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Harnessing solar to power lower-cost air quality sensors

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Air quality monitoring networks are essential for characterising spatial and temporal patterns in air pollution concentrations that inform the management of population exposure, but are often spatially sparse, limiting their ability to capture hyperlocal variation in air pollution. Lower-cost air quality sensors are increasingly used to address this challenge by complementing regulatory networks where they exist, extending monitoring into under-represented locations where monitoring is sparse, and establishing networks where monitoring is non-existent. However, deploying such sensors in practice frequently requires bespoke, context-responsive system configurations, particularly where access to power and infrastructure is limited. By deploying a lower-cost particulate matter sensor in a high-latitude context characterised by strong seasonal variability, using a customised solar-powered configuration, the paper consolidates practical considerations for the design and deployment of an off-grid air quality monitoring system, highlighting how design decisions, system trade-offs, and deployment processes could be adapted depending on context. While solar-powered systems can support hyperlocal monitoring, performance and scalability are shaped by seasonal variability, energy storage and charge-control limitations, connectivity-related power demand, siting constraints, and resilience to power interruptions. Deployment also highlighted institutional and governance considerations, including permissions, public space management, and ongoing maintenance burden. Synthesised practical considerations and recommendations are presented to inform the design and deployment of autonomous sensor networks capable of supporting hyperlocal air quality assessment, targeted mitigation, and more actionable decision-making.

KEYWORDS
air pollution, air quality, hyperlocal air monitoring, low cost sensor/monitor, solar energy (photovoltaic systems)

Introduction

Air pollution has significant environmental and human health impacts and is the single greatest environmental health threat (WHO (World Health Organization), 2024). Exposure to air pollution has been linked to a range of adverse health effects, including respiratory diseases and cardiovascular conditions (Manisalidis et al., 2020). Monitoring air quality is crucial for managing and mitigating these risks, yet air quality monitoring networks are often limited in terms of spatial coverage (Seto et al., 2019), and in some contexts, particularly informal settlements or low- and middle-income countries (LMICs), may be non-existent (Smith et al., 2025). Further, traditional air quality monitors at fixed-site networks, though highly accurate, are costly to install and maintain, limiting their deployment to mostly urban, developed areas, but even then, coverage is limited (Xie et al., 2017). This spatial sparseness in monitoring networks hinders our ability to capture the full extent of air pollution, especially in rural or underserved areas (Karambelas et al., 2018).

In response to these challenges, there has been growing interest in using lower-cost, Internet of Things (IoT)-enabled sensors to complement traditional monitoring networks. These more affordable sensors can provide data on air quality at high spatial and temporal resolutions (Lu et al., 2021). Their versatility makes them valuable tools in high-income countries (HICs), where they can "plug the gap" by filling in air quality data in locations not typically covered by traditional networks, such as in urban parks, school playgrounds (e.g., Kumar et al., 2020; Pradhan et al., 2024), rural areas (e.g., McCarron et al. *in review*), or other outdoor locations where people spend time. Similarly, in LMICs or informal settlements, where air quality is frequently poor yet (Rentschler and Leonova, 2023) monitoring is often not performed routinely due to, for example, high costs associated with monitoring infrastructure, a lack of local capacity to set-up and maintain the monitoring stations and technological incompatibility (e.g., limited power or connectivity) (Bainomugisha et al., 2023; Bainomugisha et al., 2023), lower-cost sensors offer a promising and emerging solution for establishing baseline monitoring networks (Awokola et al., 2020).

One of the main benefits of lower-cost air quality sensors is their potential for off-grid use, allowing them to be deployed in areas with limited access to infrastructure. Relying on mains-powered systems presents several limitations, including the requirement for stable power restricting deployment locations (especially where electricity infrastructure is lacking or unreliable) and power outages or blackouts (which are common in some regions) (Awokola et al., 2020). To maximise the sustainability and deployment flexibility of lower-cost air quality sensors, solar power therefore presents a promising solution. Solar-powered sensors can operate independently of the grid, reducing long-term electricity costs and minimising environmental impact. In addition, solar-powered systems provide the potential for more remote air quality monitoring, enabling the deployment of sensors in previously unviable areas. While lower-cost sensors with built-in solar are becoming available, their limited variety restricts choice, and their typically higher cost makes them inaccessible to some users. Consequently, the ability to set up a custom solar-powered system is very useful.

The aim of this paper is to describe and translate practical learnings from the design and deployment of a solar-powered, lower-cost air quality sensor system into design-relevant lessons for off-grid monitoring. Adopting a systems-orientated perspective grounded in real-world deployment, the paper consolidates technical, environmental and institutional factors shaping system feasibility, resilience and scalability, and provides an applied reference for the development of sustainable, autonomous air quality monitoring in off-grid and under-monitored settings.

Methods

Deployment context

This work was conducted in Central Scotland, UK, a region with significant seasonal variability in sunlight and temperature. Average sunshine hours range from a high of 188 h in May to a low of 32 h in December, while average monthly minimum temperatures vary between 10 °C in July and 1 °C in February (MetOffice, 2025). These factors are critical for the operation of solar-powered systems: sunshine hours directly affect the energy available for solar panels, while low temperatures can reduce the efficiency and capacity of batteries used for energy storage. Understanding these conditions is essential to design a system capable of supporting air quality sensors suitable for the climatic conditions.

Air quality sensor

The PurpleAir PA-II-SD air quality sensor (PurpleAir, Draper, UT, USA; hereafter referred to as PurpleAir) was selected for this study due to its performance compared to reference-grade instruments, its compact design and its lower-cost. The PurpleAir is an optical particle counter (OPC) that measures particulate matter (PM) with an aerodynamic diameter of 0.3–10 µm using a Plantower PMS5003 sensor. It also records additional environmental parameters, including relative humidity, temperature and barometric pressure (Bosch, Reutlingen, Germany). Laser counters within the sensor take particle readings every 5 s, with averages logged locally to an SD card every 120 s, enabling continuous air quality monitoring. In addition to the SD card, the sensor is equipped with Wi-Fi connectivity, allowing for real-time data upload to the PurpleAir online platform. However, reliable upload depends on consistent power and internet connectivity.

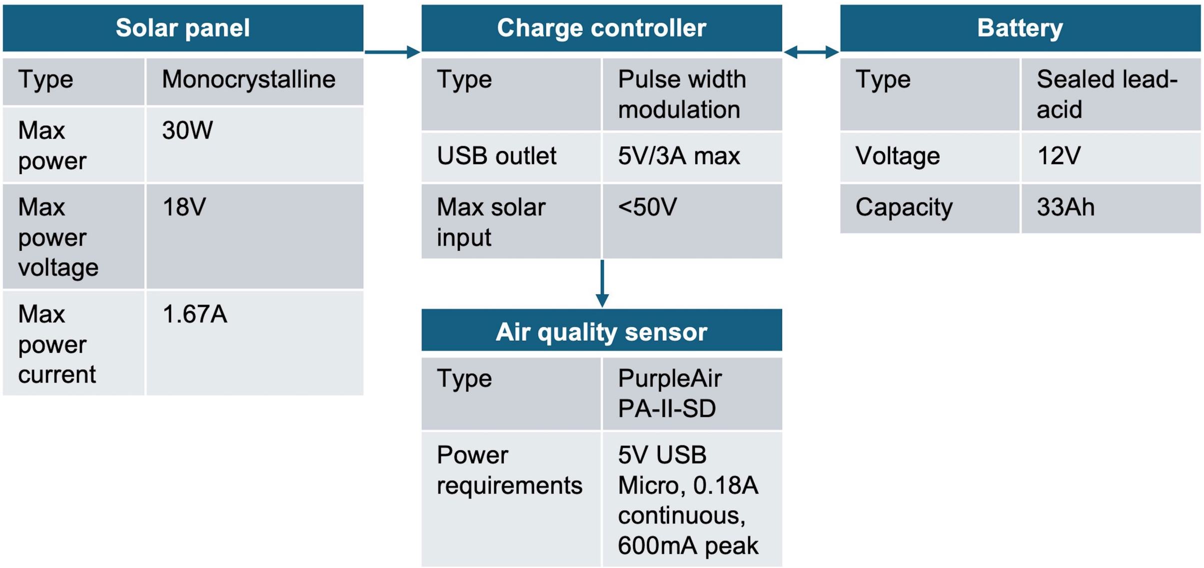
The PurpleAir sensor operates on a 5 V DC micro-USB power supply, with a continuous current draw of approximately 0.18A and peak currents up to 0.6A (Figure 1). This converts to a power consumption of about 0.9 W under typical conditions, with peaks reaching up to 3 W. Understanding the PurpleAir sensor's power requirements is vital for designing off-grid systems, as it informs the sizing of solar panels and batteries to ensure reliable operation.

Solar power system design

Based on our calculations of the PurpleAir sensor's power requirements, the instrument consumes approximately 600mAh at 5 V, equating to 3 Wh of energy per hour (or 72 Wh per 24-h period). To account for efficiency losses in solar charging and storage, we included a 1.5× safety factor, bringing the total daily energy requirement to 108 Wh.

To meet the daily energy demand, we selected a 30 W monocrystalline solar panel (Figure 1). Based on a northern hemisphere winter estimated 4 h of sunlight per day in Central Scotland, this panel would generate approximately 120 Wh per day, providing a 12 Wh surplus (120–108 = 12 Wh) to account for occasional variations in solar irradiance. The panel's size was chosen to ensure reliable energy generation under typical local conditions while maintaining a compact and cost-effective system.

The battery was chosen to provide autonomy for 2 days without sunlight, requiring a total of 216 Wh. To ensure the battery's longevity, we accounted for a 50% depth of discharge (DoD), doubling the required storage capacity to 432 Wh. Using a 12 V system, this translated to a battery capacity of 36 Ah. We selected a sealed lead-acid battery with a capacity of 33 Ah, as it closely aligned with our calculated requirements while remaining cost-effective and reliable in low temperatures (Figure 1).



Solar panel	
Type	Monocrystalline
Max power	30W
Max power voltage	18V
Max power current	1.67A

Charge controller	
Type	Pulse width modulation
USB outlet	5V/3A max
Max solar input	<50V

Battery	
Type	Sealed lead-acid
Voltage	12V
Capacity	33Ah

Air quality sensor	
Type	PurpleAir PA-II-SD
Power requirements	5V USB Micro, 0.18A continuous, 600mA peak

FIGURE 1
System architecture and key design parameters of the solar-powered, off-grid air quality sensor deployment.

The charge controller regulates the voltage and current from the solar panel to the battery, ensuring optimal charging efficiency, protecting the battery from overcharging and prolonging its lifespan. The pulse width modulation (PWM) charge controller used in our system was chosen for its affordability, compatibility with the 12 V battery and its integrated USB ports, which simplified the connection to the PurpleAir sensor (Figure 1).

Results and discussion: lessons learned and recommendations

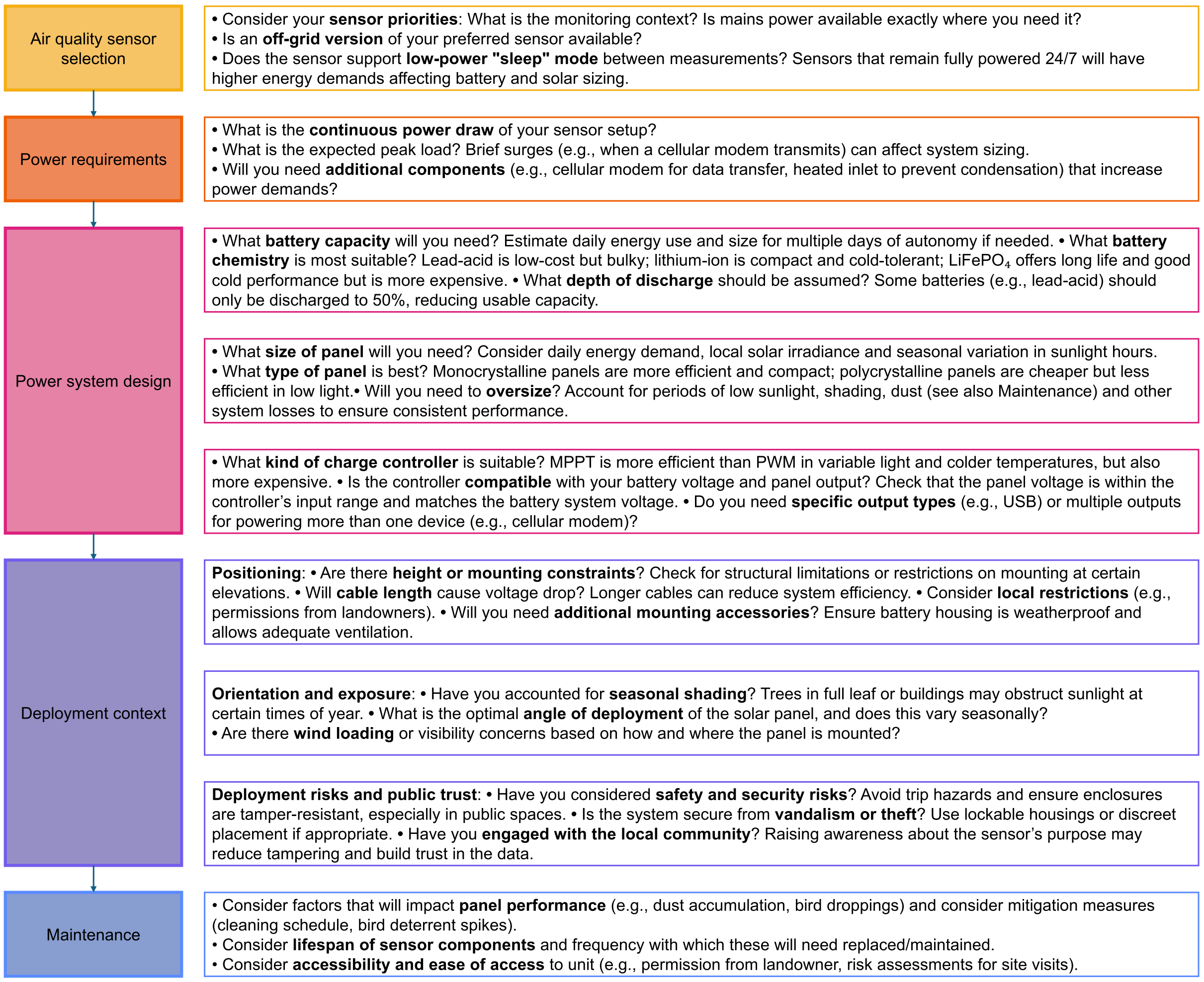
The following section draws on practical experience from designing and deploying solar-powered lower-cost air quality sensors to identify key considerations for off-grid monitoring in a range of settings. These insights are summarised in Figure 2, which brings together the technical and contextual factors influencing design and deployment decisions.

Deploying the solar-powered PurpleAir sensors in the Scottish setting provided valuable insights into the practicalities of designing and implementing a hyperlocal, off-grid air quality monitoring sensor network. Under typical conditions in Central Scotland, the solar setup - consisting of a 30 W panel and a 12 V 33 Ah battery - successfully met the energy demands of the PurpleAir sensor, demonstrating the practical feasibility of using such setups to support decentralised air quality monitoring in locations without access to mains electricity.

Modelling-based analyses of solar-powered air quality monitoring systems similarly demonstrate that optimal panel and battery configurations vary substantially across climatic contexts, with distinct failure risks emerging in cold, high-latitude regions compared to warmer, higher-irradiance environments (Shlipak et al., 2025). Given Scotland's high latitude, short winter daylight hours, and relatively cold climate, these findings are likely to be transferable to regions with more favourable solar conditions, including many LMICs. In climates with more sustained solar irradiance and higher ambient temperatures, comparable systems could likely operate with smaller panels and reduced battery capacity, potentially removing the need for bulky lead-acid storage altogether. This highlights the importance of tailoring solar power configurations to local climatic conditions rather than adopting a one-size-fits-all approach (see considerations in Figure 2). In such contexts, where solar irradiance is generally higher and grid infrastructure more limited, solar-powered sensors are not just a viable option but a critical enabler of monitoring in contexts where grid access is limited or unreliable and for extending data collection into locations where it is most urgently needed (Pinder et al., 2019).

While our deployment focused on rural and suburban contexts, the underlying design principles (e.g., portability, off-grid autonomy) are equally applicable to urban environments, particularly areas underserved by regulatory monitoring infrastructure. In such hyperlocal contexts, where spatiotemporal heterogeneity in pollution concentrations is significant but poorly characterised (Che et al., 2023), solar-powered sensor networks offer the potential to generate fine-grained data capable of informing community-level interventions and urban policy decisions.

Seasonal variability emerged as a key constraint in the design and performance of the off-grid power system. During the northern hemisphere winter months, reduced solar irradiance and lower ambient temperatures significantly impacted both the efficiency and charging capacity of the battery, as well as the performance of the PWM charge controller owing to its inability to operate the solar panel at its higher cold-weather voltage and therefore converting less of the available solar power into usable charge. This resulted in reduced storage performance and increased risk of power interruptions, especially during extended periods of low sunlight. These challenges are likely to be compounded in built-up urban areas, where factors such as tall buildings and narrow street canyons introduce persistent shading effects that reduce the consistency and predictability of solar input. Comparable sensitivities to solar power system configuration and siting have also been reported in other real-world air quality monitoring deployments, where shading, mounting constraints, and charge-storage interactions limited data continuity despite substantially larger



- Consider your **sensor priorities**: What is the monitoring context? Is mains power available exactly where you need it?
- Is an **off-grid version** of your preferred sensor available?
- Does the sensor support **low-power "sleep" mode** between measurements? Sensors that remain fully powered 24/7 will have higher energy demands affecting battery and solar sizing.

- What is the **continuous power draw** of your sensor setup?
- What is the expected peak load? Brief surges (e.g., when a cellular modem transmits) can affect system sizing.
- Will you need **additional components** (e.g., cellular modem for data transfer, heated inlet to prevent condensation) that increase power demands?

• What **battery capacity** will you need? Estimate daily energy use and size for multiple days of autonomy if needed. • What **battery chemistry** is most suitable? Lead-acid is low-cost but bulky; lithium-ion is compact and cold-tolerant; $LiFePO_4$ offers long life and good cold performance but is more expensive. • What **depth of discharge** should be assumed? Some batteries (e.g., lead-acid) should only be discharged to 50%, reducing usable capacity.

• What **size of panel** will you need? Consider daily energy demand, local solar irradiance and seasonal variation in sunlight hours. • What **type of panel** is best? Monocrystalline panels are more efficient and compact; polycrystalline panels are cheaper but less efficient in low light.• Will you need to **oversize**? Account for periods of low sunlight, shading, dust (see also Maintenance) and other system losses to ensure consistent performance.

• What **kind of charge controller** is suitable? MPPT is more efficient than PWM in variable light and colder temperatures, but also more expensive. • Is the controller **compatible** with your battery voltage and panel output? Check that the panel voltage is within the controller's input range and matches the battery system voltage. • Do you need **specific output types** (e.g., USB) or multiple outputs for powering more than one device (e.g., cellular modem)?

Positioning: • Are there **height or mounting constraints**? Check for structural limitations or restrictions on mounting at certain elevations. • Will **cable length** cause voltage drop? Longer cables can reduce system efficiency. • Consider **local restrictions** (e.g., permissions from landowners). • Will you need **additional mounting accessories**? Ensure battery housing is weatherproof and allows adequate ventilation.

Orientation and exposure: • Have you accounted for **seasonal shading**? Trees in full leaf or buildings may obstruct sunlight at certain times of year. • What is the optimal **angle of deployment** of the solar panel, and does this vary seasonally? • Are there **wind loading** or visibility concerns based on how and where the panel is mounted?

Deployment risks and public trust: • Have you considered **safety and security risks**? Avoid trip hazards and ensure enclosures are tamper-resistant, especially in public spaces. • Is the system secure from **vandalism or theft**? Use lockable housings or discreet placement if appropriate. • Have you **engaged with the local community**? Raising awareness about the sensor's purpose may reduce tampering and build trust in the data.

- Consider factors that will impact **panel performance** (e.g., dust accumulation, bird droppings) and consider mitigation measures (cleaning schedule, bird deterrent spikes).
- Consider **lifespan of sensor components** and frequency with which these will need replaced/maintained.
- Consider **accessibility and ease of access** to unit (e.g., permission from landowner, risk assessments for site visits).

FIGURE 2
Considerations for designing and deploying a solar-powered lower cost air quality sensor.

solar capacity and more favourable climatic conditions (Wei et al., 2019). This highlights the need to consider enhanced energy storage or auxiliary power solutions, particularly in built-up, high-latitude or seasonally variable environments, as well as system designs that can automatically recover from power interruptions and resume data logging without manual intervention.

Future designs would benefit from the integration of lithium-ion battery systems, which offer higher energy density and reduced volume, although their operational performance in low temperatures (typically below 0 °C) requires careful consideration, particularly in the months when sunlight hours decrease and temperatures are cooler. Additionally, using a maximum power point tracking (MPPT) charge controller would allow the system to harvest a greater proportion of the available solar energy by tracking the panel's higher winter voltage and converting it efficiently to the battery's charging voltage, thereby improving cold-season performance and overall system resilience.

Despite the technical viability of solar-powered systems for lower-cost air quality monitoring, deployment challenges remain that significantly affect their real-world applicability, particularly in urban and publicly accessible environments. The sealed lead-acid battery selected for this study, while cost-effective and relatively robust, was bulky and heavy. Its size and weight limited where it could be installed, bounded by practical and regulatory constraints (e.g., permissions from local authorities in our UK context). Mounting regulations prevented the placement of battery units above head height, which then required ground-level installations. This introduced a series of new risks including increased exposure to moisture, greater susceptibility to tampering or vandalism and potential obstructions to pedestrian access (Bulot et al., 2019). In densely built urban areas, where vertical surfaces are highly utilised and ground space limited, such limitations are likely to intensify (Guo et al., 2022). There is a growing recognition that air quality monitoring networks must be designed not only for accuracy and data reliability but also for public acceptability (e.g., Morton et al., 2021). Future work in this area should prioritise compact and integrated setups and co-design processes that account for the aesthetic, infrastructural and regulatory conditions of specific urban environments.

While the PurpleAir sensor itself has relatively modest energy requirements (~0.9 W continuous draw) (PurpleAir, 2026), the addition of a Wi-Fi dongle to enable remote data transmission significantly increased the system's overall power demand. Combined, these components required an estimated 2 W continuous load, or approximately 45.6 Wh per 24-h period. This additional energy burden presented a major constraint for year-round, solar-powered operation in a temperate, high-latitude context. Simulations using the JRC Photovoltaic Geographical Information System (PVGIS v.5.3) (European Commission, 2025) suggested that a 30 W panel with a 30 Ah lithium-polymer battery would result in power outages on around 26% of winter days in Central Scotland. Even a more robust 60 W panel reduced this only to 6.8% of days, at significantly higher cost. The lack of low-power or sleep modes in both the sensor and the dongle restricted opportunities to optimise energy use. Moreover, the absence of integrated cellular capability within the PurpleAir meant that connectivity relied on proximity to an existing Wi-Fi network or the use of a MiFi device, further increasing the system's continuous power draw and narrowing the range of viable deployment locations.

These constraints reflect a broader tension in sensor system design between energy efficiency, autonomy and reliable data transmission, particularly where solar irradiance is more limited. Recent developments in low-power wide-area networks (LPWANs) such as LoRaWAN or NB-IoT offer promising alternatives, however the continual bridging of this gap requires greater collaboration between sensor manufacturers, network providers and the research community to ensure off-grid systems remain both energy-efficient and data-reliable (Clements et al., 2017).

Beyond technical feasibility, the deployment of solar-powered air quality sensors encountered institutional and infrastructural barriers, particularly in relation to the governance of public space. Although the off-grid nature of solar-powered sensors theoretically supports flexible and decentralised deployment, the additional equipment, including solar panels and battery housing, raises practical concerns around safety and visibility. In this pilot, permission to mount sensors on lighting columns required extensive negotiation, including structural assessments in some cases, and was refused outright in others due to concerns about wind loading on ageing infrastructure. Similar constraints on where sensors can be safely and permissibly installed have been noted in urban sensor network research, where placement decisions are shaped by contested governance arrangements and infrastructural limitations rather than technical feasibility alone (Robinson et al., 2022). These experiences highlight a key tension between the decentralised potential of solar-powered sensors and centralised governance of infrastructure/land. This tension can constrain the ability of lower-cost, solar-powered monitoring systems to enhance spatial coverage and support wider public engagement (e.g., McCarron et al. *in review*). Overcoming this barrier will require not only technical adaptation (e.g., lighter, more compact solar components), but also greater institutional willingness (at both national and local levels) to support innovative monitoring approaches. Without more enabling governance arrangements, the potential of solar-powered, lower-cost sensor systems to fill critical gaps in monitoring coverage, particularly in hyperlocal urban or underserved setting, may remain unrealised.

Conclusion

Drawing on a real-world deployment, this paper highlights how technical design choices, environmental conditions, and institutional constraints collectively shape the feasibility, resilience, and scalability of solar-powered, off-grid air quality monitoring systems. These interdependencies are rarely considered together in existing work yet are central to the practical deployment of off-grid air quality monitoring systems.

Looking forward, improving the feasibility and scalability of solar-powered air quality sensor deployments will require attention not only to technical advancements (e.g., battery chemistry, panel efficiency) but also to the institutional and infrastructural arrangements that enable long-term sustainability. In urban contexts, particularly in areas where hyperlocal air quality concerns intersect with gaps in monitoring infrastructure, or in less-developed regions where air quality monitoring infrastructure is scarcer, solar power offers a practical solution for autonomous sensing at the street or neighbourhood scale.

While this pilot focused on a temperate, high-latitude environment which offers its own challenges, the insights gained are applicable to a wider range of settings and have broader relevance for infrastructurally constrained areas. The transferability of solar-powered air quality monitoring systems is shaped not just by hardware, but by the presence of local capacity to install, maintain and interpret data from these systems. As hyperlocal monitoring gains prominence as a tool for identifying and addressing hyperlocal air quality issues, there is a need for governance models and funding structures that support the deployment of autonomous, context-responsive sensing technologies at scale. Hyperlocal sensors powered by renewable energy (e.g., wind) could support baseline exposure assessments and enable more targeted air quality interventions, especially in rapidly urbanising or industrialising areas where pollution sources are poorly mapped.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AM: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. SS: Conceptualization, Supervision, Writing – review & editing. MB: Investigation, Methodology, Resources, Writing – review & editing. RB: Methodology, Resources, Writing – review & editing. JM: Investigation, Resources, Writing – review & editing, Methodology. HP: Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

JM was employed by Scotswolds Ltd.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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