User-Friendly IoT Infrastructure for Deploying Wireless Sensor Networks in Outdoor and Indoor Monitoring

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Introduction – Lorenzo Tenti (PhD)

Data Engineer · MLOps Specialist · Researcher

- Background in theoretical and computational chemistry (PhD, University of Ferrara)
- Moved from science to data engineering and applied machine learning
- Consultant designing and deploying production-grade, data-intensive systems that leverage machine learning and AI
- Postdoctoral fellow at ISP-CNR (**MISO** project, environmental and health data)
  - Many overlaps with the **healthRiskADAPT** project
- Interested in exploring and applying innovative technologies that connect **IoT, data, and machine learning**

Introduction – IoT

The Internet of Things (IoT) refers to a **network of interconnected devices** - such as sensors, appliances, vehicles, and machines - that can **collect**, **exchange**, and **act** on **data through** the **internet**. These devices are often equipped with sensors and communication capabilities, allowing them to monitor their environment, share information in real time, and be controlled remotely.

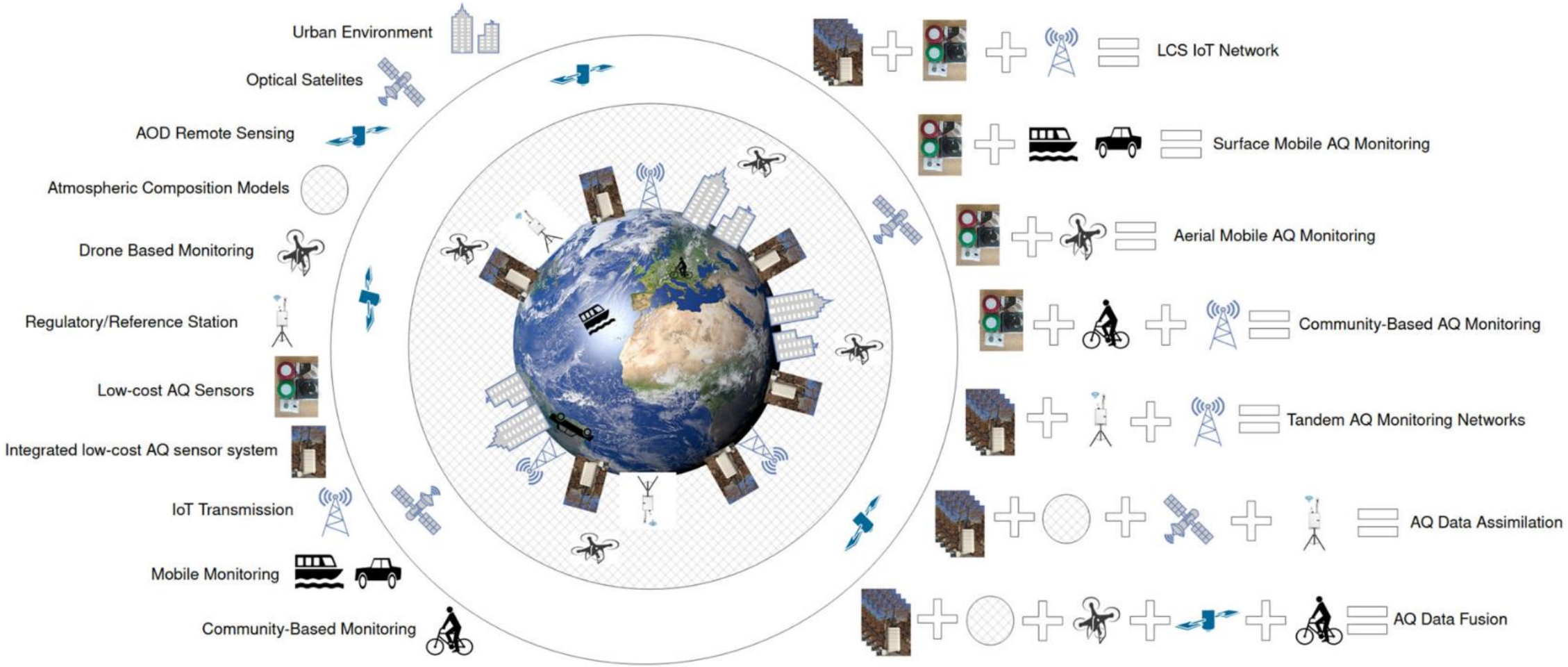
In essence, **IoT bridges the physical and digital worlds**, enabling smarter systems in areas such as environmental monitoring, healthcare, transportation, and home automation.

International Telecommunication Union (ITU). (2012). *Overview of the Internet of Things*. ITU-T Y.2060. Geneva: ITU. https://www.itu.int/rec/T-REC-Y.2060-201206-I/en

Introduction – IoT Trends

Methods & Technologies

Applications



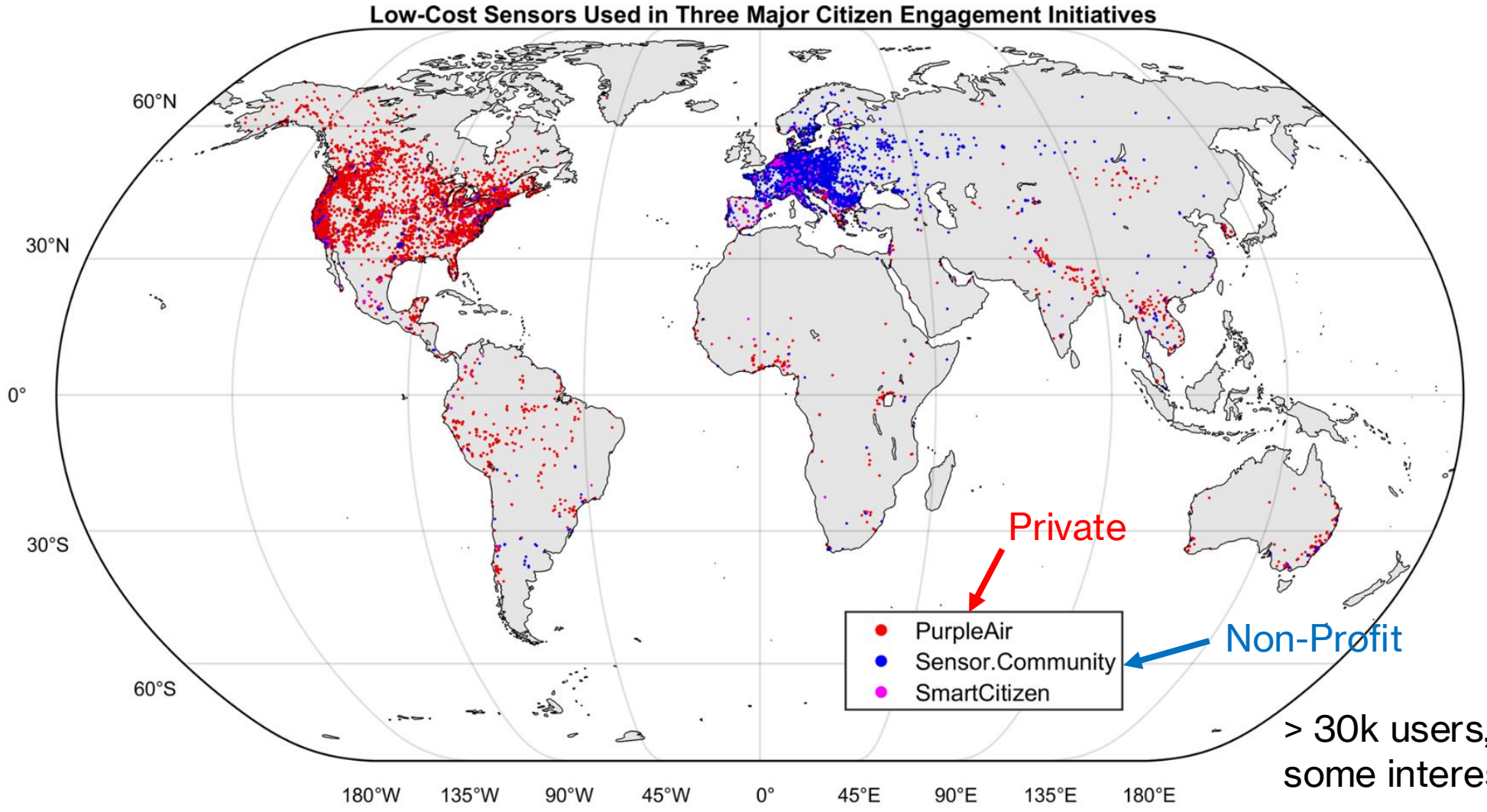
Source: npj Climate and Atmospheric Science | (2025)8:335

Introduction – Why Air Quality (AQ)?

- Air pollution is the **second leading risk factor for death globally**[1] after high blood pressure
- Air pollution is **linked to up to 90% of the disease burden** from noncommunicable diseases, including heart disease, stroke, diabetes, lung cancer, and chronic obstructive pulmonary disease [2]
- 6.7 million premature deaths in 2019 from exposure to ambient and household air pollution [2]
- 2.1 billion people primarily rely on polluting fuels and technologies for cooking in 2023 [2]
- 99% of the world's population live in places where air pollution levels exceed WHO guideline limits [2]

[1] IHME, Institute for Health Metrics and Evaluation
[2] WHO, Total burden of disease from household and ambient air pollution

Introduction – IoT AQ Examples



> 30k users, quite some interest!

Source: npj Climate and Atmospheric Science | (2025)8:335

The problem – Indoors

- **90% of exposure to air pollution happens indoors**
  - Infiltration of outdoor air pollution
  - Indoor activities (e.g., cooking, cleaning, … smoking)
- The indoor environment is VERY complex
  - Building type (age, size, insulation, equipement installed, …)
  - Occupants (number, age, behaviour, …)
  - Location (climate, sources, built environments, …)
  - Indoor and outdoor sources of air pollution
  - Human Behaviour and Gender Dimension
  - …

https://iaq.ucdavis.edu/
--> great video series

Exposure to Air Pollution: Largely Unknown, with Health Impacts Accounting for Only 10% of time spent outdoors → We need tools to measure indoor spaces

The problem – Needs

- Necessary to build new tools (models and data) to estimate
  - **Indoor exposure** to air pollution
  - Main **causes** (activities, building factors, infiltration, etc)
- The results will be used
  - to inform target stakeholders (municipalities, building sector, environmental agencies, ...)
  - to develop specific intervention (e.g., new ERF, greening, enhance air filtration in buildings, ...)

→ EU funded project **healthRiskADAPT**

WP leader
ISP-CNR

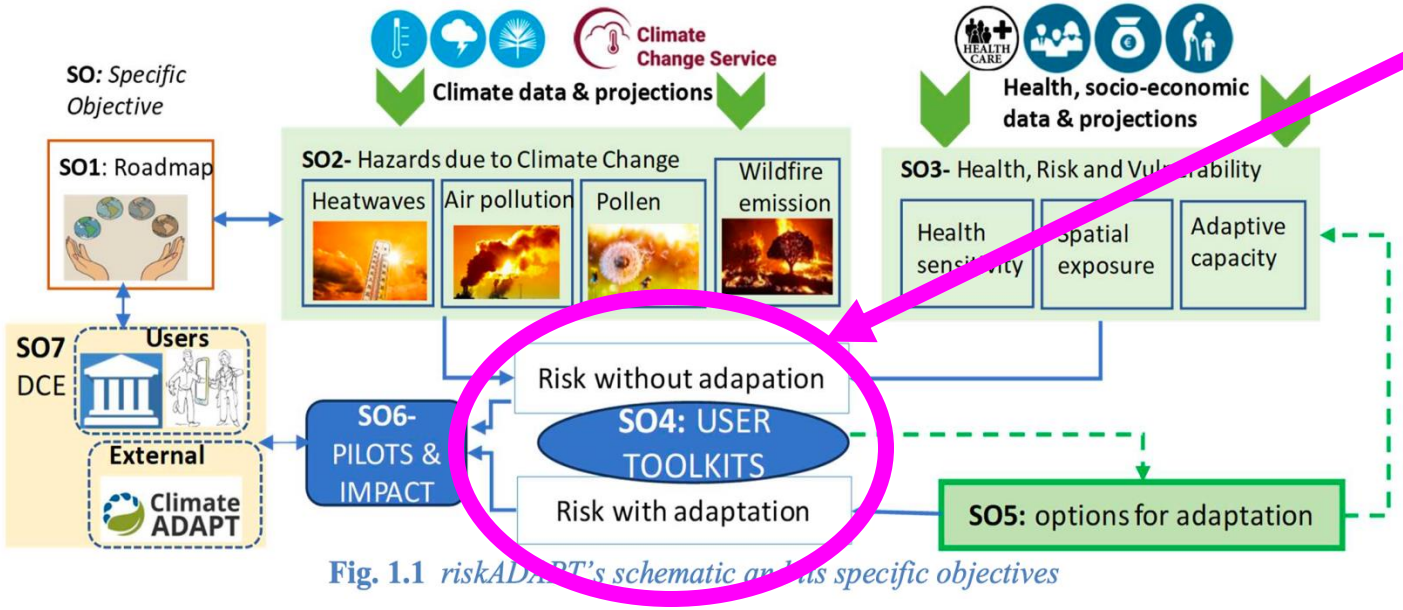
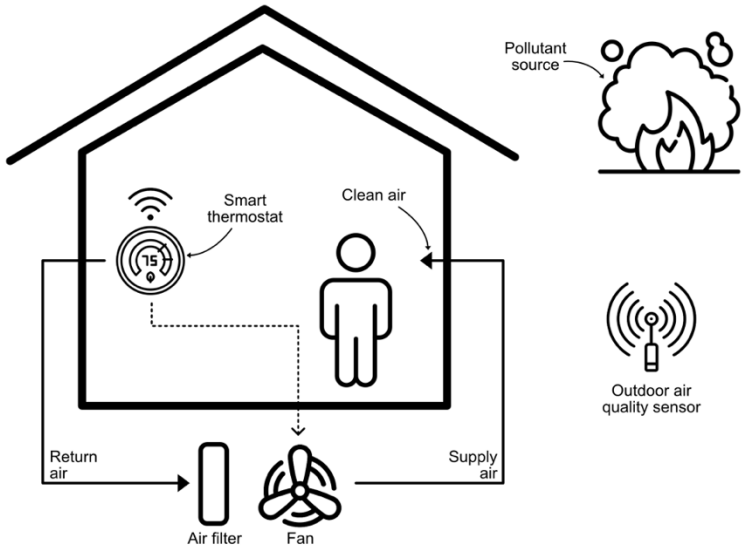
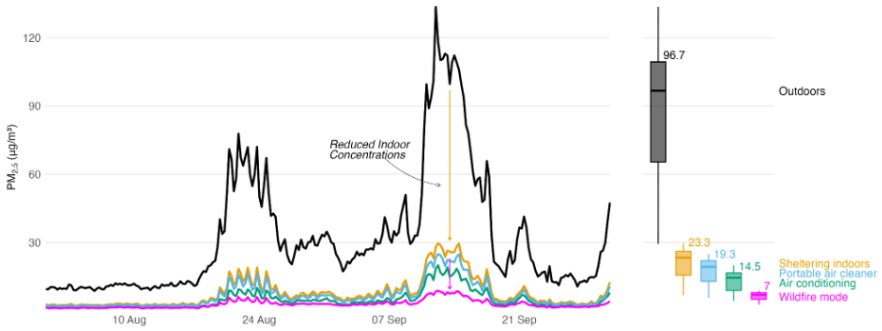


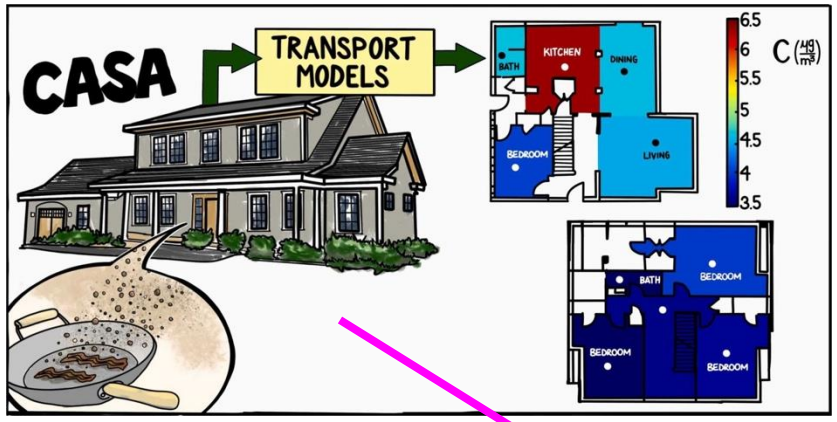
Fig. 1.1 *riskADAPT's schematic and its specific objectives*

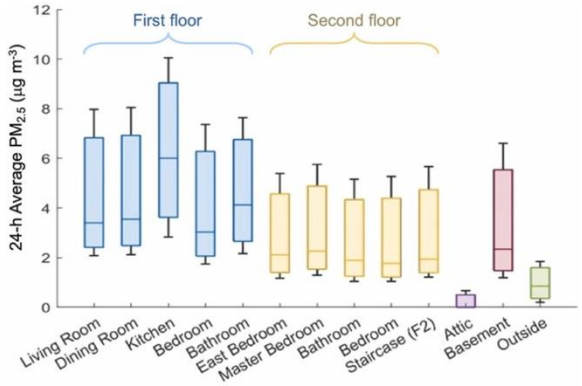
The problem – Existing Solution





Dallo, Federico, et al. "Using smart thermostats to reduce indoor exposure to wildfire fine particulate matter (PM2. 5)." Indoor Environments (2025): 100088.





Martin, Andrew B., et al. "Investigating transport of particulate matter from cooking emissions in a multi-story house using low-cost sensor measurements and different modeling approaches." Indoor Environments (2025): 100126.

e.g., using Purple Air sensors

The problem – why so relevant?

- **Commercial and 'Open-Source' monitoring devices already exist...**
  - Purple Air
  - Sensor.Community

→ **Lack of IoT application/framework to be focused on Indoor Environments** ←

Public Health, Building Control and also **Education***

***Why this is also relevant for remote areas?**
Cities: ~4% of EU landcover

- 75% population lives
- Consumption > 65% of global energy
- 70% CO_2 emissions

→ Environmental co-benefits are huge

EU Missions:

- Climate Resilience
- Climate-Neutral Cities

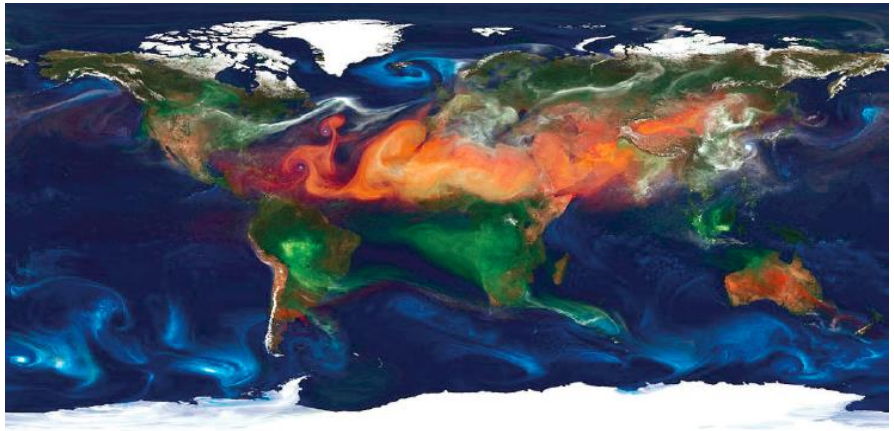


FIGURE 2-6 Output from a NASA model showing the different sources of particulate matter. Red = dust, blue = sea salt, green = smoke, and white = sulfate. SOURCE: Farmer slide 3 (NASA Center for Climate Simulation at Goddard Space Flight Center).

National Academies of Sciences, Engineering, and Medicine. 2022. Indoor Exposure to Fine Particulate Matter and Practical Mitigation Approaches: Proceedings of a Workshop. Washington, DC: The National Academies Press. https://doi.org/10.17226/26331.

The solution – what?

Device/s

Indoor/Outdoor

Indoor

MVP
- Device Firmware ✓

Next Steps
- Commercial Device Integration trough HomeAssistant (~6 months)
- Integration with Industry Partner Building Automation System (~1 yr)

Device GUI – WiFi AP

"One-time" GUI ✓
- Device Configuration
- Local Raw-Data Visualization (debug)

User Interface/s

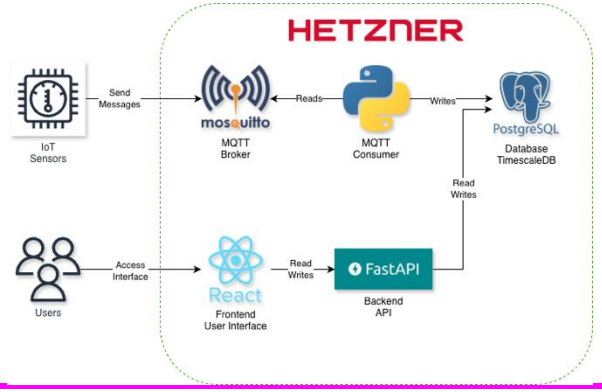
Web App

User Application ✓
- User Registration
- Sensor Networks Configuration
- Data Visualization / Download

Next Steps
- Improve Design

data

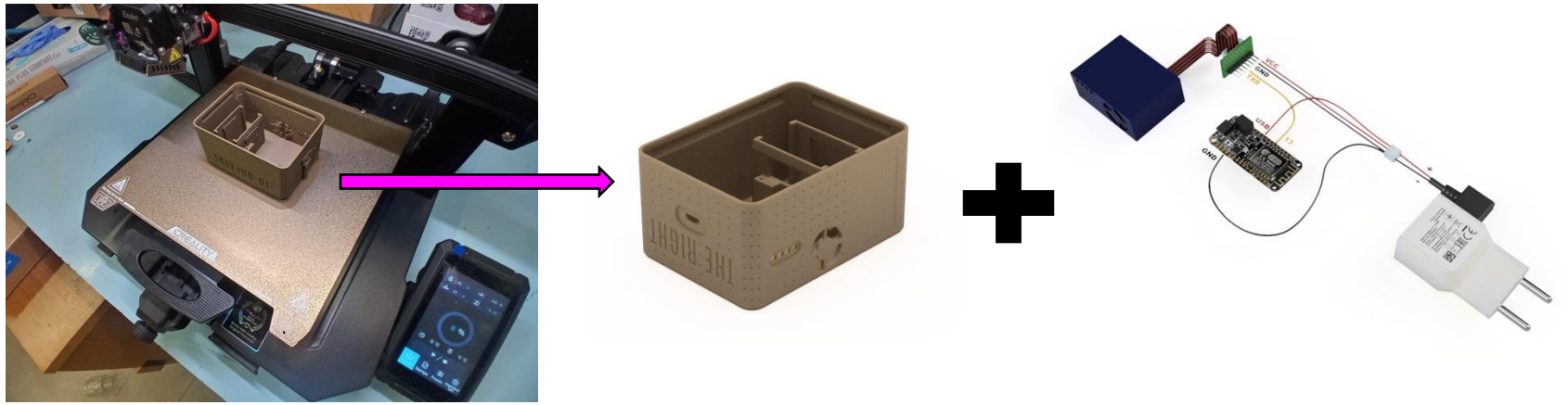
Data Management



Core Application ✓
- Device Registration
- Data Handling
- Backend

Next Steps
- Mass Balance Model Integration

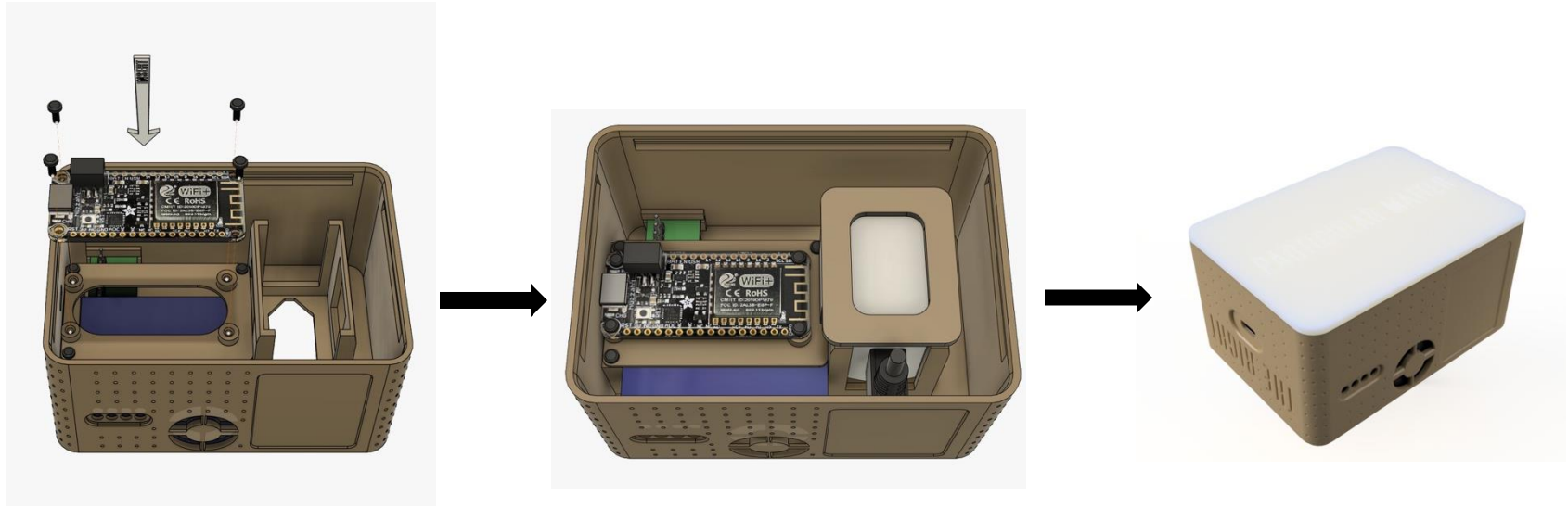
DIY Device – Hardware



Building Materials:

- 3D printed enclosure ←
- ESP microcontroller
- Plantower PMS5003
- bme280 T-RH-P
- micro-USB power supply

→ soon: Senseair CO_2 sensor



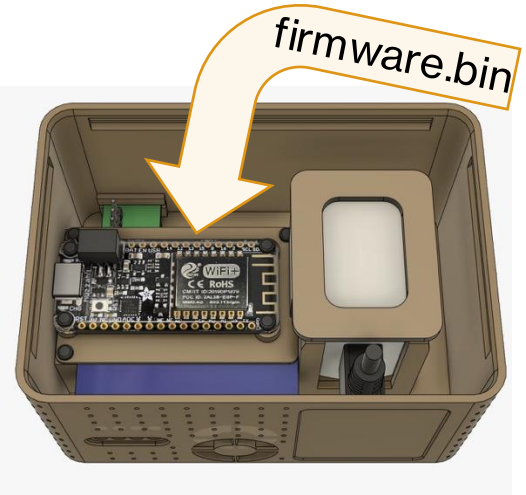
STL file

Download STL File for 3D printer: https://makerworld.com/en/models/1912756-particulair-in-1

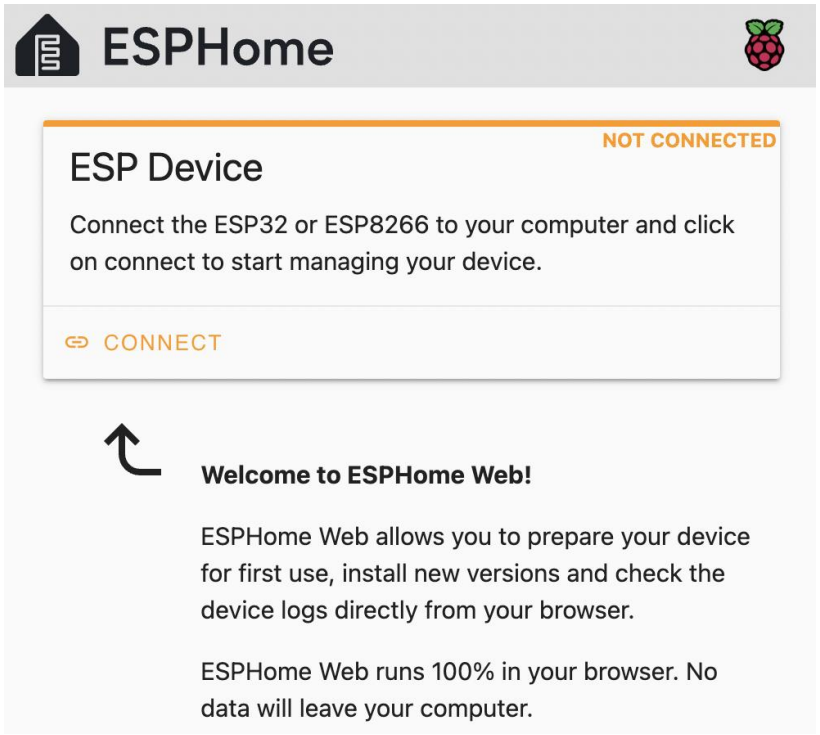
DIY Device – Firmware

1) GitHub →

2) GoTo: https://web.esphome.io/



*the firmware is a file that contains the instructions for the microcontroller



Download “firmware.bin” for ESP8266: https://github.com/.../src/build/esp8266/firmware.bin

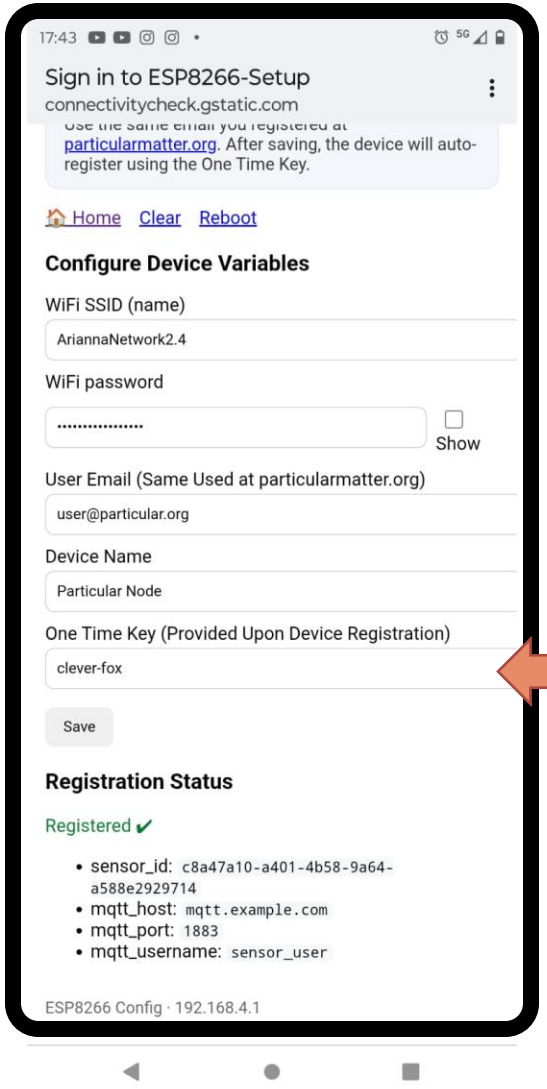
*No need to Install any Software

DIY Device – Registration

1) Plug the device to connect to the WiFi Access Point:

SSID: ParticularMatterDevice-Setup
PWD: particularmatter

Automatic Redirect (e.g., like airports' captive portals)



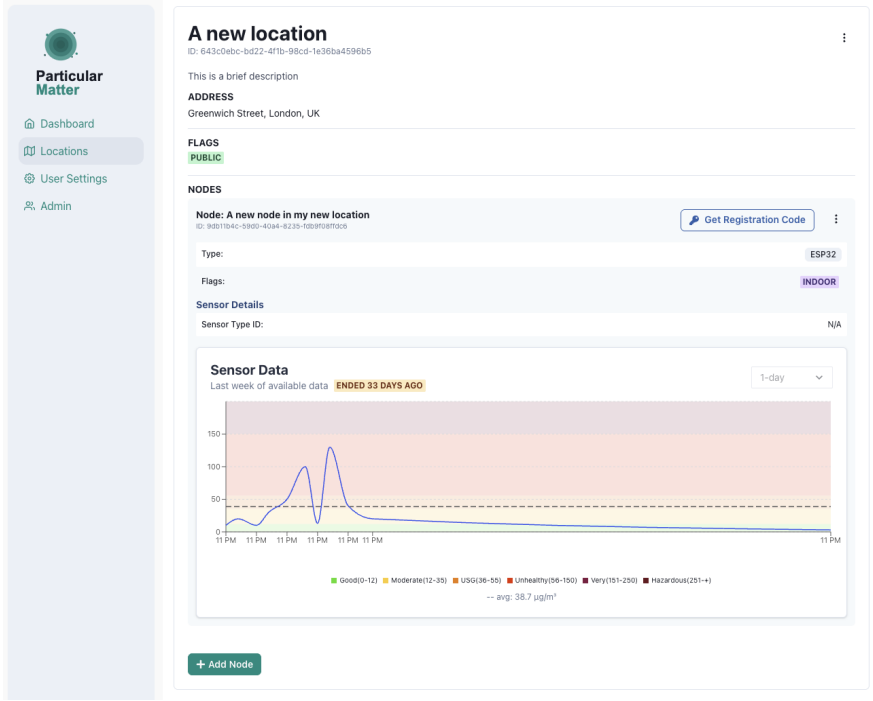
The One Time Key is generated in the Web App by the User

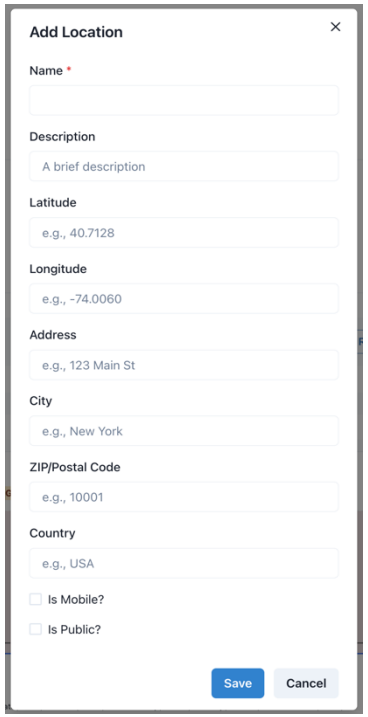
(next slide)

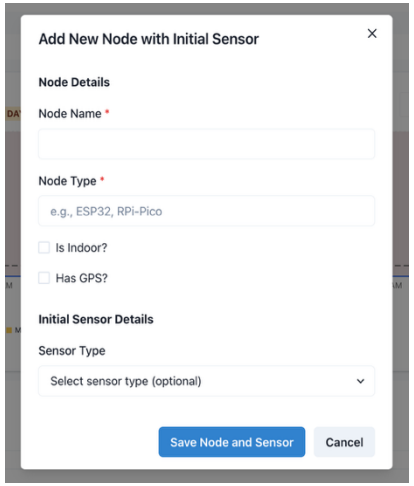
WebApp – Sensor Networks Configuration

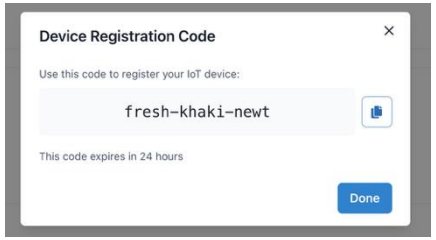
- Web App
  - Create User
    - Location 1
      - Node 1
      - ...
      - Node *n*

One Time Key





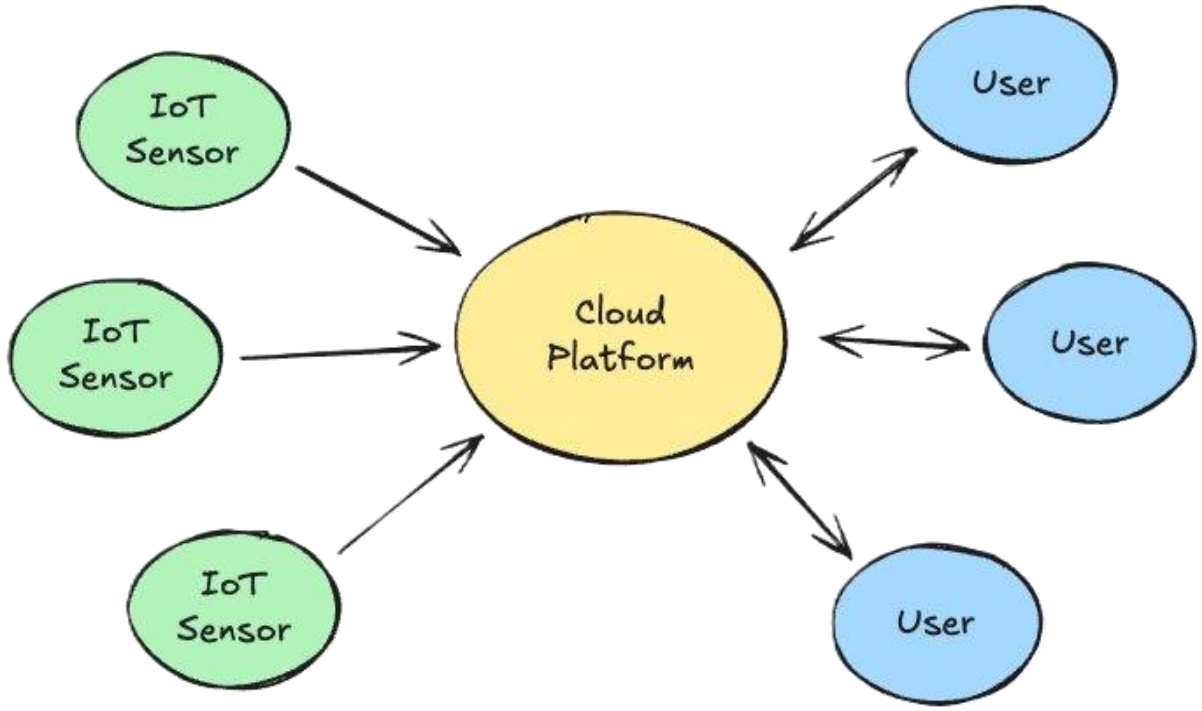




System Overview

Three main parts working together:

- Edge Layer (IoT sensors)
  - Data measurement
  - Data collection
- Platform Layer
  - Data processing
    - Mass Balance Model (e.g., I/O ratio)
  - Storage
- User Layer (via web interface)
  - Data access
  - Visualizations

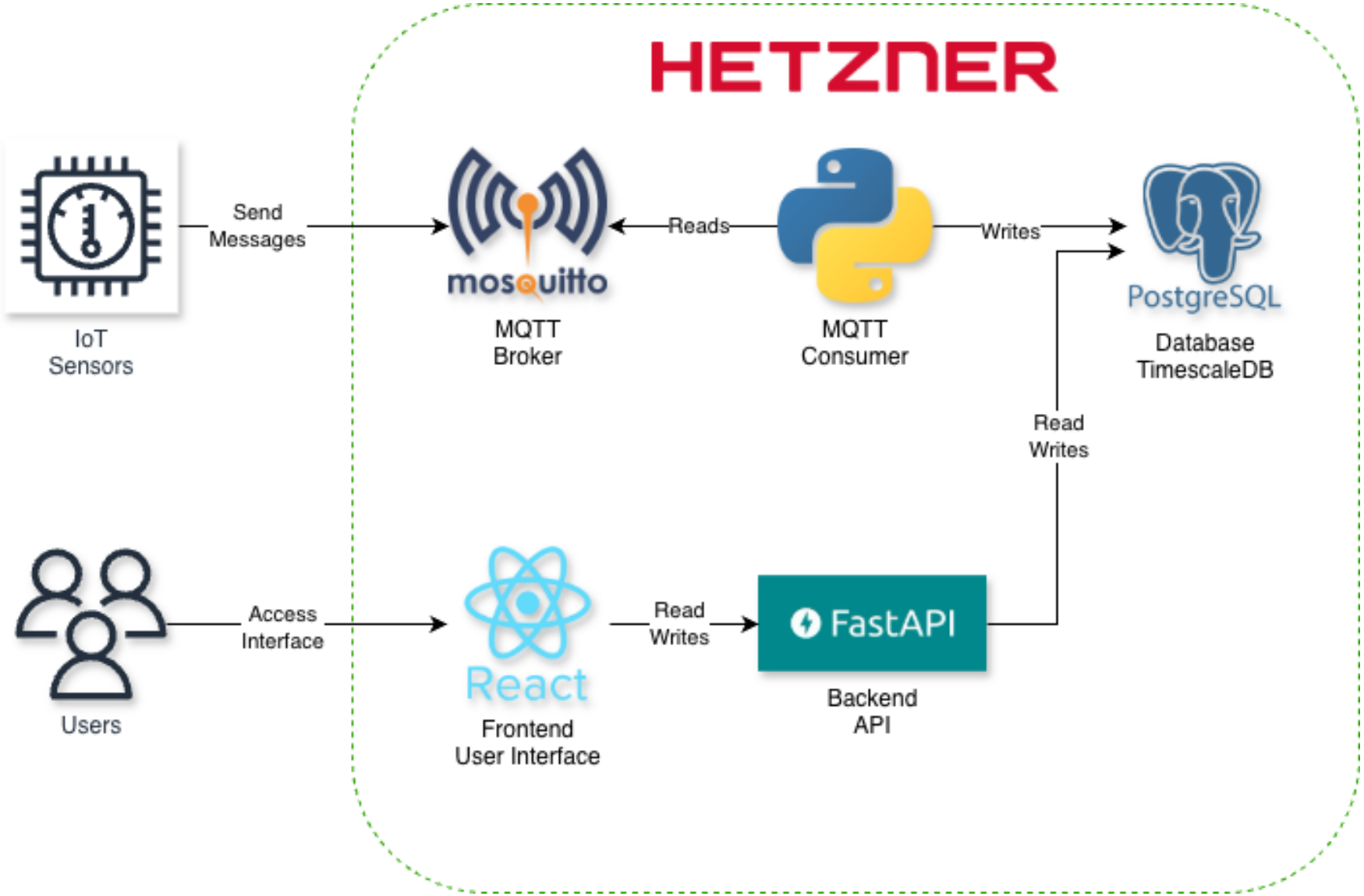


WebApp – Key Features

Some of the features we wanted the platform to have

- 📊 Near-real-time data visualisation
- 🗺️ Interactive map view of all sensors (public & private)
- 📱 Responsive design (works on phone, tablet, computer)
- 🔐 Secure user accounts and data privacy
- 📈 Historical data, trends, and analytics
- 🐣 **Easy-to-Use**

System Architecture Overview

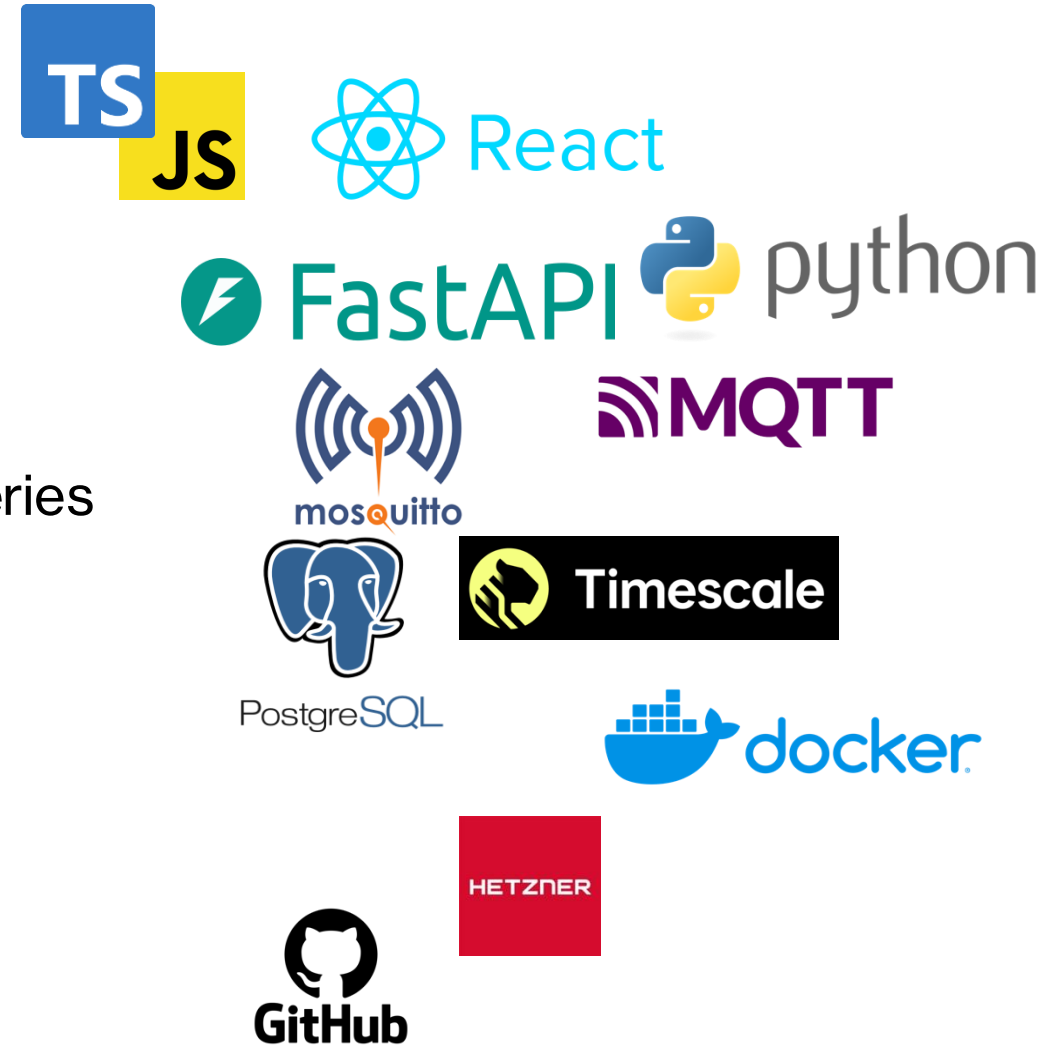


System Architecture

- Web Dashboard: React - frontend
- API Server: FastAPI – backend
- MQTT Broker: Mosquitto - message queue
- Database: PostgreSQL + TimescaleDB for time series

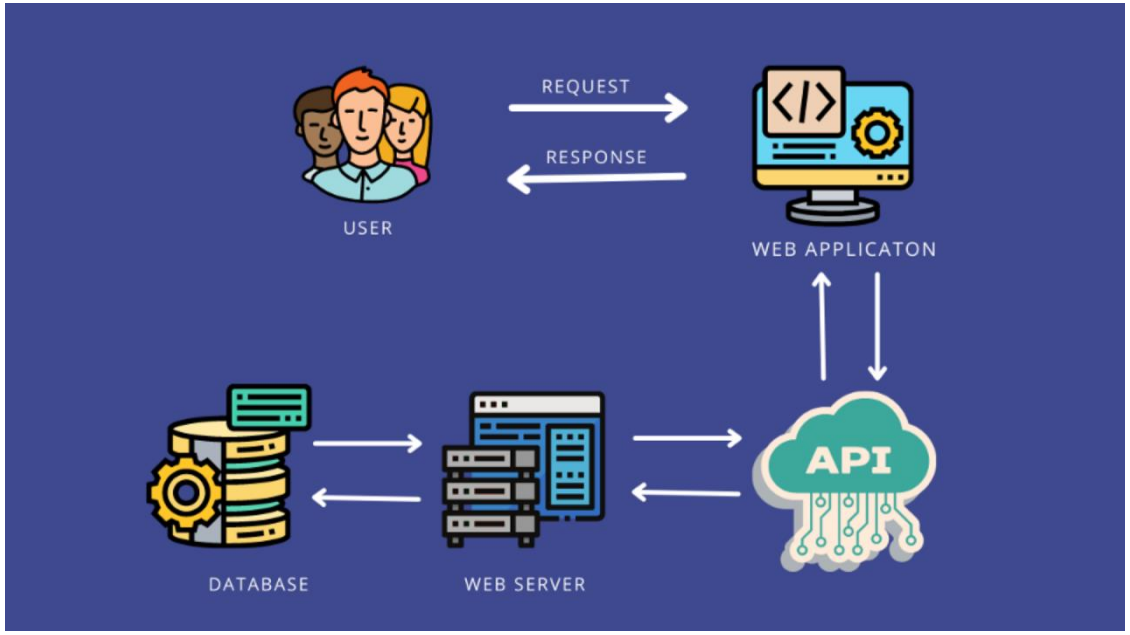
Automated deployment with

- Hetzner
- GitHub workflows
- Docker Compose



Tech Stack – frontend and backend

- Typescript & React
  - Modern, fast, and maintainable web interface
  - Reusable components
- Python & FastAPI
  - High-performance backend
  - Built-in API docs
- Clean separation
  - Frontend <-> API via REST
  - Easier scaling and updates



TS JS React FastAPI python

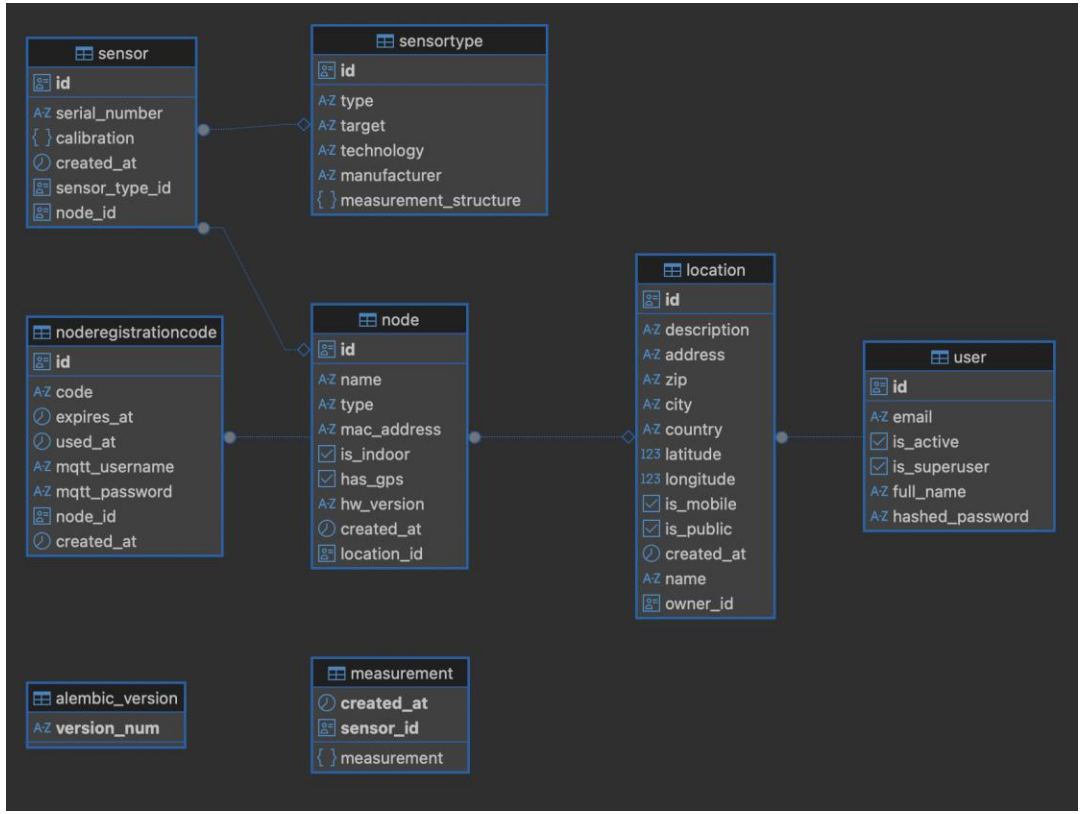
Tech Stack – MQTT Mosquitto

- Lightweight protocol
  - Ideal for small IoT devices
  - Minimal bandwidth and power use
- Reliable messaging
- Real-time communication
  - Low latency between sensors and cloud
  - Support many devices simultaneously
- Open standard
  - Works with ESPHome and other IoT systems

```
mosquitto_pub \
  -h mqtt.particularmatter.org \
  -p 1883 \
  -u <node_id> \
  -P <password> \
  -t measurements/<node_id>/<sensor_id> \
  -m '{"measurement": {"pm25": 100}}'
```

Tech Stack – TimescaleDB

- Built on PostgreSQL
  - Fast, reliable
  - Industry standards, easy integration
- Time-series optimised
  - Perfect for continuous sensor data
  - Handles millions of rows efficiently
- Performance features
  - Automatic data compression
  - Fast aggregation over time windows
- Scalable & stable

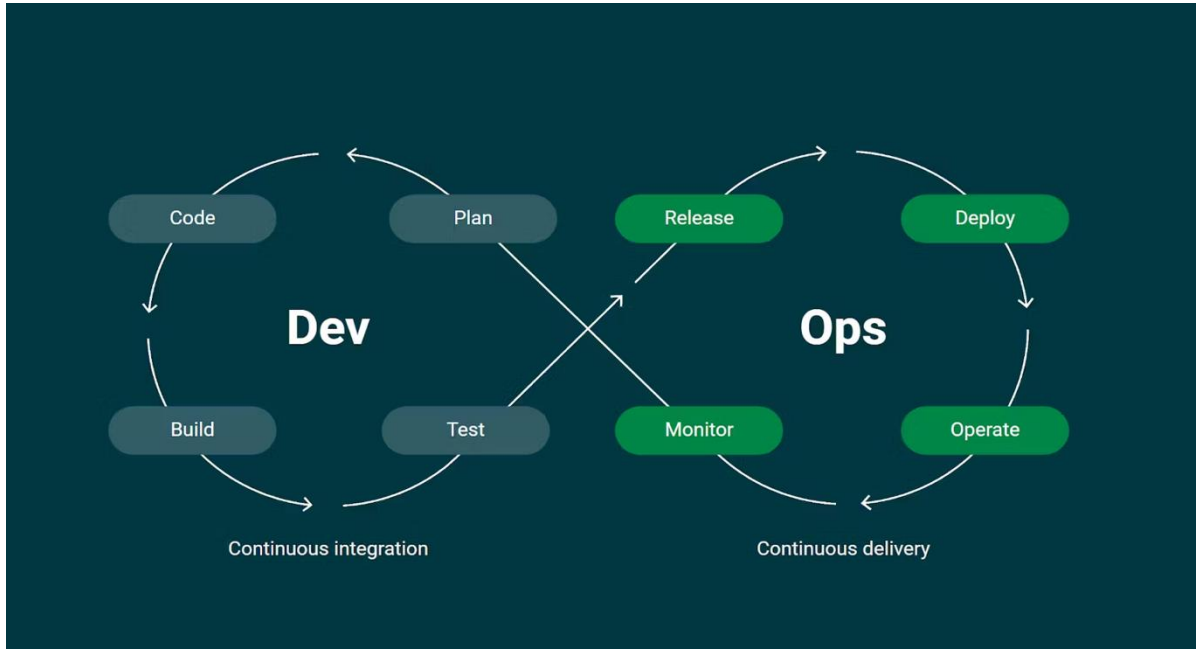


Timescale

PostgreSQL

Tech Stack – DevOps

- Docker
  - Isolated, portable services
  - Consistent local and cloud setup
- GitHub Actions
  - Automatic build, test, deploy
  - Quick and safe releases
- Hetzner
  - European servers
  - High performance at low cost
- Self-Hosted
  - Full control over data

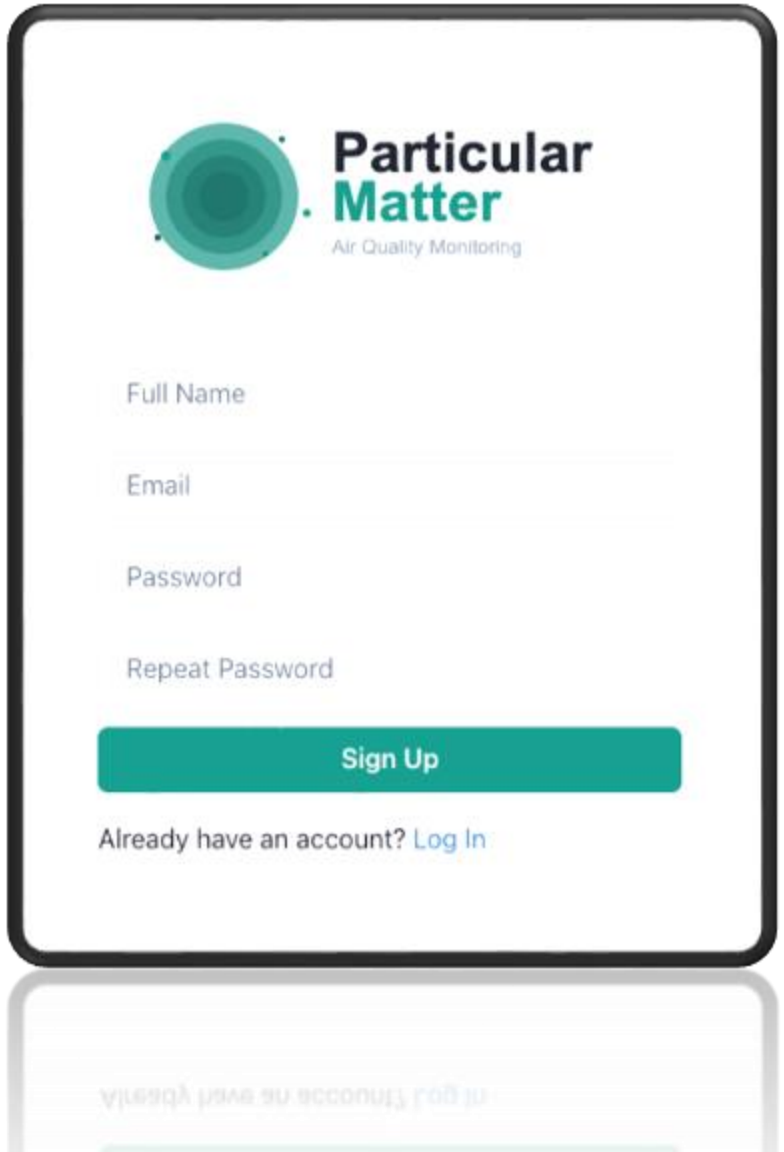


Security and Data Privacy

- Secured authentication using JWT tokens
- Encrypted connections (HTTPS, TLS)
- Each device has unique credentials
- Role-based access control

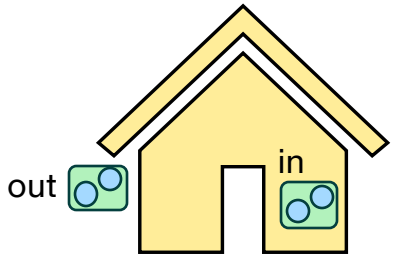
WebApp – Getting Started

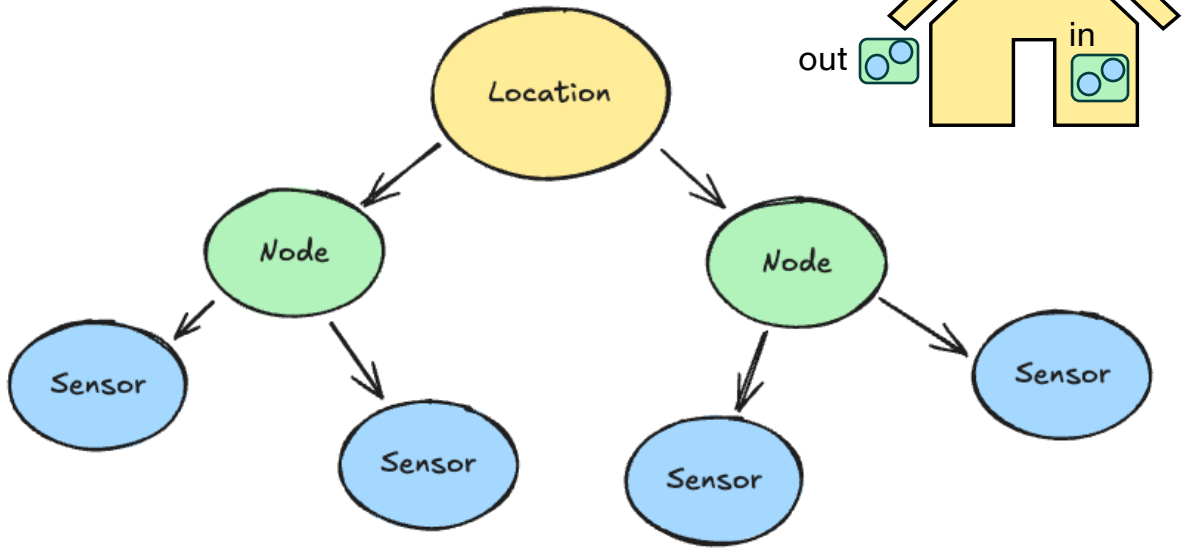
- New users can
  - Navigate to dashboard.particularmatter.org
  - Create an account
  - Start adding locations, nodes, and sensors

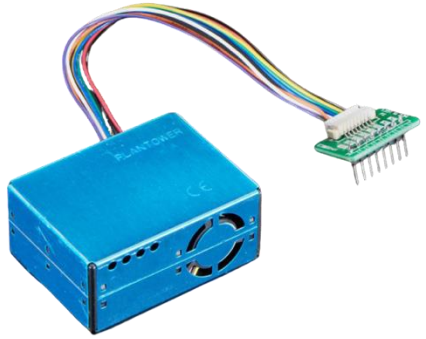


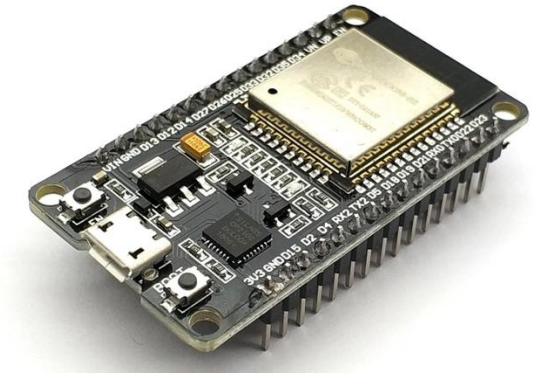
Locations & Sensors Management

- **Locations**
  - Represent physical places (e.g. home, school, park)
  - Group multiple devices under one area
  - Store GPS coordinates, address, and metadata
- **Nodes (Devices)**
  - Each *Node* = one physical device (ESP8266 or similar)
  - Connects to Wi-Fi and sends data to the platform
  - Identified by a unique registration code
- **Sensors**
  - The actual measurement components attached to a node
  - Examples: PM2.5, PM10, temperature, humidity, pressure
  - Each sensor produces time-series data
  - Easily configurable and replaceable

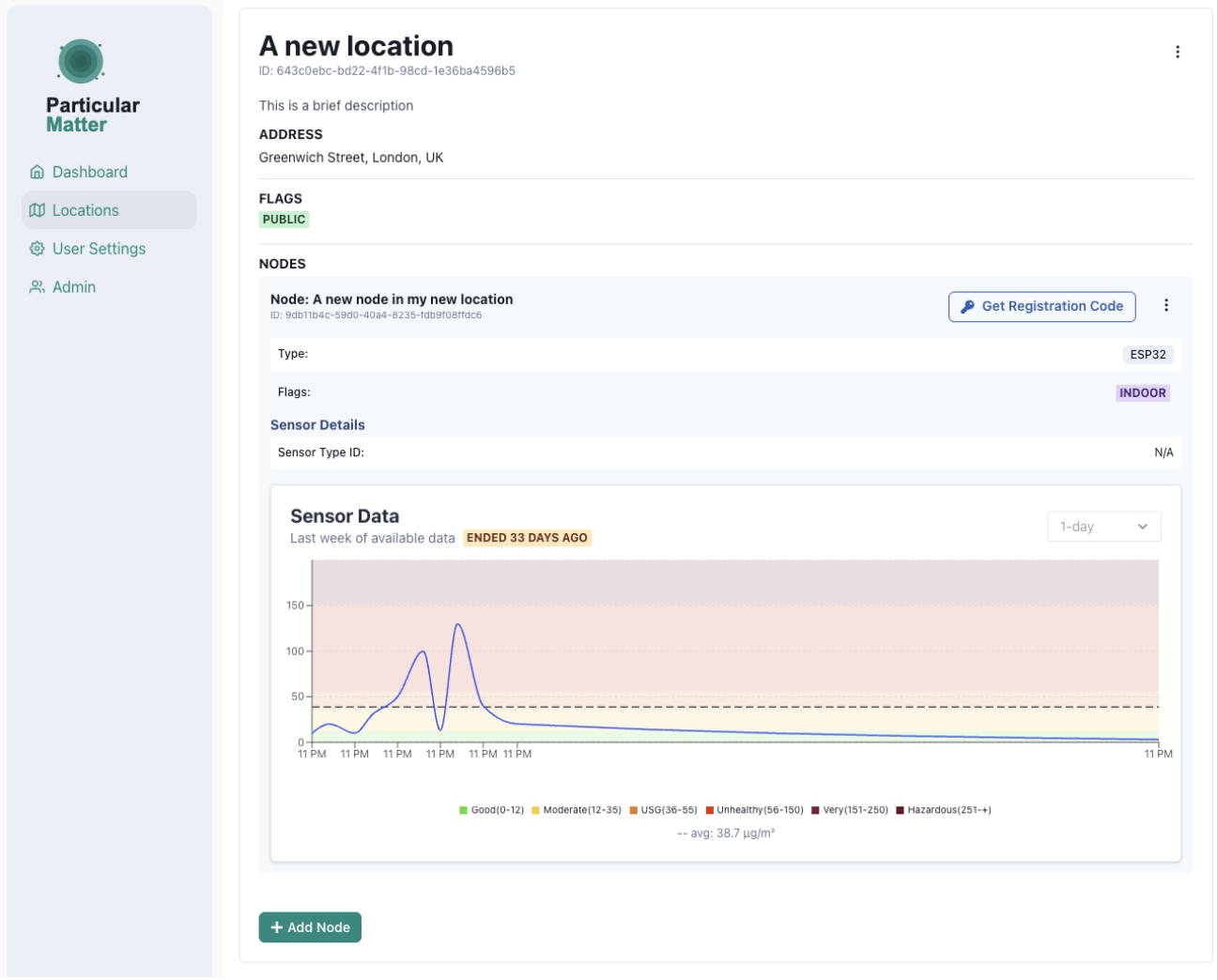




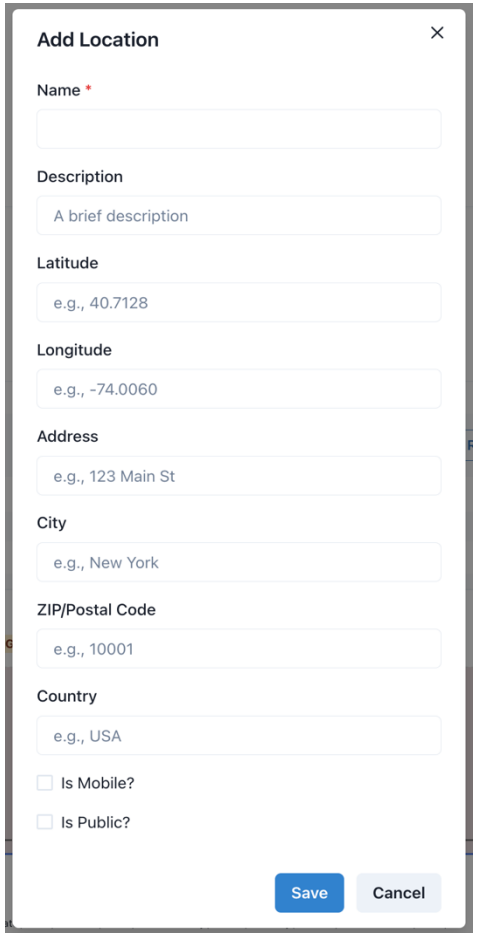


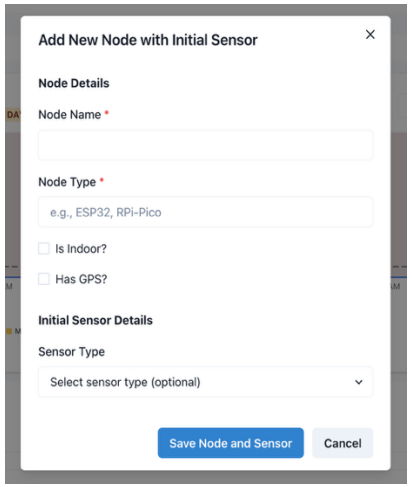


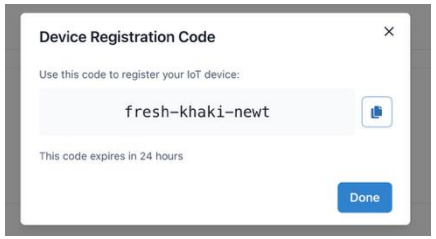
Locations & Sensors Management



Forms to create and register locations, nodes, and sensors:

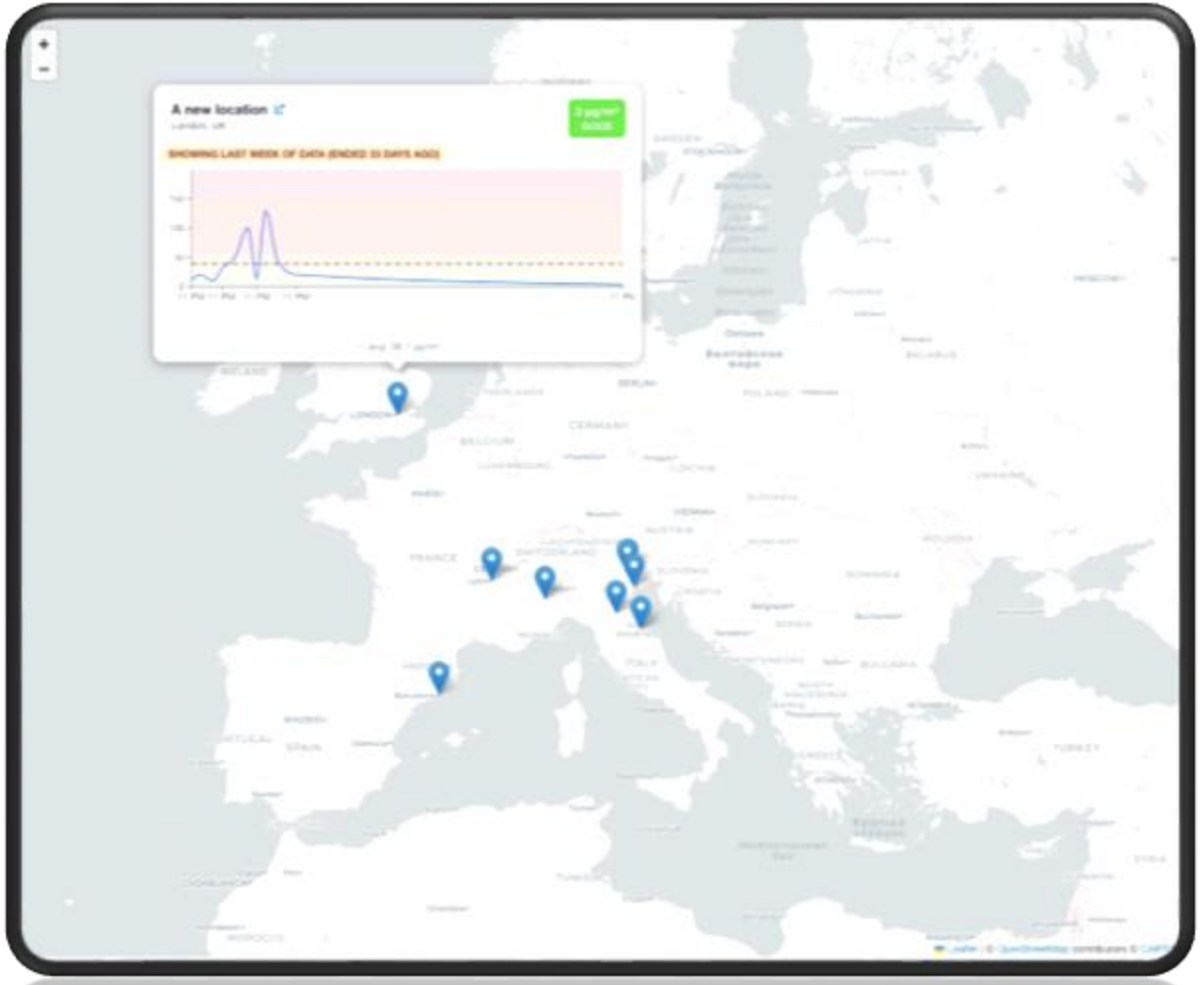






WebApp – Main Dashboard & Map

- **Explore and Visualise Data**
  - View all sensors at a glance on an interactive map (clustered or individual markers).
  - See both your private locations' data and all publicly available data.
  - Click on a marker to open a popup with live sensor readings (e.g. PM2.5, temperature, humidity).
- **Access Analytics Quickly**
  - From the map, navigate directly to a location or sensor's detail page with historical charts.
  - View aggregated air quality indicators (averages, AQI, etc.) for visible areas or selected devices.



Recap for Users!

Web App

Create User

Location 1

Node 1

...

Node *n*

One Time Key

*Application Output

To the Dashboard

Build Device

Install Firmware

Power Up

Access Dev. WiFi

*User Input

One Time Key

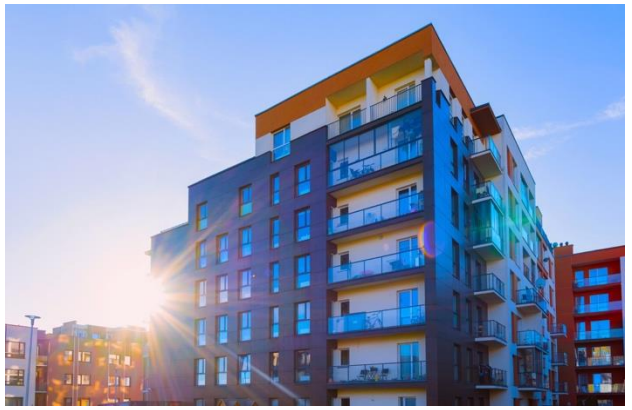
Measurements

Database

Credential Check and Device Registration

Use Cases & Applications

- 🏠 Homeowners monitoring indoor air quality
- 🏫 Schools evaluating classroom air quality
- 🌳 Community groups measuring local pollution
- 🔬 Researchers collecting environmental data
- 🏢 Businesses assessing workspace environmental quality
- 🚜 Farmers tracking greenhouse emissions



Conclusions – a production-ready platform

This is a production-ready platform, not just a prototype

Areas of development:

- Backend API
- Frontend web application
- MQTT broker for IoT communication
- Database design and optimization
- Security implementation
- Deployment automation
- Testing infrastructure
- Documentation
- Hardware integration templates

Thank You

Visit dashboard.particularmatter.org

Create an account

Order hardware (shopping list provided on git)

Follow setup guide

Start monitoring!

Corresponding email: federico.dallo@cnr.it