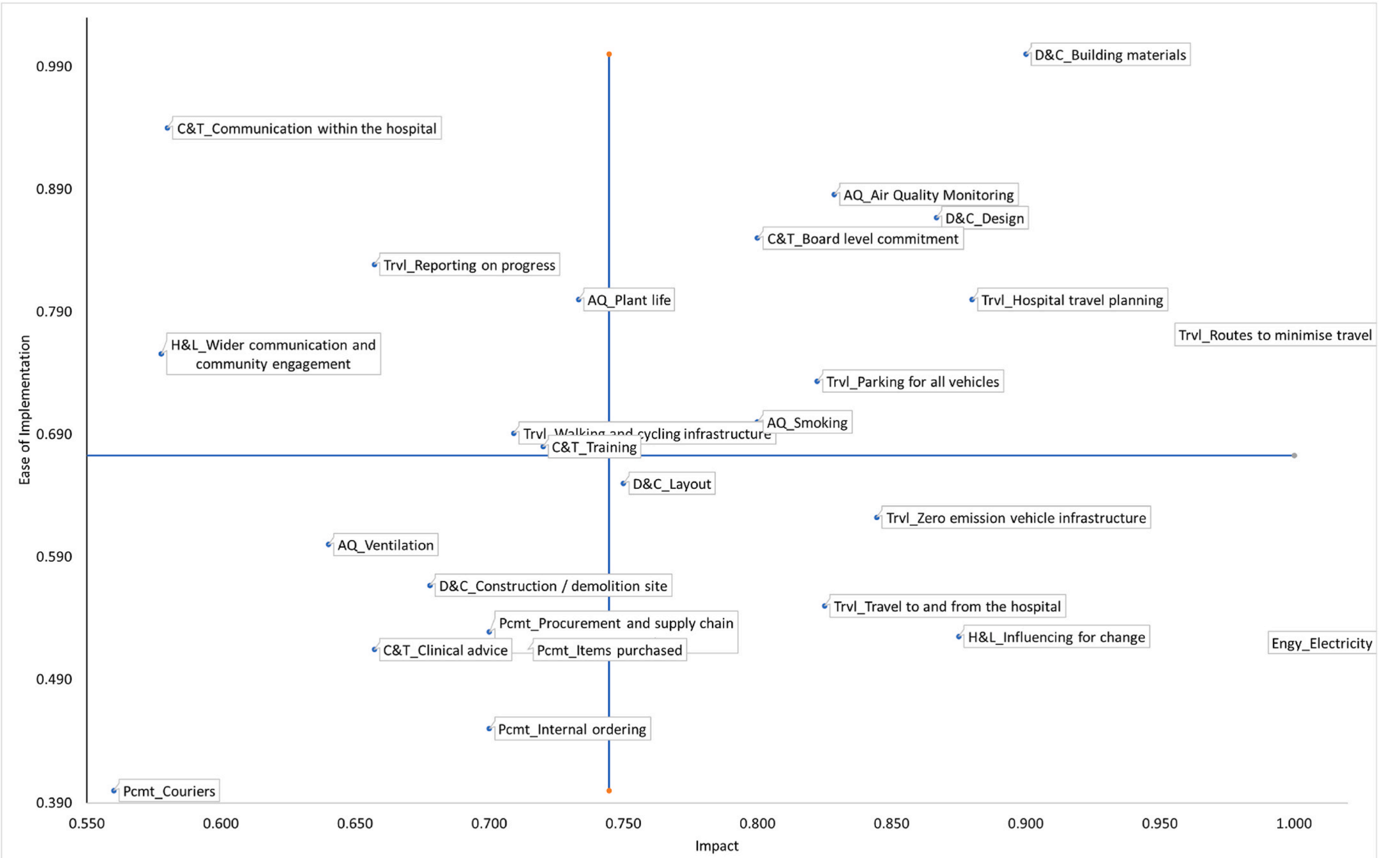

Fig. 12. Quadrant plot for the prioritisation of CAHF actions.

Continuous monitors, such as the AQMesh and Urban Observatory instruments are more expensive and so can only be located at a limited number of locations. They are also prone to sensor errors and downtime and so need regular maintenance, as well as quality assurance monitoring of the data produced. However, even given these limitations, the collection of a multi-year dataset, as is our intention, should allow the detection of subtle policy-driven underlying trends, whether resulting from CAHF implementation or from wider local and national government air quality initiatives.

The instigation of a widespread air quality monitoring programme, supported by modelling, has facilitated progress in the Local Air Quality CAHF category. Good progress has also been made in the Travel category, particularly in identifying (though the Mobilityways platform) optimal sustainable travel options for Trust staff and highlighting the need for a modal shift to active travel, car-share or public transport via personalised travel plans. Other successful CAHF actions have focused on parking policy, energy efficiency improvements, staff training & education, the adoption of sustainable procurement policies and the incorporation of sustainable travel considerations into new infrastructure designs. Nevertheless, with the 2024 CAHF score for the Trust at 38 %, there is still some way to go to reach the 'Excellent' target of 70 %. Procurement (13.9 % of the maximum) and energy generation (16.4 %) are the two areas where least progress has been made, mainly due to the existence of longer-term procurement contracts.

To facilitate and accelerate progress in meeting CAHF requirements, both for UK Hospital Trusts and overseas adopters, it is recommended that the framework is integrated as fully as possible into corporate governance and reporting structures. In this way, CAHF is transformed from a voluntary self-evaluation process to a set of key performance indicators that are considered at board level. This process is already underway at the Newcastle Hospitals Trust, with CAHF overall targets and progress included in the Sustainable Healthcare in Newcastle (Shine) annual report (Newcastle upon Tyne Hospitals NHS Foundation Trust, 2024), which is endorsed at board level. Other recommendations are to continue work on the integration of CAHF requirements into procurement processes and construction projects, to form clean air partnerships with municipal authorities and large local employers and to increase the automation of collecting key CAHF baseline data.

The findings obtained in this study serve as an exemplar for hospitals to engage in a systematic process to improve air quality, aligned with Net-Zero ambitions. Moreover, CAHF offers a transferable and adaptable (e.g. relative category weightings) framework that can be adopted by other institutional sectors, in the UK and abroad.

CRediT authorship contribution statement

Babatunde Okeowo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **James Dixon:** Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Jane A. Entwistle:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition. **Philip James:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Funding acquisition, Data curation. **David Malone:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis. **Laura Middlemass:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Anna-Lisa Mills:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Anil Namdeo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation. **Michael E. Deary:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Babatunde Okeowo reports financial support was provided by Newcastle upon Tyne Hospitals NHS Foundation Trust. Babatunde Okeowo reports financial support was provided by Engineering and Physical Sciences Research Council. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126468.

Data availability

Data will be made available on request.

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