



# Deploying small vertical axis wind turbines on urban rooftops — A parametric, dynamic, and hybrid life cycle energy and greenhouse gas emissions analysis

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## ABSTRACT

Deploying small wind turbines in urban areas can reduce electricity transmission losses and provide nighttime electricity generation. However, despite a growing recognition of the potential benefits of small urban wind turbines, uncertainties in environmental effects and life cycle environmental performance still hinder widespread adoption. This paper conducts a comprehensive parametric analysis and quantifies: (1) the life cycle energy and greenhouse gas emissions performance of a small urban vertical-axis wind turbine using a hybrid life cycle inventory approach and across 163 170 scenarios, and (2) the large-scale deployment of such turbines across 5 193 urban rooftops, using Brussels, Belgium as a case study. Key findings highlight that (1) Process-based life cycle analysis underestimates embodied energy and greenhouse gas emissions by 61 % and 52 %, respectively, highlighting the need to use hybrid life cycle approaches; (2) The wind energy resource is significantly variable when measured across the urban rooftop canopy; (3) The greenhouse gas emissions return on investment depends on the displaced energy source; (4) The energy return on investment is variable across all rooftop heights, but higher-yield tall buildings with favourable wind conditions should be a priority for urban deployment; and (5) Small urban wind turbines are a viable renewable energy source, offering seasonal and nighttime generation that reduces battery storage needs and associated emissions.

## Abbreviations and potential units

AWEP: Annual Wind Energy Potential (kWh/annum)  
BCR: Brussels Capital Region  
CFD: Computational fluid dynamics  
EFel : Greenhouse gas emissions factor for grid electricity generation (kgCO<sub>2</sub>e/GJ<sup>PRIMARY</sup>)  
EROI: Energy return on investment (1)  
GHGROI: Greenhouse gas emissions return on investment (1)  
GIS: Geographical Information System  
ML: Machine learning  
PEFel: Primary energy conversion factor for grid electricity generation (GJ<sup>PRIMARY</sup>/GJ<sup>DELIVERED</sup>)

## 1. Introduction

With catastrophic human-induced climate change upon us, humanity is tasked with a rapid reduction of greenhouse gas emissions in the coming years, notably through the reliance on renewable energy sources (Clarke et al., 2022). Relying on renewable energy sources is also often linked to the electrification of energy processes, resulting in significant demand for renewable electricity production systems, notably solar and wind (COP28, 2023).

Based on data from IRENA (2024), solar and wind electricity generation have grown significantly in recent years, by 3 900 % and 512 % from 2010 to 2022, respectively. This significant increase for solar energy was largely through the installation of photovoltaic panels, representing 99 % of total solar electricity generation in 2022. When it comes to wind energy, most installations are large-scale wind turbines, with

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**Table 1**

Summary of existing studies on the energy and/or greenhouse gas emissions analysis of small wind turbines.

| Authors                                           | Wind turbine type | Scale of the study | Number of turbines used | Number of settings assessed                                                    | Life cycle assessment | Life cycle inventory approach | Wind flow estimation                                                                                              |
|---------------------------------------------------|-------------------|--------------------|-------------------------|--------------------------------------------------------------------------------|-----------------------|-------------------------------|-------------------------------------------------------------------------------------------------------------------|
| <a href="#">Celik et al. (2007)</a>               | HAWT              | Single Turbine     | 1                       | 5 sites                                                                        | ✓                     | Process                       | Average wind speed at an hourly basis                                                                             |
| <a href="#">Allen et al. (2008)</a>               | HAWT              | Single Turbine     | 1                       | 2 sites                                                                        | ✓                     | Process                       | Average wind speed at an hourly basis collected from rural and urban weather stations and processed statistically |
| <a href="#">Glassbrook et al. (2014)</a>          | HAWT              | National           | 4                       | 10 wind classes                                                                | ✓                     | Process                       | Average wind speeds with probabilistic approach                                                                   |
| <a href="#">Troullaki et al. (2019)</a>           | HAWT              | Single turbine     | 1                       | 1 site                                                                         | ✓                     | Process                       | Single average wind speed                                                                                         |
| <a href="#">Kouloumpis et al. (2020)</a>          | VAWT              | Single turbine     | 1                       | 1 site                                                                         | ✓                     | Process                       | Measured                                                                                                          |
| <a href="#">(Zabarjad Shiraz et al., 2020)</a>    | VAWT              | Urban              | 1                       | 2 sites                                                                        |                       | N/A                           | CFD simulation for two different urban environments                                                               |
| <a href="#">Ngoc et al. (2022)</a>                | VAWT              | Single turbine     | 1                       | 8 Wind directions                                                              | ✓                     | Process                       | Average wind speeds (but measured power generation)                                                               |
| <a href="#">Brandi and Manoli (2025)</a>          | VAWT              | Urban/Regional     | 3                       | 2 sites + 1 extra condition                                                    |                       | N/A                           | Large scale CFD simulation using the Weather Research and Forecast (WRF) model version 4.5.1                      |
| <a href="#">Pfadt-Trilling and Fortier (2025)</a> | VAWT              | Single turbine     | 1                       | 2 urban sites (Lausanne and Geneva) with multiple local climate zones for each | ✓                     | Process                       | Average 15-mins timestep weather data                                                                             |
|                                                   |                   |                    |                         | 26 zip codes in Austin, Texas and Minneapolis, Minnesota, USA                  |                       |                               |                                                                                                                   |

Note: HAWT: horizontal axis wind turbine, VAWT: vertical axis wind turbine; CFD: computational fluid dynamics; N/A: not applicable.

onshore wind turbines generating 92 % of wind electricity and offshore turbines contributing 8 %, while increasingly larger turbines are being installed, due their greater efficiency. This means that smaller-scale decentralised wind turbine deployments have been comparatively underexplored.

Deploying small wind turbines in urban areas can provide multiple benefits from an energy perspective ([Tummala et al., 2016](#)). Firstly, wind resources in cities can peak locally, notably on the roofs of tall buildings and in wind corridors. This can provide significant opportunities for local energy production. Secondly, producing energy locally can significantly reduce transmission losses, as seen with photovoltaic panels. Thirdly, small urban wind turbines are not affected by the diurnal intermittency of solar photovoltaic panels, converting wind flows into electricity during the day and night. Finally, depending on the location, wind flows can have an inverse seasonality to solar radiation. For example, in certain areas, wind may be stronger in winter, when the sun shines less. This could provide significant opportunities to fill the electricity generation gap of solar photovoltaic panels during that period. Certainly, small urban wind turbines come also with environmental effects, such as potential effects on biodiversity through impact with flying animals, flickering, and potential noise and vibrations. These are discussed in detail in [Tsionas et al. \(2025\)](#) or [Bošnjaković et al. \(2025\)](#).

While a few studies have explored the life cycle energy and greenhouse gas emissions balance of small wind turbines, these often suffer from the following limitations, as summarised in [Section 2](#): (1) reliance on process based life cycle inventory analysis to quantify embodied energy and greenhouse gas emissions, resulting in their significant underestimation ([Lenzen, 2000](#)); (2) focus on a single turbine instead of on the deployment of turbines across an entire cityscape; (3) focusing on a turbine in non-urban settings, where wind flows differ intrinsically in terms of turbulence, obstacles, and other aspects.

As such, there is a need to better understand the life cycle energy and greenhouse gas emissions of a single small urban wind turbine using comprehensive life cycle inventory approaches and for a broad range of operational parameters, and of deploying such wind turbines across a section of city, using actual building geometries and computational fluid dynamics.

### 1.1. Aim and scope

The aim of this paper is to quantify the life cycle energy and greenhouse gas emissions profile of a single small urban wind turbine and of deploying such turbine across the roofs of a city.

The paper focuses on energy and greenhouse gas emissions as two critical metrics and excludes other environmental flows and effects (see [Section 5.6](#) for a discussion on limitations). It uses the city of Brussels, Belgium, as a case study for deploying small vertical wind turbines in an urban setting.

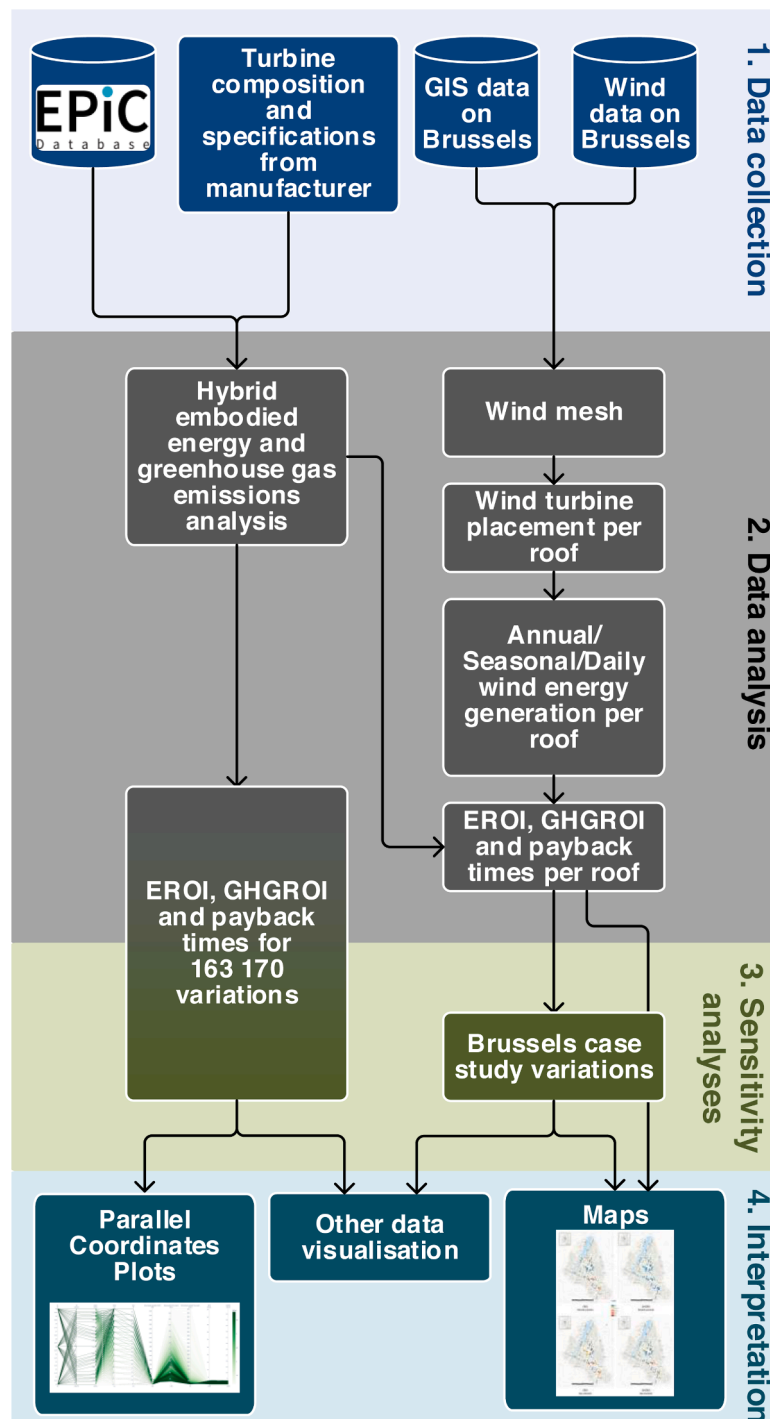
This paper is organised in five sections. [Section 2](#) reviews the existing literature on the topic. [Section 3](#) describes the research method. [Section 4](#) presents the life cycle energy and greenhouse gas emissions profile of a single vertical urban wind turbine and its deployment across the roofs of an entire cityscape. [Section 5](#) discusses these findings and flags limitations before concluding.

## 2. Existing studies on small wind turbines

[Table 1](#) presents a summary of existing studies on the life cycle energy and/or greenhouse gas emissions analysis of small wind turbines. It is important to flag that the selection of studies is by no means systematic nor comprehensive but rather aims to provide a meaningful sample of studies that represent the current scientific literature on the matter. Importantly, very few studies focus on the life cycle environmental performance of urban wind turbines. For instance, while [Bošnjaković et al. \(2025\)](#) have provided a recent scoping review of the topic and [Zhang et al. \(2022\)](#) have studied the wind flow in a neighbourhood, both studies do not mention embodied environmental flows once.

As can be seen in [Table 1](#), existing studies on the life cycle energy and greenhouse gas emissions of small wind turbines suffer from three main limitations. These are flagged below.

Firstly, all existing studies rely on the so-called process analysis for their life cycle inventory. This means that embodied energy and greenhouse gas emissions of wind turbines are based on bottom-up industry data. While these data tend to be reliable in terms of what they represent, they are systematically underestimating embodied flows because of the established truncation error (see [Section 3.2.1](#)). In essence, with complex globalised supply chains, it becomes quickly impossible to ascertain the environmental flows associated with certain



**Fig. 1.** Overall research approach. Note: EROI = Energy return on investment, GHGROI = Greenhouse gas emissions return on investment, original in colour.

activities. What is the embodied energy share of the truck used to mine the copper used in the wires of the wind turbine? The answer to this question is often: “this should be small, and we do not know, so let us exclude it”. While the latter is true, the sum of tens of thousands of similarly small inputs can be quite large, as demonstrated in the EPiC database, which reveals an average truncation error of 49 % across 409 different construction materials and for embodied energy, greenhouse gas emissions, and water (Crawford et al., 2024). As such, current studies underestimate the embodied energy and greenhouse gas emissions of wind turbines, resulting in more optimistic energy and greenhouse gas emissions return on investment than is true. Using a comprehensive hybrid life cycle inventory approach (see Section 3.2.1)

to ensure a complete system boundary of the supply chain is therefore needed to provide realistic estimates of the embodied environmental flows of wind turbines. This has been done in two previous studies focusing on large scale horizontal wind turbines (Crawford, 2009; Wiedmann et al., 2011). However, there is a significant difference in material composition and power curve of small vertical axis wind turbines, and in their ambient conditions (i.e. turbulent, erratic, lower-velocity wind flows). Furthermore, existing studies using a hybrid life cycle inventory approach were conducted around 15 years ago, when both process and input-output data were less accurate and reliable as compared to the time of writing. As such, a hybrid life cycle assessment of small urban wind turbines is warranted.

**Table 2**

Sensitivity analysis parameters for the life cycle energy and greenhouse gas emissions analysis of the single wind turbine.

| Parameter                                                   | # values               | Values                                                                                                                                                                                                                                                                                                                                            | Comments                                                                                                                                                                                                            |
|-------------------------------------------------------------|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Average annual energy production                            | 35                     | 100–3 500 kWh/a in 100 kWh/a increments                                                                                                                                                                                                                                                                                                           | A broad range of annual energy generation per turbine is explored to represent a variety of wind velocities in urban settings                                                                                       |
| Primary energy conversion factor for electricity generation | 14                     | 3.8, 3.6, 3.4, 3.2, 3, 2.8, 2.6, 2.4, 2.2, 2, 1.8, 1.6, 1.4, 1.2                                                                                                                                                                                                                                                                                  | Varying the primary energy conversion factor for electricity from a high value of 3.8 (e.g. Lebanon) to a low value of 1.2 (e.g. Belgium in 2050)                                                                   |
| Emissions factor for electricity                            | 3 for each PEFel       | 14 values from 90 to 5 kgCO <sub>2</sub> e/GJ <sup>PRIMARY</sup> matched to the primary energy conversion factors above. For each PEFel, we investigate a further $\pm 10$ % of variation of the emissions factor, resulting in $14 \times 3 = 42$ values of emissions factors. For example:<br>PEF 3.8 = [99, 90, 81]<br>PEF 1.2 = [5.5, 5, 4.5] | Varying the greenhouse gas emissions factor for electricity from 90 kgCO <sub>2</sub> e/GJ <sup>PRIMARY</sup> (e.g. coal) to 5 kgCO <sub>2</sub> e/GJ <sup>PRIMARY</sup> (e.g. an almost totally decarbonised grid) |
| Uncertainty on embodied flows                               | 36 + the nominal value | Three levels of uncertainty are considered, low ( $\pm 20$ % process; $\pm 50$ % input-output), medium ( $\pm 30$ % process; $\pm 60$ % input-output), and high ( $\pm 40$ % process; $\pm 70$ % input-output).                                                                                                                                   | Uncertainty in the data behind the embodied environmental flows can be significant. Uncertainty based on Stephan (2013) and inspired by figures from Lenzen (2000).                                                 |
| Service life                                                | 3                      | 20, 25 and 30 years                                                                                                                                                                                                                                                                                                                               | Three values of 20, 25 and 30 years were assumed based on using the maximum provided warranty from existing suppliers and doubling that number (reaching $\sim 25$ years), then modifying by $\pm 5$ years.         |

Secondly, many existing studies do not appropriately consider wind flows in urban conditions, either by locating the study on the periphery of urban areas (e.g. Glassbrook et al. 2014), or by not relying on advanced computational fluid dynamics to estimate the wind flow at a high resolution (e.g. Troullaki et al. 2019). It is important to flag that some recent studies, such as Brandi and Manoli (2025) or Zabarjad Shiraz et al. (2020) use advanced wind simulation or measurement approaches, but these do not conduct a life cycle assessment of the wind turbine. Similarly, some studies focus exclusively on the estimation of wind potential on rooftops, such as Hou and Jafari (2020) or Lv et al. (2022), but these again do not integrate the life cycle environmental performance of wind turbines. To appropriately understand the life cycle energy and greenhouse gas emissions implications of deploying small wind turbines in an urban environment, adequate approaches to model the urban environment and urban wind flows need to be used. Those that do consider more advanced wind simulations tend not to adopt a life cycle assessment approach.

Thirdly and finally, many studies focus on a single wind turbine (e.g. Kouloumpis et al. 2020, Pfadt-Trilling and Fortier 2025), not taking into account their deployment at scale. While monitoring the actual performance of a single small wind turbine is certainly praiseworthy and can provide insights into actual versus theoretical performance, there is a need to quantify the implication of deploying hundreds of urban turbines on hundreds of roofs to understand variations in their performance, trends and overall feasibility and life cycle environmental performance.

In addition to the review of selected literature on the topic, recent review papers on the matter provide further reinforcement to the need for this study. These include the need to better understand wind energy harvesting on tall buildings (Škvorec & Kozmar, 2021) and the need to integrate life cycle assessment with detailed roof geometry and computational fluid dynamics (Qin & Wang, 2025; Salvador-Gutierrez et al., 2025).

To summarise, the research gaps identified by the review of the literature and recent review papers on the matter clearly demonstrate the need for a study that quantifies the life cycle energy and greenhouse gas emissions performance of small urban wind turbines (using the advanced hybrid life cycle inventory approach), both studied individually and deployed at scale in urban settings. The urban setting deployment should rely on advanced computational fluid dynamics modelling techniques to capture the urban canopy (Wen et al., 2025), moving away from the reliance on average wind speeds.

### 3. Method

#### 3.1. Research approach

Fig. 1 depicts the overall research approach used in this paper. Firstly, various datasets are gathered to be able to characterise a single small vertical axis wind turbine as well as urban data for simulating wind flows on roofs. Secondly, the embodied energy and greenhouse gas emissions of the single wind turbine are computed and combined with a range of different annual electricity generation conditions. In parallel, the urban data for Brussels, Belgium are combined into a computational fluid dynamics model and the wind velocities on roofs are simulated. This enables identifying roofs where wind turbines would generate enough electricity. Wind turbines are deployed on these roofs, and their annual electricity generation is computed, specifically for this turbine model and the local wind flow. Embodied energy and greenhouse gas emissions are added to compute key indicators on a roof basis, for the context of Brussels. Thirdly, the sensitivity of the results to broad ranges of uncertainty and variability in key variables is tested. Finally, results are visualised for interpretation.

#### 3.2. Establishing the life cycle energy and greenhouse gas emissions analysis of a single vertical axis wind turbine

##### 3.2.1. Quantifying embodied energy and greenhouse gas emissions

Embodied environmental flows can be quantified using three approaches, namely process analysis, input-output analysis, and hybrid analysis. Process analysis relies on bottom-up industry data that maps the different processes associated with the production and delivery of a service of products, and quantifies the inflows and outflows at each stage (Finnveden et al., 2009). As such, process analysis uses the most accurate existing data to represent a given process. The issue arises when we move further upstream in the supply chain or sideways, and there are no data. Process analysis assumes these contributions to be equal to zero. While the individual contribution of one supply chain pathway 12 stages upstream can be very small (e.g. less 0.001 %), the sum of hundreds of thousands of omitted pathways can represent a significant proportion of the supply chain. This means that process analysis suffers from the so-called ‘truncation error’ and systematically underestimates the embodied environmental flows of products and services (Dixit et al., 2015; Lenzen, 2000; Majeau-Bettez et al., 2011). Input-output analysis is a top-down macroeconomic approach that represents the entire economy and classifies it into sectors (Leontief, 1970). As such, a given



product, e.g. cold rolled steel, is allocated to the economic sector producing it. Using so-called environmental extensions, direct and total environmental intensities per currency unit can be derived for each economic sector. Knowing the cost of a product or service and multiplying it by the environmental intensity of the associated sector can therefore provide an estimate of its embodied environmental flows. This approach is very coarse compared to process analysis, but it is systematically complete, capturing all supply chain pathways across the economy. Hybrid analysis combines process and input-output analysis to eliminate the drawbacks of both methods. It uses the more accurate process analysis where data are available and fills the missing parts of

in flow unit/currency unit (e.g. kgCO<sub>2</sub>e/AUD for greenhouse gas emissions);

### 3.2.2. Quantifying annual energy production and displaced greenhouse gas emissions

The energy produced annually by the wind turbine is converted to primary energy by considering the type of electricity it is replacing. Displaced greenhouse gas emissions are quantified by multiplying the avoided primary energy by a corresponding greenhouse gas emissions factor. Eq. (2) represents these calculations.

$$OPSGHG_{wt} = \sum_{y=0}^{POA} \left( \sum_{h=1}^H PC_{wt}(WS_h) \right) \times \frac{3.6}{1000} \times PEF_y^{EL} \times EF_y^{EL} \quad (2)$$

*APES<sub>wt</sub>* = Annual primary energy saved  
*AGHGS<sub>wt</sub>* = Annual greenhouse gas emissions displaced

the supply chains with coarse input-output data to be systemically complete. For a detailed review of hybrid life cycle inventory methods, see Crawford et al. (2018).

In this paper, embodied energy and greenhouse gas emissions are quantified by converting the quantities of materials within a typical vertical axis wind turbine into associated embodied energy and greenhouse gas emissions, using coefficients from the EPiC Database (Crawford et al., 2022, 2024). The EPiC Database is chosen as the only publicly available database of hybrid embodied environmental flow coefficients for construction materials, globally. This covers stages A1-A3 of the construction process, as per EN15978 (European Standard 15978, 2011). To account for stages A4 and A5, pure input-output data covering the entire associated supply chain is used. For stage A4, this is done by first extracting the so-called stage 1 inputs of road transport into the *Civil Construction and Infrastructure* sector used in the EPiC Database and multiplying its energy and emissions intensity by the cost of the wind turbine. For stage A5, the direct intensity of the associated input-output sector is used. In addition, the so-called input-output remainder is added to the total embodied flows, covering essentially non-material pathways in the supply chain. It is important to note that the input-output remainder has been corrected in this attempt as no sector properly represents the construction of a vertical axis wind turbine. As such, inputs of materials not used in the turbine, e.g. cement and concrete products, were removed. This results in an 'adjusted' remainder. The details of these calculations are all provided in the supplementary information, see Section Data availability.

$$IEF_{wt} = \sum_{m=1}^M (Q_{m,wt} \times FC_m) + \left( TFIS - NATFR_{wt} - \sum_{m=1}^M TFR_{m,wt} \right) \times C_{wt} \quad (1)$$

Where:  $IEF_{wt}$  is the initial embodied flow of the wind turbine  $wt$  in flow unit (GJ for energy);  $M$  is the total number of materials in the wind turbine  $wt$ ;  $Q_{m,wt}$  is the quantity of material  $m$  in the wind turbine  $wt$  (e.g. kg of steel);  $FC_m$  is the hybrid flow coefficient of material  $m$  in flow unit per functional unit of material (GJ/kg);  $TFIS_{wt}$  is the total flow requirement of the input-output sector associated with infrastructure assets, in flow unit/currency unit (e.g. kgCO<sub>2</sub>e/AUD for greenhouse gas emissions);  $NATFR_m$  is the total flow requirement of all input-output pathways not associated with the installation or production process of wind turbine  $wt$ , in flow unit/currency unit (e.g. kgCO<sub>2</sub>e/AUD for greenhouse gas emissions), e.g. pathways representing concrete inputs into the infrastructure sector; and  $TFR_{m,wt}$  is the total flow requirement of the input-output pathway representing material  $m$  in wind turbine  $wt$ ,

Where:  $OPSGHG_{wt}$  is the displaced operational greenhouse gas emissions of wind turbine  $wt$ , in kgCO<sub>2</sub>e;  $POA$  is the period of analysis, in years;  $H$  is the total number of hours in a year, i.e. 8760;  $PC_{wt}$  is the power curve of wind turbine  $wt$ , in kW/(m·s), as function of the wind speed  $WS$ ;  $WS_h$  is the average wind speed for hour  $h$ , in m/s;  $PEF_y^{EL}$  is the primary energy conversion factor for electricity, in GJ<sup>PRIMARY</sup>/GJ<sup>DELIVERED</sup>, for year  $y$ ;  $EF_y^{EL}$  is the greenhouse gas emissions factor for electricity, in kgCO<sub>2</sub>e/GJ<sup>PRIMARY</sup>, for year  $y$ ;  $APES_{wt}$  is the annual primary energy saved by the wind turbine  $wt$ , in GJ<sup>PRIMARY</sup>/annum; and  $AGHG_{wt}$  is the annual greenhouse gas emissions displaced by the wind turbine  $wt$ , in kgCO<sub>2</sub>e/annum.

### 3.2.3. Quantifying payback time and energy and greenhouse gas emissions return on investment

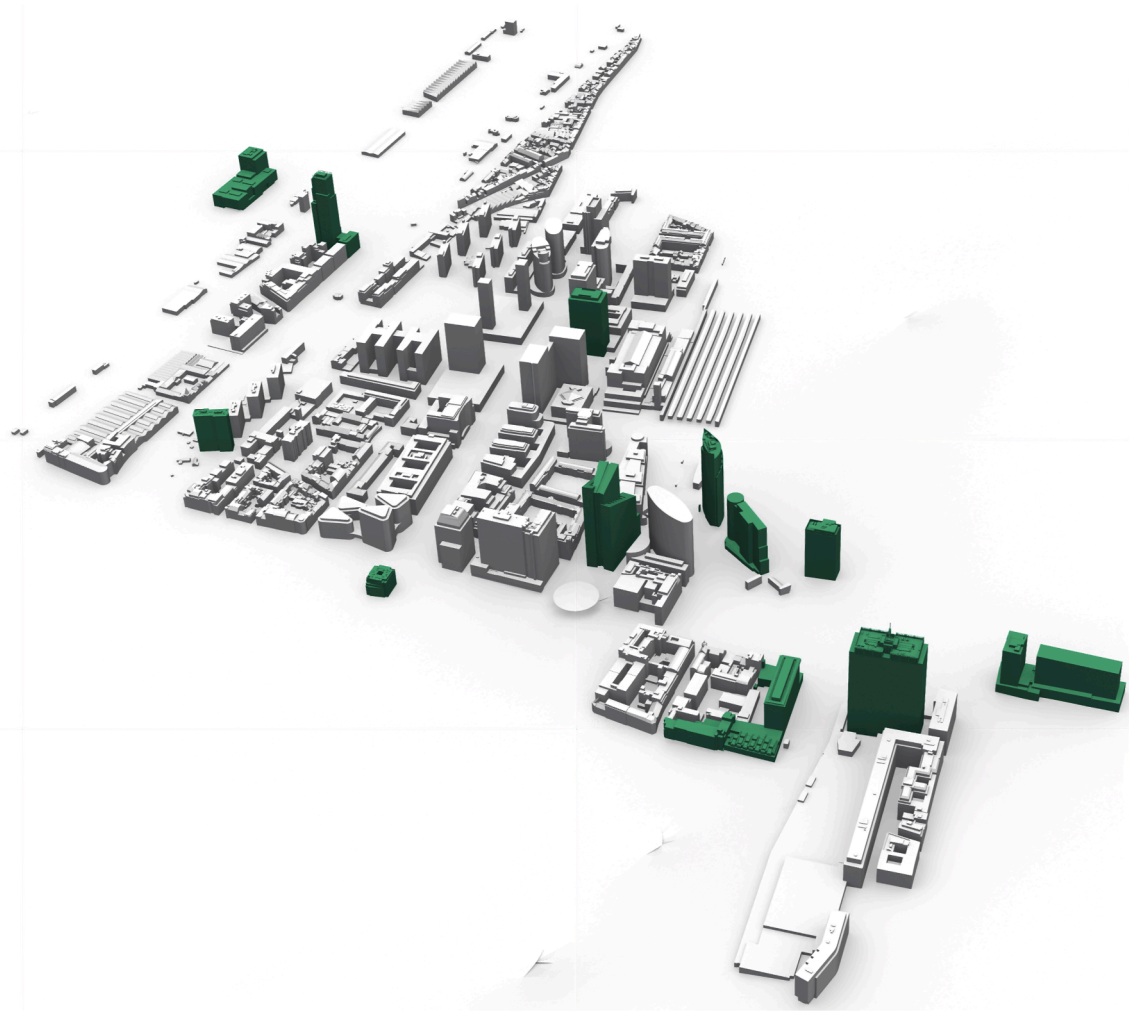
To integrate the embodied energy and greenhouse gas emissions of a wind turbine, four indicators are quantified in this paper, namely the energy and greenhouse gas emissions payback times as well as the energy and greenhouse gas emissions return on investment. The payback times consist of the number of years needed for a wind turbine to produce or displace the energy or greenhouse gas emissions needed for its production, respectively. The energy and greenhouse gas emissions returns on investment represent the ratio of the total amount of energy produced or greenhouse gas emissions displaced, over the life of a turbine, over the total amount of energy or greenhouse gas emissions needed for its production. Eqs. (3) and (4) provide the formulae for the quantification of a payback time and a return on investment, respectively.

$$FPB_{wt} = \frac{IEF_{wt}}{AFS_{wt}} \quad (3)$$

Where:  $FPB_{wt}$  is the flow payback time of wind turbine  $wt$ , in years;  $IEF_{wt}$  is the initial embodied flow of the wind turbine  $wt$  in flow unit (e.g. GJ for energy); and  $AFS_{wt}$  is the average annual flow saved for wind turbine  $wt$ , in flow unit, (e.g. GJ/annum for energy).

$$FROI_{wt} = \frac{OPFS_{wt}}{IEF_{wt}} \quad (4)$$

Where:  $FROI_{wt}$  is the flow return on investment of wind turbine  $wt$ ;  $OPFS_{wt}$  is the operational flow savings for wind turbine  $wt$ , in flow units (e.g. GJ for energy); and  $IEF_{wt}$  is the initial embodied flow of the wind turbine  $wt$  in flow unit (e.g. GJ for energy).



**Fig. 2.** Three-dimensional model used for the computational fluid dynamics simulations. Highlighted buildings in green were manually edited to add more details on the rooftops. Note: Original in colour.

### 3.2.4. Parametric analysis of a single vertical axis wind turbine

The life cycle energy and greenhouse gas emissions performances of a single turbine are affected by various factors, including: its annual electricity generation, the primary energy conversion factor for the grid electricity being replaced, the greenhouse gas emissions factor for the grid electricity being replaced, uncertainty in the embodied energy and greenhouse gas emissions factors and the service life of the turbine.

The annual electricity generation of the wind turbine was parametrically constrained between 100 and 3 500 kWh/annum to account for a broad range of urban situations and based on the minimum and maximum values yielded by the wind turbine in the context of Brussels, Belgium (see [Section 3.3](#)).

These annual energy production increments were then converted to primary energy accounting for the replacement of grid energy that would otherwise be used. This is to account for the substitution of grid energy by urban wind energy. The primary energy conversion factor for electricity was also parametrically constrained, between a maximum of 3.8, representing a heavy fuel oil and private diesel generators electricity production as in Lebanon ([Stephan & Stephan, 2014](#)) down to a minimum of 1.2, representing a grid based on renewable energy sources, as in Belgium in 2050 ([Elia Transmission Belgium, 2024](#)).

Similarly, greenhouse gas emissions factors for electricity generation are paired with the primary energy conversion factors to represent energy mixes that are emissions-intensive ( $90 \text{ kgCO}_2\text{e/GJ}^{\text{PRIMARY}}$ ) ([Department of Industry, 2021](#)) as the highest value, down to

decarbonised grid ( $5 \text{ kgCO}_2\text{e/GJ}^{\text{PRIMARY}}$ ). This means that the calculation of displaced greenhouse gas emissions is compounded by first multiplying the electricity production of the wind turbine by the primary energy conversion factor and then by the greenhouse gas emissions factor. Three different greenhouse gas emissions factors were considered for each primary energy conversion factor for electricity.

Regarding embodied environmental flows, three levels of uncertainty are computed: low, medium and high. For each level of uncertainty, a range is applied to the portion of the embodied flows that derive from process and input-output data as these data sources have different degrees of uncertainty.

Importantly, three different service lives for the turbine were investigated. This enables testing the sensitivity of results to this important variable.

[Table 2](#) summarises all the different values used in the sensitivity analysis of the single wind turbine. In total, 52 920 variations for the EROI and energy payback were simulated ( $35 \text{ annual wind energy generation} \times 14 \text{ PEFel} \times (6 \text{ process data uncertainty values} \times 6 \text{ input-output data uncertainty values} + 1 \text{ nominal value}) \times 3 \text{ service lives}$ ), multiplied by three for the GHGROI and the greenhouse gas emissions payback time, for a total of 163 160 variations.

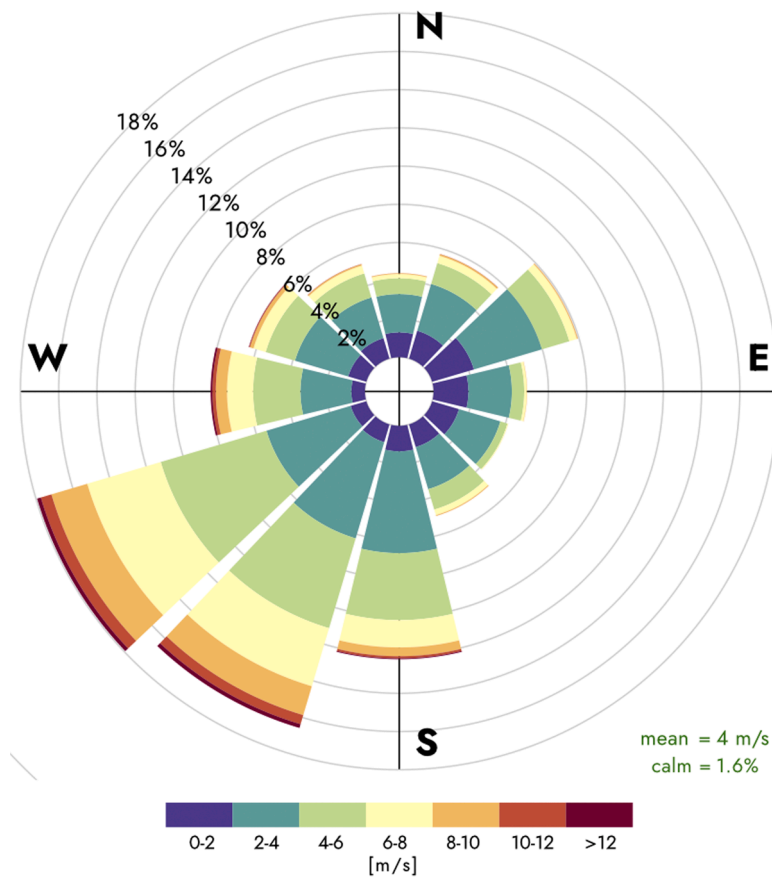


Fig. 3. Wind rose - Brussels for the period 1983–2023. Note: Original in colour.

### 3.3. Deploying the wind turbine across the roofs of the Brussels Capital Region, Belgium

#### 3.3.1. Urban morphology

The case study area presented focuses on the northwestern part of the Brussels Capital Region (BCR) - namely the North Quarter of Brussels-comprising parts of Brussels, Sint-Joost-ten-Node, Schaerbeek, and Sint-Jans-Molenbeek municipalities. The North Quarter of Brussels, covering 53 hectares (0.53 km<sup>2</sup>), is also part of the Positive Energy Districts

initiative of the BCR, which aims to create sustainable and diverse neighbourhoods that produce more energy than they use for their operation (City of Brussels, 2024). This area is particularly suitable for studying wind energy potential due to the presence of high-rise buildings – many around 100 m tall, which are prime candidates for small vertical urban wind turbine deployment, as their roofs typically experience higher wind speeds than lower surrounding structures

The 3D model of the city was obtained from the open data store of the BCR (Brussels Datastore, 2024) and consists of simplified topography

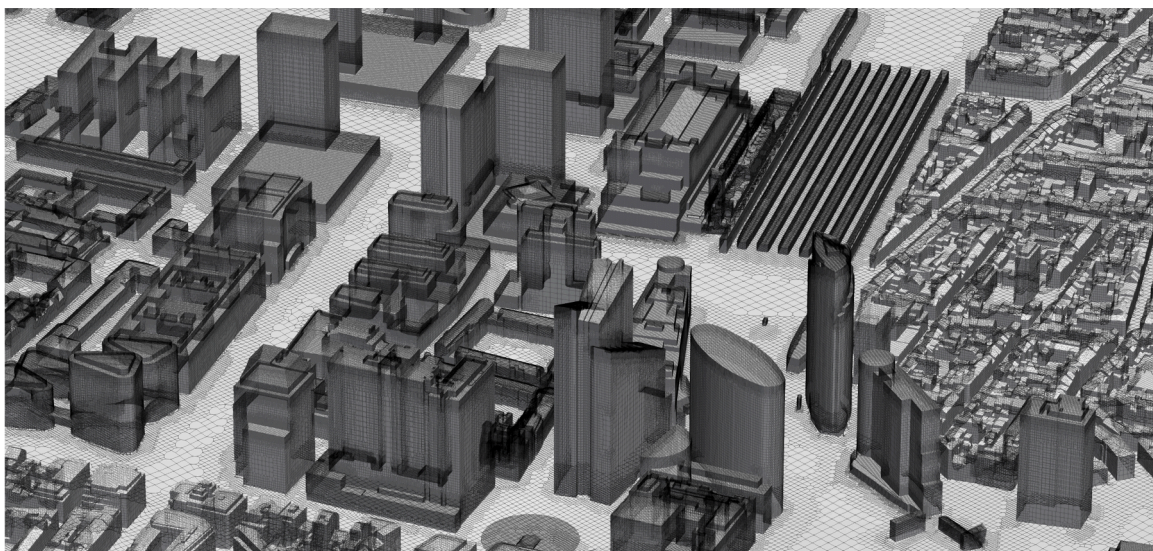


Fig. 4. Computational mesh used for computational fluid dynamics simulations.



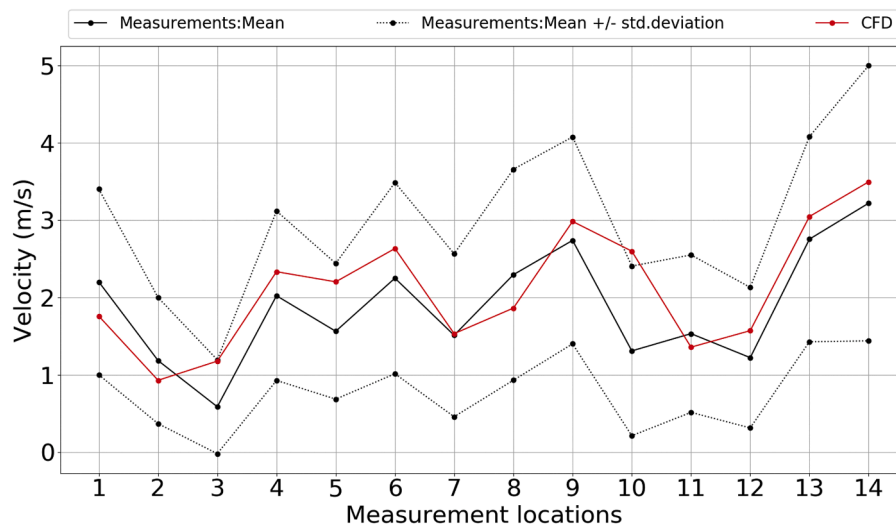


Fig. 5. Wind speed validation from Oklahoma Joint Urban Campaign 2003 performed for the CFD model in Raghunathan Srikumar et al. (2024).

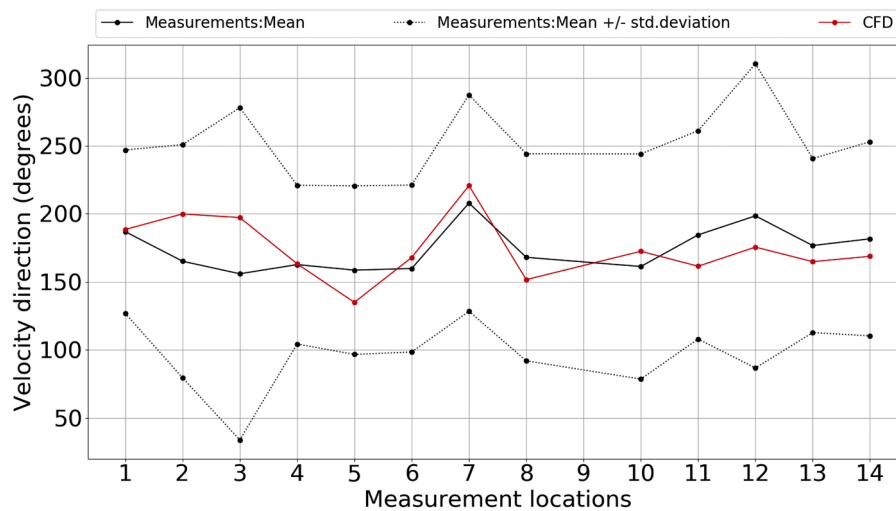


Fig. 6. Wind direction validation from Oklahoma Joint Urban Campaign 2003 performed for the CFD model in Raghunathan Srikumar et al. (2024).

and building geometries, including some roof representations. The model consists mainly of extruded footprints. The footprint and height are relatively accurate. As such, the basic volumetry of the urban fabric is captured in the 3D model. However, since the wind resource on a rooftop is very sensitive to detailed geometrical variations at the roof level, improving the modelling of rooftops was deemed important. As such, point cloud data (Brussels Datastore, 2021) was used to improve the geometry of seven high-rise buildings, particularly at the roof level. In addition, for one of the highest roofs in the area, the authors conducted their own laser-scanning campaign and were able to capture a very high-resolution model of this roof. Fig. 2 depicts the 3D model of the studied urban area with the more detailed buildings shown in green.

### 3.3.2. Wind field calculations

The assessment of the wind energy potential on rooftops was performed using Computational Fluid Dynamics (CFD) simulations, which provide highly detailed information regarding local wind speeds and directions. This is especially important given wind conditions are not uniform even on a single roof. CFD is a powerful tool to discern complex wind patterns on urban rooftops that are affected by all the surrounding buildings. To set up the simulations, firstly, statistical wind data from the last 40 years were collected from the nearest meteorological station. These were used to specify the inlet boundary conditions. Fig. 3 shows

the wind rose for Brussels from 1983–2023, based on data from Zaventem airport, Brussels.

To take into effect the influence of the built area on wind patterns, a detailed 3D model of the North Quarter of Brussels context area was used as described in Section 3.3.1. The computational mesh was created using the open-source hexahedral mesh generator *snappyHex* mesh utility within Open Foam v2206 (Open Foam, 2022) resulting in the final mesh size of 52 million cells within the computational domain (Fig. 4) (minimum cell size of 20 cm close to buildings, and a maximum of 30 m in the freestream).

Using this mesh, steady-state, incompressible Reynolds Averaged Navier-Stokes (RANS) simulations were performed for multiple wind speeds and directions using the open-source finite-volume solver OpenFOAM v7 (Open Foam, 2020) and adopting a modified version of *k- $\omega$*  Shear Stress Transport (SST) model for turbulence closure, with an improved Atmospheric Boundary Layer (ABL) formulation from Belleboni et al. (2023) and Raghunathan Srikumar et al. (2024). The CFD approach used to perform these simulations was validated both for standard wind tunnel test cases in Belleboni et al. (2023) as well as with a realistic urban-scale measurement campaign (Raghunathan Srikumar et al., 2024). Figs. 5 and 6 show the wind speed and direction validation obtained for the Oklahoma Joint Urban campaign (see Raghunathan Srikumar et al. (2024)) using the current CFD approach. To the best of

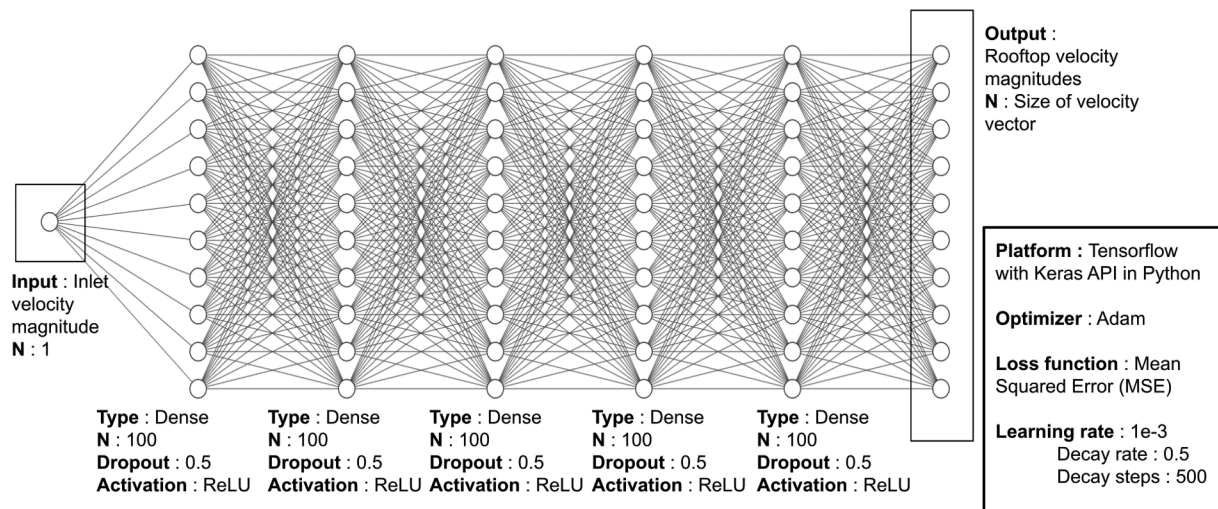


Fig. 7. Architecture of the deep neural network used in the current work to build the surrogate model.

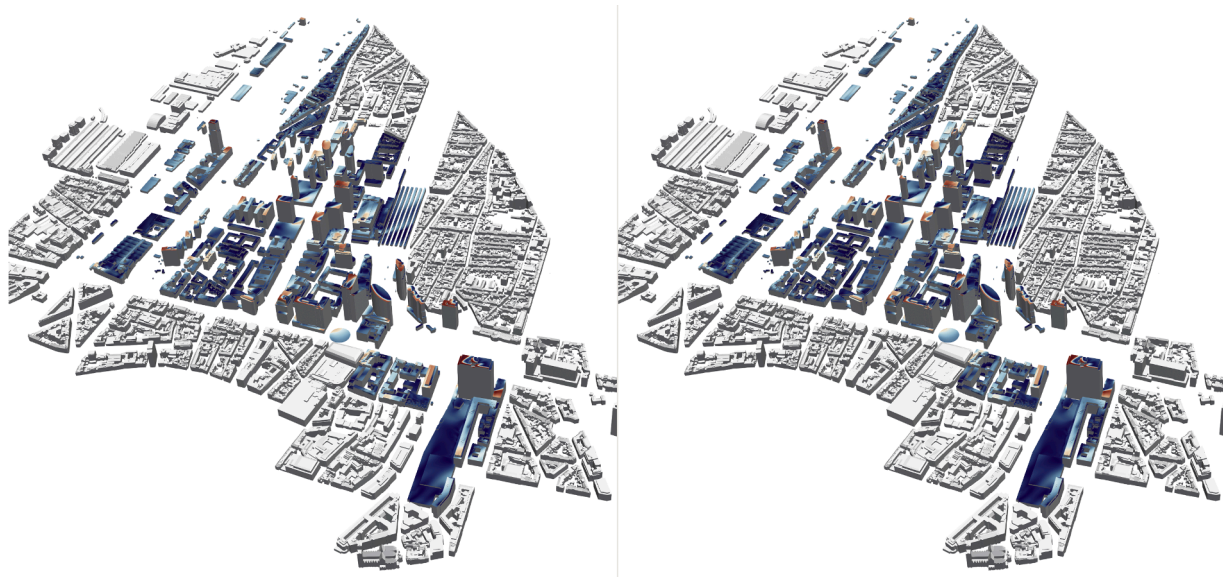


Fig. 8. Comparison of velocity magnitudes at  $z = 5$  m from the roof for the dominant wind direction (240 N) obtained with only computational fluid dynamics (CFD) (left) and with machine learning (ML) (right) for an inlet speed corresponding to  $\text{Mean} + 2\sigma$ . Samples used in the training data were data corresponding to inlet speeds  $\text{Mean} - \sigma$ , Mean, Mode, and  $\text{Mean} + 3\sigma$ .

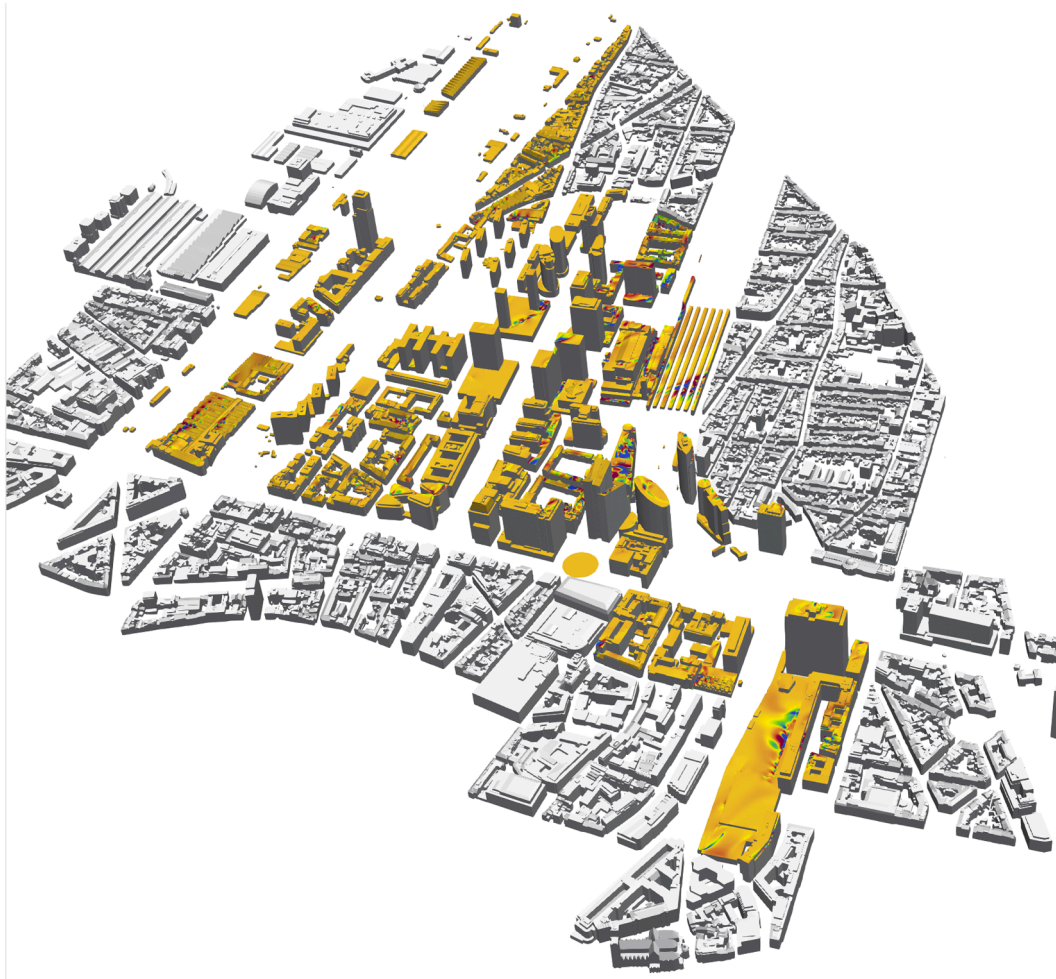
the authors' knowledge, there were no such reliable, large-scale measurement campaigns performed for the exact area under investigation at the time of this research. Therefore, the authors could not perform an exact velocity comparison at locations within the area under study. Nevertheless, since the same CFD approach from [Raghunathan Srikumar et al. \(2024\)](#) has been used and that it was compared to in-situ measurements for a similar urban-scale setting, results can be considered reliable.

From all the simulations of different wind speeds and directions, velocity values were extracted from regions close to the rooftops of all buildings, which served as a database to train a Machine Learning (ML) model. The ML model was used to give a prediction of all possible wind scenarios that can be expected in investigation which were then utilised to perform the final rooftop Annual Wind Energy Potential (AWEP) assessment for the considered small vertical urban wind turbines. The physics-based ML model also allowed to perform seasonal and monthly energy yield assessments by inputting wind conditions specific to each time.

The machine learning framework was implemented in Python using Tensorflow API, which is an open-source platform for implementing production-grade ML models. A surrogate model was created using Deep Neural Network architecture, which takes as input the inlet velocity conditions and predicts the wind velocities on the buildings' rooftops. The architecture used in the current work to build the surrogate model is shown in [Fig. 7](#). The model takes as input the inlet velocity magnitudes, and outputs the rooftop velocity magnitudes. There are 5 hidden layers with 100 neurons each, which are fully connected dense layers. Each layer has a dropout of 0.5 to prevent over-fitting of the model ([Srivastava et al., 2014](#)) and has a Rectified Linear Unit (ReLU) activation layer assigned. The model was compiled with the Adam optimiser with a learning rate of 0.001, which decays by 0.5 for every 500 epochs. The loss function used to perform the training was the Mean-Squared-Error (MSE), which is generally preferred for similar regression analyses ([Calzolari et al., 2021](#)).

[Fig. 8](#) shows a comparison of rooftop (5 m from the roof) velocity magnitude values obtained from CFD and ML, for the inlet speed





**Fig. 9.** percentage difference between the velocity magnitudes at  $z = 5$  m from the roofs for the dominant wind direction (240 N) obtained with computational fluid dynamics (CFD) only and with machine learning (ML), for an inlet speed corresponding to  $\text{Mean} + 2\sigma$ . A positive value implies that the CFD velocity magnitude is higher than the value obtained with ML.

corresponding to  $\text{Mean} + 2\sigma$  and dominant wind direction (240 N). **Fig. 9** shows their corresponding error percentage contours. For most roofs, the relative differences between velocities predicted by the ML and CFD are  $< 10\%$ . However, there are a few locations where the error is close to 30 %. Those correspond to regions of very low velocity magnitudes, i.e. the dark blue zones in the velocity magnitude contours, where typically velocities are lower than 1 m/s. Such behaviour of the model is expected, given the fact that the contribution of such spots to the mean-squared-error loss function is very minimal compared to the high-velocity areas. Moreover, in the context of performing wind energy estimation analyses, these low-velocity spots are irrelevant, as the cut-in speed of typical small urban wind turbines is usually above 2 m/s (Peacock et al., 2008). The readers are referred to Gambale et al. (2023) where the details of the CFD+ML approach to perform AWEF assessments are discussed in even greater detail.

### 3.3.3. Wind turbine placement and estimation of electricity generation

After estimating the AWEF for each  $20 \text{ cm} \times 20 \text{ cm}$  cell of the roof and for the selected small wind turbine, wind turbine siting analyses were conducted to determine the optimal number of turbines that can be installed on each roof to maximise energy output. When placed too close to each other, wind turbines drastically affect the flow field around them through wake interactions, thereby reducing the total energy output of the system (Kinzel et al., 2012; Ouro et al., 2019; Rolin & Porté-Agel, 2018). Therefore, it is very important to optimise the placement of each turbine as to minimise the effect of one on the other. The most effective

approach for this analysis is to model turbine-to-turbine interactions using CFD, considering various turbine placement configurations. However, those analyses are very complex, and computationally expensive, especially when conducted for a whole neighbourhood as in the present study. Therefore, in this article, a simplified approach was adopted based on the work of Kinzel et al. (2012), Rolin and Porté-Agel (2018), and Ouro et al. (2019), where they investigated the wake recovery of various small vertical axis wind turbines placed in a wind tunnel, and concluded that beyond a distance of five turbine diameters from the wind turbine hub in the wake, the velocity recovers to approximately 95 % of the free-stream velocity. This was the main criterion employed to obtain the best possible configuration and number of wind turbines on each rooftop.

In addition to inter-turbine spacing, two additional constraints were introduced: (1) a wind turbine can only be placed at least 0.5 m away from the roof ledge, and (2) a financial payback of a maximum of 15 years based on the current Belgian electricity costs, green certificates, and wind turbine cost was considered to get a threshold of minimum rooftop AWEF for each wind turbine. Due to a lack of reliable information on the cost of wind turbines, an average price of 1500 Euros was assumed based on different turbines prices for Belgium, with the chosen price closely matching the actual price of the turbine selected for the analysis. An average electricity price of 0.28 EUR/kWh was taken for the year 2023 (Eurostat, 2024), which included all taxes and levies for non-household consumers. In Belgium, green energy certificates are provided for every 1000 kWh of self-generated renewable energy to

**Table 3**

Sensitivity analysis parameters for the life cycle energy and greenhouse gas emissions analysis of the wind turbine as applied to the case study of Brussels.

| Parameter                                                   | Values                                                                                                                                                                                                             | Comments                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|-------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Primary energy conversion factor for electricity generation | +20 % (decarbonising grid scenario only)                                                                                                                                                                           | The likelihood of underestimating the primary energy conversion factor for electricity is significant, notably within the decarbonising grid scenario (which is an optimistic scenario)                                                                                                                                                                                                                                                                                   |
| Emissions factor for electricity                            | +20 % (decarbonising grid scenario only)                                                                                                                                                                           | The likelihood of underestimating the greenhouse gas emissions factor for electricity is significant within the decarbonising grid scenario (which is an optimistic scenario)                                                                                                                                                                                                                                                                                             |
| Wind turbine annual energy production                       | Varies per roof<br>Minimum across all roofs (−100 %)<br>Average   Median minimum across all roofs (−53 %   −53 %)<br>Maximum across all roofs (+208 %)<br>Average   Median maximum across all roofs (+17 %   +6 %) | The actual wind energy generation is variable and can be affected by potential modifications to either wind patterns or local geometry. The bounds are calculated based on the minimum and maximum accumulated annual energy generation for a single turbine on each roof (based on minimum and maximum local wind flows), compared to the average energy production per turbine for that rooftop. The bounds used are the average figures of these relative differences. |
| Uncertainty on embodied flows                               | The maximum level of uncertainty is considered, i. e. high (±40 % process; ±70 % input-output).                                                                                                                    | Uncertainty in the data behind the embodied environmental flows can be significant. Uncertainty ranges are based on Stephan (2013) and are inspired by values from Lenzen (2000).                                                                                                                                                                                                                                                                                         |

support and promote green energy production (Sibelga, 2025). These certificates are valid for 10 years and can be sold to various energy suppliers and intermediaries. The selling price varies a lot depending on the buyer. Therefore, an average price of 0.08 EUR/kWh was taken as the payback from selling the energy certificates. Based on all the above information, for a financial payback of 15 years, a single turbine should produce a minimum of 300 kWh per year. This annual wind energy potential threshold, along with the inter-turbine spacing of five diameters, and roof ledge spacing of 0.5 m were taken as constraints to perform the optimisation for each rooftop, maximising the total energy output per rooftop. The final optimised set of points were then analysed for life cycle assessment.

### 3.3.4. Life cycle energy and greenhouse gas emissions parameters

For the specific case of the Brussels Capital Region, in Belgium, two scenarios were considered for the primary energy conversion factor and the greenhouse gas emissions factor for electricity generation, i.e. urban wind energy replacing a decarbonising electricity grid (average mix) over time, and urban wind energy replacing electricity generated using gas turbines. These scenarios were broadly based on the report by Elia Transmission Belgium (2024). Table A1, Appendix A, presents the annual values used to model the two different scenarios. In the first scenario, a dynamic approach is taken where the primary energy conversion factor for electricity generation decreases linearly from 2.5 (current value) to 1.1 (renewables). Similarly, the greenhouse gas emissions factors vary from 17 kgCO<sub>2</sub>e/GJ<sup>PRIMARY</sup> (Elia Transmission

Belgium, 2024) to 0. In the second scenario, a static approach is adopted where these values remain constant at 2 GJ<sup>PRIMARY</sup>/GJ<sup>DELIVERED</sup> and 60.2 kgCO<sub>2</sub>e/GJ<sup>PRIMARY</sup>. These scenarios have a significant influence on the energy return on investment and the greenhouse gas emissions return on investment values as visible in the Section 4.

### 3.3.5. Sensitivity analyses at the urban scale

When deploying the wind turbines to the roofs of the North Quarter of Brussels, a sensitivity analysis needs to be conducted to ensure the robustness of the findings and account for uncertainty and variability in the parameters and outputs. This is done by varying key variables by certain ranges, as presented in Table 3.

## 4. Life cycle energy and greenhouse gas emissions results

### 4.1. Single vertical axis wind turbine

Results of the single vertical axis wind turbine are summarised in Table 4 as well as Figs. 10 and 11. It is important to flag that only the three main takeaways are summarised here due to length requirements. Significant additional insights can be extracted from the generated data cube. We invite the reader to explore the interactive parallel plots (see links in the Data availability Section) or to use the provided python code to regenerate the data cube and conduct their own data analysis.

Firstly, the significance of the hybrid life cycle inventory approach is clearly demonstrated by the difference in embodied energy and greenhouse gas emissions as compared to when using process analysis. Relying strictly on process-based figures underestimated the embodied energy and greenhouse gas emissions of the wind turbine by 61 % and 52 % as compared to using a hybrid approach, respectively. This means that all computed performance metrics, such as the energy/greenhouse gas emissions return on investment and the energy/greenhouse gas emissions payback time are systematically 2.56 times (1/ (1−0.61)) and 1.92 times (1/ (1−0.52)) better when using process data as compared to when using hybrid data. As such, we recommend systematically using a hybrid life cycle inventory approach to ensure that a much more robust assessment of life cycle environmental performance of deploying wind turbines or other renewable energy systems.

Secondly, the primary energy conversion factor for electricity generation and the associated greenhouse emissions factor are significant parameters that result in a broad spread of EROI and GHGROI values for the same embodied energy and greenhouse gas emissions, service life, and annual electricity generation. For example, for a service life of 25 years, using the nominal embodied energy and greenhouse gas emissions and an annual electricity generation of 700 kWh/annum, the EROI varies between ~1.1 and ~3.5, and the GHGROI between ~0.1 and ~4.8. Also, the minimum annual delivered electricity generation for a wind turbine to result in an energy return on investment that is systematically higher than 1, over 25 years, is at least 700 kWh/annum. Interestingly, this is more than double the value of the adopted threshold (300 kWh/annum) to install wind turbines in Brussels for a 15-year financial payback time (see Section 3.3.3). Current financial costs and yields are not aligned with energy and greenhouse gas emissions costs and savings. This is further discussed in Section 5.3.

Thirdly, the broad parametric analysis demonstrates the significant variability in results with very broad ranges of EROI, GHGROI and payback times. For instance, the maximum EROI is ~51, the minimum ~0.08, and the standard deviation is 6.26. As such, when installing a vertical axis wind turbine in an urban setting, it is important to estimate a reasonable service life, to understand what energy source is being replaced, and to explore different scenarios in this regard. In addition, characterising the annual wind flow and associated annual electricity generation using advanced computational fluid dynamics is critical, as well as using a hybrid life cycle inventory approach for the quantification of embodied environmental flows, while considering uncertainty. The results of applying these takeaways to the North Quarter of Brussels,

**Table 4**

Key results at a single vertical wind turbine level.

| Variable                                                         | Value             | Unit                | Comment                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|------------------------------------------------------------------|-------------------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Embodied energy (hybrid life cycle inventory)                    | 68 291            | MJ                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| Embodied energy (process life cycle inventory)                   | 26 618            | MJ                  | The process-based embodied energy figure is lower than its hybrid counterpart, demonstrating a truncation error of at least 61 % at a whole vertical axis wind turbine level. This has significant implications for the associated EROI and energy payback time.                                                                                                                                                                                                |
| Embodied greenhouse gas emissions (hybrid life cycle inventory)  | 4 979             | kgCO <sub>2</sub> e |                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| Embodied greenhouse gas emissions (process life cycle inventory) | 2 380             | kgCO <sub>2</sub> e | The process-based embodied greenhouse gas emissions figure is lower than its hybrid counterpart, demonstrating a truncation error of at least 52 % at a whole vertical axis wind turbine level. This has significant implications for the associated GHGROI and greenhouse gas emissions payback time.                                                                                                                                                          |
| Median EROI                                                      | 5.3 (N = 54 390)  | 1                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| Median EROI >1                                                   | 5.9 (N = 49 618)  | 1                   | The median EROI of values higher than 1 is 5.9 (+11 % as compared to that of all values) and excludes 8.8 % of the variations (n = 4 772). This demonstrates that in most cases these vertical axis wind turbines generate 5–6 times more energy than the energy used to produce them.                                                                                                                                                                          |
| Median GHGROI                                                    | 2.9 (N = 163 170) | 1                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| Median GHGROI >1                                                 | 4.8 (N = 119 249) | 1                   | The median GHGROI of values higher than 1 is 4.8 (+~66 % as compared to that of all values) and excludes 26.9 % of the variations (n = 43 921). This is significantly different from the EROI results, demonstrating the sensitivity of the GHGROI results to the investigated parameters, notably the emissions factor for electricity generation.                                                                                                             |
| Median energy payback time                                       | 4.7 (N = 54 390)  | years               |                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| Median energy payback time < 30 years                            | 4.3 (N = 50 661)  | years               | The median energy payback time of values lower than 30 years is 4.3 years (~9 % as compared to that of all values) and excludes 6.9 % of the variations (n = 3 729). This demonstrates that in most cases these vertical axis wind turbines will payback their embodied energy well before the end of their service life and within 4–5 years.                                                                                                                  |
| Median greenhouse gas emissions payback time                     | 8.5 (N = 163 170) | years               |                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| Median greenhouse gas emissions payback time < 30 years          | 5.5 (N = 124 749) | years               | The median greenhouse gas emissions payback time of values lower than 30 years is 5.5 years (~35 % as compared to that of all values) and excludes 23.5 % of the variations (n = 38 421). This demonstrates that in most cases these vertical axis wind turbines will payback their embodied greenhouse gas emissions well before the end of their service life and within 5–9 years. We can observe an additional 1–4 years to pay back as compared to energy. |

Note: EROI = Energy return on investment, GHGROI = Greenhouse gas emissions return on investment.

Belgium are presented in [Section 4.2](#).

#### 4.2. Deploying vertical axis wind turbines on the roofs of Brussels, Belgium

Deploying the studied vertical axis wind turbines on the roofs of buildings in the Northern Quarter of Brussels, Belgium reveals various insights about the local urban settings that significantly affect the life cycle energy and greenhouse gas emissions performance of these turbines. Aggregate results are discussed first, followed by spatialised results. These results also have limitations, as discussed in [Section 5.6](#).

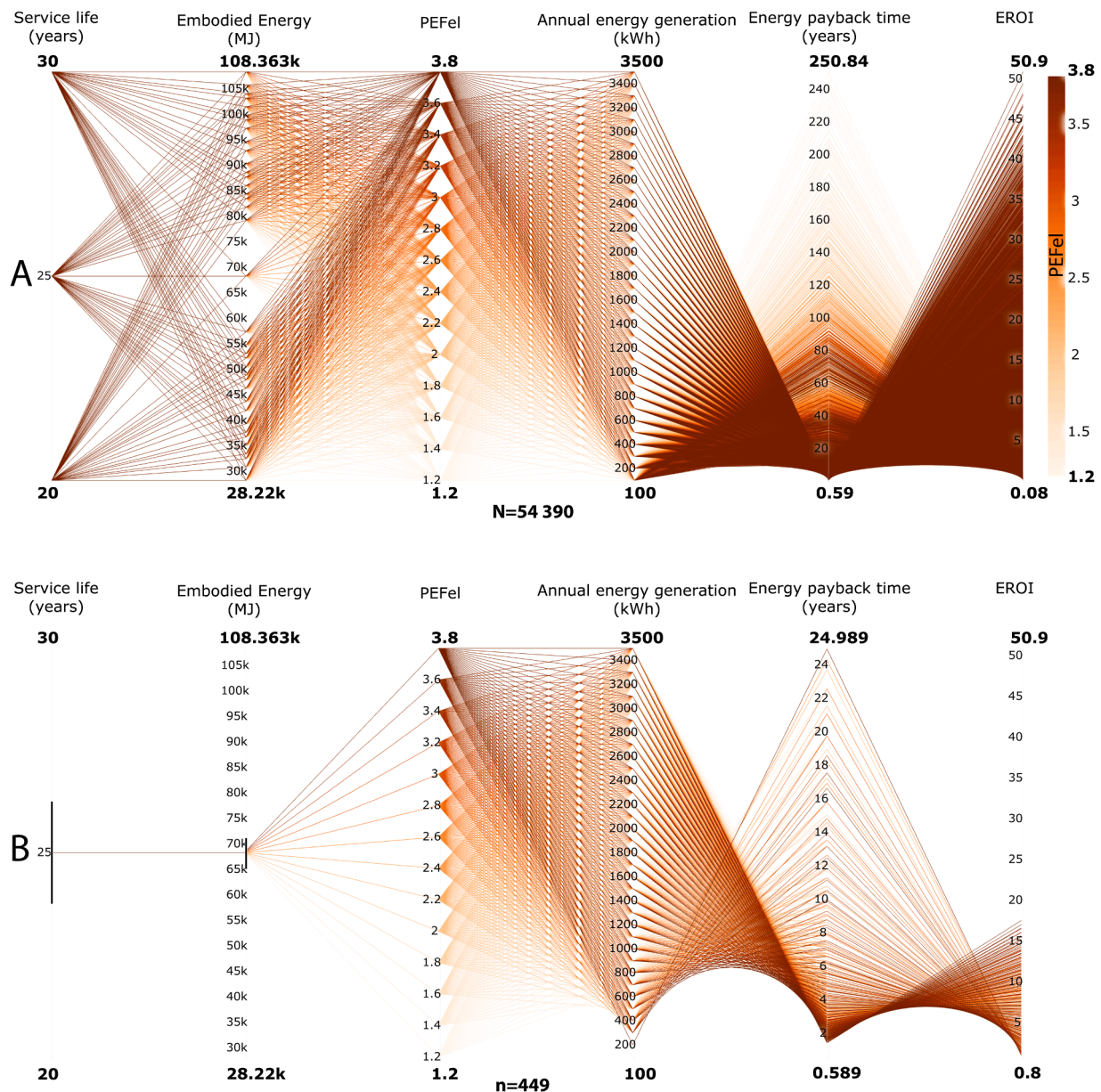
[Table 5](#) summarises the main aggregated results of the Brussels case study. Two main results can be highlighted, namely the extreme variability and localised nature of urban wind energy production and the significance of the electricity source being replaced. Firstly, of the 5 193 roofs investigated, only 697 (13.4 %) yielded enough wind to generate 300 kWh of electricity with the selected wind turbine. This means that 86.6 % of roofs in the Northern Quarter of Brussels do not receive enough wind to make them financially viable to install a wind turbine. If using the 700 kWh of annual electricity generation per turbine threshold for energy and greenhouse gas emissions payback identified in [Section 4.1](#), only 105 roofs would meet this criterion (i.e. 2 %). This shows that local conditions dominate the life cycle environmental performance of urban wind turbines. Secondly, the 2 287 wind turbines installed on the 697 roofs produce 1 374 940 kWh of delivered electricity per year but require 156 182 GJ of embodied energy (43 383 889 kWh) in primary energy terms. Under the decarbonising grid scenario, the median EROI and GHGROI are both less than one. This means that deploying these wind turbines using the financial inclusion criterion of 300 kWh of

annual delivered energy is incompatible with the life cycle energy and greenhouse gas emissions criteria. Filtering for EROI and GHGROI of values above one results in having only 294 roofs with an EROI larger than one, but not a single roof with a GHGROI above 1. The already decarbonised grid and decarbonising grid of Belgium makes it very hard to payback the embodied greenhouse gas emissions of the wind turbines. Also, calculating these using hybrid life cycle analysis results in embodied greenhouse gas emissions >2× higher as compared to using traditional process data (see [Section 4.1](#)). When strictly replacing gas throughout the 25 years of service life, the life cycle energy and greenhouse gas emissions are improved. The number of roofs yielding a GHGROI higher than one changes from zero to 233. These findings clearly demonstrate that the feasibility of deploying small vertical axis wind turbines on urban roofs, in the case of Brussels, Belgium, is not warranted. There is a need for a detailed and case-by-case approach to the deployment of vertical axis wind turbines in an urban area. Implications are discussed in [Sections 5.2](#), [5.3](#), and [5.4](#).

[Fig. 12](#) shows that in general terms the variability in wind availability is such that it introduces too much noise for a clear correlation between EROI (and by extension GHGROI) and roof height. Indeed, a linear correlation results in an  $R^2$  value of 0.24 (and of a very similar magnitude for power, second degree polynomial, and other correlations). Despite this weak correlation, it is also clear that 92 % of roofs with an EROI higher than 3 are >60 m-high.

To further investigate this relationship, a combination of non-parametric and distributional statistical methods was used. A locally weighted scatterplot smoother (LOESS) was first applied to visualise potential non-linear trends in the presence of the significant noise. The monotonic association between building height and EROI was





**Fig. 10.** Parallel coordinates plot of the energy payback time and energy return on investment (EROI) of a single vertical axis wind turbine, for the 54 390 investigated variations (A) and zoomed in ( $n = 449$ ) for the nominal service life (25 years), embodied energy (68 291 MJ) and energy payback time strictly <25 years. See interactive plot at: <https://doi.org/10.6084/m9.figshare.28440332>.

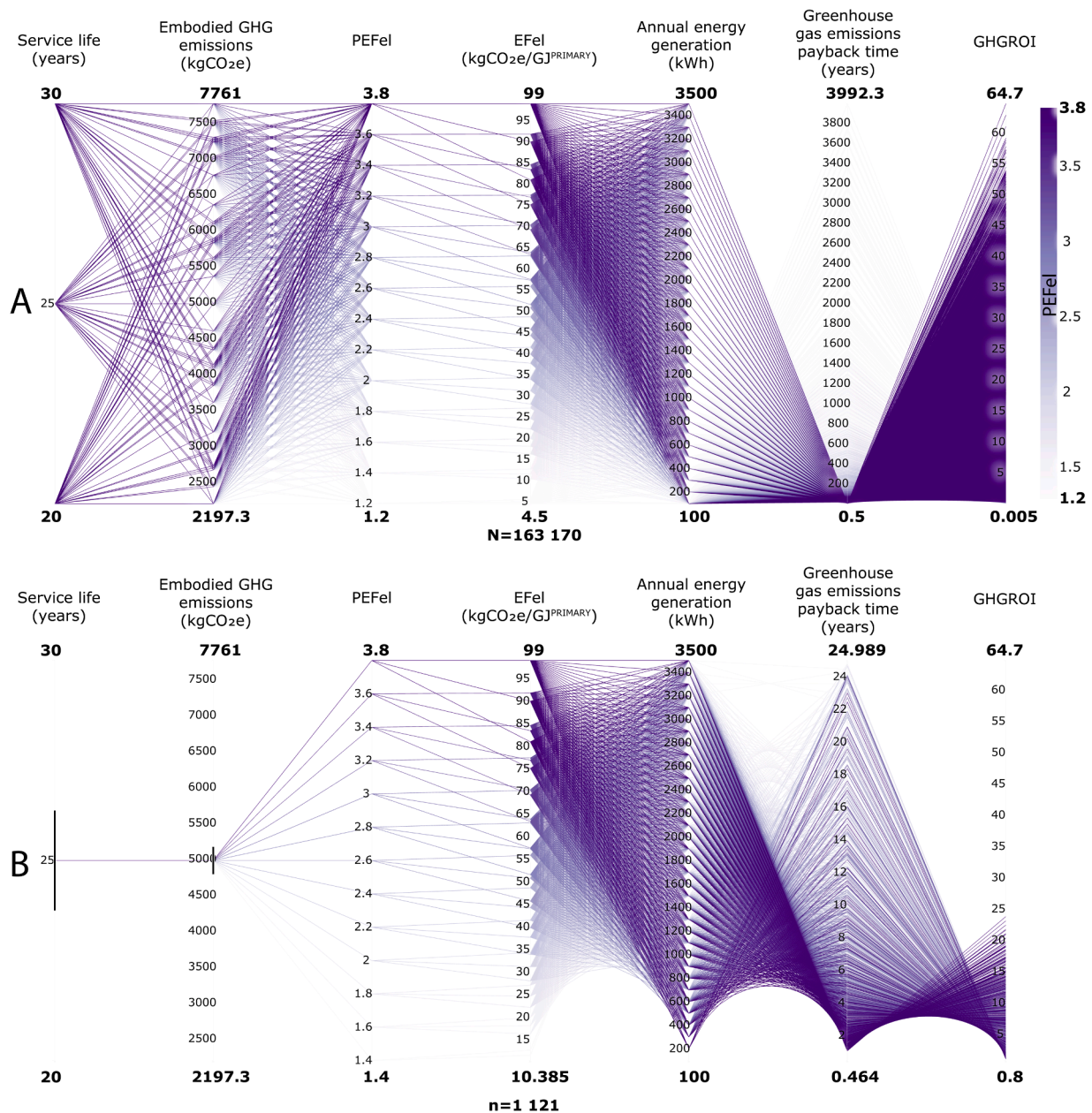
quantified using Spearman's rank correlation. To evaluate whether mean EROI values differed across height groups, building heights were divided into tertiles and subjected to both one-way analysis of variance (ANOVA) and the non-parametric Kruskal–Wallis test, providing complementary parametric and distribution-free assessments of group-level differences. Finally, quantile regression models were fitted at the 25th, 50th (median), and 75th percentiles to characterise how different segments of the EROI distribution respond to increases in building height.

Spearman's correlation indicated a moderate but highly significant monotonic association between building height and EROI ( $\rho = 0.501$ ,  $p < 5.922 \times 10^{-45}$ ). Group-level analyses further confirmed significant differences in EROI across height segments (ANOVA:  $F = 86.27$ ,  $p = 5 \times 10^{-34}$ ; Kruskal–Wallis:  $H = 154.62$ ,  $p = 2.66 \times 10^{-34}$ ), indicating that taller buildings yield higher average returns. Quantile regression revealed heterogeneity across the distribution: the 25th percentile slope was positive but very shallow, suggesting that poorly performing rooftops benefit marginally from additional height; the median regression

(50th percentile) slope was slightly more pronounced, indicating modest gains at typical sites; and the 75th percentile showed a substantially steeper positive slope, demonstrating that the highest-performing quartile of sites benefit disproportionately from greater rooftop elevation. Together, these statistical results, combined with the scatter plot in Fig. 12, demonstrate that while building height is positively associated with EROI on average, the strength of this effect is uneven, with rooftops that have favourable wind conditions benefiting disproportionately from height. As such, tall buildings are the preferred location to install wind turbines, but their height does not guarantee that these turbines will produce more energy than their embodied energy. Other parameters related to wind resource availability need to be considered.

Fig. 13 shows the maps of the EROI and GHGROI for the gas scenario, for the Northern Quarter of Brussels, Belgium. The maps reveal which buildings have the highest potential and further demonstrate that high roofs tend to offer the best potential for installing wind turbines. The maps also clearly demonstrate significant variability within the same





**Fig. 11.** Parallel coordinates plot of the greenhouse gas emissions payback time and greenhouse gas emissions return on investment (GHGROI) of a single vertical axis wind turbine, for the 163 170 investigated variations (A) and zoomed in ( $n = 1\ 121$ ) for the nominal service life (25 years), embodied greenhouse gas emissions (2 380 kgCO<sub>2</sub>e) and greenhouse gas emissions payback time strictly <25 years. See interactive plot at: <https://doi.org/10.6084/m9.figshare.28440332>.

location (roofs in blue (EROI or GHGROI <1) next ones in dark red (EROI or GHGROI >5)). These maps provide a significant resource for decision making, notably their interactive three-dimensional version, which includes metadata for each roof.

Fig. 14 depicts a box plot of the percentage of annual wind electricity generation, by month, as well as the diurnal averages, by season. Results show that January is the most productive month, representing alone around 10 % of the total output. Electricity generation is lower in spring and summer months. Generally, the variation is not very significant, with April being the least productive month, generating on average 7 % of the total. Results are most variable in October, November and April and most consistent in September, August and January. Overall, 28 % of the output occurs in winter, followed by autumn (25.1 %), summer (23.9 %) and spring (23 %). From a diurnal variation perspective, 46.8 % of electricity generation occurs at night, throughout the year, on average. This varies greatly between seasons, with winter and Autumn

representing a higher nighttime generation than daytime (17.4 % vs 10.6 % and 13.3 % vs 11.8 % of the annual electricity generation, respectively) and the reverse for summer and spring. The seasonal and diurnal availability of wind electricity make it very relevant to combine with rooftop solar photovoltaic, as discussed in Section 5.1.

#### 4.2.1. Sensitivity analysis of urban scale results

The sensitivity analysis of the urban scale results is conducted using the variations specified in Table 3, Section 3.3.5. This results in four variations for each of the EROI and the GHGROI.

Fig. 15 is a box plot representing the base case decarbonising grid and gas scenarios, and the sensitivity analysis of the EROI and GHGROI to the parameters described above. Three main observations can be drawn from this sensitivity analysis. Firstly, the EROI and GHGROI results can be significantly affected by uncertainty in the results, mostly in a positive manner (i.e. values are seen increasing). This is largely due to

**Table 5**

Key results of deploying vertical wind turbines on the roofs of the Northern Quarter area in Brussels, Belgium.

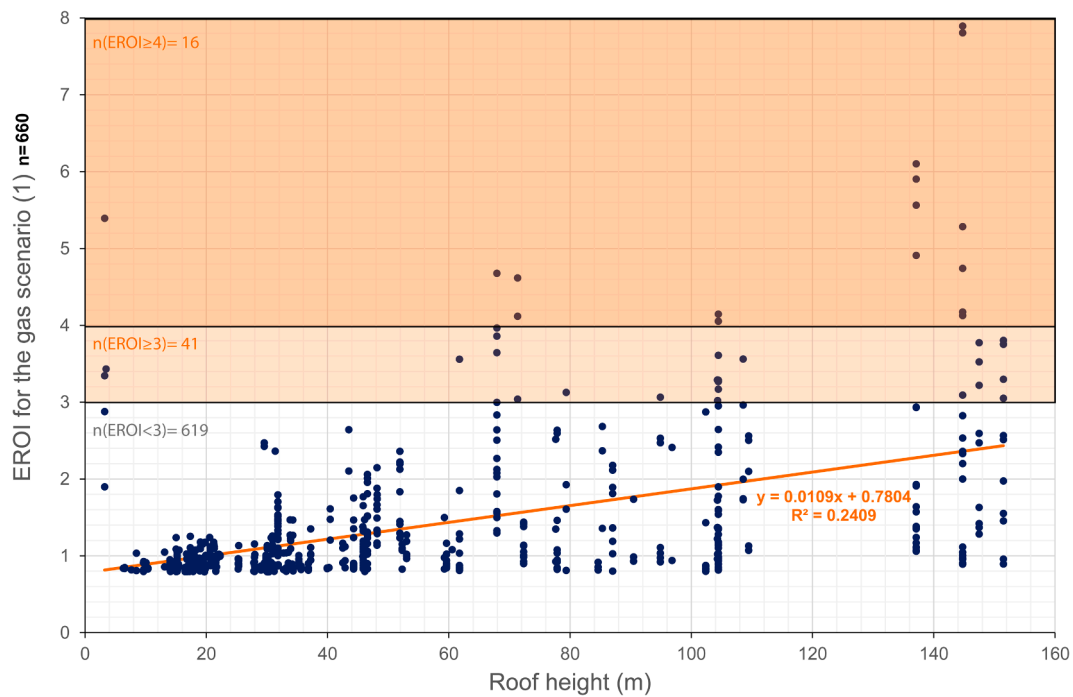
| Variable                                                                                         | Value                                        | Unit                | Comment                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|--------------------------------------------------------------------------------------------------|----------------------------------------------|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Total number of roofs hosting at least one wind turbine                                          | 697                                          | 1                   | $n = 697$ out of $N = 5\,193$ roofs (13.4 %) yielded enough annual wind energy production to host a wind turbine. This demonstrates the significant variability of the wind resource at an urban level. Using average wind data from a nearby weather station is a very poor representation of reality.                                                                                                                                                                                  |
| Total number of vertical axis wind turbines installed                                            | 2 287                                        | 1                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Total embodied energy of installed wind turbines (hybrid life cycle inventory)                   | 156 182<br>(68 291/1000<br>$\times 2\,287$ ) | GJ                  | Equivalent to the initial embodied energy of 19 046 m <sup>2</sup> of Australian houses based on 8.2 GJ/m <sup>2</sup> , the median value for 8 159 houses in <a href="#">Stephan and Athanassiadis (2017)</a> .                                                                                                                                                                                                                                                                         |
| Total embodied greenhouse gas emissions of installed wind turbines (hybrid life cycle inventory) | 11 386 973<br>(4 979 $\times$ 2<br>287)      | kgCO <sub>2</sub> e | Equivalent to $\sim 16$ return trips from Brussels to Melbourne for one A350 (65 gCO <sub>2</sub> e/pkm of tailpipe emissions over 2 $\times$ 16 000 km with a 95 % occupancy of 337 passengers, direct).                                                                                                                                                                                                                                                                                |
| Total annual delivered electricity production                                                    | 1 374 940                                    | kWh/<br>year        | This is enough electricity to power 343 houses for a year (assuming 4 000 kWh of delivered electricity demand per year).                                                                                                                                                                                                                                                                                                                                                                 |
| Total average annual delivered electricity production per turbine                                | 601                                          | kWh/<br>year        | The average electricity production per turbine is relatively low for a 2.5 kW turbine. Note that the minimum is 300 kWh (inclusion criterion) and the maximum was 2 996 kWh, with a standard deviation of 217 kWh.                                                                                                                                                                                                                                                                       |
| Median EROI (decarbonising grid scenario)                                                        | 0.92 ( $n = 697$ )                           | 1                   | The median EROI across the 697 roofs is $<1$ for the decarbonising grid scenario. This shows that urban vertical axis wind turbines do not payback their embodied energy when replacing a relatively efficient grid with renewables. Importantly, the median EROI jumps above one when using process data for the life cycle inventory. The minimum EROI is 0.72 and the maximum is 7.2 with a standard deviation of 0.82.                                                               |
| Median EROI $>1$ (decarbonising grid scenario)                                                   | 1.41 ( $n = 294$ )                           | 1                   | Filtering for roofs that result in an EROI of $>1$ results in excluding 403 roofs or 57.8 % of roofs, retaining only 294 roofs. This brings the value of the median to 1.41.                                                                                                                                                                                                                                                                                                             |
| Median EROI (gas scenario)                                                                       | 1.01 ( $n = 697$ )                           | 1                   | When considering that gas scenario where wind turbines replace gas on the grid, the median EROI is 1.01, with a minimum of 0.79 and a maximum of 7.9. This shows that even when replacing fossil fuels, urban vertical wind turbines cannot be deployed at scale without carefully examining local wind conditions as they might never payback their embodied energy. The minimum and maximum EROIs for the gas scenario are 0.79 and 7.9, respectively. The standard deviation is 0.9.  |
| Median EROI $>1$ (gas scenario)                                                                  | 1.37 ( $n = 369$ )                           | 1                   | Considering roofs with an EROI that is larger than one excludes 328 roofs (47 %). In short, 75 additional roofs result in an EROI larger than 1 when considering the gas scenario compared to the decarbonising grid scenario.                                                                                                                                                                                                                                                           |
| Median GHGROI (decarbonising grid scenario)                                                      | 0.12 ( $n = 697$ )                           | 1                   | The GHGROI is much lower than the EROI in the decarbonising grid scenario, with a median of 0.12 and a maximum of 0.95. This means that replacing average Belgian electricity with urban wind turbines never displaces their embodied greenhouse gas emissions. This is a critical finding and will be discussed further.                                                                                                                                                                |
| Median GHGROI $>1$ (decarbonising grid scenario)                                                 | N/A ( $n = 0$ )                              | 1                   | Importantly, there is not a single roof that has a GHGROI higher than one in the decarbonising grid scenario.                                                                                                                                                                                                                                                                                                                                                                            |
| Median GHGROI (gas scenario)                                                                     | 0.83 ( $n = 697$ )                           | 1                   | In the gas scenario, the median GHGROI moves up to 0.83, with a minimum of 0.65.                                                                                                                                                                                                                                                                                                                                                                                                         |
| Median GHGROI $>1$ (gas scenario)                                                                | 1.52 ( $n = 233$ )                           | 1                   | Filtering to include only the roofs with a GHGROI higher than one for the gas scenario excludes 464 roofs (67 %). This results in a median GHGROI of 1.52 and a maximum of 6.52. This means that considering all indicators, it is environmentally viable to install the specified vertical axis wind turbines on 233 roofs out of a total of 5 193 (4.5 %) roofs in the Northern Quarter of Brussels, further demonstrating the extreme sensitivity of wind energy to local conditions. |

the performance of outliers being significantly increased with the chosen uncertainty variations, as depicted by the gap between the mean ( $\times$ symbol) and the median ( $-$  symbol). Secondly, uncertainty in the results affects mostly the EROI, with changes to the median between  $\sim 50$  % and  $\sim 500$  %. Importantly the spread is affected significantly, with many EROI values above 3. In contrast, while GHGROI witnesses similar relative variations, its absolute value is much less affected, as depicted by the very low spread of results. Thirdly, as predicted, the variation that results in the most significant deviation of results is the one with the minimum embodied energy/greenhouse gas emissions and maximum electricity production. This variation leads to significant increases in the median and mean of the EROI and GHGROI, namely to 5 and 19.2, and 0.83 and 3.17, respectively. Overall, the sensitivity analysis reveals that while EROI could be significantly affected by uncertainty in key parameters, the GHGROI remains generally unaffected (and with low values) in Belgian conditions, due to the already largely decarbonised grid.

## 5. Discussion and conclusion

### 5.1. Contribution to knowledge and innovation

This paper has conducted one of the most comprehensive parametric analyses of the life cycle energy and greenhouse gas emissions performance of urban vertical axis wind turbines to date, while using a hybrid life cycle inventory approach. It has also conducted the first city-wide application of vertical axis wind turbines, combining advanced computational fluid dynamics, spatialisation, building geometry and highly granular data and timesteps. This provides unprecedented insights into the deployment of small vertical axis wind turbines on urban rooftops. The innovation in this paper lies in its integration of life cycle energy and greenhouse gas emissions analysis using a hybrid life cycle inventory approach, three-dimensional building geometry with detailed geometry for selected roofs, advanced computational fluid dynamics for the estimation of wind energy potential, and a broad sensitivity analysis at both the single turbine level and the urban level. This answers the calls for more research in this direction by recent review papers in the field ([Qin & Wang, 2025](#); [Salvador-Gutierrez et al., 2025](#)).



**Fig. 12.** Energy return on investment (EROI) versus roof height for 660 roofs in the Northern Quarter of Brussels, Belgium, for the scenario where wind turbines replace gas-generated electricity.

## 5.2. Key findings

The outcomes of this research can be summarised into five key take-away findings. These are listed below.

Firstly, results clearly demonstrate the significance of the life cycle inventory approach on life cycle environmental performance. Indeed, using a process-based life cycle inventory results in much more positive energy and greenhouse gas emissions return on investment values, since the embodied energy and greenhouse gas emissions are underestimated by the significant figures of 61 % and 52 %, respectively. To ensure actual climate change mitigation, it is critical that the more comprehensive hybrid life cycle inventory approach is used, as called for in previous studies on large-scale wind turbines, i.e. Crawford (2009) and Wiedmann et al. (2011).

Secondly, results clearly demonstrate the significance of variability and uncertainty on the actual performance of wind turbines (see Figs. 10 and 11, as well as Fig. 12) due to complex building geometry, as identified by Qin and Wang (2025) and Wen et al. (2025). As such, selecting roofs with the highest energy and greenhouse gas emissions returns on investment is critical, ensuring a certain margin for potential under-performance. This will ensure that the deployed turbines result in a net positive life cycle energy and greenhouse gas emissions balance, despite potential variability in the wind resource as well as potential uncertainties in their embodied environmental flows.

Thirdly, results demonstrate that one of the key questions to ask is “What energy source are we replacing?”. When replacing the Belgian decarbonising electricity grid, the greenhouse gas emissions return on investment was systematically below 1, for all the investigated rooftops (see Table 5 and Fig. 13). Similarly, Figs. 10 and 11 clearly show that for low values of the primary energy conversion factor for electricity generation and of the greenhouse gas emissions factors for electricity generation, the EROI and the GHGROI values are very low. This joins similar conclusions at the building level about the importance of the energy source (Gustavsson & Joelsson, 2010).

Fourthly, one of the key findings of this paper is that the energy return on investment of wind turbines is not generally correlated with height, as significant variability in the results exists for the same roof

height. However, results also confirm that while height does guarantee a high EROI, all roofs with high EROIs are roofs of tall buildings. As such, the roofs of tall buildings should systematically be considered first when deploying wind turbines at an urban scale, reinforcing the focus on tall buildings made by Škvorc and Kozmar (2021).

Fifthly and finally, this paper demonstrates that small urban wind turbines are a viable renewable energy source, to be considered seriously. This is reinforced by their seasonal and night availability (see Fig. 14), as compared to photovoltaic panels. For instance, nighttime electricity generation would avoid having to install batteries. For the selected district in Brussels, the average daily nighttime generation amounts to  $643\,472/365 = 1\,763$  kWh. Let us assume that this energy was stored in lithium batteries. Let us use an average embodied greenhouse gas emissions intensity of lithium batteries of 121–195 kgCO<sub>2</sub>e/kWh(capacity) (based on Lai et al. (2022)), and computing an average figure based on Table 5 (page 12 in their manuscript) and augmenting their 93 kgCO<sub>2</sub>e/kWh(capacity) process-based figure to cover truncation error by a factor of 1.3 (lower bound) and up to 2.09 (as for wind turbines). Let us also assume that batteries need replacement every 5–10 years. With these assumptions, the use of wind turbines avoids, on average, an additional 427–1 031 tCO<sub>2</sub>e associated with electricity storage overnight. This amount of embodied greenhouse gas emissions represents 3.75–9 % of the embodied greenhouse gas emissions of the 2 287 wind turbines across all rooftops in this study. This is a quick estimation that only sets an order of magnitude. A much more detailed quantification is needed.

## 5.3. Policy recommendations

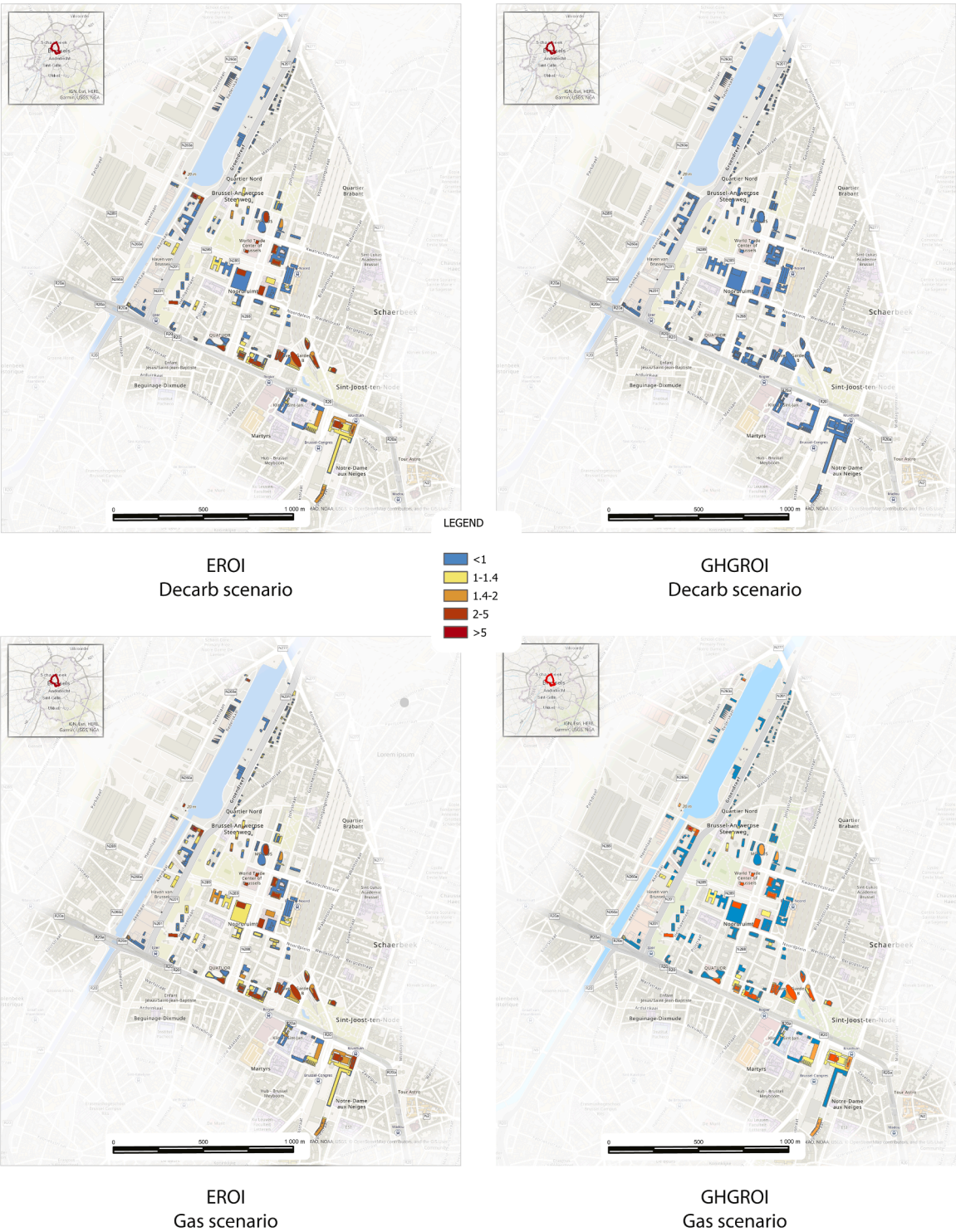
The main policy recommendation of this paper is to mandate computational fluid dynamics simulations of the wind energy potential of all tall buildings in an urban area. For different wind turbines, a hybrid life cycle assessment should be conducted to establish the energy and greenhouse return on investment of deploying vertical axis wind turbines on the roof. With nighttime generation also consequentially saving embodied energy and emissions for electricity storage (see Section 5.2), new EROI and GHGROI should be computed if wind turbines



are being compared to other renewable energy sources, such as solar photovoltaic. This would help identify key urban sites with potentially significant EROI and GHGROI for vertical axis wind turbines, if these wind turbines replace greenhouse-gas emissions-intensive electricity production. Non-tall buildings located in prominent wind corridors could also result in a high life cycle energy and greenhouse gas emissions performance of vertical axis wind turbines, but the observations in this study reveal that tall buildings should be clearly prioritised (see Fig. 12).

Another policy recommendation lies around data transparency around the material composition of wind turbines (both horizontal and vertical). Given the very poor experience we had in trying to obtain data from turbine manufacturers and suppliers, this information should be made available in public, to enable studies such as this one, as well as feasibility studies, to be conducted.

In addition, our findings find that financial payback is achieved from the generation of 300 kWh per wind turbine per annum, while the



**Fig. 13.** Spatialised energy return on investment (EROI) and greenhouse gas emissions return on investment (GHGROI) for rooftop wind turbines replacing a decarbonising grid (decarb scenario) and strictly gas-generated electricity (gas scenario). Note: Original in colour. For a three-dimensional browsable version of the maps, visit: <http://urbanwindenergy.org>.

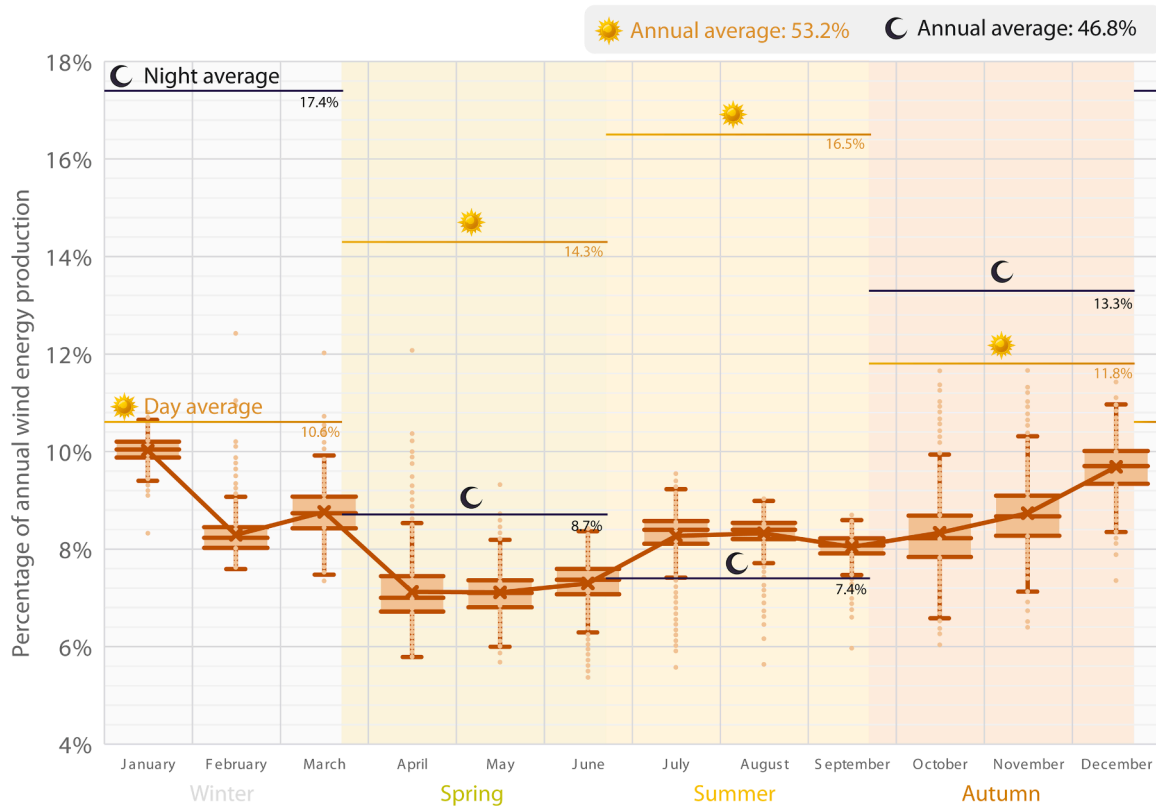


Fig. 14. Boxplot of wind energy production by month, with average seasonal diurnal energy production.

energy payback is only achieved from the generation of 700 kWh. This clearly shows that current electricity prices and feedback tariffs do not consider the full life cycle energy use of the wind turbine. There is a need to internalise life cycle energy use and all other environmental effects into the financial cost as per the ‘polluter-pays-principle’, coined by the [Organisation for Economic Co-operation and Development \(1972\)](#) >50 years ago, and thought of for even longer. Otherwise, the misled decision-making based on financial performance that does not internalise life cycle environmental effects leads to an ever-increasing environmental debt to the Earth, and to environmental collapse.

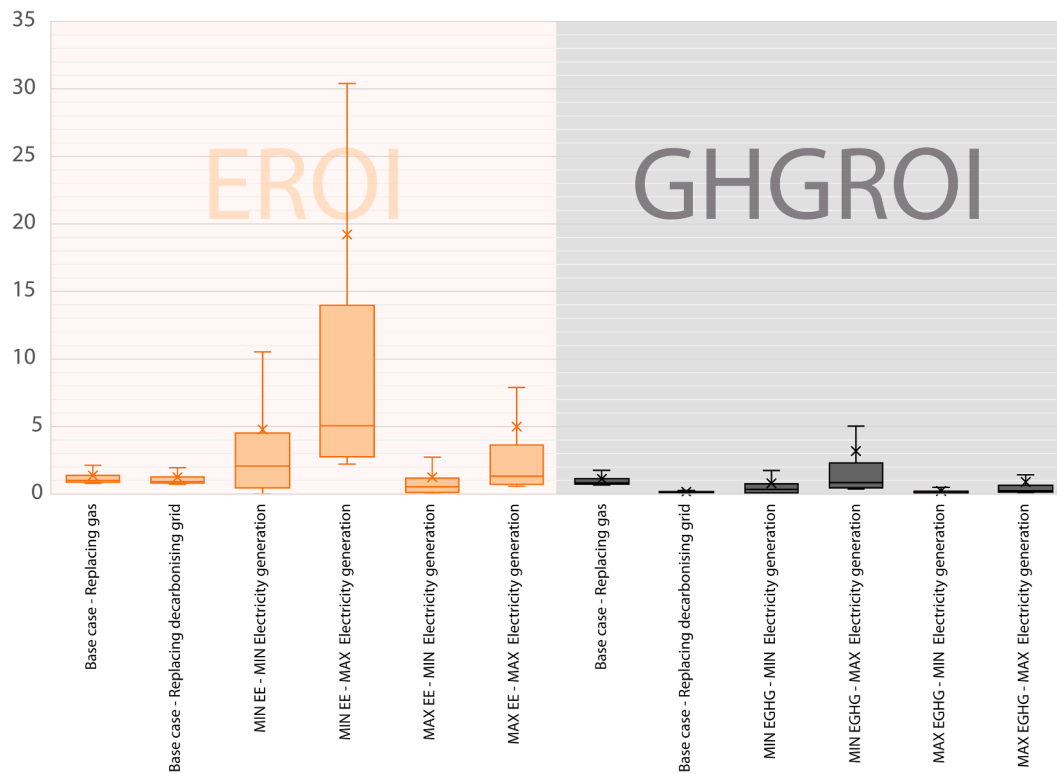
#### 5.4. Applicability of results in other contexts

The results of this study are applicable in a broad range of different contexts. The results at a single turbine scale are applicable anywhere, as long as the values of the parameters that are chosen are representative of local conditions. We deliberately chose very broad value spans for our different parameters to enhance the external validity of our results.

The urban scale results for Brussels would be potentially transposable for cities with a similar urban geometry, wind patterns and a similar electricity grid. These would include other cities in the Benelux, such as Antwerp, Amsterdam, Rotterdam, or Luxembourg, as well as neighbouring cities such as Lille, France. Logically, the spatial distribution and specific rooftop yields will vary by city, but the general trend of having most roofs not paying back and having specific locations with a high yield potential from an EROI and GHGROI are similar. The energy grid in France is relatively similar to Belgium albeit with a much higher proportion of Nuclear power and hydraulic power ([Electricité de France, 2025](#)), which will further decrease the GHGROI. In the Netherlands, a higher current greenhouse gas emissions intensity of electricity resulting from the use of gas and coal ([International Energy Agency, 2025](#)) means a higher average GHGROI.

The approach adopted in this paper can be applied to any city, if the underlying data exist. This means obtaining 3D geometry for the

buildings, simulating a wind mesh using the algorithm developed here which will yield the wind energy potential for each rooftop, and combining that with power curves and life cycle environmental performance data for potential wind turbines. There are two critical nodes in this workflow, i.e. the availability of 3D models for buildings, and the generation of a wind field that enables placing turbines on relevant rooftops. The first critical node is rooted in data availability. With improved geographical information systems (GIS) coverage for an increasing number of cities worldwide, the accessibility of 3D models for cities is growing significantly. The second critical node is a computation-intensive and knowledge-intensive bottleneck. In this research, the authors had in-house expertise through BuildWind, which specialises in wind field calculations in urban settings. To conduct the CFD calculations for the case study area of 1.6 km<sup>2</sup>, a mesh of 52 million cells was used. These necessitated a total of 106 560 central-processing-unit-core-hours (CPU-core-hrs) (considering all cells, for 12 wind directions and five different inlet wind speeds and running on CPU - AMD EPYC Milan 74F3 24C/T48 240 SP3 256 MB with 4 nodes, each including 48 cores, with 256 GB RAM per node, and a 100 Gb/s network). Upscaling the described approach to a 50 km<sup>2</sup> area and with the same high-resolution mesh would result in ~1.6 billion cells. Using the same CPU-cores, assuming a linear scaling, and no memory issues, this would require 3 330 000 CPU-core-hrs. As an indication, as of 2025, the Spartan computing cluster of the University of Melbourne, Australia contains 2 656 graphical-processing-unit-cores. Assuming that these GPU-cores are only 1.5× faster than the CPU-cores used for this study (to be very conservative), and mobilising all of them, would necessitate a total of 836 h, or 1 month and 5 days to run a simulation for a 50 km<sup>2</sup> area. As such, upscaling to larger areas would require significant computational costs and time but is technically feasible. Most probably, chunking, i.e. dividing the study area into sub-areas, would optimise runtimes and memory allocations. Importantly, the influence of one urban area on another is very likely to decrease significantly with distance. As such, only neighbouring areas would need to be modelled. Depending on the



**Fig. 15.** Sensitivity analysis of the energy return on investment and greenhouse gas return on investment at the urban scale. Note: MIN = minimum, MAX = maximum, EE = embodied energy, EGHG = embodied greenhouse gas emissions.

study area, this could save significant computation resources.

### 5.5. Broader implications

For small VAWTs to be deployed at scale, several implications should be considered. Three of these are discussed below.

Firstly, social acceptance is a critical factor, as highlighted and discussed in Tsionas et al. (2025) and Bošnjaković et al. (2025). While declared noise levels of VAWT manufacturers seem to be very low, their visual presence in the urban fabric might not be accepted. More objectively, such turbines can induce flickering and attract attention as a moving object. In addition, their installation on the roofs of buildings might induce structural vibrations if no dampers are installed at their base, which might negatively impact social acceptance from building occupants. As such, pioneering installations need to consider these aspects carefully.

Secondly, the capital expenditure associated with the installation of wind turbines, as well as their maintenance, can represent significant financial expenditures. These expenditures represent key decision-making thresholds in terms of installing VAWTs or not. This is combined with the risk of trialling a novel technology. As such, financial incentives might be needed to support the deployment of VAWTs in urban settings, as was the case for photovoltaic panels (Şahin et al., 2025).

Thirdly, it is important to remember that the deployment of VAWT on urban rooftops constitutes one part of the transition to renewable energy sources. For example, the combination of VAWTs with solar photovoltaic panels, notably on tall buildings, could result in a hybrid renewable energy system that is better than each of its two components taken alone. Excess wind energy generation at night could also be stored in gravity-based systems within tall buildings for use later. Further studies are needed to investigate the implications of deploying urban VAWTs on the broader electricity system.

### 5.6. Limitations and future research

The nature of science is that it is bounded by limitations. As such, this paper, like any other, also has limitations which provide pathways towards future research.

Firstly, we had to rely on an Australian hybrid life cycle inventory database for a Belgian case study, given the current lack of hybrid databases for construction materials outside Australia. This certainly calls for multi-regional hybrid life cycle inventory databases that would provide better suited data for conducting such studies. This database would need to be consistent in its hybridisation approach and transparent in its datapoints. Having such database would also enable comparing the levels of truncation errors in process data by region and to compare embodied energy and greenhouse gas emissions intensities for the same product across regions, enabling a quantification of geographical uncertainties (Huijbregts et al., 2001). This uncertainty is already tackled in the paper through the sensitivity analysis. A further comparison of the results with embodied energy and greenhouse gas emissions figures calculated using a European life cycle inventory, such as ecoinvent (Wernet et al., 2016) would be an interesting exercise.

Secondly, the roof geometries used for the Brussels case study do not capture the full details of each roof, as they are based on geographical information systems data. This typically leads to an overestimation of wind potential, given that additional objects on roofs typically result in an average increase in friction and lower average wind speeds. More detailed roof geometries should be used where available.

Thirdly, this paper used one vertical axis wind turbine applied to a single case study city. While the broad sensitivity analysis captures a broader spectrum of turbines and contexts, repeating the same exercise across multiple cities, urban forms and using different turbines would result in generating much more robust datasets and correlations that can better support the deployment of vertical axis wind turbines in urban environments.

Fourthly, this paper did not investigate any structural reinforcement



requirements for the installation of vertical axis wind turbines on rooftops. The embodied energy and greenhouse gas emissions of such reinforcement would reduce the calculated energy and greenhouse gas emissions return on investments due to the additional structural premium, as for vanity heights (Helal et al., 2024).

Fifthly, we did not consider the end-of-life stage and circularity potential of the wind turbines. While these stages typically have a relatively limited influence on the embodied energy and greenhouse gas emissions of the first life cycle, they have significant repercussions regarding material flows, waste and the embodied environmental flows of a second life cycle or of recycled materials streams (Kouloumpis et al., 2020). As such, more studies on improving the circularity of small vertical axis wind turbines are certainly needed before large scale deployments. Finally, this study used an average price of 1 500 EUR per turbine. While this price was close to the actual price of the chosen turbine for modelling, a broad sensitivity analysis of the results to the price would further reinforce their robustness. However, it is anticipated that variations to the price of the turbine will not modify the key findings of the study. While variations to the cost value would affect the financial cut-off production of 300 kWh, findings demonstrate that the environmental annual yield cut-off is more than twice this value. Using a linear electricity pricing model, the cost of the turbine would need to be more than double to match this value. In addition, the input-output remainder of the turbine, calculated using the cost value, represents 16 % and 14 % for embodied energy and greenhouse gas emissions, respectively. Therefore, fluctuations to the cost would need to be extremely significant to alter the embodied energy and emissions enough to modify the findings in terms of EROI and GHGROI.

Sixthly, the modelled wind flows would benefit greatly from validation, through then installation of anemometers and weather stations on multiple roofs and cross-validating measured wind speeds with simulated ones. While this would be a costly exercise, it would help ensure that the anticipated wind potential is actually what the model is estimating.

If we are to attempt to mitigate the severity of the now unavoidable climate change for current and future humans and other living beings on Earth, we need to use all possible levers that we have. Installing vertical axis wind turbines in cities is currently an untapped lever that can help accelerate the reduction of greenhouse gas emissions. This will need to be accompanied with systematic vertical axis wind turbines reuse and recycling streams, as well as experimentation in using bio-based materials for manufacturing wind turbines. These efforts, alongside a plethora of other actions, might play a crucial role in fostering a more circular urban wind energy sector with a high life cycle environmental

performance, further accelerating the transition to a future within planetary boundaries (Richardson et al., 2023).

### Data availability

The following dataset and data visualisations are made available in open access:

The excel sheet containing the data and the main graphs at the urban scale: <https://doi.org/10.6084/m9.figshare.28440332>.

The interactive parallel coordinates plots in html: <https://doi.org/10.6084/m9.figshare.28440332>.

The python code used to generate the data for the single vertical axis wind turbine as well as the parallel coordinates plots: <https://doi.org/10.6084/m9.figshare.28440332>.

A three-dimensional atlas of the whole research project, including the 3D urban environment of the EROI and GHGROI: <http://urbanwindenergy.org>.

### CRediT authorship contribution statement

**André Stephan:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sampath Kumar Raghunathan Srikumar:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Ioannis Tsionas:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Maider Llaguno-Munitxa:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Alessandro Gambale:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

### Declaration of competing interest

The 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. Additional information on the electricity grid modelling in Brussels, Belgium

**Table A1**

Annual primary energy conversion factor and greenhouse gas emissions factor for electricity generation until 2050, in Brussels, Belgium, for urban wind energy replacing a decarbonising grid or replacing gas-generated electricity.

| Year | Decarbonising grid scenario                             |                                                   | Replacing gas-generated electricity scenario            |                                                   |
|------|---------------------------------------------------------|---------------------------------------------------|---------------------------------------------------------|---------------------------------------------------|
|      | PEFel (GJ <sup>PRIMARY</sup> /GJ <sup>DELIVERED</sup> ) | EFel (kgCO <sub>2</sub> e/GJ <sup>PRIMARY</sup> ) | PEFel (GJ <sup>PRIMARY</sup> /GJ <sup>DELIVERED</sup> ) | EFel (kgCO <sub>2</sub> e/GJ <sup>PRIMARY</sup> ) |
| 2025 | 2.5                                                     | 17                                                | 2                                                       | 60.2                                              |
| 2026 | 2.44                                                    | 16.29                                             | 2                                                       | 60.2                                              |
| 2027 | 2.39                                                    | 15.58                                             | 2                                                       | 60.2                                              |
| 2028 | 2.33                                                    | 14.88                                             | 2                                                       | 60.2                                              |
| 2029 | 2.28                                                    | 14.17                                             | 2                                                       | 60.2                                              |
| 2030 | 2.22                                                    | 13.46                                             | 2                                                       | 60.2                                              |
| 2031 | 2.16                                                    | 12.75                                             | 2                                                       | 60.2                                              |
| 2032 | 2.11                                                    | 12.04                                             | 2                                                       | 60.2                                              |
| 2033 | 2.05                                                    | 11.33                                             | 2                                                       | 60.2                                              |

(continued on next page)

Table A1 (continued)

| Year | Decarbonising grid scenario                             |                                                   | Replacing gas-generated electricity scenario            |                                                   |
|------|---------------------------------------------------------|---------------------------------------------------|---------------------------------------------------------|---------------------------------------------------|
|      | PEFel (GJ <sup>PRIMARY</sup> /GJ <sup>DELIVERED</sup> ) | EFel (kgCO <sub>2</sub> e/GJ <sup>PRIMARY</sup> ) | PEFel (GJ <sup>PRIMARY</sup> /GJ <sup>DELIVERED</sup> ) | EFel (kgCO <sub>2</sub> e/GJ <sup>PRIMARY</sup> ) |
| 2034 | 1.99                                                    | 10.63                                             | 2                                                       | 60.2                                              |
| 2035 | 1.94                                                    | 9.92                                              | 2                                                       | 60.2                                              |
| 2036 | 1.88                                                    | 9.21                                              | 2                                                       | 60.2                                              |
| 2037 | 1.83                                                    | 8.50                                              | 2                                                       | 60.2                                              |
| 2038 | 1.77                                                    | 7.79                                              | 2                                                       | 60.2                                              |
| 2039 | 1.71                                                    | 7.08                                              | 2                                                       | 60.2                                              |
| 2040 | 1.66                                                    | 6.38                                              | 2                                                       | 60.2                                              |
| 2041 | 1.60                                                    | 5.67                                              | 2                                                       | 60.2                                              |
| 2042 | 1.54                                                    | 4.96                                              | 2                                                       | 60.2                                              |
| 2043 | 1.49                                                    | 4.25                                              | 2                                                       | 60.2                                              |
| 2044 | 1.43                                                    | 3.54                                              | 2                                                       | 60.2                                              |
| 2045 | 1.38                                                    | 2.83                                              | 2                                                       | 60.2                                              |
| 2046 | 1.32                                                    | 2.13                                              | 2                                                       | 60.2                                              |
| 2047 | 1.26                                                    | 1.42                                              | 2                                                       | 60.2                                              |
| 2048 | 1.21                                                    | 0.71                                              | 2                                                       | 60.2                                              |
| 2049 | 1.15                                                    | 0                                                 | 2                                                       | 60.2                                              |

Note: PEFel = Primary energy conversion factor for electricity generation, EFel = greenhouse gas emissions factor for electricity generation.

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