Techno-economic comparison of rooftop-mounted photovoltaics and small wind turbines: a case study for Brussels

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Abstract

As rooftops in cities are mostly underused, they have a large potential for decentralised electricity production. In that context, photovoltaic (PV) panels have proven to be an effective solution. Meanwhile, the market of small wind turbines (SWT) is increasing and some building owners have already installed one or more units on their roof. While the economic comparison between PV panels and wind turbines has already largely been addressed in general, the space constraint of a rooftop has never been taken into account. In this work, we propose a methodology to compare the energy production and the return on investment both for rooftop-mounted PV panels and wind turbines. The comparison is made for relatively tall buildings (≥ 60 m) with good wind conditions (≥ 5 m/s annual mean wind speed). Using a brute-force approach, the paper presents the results of the methodology applied to a case study: the Brussels Region.

On tall rooftops, considering the space already taken by other installations and assuming an average wind speed of 5 m/s, small building-mounted wind turbines are shown to produce more energy than PV panels. Nevertheless, their return on investment is always lower than that of the PV panels.

1 Introduction

Europe is moving from a centralised, fossil-fuel and nuclear-based energy production towards decentralised small-scale renewable energy generation [1]. In particular, the share of grid-connected distributed generation of photovoltaic electricity is estimated at 60 % of the installed PV capacity in 2017 [2]. When it comes to energy production in cities, the dominant constraint is space. Free ground space in cities is scarce. Moreover, renewable energy systems (RES) need much more space than other energy systems. For instance, PV panels use 17 times the space needed for the same amount of energy produced when compared to coal. This ratio increases to 80 for wind energy production [3, 4].

Rooftops in cities represent the last bit of free, usable space and therefore have, at least in principle, a large potential for sustainable power production. It is also where, in cities, the available resources (wind and solar irradiation) are the least obstructed. In general, rooftops that generate electricity mainly use photovoltaic (PV) panels. However, there exist a number of building-mounted
small wind turbines (SWT) [5, 6]. That speaks to the question of why owners would choose one system rather than the other.

The comparison between the two energy systems has been approached in a number of research papers [7, 8, 9]. Current papers focus on hybrid energy production systems combining PV panels and wind turbines with other energy production systems, e.g. batteries, fuel cells, diesel generator and biomass, and storage. There are review papers that classify these papers by topic [10, 11, 12]. More specifically, Giraud et al. studied the combination of PV panels and a wind turbine on a rooftop [13]. Nevertheless, none of these articles considered space as a limitation. However, for rooftop energy production, the relative competitiveness of the different solutions depends on the available space.

In this paper, we want to determine under which conditions, if at all, SWT may be a good alternative to PV panels for rooftop energy production. This article proposes a techno-economic comparison of both energy systems. The scope is limited to tall buildings to avoid wind shadowing and solar shade from the near environment. Because these tall buildings are often owned by companies, the economic study is performed for their legal advantages.

The structure of the article is as follows: section 2 explains the methodology developed to compare PV panels and SWT installed on a rooftop. Section 3 applies the methodology on the case study of Brussels, Belgium. Section 4 provides a sensitivity analysis that studies the variation of the economic metrics for different scenarios. Section 5 concludes the paper and discusses the perspectives of the research.

2 Methodology

This section explains the methodology used to compare wind turbines and PV panels installed on a rooftop in urban areas. The methodology has two main steps. First, we determine the ‘local parameters’ that will affect the efficiency of both energy systems. In particular, the shadow from existing installations, the effect of surrounding buildings and the structure of the rooftop are neglected and postponed to a further study. Therefore, in this paper, we focus on the rooftop morphologies and the climate conditions. In the second step, we choose the techno-economic metrics that will be used in the comparison. These two steps are clarified further in Sec. 2.1, 2.2 and 2.3.

2.1 Morphological features of rooftops

For a reliable and fair comparison between SWT and PV panels, one needs to identify rooftops where both energy systems can optimally work. In cities, high-rise buildings are convenient because they minimise wind shadowing and solar shade from the near environment [14].

The rooftop morphologies of tall buildings are different in terms of shape, size and occupation. To draw general conclusions, it is necessary to identify the most common morphologies in the studied area. We focus on the aspect ratio (ratio between the length and the width of a rectangular rooftop) and the roof surface of the tallest buildings. These characteristics can be gathered from maps that are available for many cities. This will be further developed in Sec. 3.1.

2.2 System spacing

PV panels: The energy production of solar energy systems is strongly dependent on solar irradiation. Depending on the orientation of the building and the climate conditions, the number of
PV panels that can be installed on a rooftop will vary. The energy output of PV panels might be affected by shading from neighbouring collector rows. In this paper, the trigonometric method is used to deduce the required distance between rows [15]. The minimum distance between two rows of panels can be expressed as:

\[ d_{\text{min}} = l \left( \cos \beta + \frac{\sin \beta}{\tan \alpha} \right), \]  

where \( l \) is the length of the panel, \( \beta \) is the optimum inclination angle of the panel and \( \alpha \) is the elevation of the sun. The angle \( \alpha \) represents the sun’s height, when the sun is at its lowest [15] (which means the longest shadow cast on the roof). A setback distance of 1.5 metres between the edge of the roof and the panels is imposed for maintenance [16].

**Wind turbines:** To prevent array losses and excessive fatigue, wind turbines should be placed sufficiently far apart. In accordance with standard practice, we use a 10-rotor diameter (10 D) spacing in the downwind direction and a 3-rotor diameter (3 D) spacing in the crosswind direction [17]. Wind turbines are generally installed on an external structure that transmits the loads to the building. From [18], we assume that every turbine needs a 5 by 5 m\(^2\) area to be installed on the roof.

### 2.3 Techno-economic analysis of PV panels and WT

Three metrics are used to evaluate the energetic and economic performance of the PV panels and SWT, i.e. the annual energy production (AEP), the levelised cost of energy (LCOE) and the internal rate of return (IRR). The chosen values to calculate the energetic and economic parameters will be further discussed in the case study in Sec. 3.

Tall buildings generally have a large energy consumption and their instantaneous energy consumption can reasonably be assumed to be always larger than the instantaneous energy production given by the renewable energy system. The energy produced is entirely consumed by the building and the use of batteries is therefore not useful. In Fig. 1, a simple block diagram shows the energy conversion process considered in this article.

#### 2.3.1 Annual Energy Production

**PV panels:** The annual energy production of a photovoltaic panel depends on the annual solar irradiation \( G_T \) (in kWh/m\(^2\)/year), the number of square metres \( A_{PV} \) installed, the efficiency \( \eta_{PV} \) of the panel and the performance ratio \( \text{PR} \) of the system. The efficiency of a PV panel is the percentage of irradiance that the panel can transform into electricity. The quality of a PV panel (given by the performance ratio) represents all losses occurring during the energy conversion process.
(inverter, cables, temperature, snow, etc.) [19, 20, 21]. Here, the annual energy production for PV panels ($E_{PV}$) is given by:

$$E_{PV} = G_T A_{PV} \eta_{PV} \text{PR}.$$  
(2)

**Wind turbines:** To estimate the annual energy production of a wind turbine, the IEC61400 standard recommends to use hub-height wind measurements combined with the detailed power curve of a wind turbine [22]. The annual energy produced for wind turbines ($E_{WT}$) is given by:

$$E_{WT} = 8760 \bar{P},$$  
(3)

where $\bar{P}$ is the average power output of a wind turbine. It can be expressed as:

$$\bar{P} = \int_{0}^{\infty} P(V) \phi(V) dV$$  
(4)

where $P(V)$ (in kW), is the power curve of the wind turbine and $\phi(V)$ is the probability density function of a given wind regime.

In this paper, we aim to develop a generic method to compare both energy systems on tall buildings. However, the method described in the International Electrotechnical Commission (IEC) standard is used to determine the wind conditions at a specific position. In urban environment, the wind conditions vary significantly with the position of the wind measurement mast and the height of the measuring devices. To draw general conclusions on the tallest rooftops of a region, one can use the IEC certification reports for chosen wind turbines. If one knows the range of wind speed above rooftops in that region, these IEC certification reports give the AEP for average wind speeds varying from 4 to 11 m/s, assuming that the wind speed is Rayleigh-distributed.

### 2.3.2 Levelised Cost Of Energy

The LCOE metric is useful to compare alternative energy generation systems with different scales of operation or different investment and operating time periods [23]. To be valid, the equation must take into account the present value of future expenses [24]. This metric is determined as the total life cycle cost (TLCC) divided by the discounted energy production (TDEP). The total life-cycle cost can be expressed as:

$$\text{TLCC} = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n},$$  
(5)

where $C_n$ is the cost in year $n$, $N$ the lifetime of the turbine in years and $r$ the discount factor. Generally, one assumes that the only costs are the initial investment cost ($I_0$) and the operation- and-maintenance costs ($C_{OM}$) [25]. The initial investment $I_0$ is considered to be a one-off payment [26].

$$C_n = \begin{cases} I_0, & \text{if } n = 0 \\ C_{OM}, & \text{if } n \geq 1 \end{cases}$$  
(6)
The TDEP can be expressed as:

\[
TDEP = \sum_{n=1}^{N} \frac{E_n}{(1 + r)^n},
\]

where \( E_n \) is the energy production in year \( n \). If we assume that the operation-and-maintenance costs and the annual energy production are constant, the expressions for TLCC and TDEP can be simplified using the annuity factor \( a \), defined as:

\[
a = \sum_{n=1}^{N} \frac{1}{(1 + r)^n} = \frac{1 - (1 + r)^{-N}}{r}.
\]

Using eqs. (5), (7) and (8), the LCOE can then be written as:

\[
LCOE = \frac{I_0 + aC_{OM}}{aE},
\]

where \( E \) is the annual energy production. The LCOE is given in [EUR/kWh].

### 2.3.3 Internal Rate of Return

The internal rate of return (IRR) of a project is a metric derived from the net present value (NPV) [23]. The IRR is the discount rate at which the NPV of the project equals zero. The IRR allows to compare different kinds of investments, e.g. energy production systems or real estate. The IRR is defined as:

\[
NPV = 0 = \sum_{n=1}^{N} \frac{CF_n}{(1 + IRR)^n} - I_0,
\]

where \( CF_n \) is the cash flow in year \( n \). When the NPV of a project is positive, it indicates that the expected earnings are higher than the foreseen costs. A positive NPV shows that the investment is profitable while a negative NPV demonstrates that the returns are worth less than the initial investment. Although the NPV is positive, it does necessarily not mean that the investment is cost-effective. The analyst must be careful and compare the result with other potential investments. Finally, because the variability of renewable resources can have a major impact on the economic viability of RES projects [27], this effect is discussed in the next section.

### 3 Case study: Brussels and its rooftops

The methodology discussed in Sec. 2 is applied to the Brussels region in Belgium. The main parameters used in this case study are gathered in Table 1.

#### 3.1 Typical rooftops in Brussels

For a reliable comparison between both energy systems, this study focuses on the tallest buildings of the region (Sec. 2.1). In this paper, we set 60 m as a height above which a building is considered as ‘tall’.
Table 1: Values for the main variables used in the case study. The number of PV panels and SWT units installed on the roof depends on its size and the spacing requirements explained in Sec. 2.2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value/information</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof surfaces [m²]</td>
<td>from 100 to 4100</td>
<td>-</td>
</tr>
<tr>
<td>( A^{PV} ) [m²]</td>
<td>1 x 1.6</td>
<td>-</td>
</tr>
<tr>
<td>( A^{WT} ) [m²]</td>
<td>5 x 5</td>
<td>[18]</td>
</tr>
<tr>
<td>( \alpha ) [°]</td>
<td>16</td>
<td>[28]</td>
</tr>
<tr>
<td>( \beta ) [°]</td>
<td>35</td>
<td>[28]</td>
</tr>
<tr>
<td>( d_{\text{min}} ) [m]</td>
<td>4.51</td>
<td>-</td>
</tr>
<tr>
<td>PV panels [#]</td>
<td>14 to 856</td>
<td>-</td>
</tr>
<tr>
<td>PV power [Wp]</td>
<td>216</td>
<td>-</td>
</tr>
<tr>
<td>WT units [#]</td>
<td>1 to 9</td>
<td>-</td>
</tr>
<tr>
<td>WT power [kW]</td>
<td>3.2, 5.2 and 10</td>
<td>[29, 30, 31]</td>
</tr>
<tr>
<td>( D ) [m]</td>
<td>4.4, 5.6 and 13.2 resp.</td>
<td>[29, 30, 31]</td>
</tr>
<tr>
<td>( G_T ) [kWh/m²/year]</td>
<td>1250</td>
<td>[32]</td>
</tr>
<tr>
<td>( \eta^{PV} ) [%]</td>
<td>13.5</td>
<td>[33]</td>
</tr>
<tr>
<td>PR [%]</td>
<td>78</td>
<td>[34]</td>
</tr>
<tr>
<td>wind speeds [m/s]</td>
<td>from 5 to 8</td>
<td>[35]</td>
</tr>
<tr>
<td>( E^{PV} ) [kWh/unit]</td>
<td>210.6</td>
<td>-</td>
</tr>
<tr>
<td>( E^{WT} ) [kWh/unit]</td>
<td>5777.4, 8367.3 and 34931.6 resp.</td>
<td>-</td>
</tr>
</tbody>
</table>
Having identified the tallest buildings, the morphological features of their rooftops can be determined. The majority of the rooftops are rectangular and flat with varying size and aspect ratio. Using digital vector maps, the size and aspect ratio of these rooftops were measured. Areas ranging from 80 to 4100 m$^2$ and aspect ratios varying between 1 and 8 were found. Fig. 2 shows a plot of the aspect ratio and the rooftop area of these buildings.

In this study, we first focus on flat, rectangular rooftops with a fixed aspect ratio of 3 and a size varying between 100 and 4000 m$^2$. Later, we perform a sensitivity analysis (Sec. 4) to evaluate the impact of the aspect ratio.

### 3.2 System spacing

#### 3.2.1 General considerations

To ensure that both systems operate optimally, we further assume that the rooftop filled with PV panels faces the south orientation and the rooftop filled with wind turbines faces the south-west orientation. South-west has been shown to be the dominant wind direction on Brussels' rooftops [25]. Therefore, a turbine installed at the most southwest edge is expected to produce more energy annually. Finally, this artifice will maximise the energy production of both systems and prevent the choice of an orientation that would favour one system over the other.

**PV panels:** The optimal orientation and inclination of PV panels in Belgium is towards the south ($\beta = 35^\circ$ Table 1). To avoid shadow from neighbouring rows of panels, the minimal spacing distance is calculated with eq. (1). Considering a panel length of 1 m, the optimal panel inclination $\beta$ and of the sun angle $\alpha$ (Table 1), the minimal distance $d_{\text{min}}$ between two rows is 4.51 m. For maintenance reasons, a setback distance of 1.5 metres between the edge of the roof and any panel is respected.

**Wind turbines:** In Belgium, the wind blows mostly from the southwest. We recall (Sec. 2.2) that the spacing is 3 D in the crosswind direction and 10 D in the downwind direction. For example,
based on the rotor dimensions of the three chosen turbines, (Table 1), the spacing between two masts in the crosswind direction are 13.2, 16.8 and 39.6 meters respectively.

### 3.2.2 Example of a wind or solar installation on one roof

As an example, we consider the average rooftop surface and aspect ratio of tall buildings in Brussels, i.e. 1280 m² and 3 respectively. This means the length of the roof is 61.97 m and the width is 20.66 m. The longest edge faces the optimum orientation of the system, and the roof is free of other installations.

The algorithm first calculates the number of panels in a row, then the number of rows. The setback distance is subtracted from each side of the roof (2 times 1.5 m). In this example, 58 PV panels with a width of 1 m can be installed in one row. The number of rows depends on $d_{\text{min}}$ (Table 1) and the setback distance from the edge of the roof. In this example, 4 rows of panels can be installed. The average rooftop can therefore be installed with 232 PV panels.

The maximum number of turbines in both directions (crosswind and downwind) can be calculated in a similar way. The minimum spacing is 13.2 m (3 D) in the crosswind direction and 44 m (10 D) in the downwind direction (Table 1). In this paper, we suppose that the longest edge of the roof faces the south-west orientation and we use the crosswind spacing to install turbines along that edge. For this example, only 5 turbines can be installed in the length of the roof. This can be repeated for the 5.2 kW and the 10 kW turbine based on their rotor dimensions.

The full range of PV panels and wind turbines for all roof surfaces is given in Table 1.

### 3.3 Annual energy production

#### 3.3.1 Parameter values

**PV panels:** Eq. (2), used to determine the energy production from a photovoltaic panel, requires 4 parameters: yearly irradiation, panel efficiency, performance ratio and surface of PV panels. This paper uses multi-crystalline technology, as it is the leading technology in the PV market [36]. The chosen values for these 4 parameters come from recent references and express the mean values from the literature (see Table 1). Finally, a PV system will suffer from a decrease of power output over time, expressed by a degradation rate. The mean value estimated over 2000 degradation rates for multi-crystalline PV is 0.5 %/year [37]. This value is used in this case study.

**Wind turbines:** As mentioned in Sec. 2.3, we estimate the AEP of a wind turbine from IEC test reports. In this study, 3 different small wind turbines are considered: 3.2, 5.2 and 10 kW [29, 30, 31]. This range of power has been selected based on existing rooftop-mounted turbines [5, 6]. Wind turbines have several potential impacts on their surroundings, e.g. vibrations, noise, shadow flicker. Recent papers [38, 18] studied the feasibility of installing SWT (up to 5.2 kW) on high-rise buildings. They concluded that the installation generally has little impact on the building and its nearby environment. It should be emphasised that the results of [18, 38] are for particular buildings, and it is not clear to what extent the conclusions can be generalised to other buildings.

All small turbines certified according to the IEC provide a test report with the measured power curve and the estimated AEP for several wind speeds (integer values between 4 m/s and 11 m/s). The wind speed can significantly vary with the height of the building, the position in the city and even the location and height of the turbine on the roof. In this study, we used wind speeds between
5 and 8 m/s. On rooftops in Brussels one can expect mean wind speeds up to 6 m/s, which is reasonable for very tall buildings [35]. We also assume that the wind turbines are installed at a height of 10 to 15 m, which corresponds to the wind speed measurements performed in Brussels.

Based on several reports for different turbines scale, we found downtime periods ranging from 1.6 % to 6.5 % per year [39, 40, 41]. From these reports, we chose to follow the worst-case scenario and used 6.5 %. As the literature on wind turbines degradation is inconclusive [42], we do not include a degradation rate.

3.3.2 Results

The AEP of PV panels and SWT at different wind speeds is shown for varying rooftop surfaces in Fig. 3. Two conclusions can be drawn from the figures:

1 - For good wind conditions, turbines usually produce more electricity than PV panels.

For very good wind conditions (6 m/s), it is interesting to observe that the 5.2 kW and 10 kW turbines produce more energy annually than the PV panels on rooftops smaller than 1500 m². Only 6 roofs from the tallest buildings in Brussels have larger surfaces than 1500 m². In good wind conditions (5 m/s), that surface decreases to 1000 m², which corresponds to 56 % of the tallest rooftops. This surface does not consider obstacles so the true turning point could be a little larger, at the advantage of the wind turbines. This is further studied for the three turbines in Sec. 3.3.3.

2 - Both energy systems show step curves.

In the PV curves, each step represents the scenario where one extra row of panels can be installed. For the wind turbines, each step represents the addition of one turbine. Given the downwind constraint of 10 D (Sec. 2.2), the scenario of a second row of turbines is not reached for a limiting area of 4,100 m².
Figure 4: Left: rooftops surfaces for the 31 tallest rooftops (black dashed line). The buildings are ordered from smallest to largest rooftop size. For each rooftop, its available surface for PV panels (orange) and for WT (blue) is given. Right: for the three turbines (3.2, 5.2 and 10 kW rated power, at a 5 m/s average wind speed), the minimum rooftop surface required so that PV panels produce more energy annually than the turbines is calculated. The calculation is performed for varying percentages of available rooftop surface.

3.3.3 Impact of obstacles

In this paper, we so far considered that rooftops were completely free of other installations. In reality, these buildings have several existing installations (e.g. chimneys, masts, ventilations systems) that limit the available space for renewable energy production. For the 31 tallest buildings in the region (Sec. 3.1), we have assessed the available surface for the installation of PV panels and wind turbines (Fig. 4, left). One observes that the impact is larger for the PV panels than for the wind turbines. In fact, in terms of space, wind turbines are less affected by the presence of other installations because of their system spacing requirements (Sec. 3.2). The surface taken by these ‘obstacles’ is (often) a surface that is not used by the wind turbines.

It is therefore interesting to calculate the rooftop surface at which the PV panels produce more energy than the wind turbines, for different percentage of available surface (Fig. 4, right). This figure is drawn for the same assumptions as presented in Sec. 3.1, and for a wind speed of 5 m/s. For the three considered turbines, the surface above which the PV panels produce more energy annually is shown. For the 31 rooftops, the average available surface is 45 %. For that percentage, there is only one rooftop surface on which the PV panels will produce more energy than the wind turbines. In fact, considering their real available rooftop surface (that is between 10 and 80 % of the total rooftop surface), these wind turbines will generally produce more energy annually than the PV panels for the 31 buildings.

3.4 Economic assessment

3.4.1 Levelised cost of energy

**PV panels:** The LCOE depends on the AEP and the total cost of the system. In this study, only the investment cost (i.e. purchase, installation and balance of system components costs) and the operation and maintenance cost are considered. The price of the PV investment depends on many
factors (e.g. the type of cells, the installation method, the connection to the grid and the size of the array). As it is a Belgian case study, we further use the European currency, i.e. the Euro (EUR). At the time of the case study, the current exchange rate with dollars is 1 EUR = 1.1 USD. We used a decreasing price based on the array size (2000 EUR/kWp below 5 kWp, 1800 EUR/kWp between 5 and 10 kWp and 1500 EUR/kWp for larger arrays), based on [43, 44]. A federal tax of 6 % is applied on these costs.

**Wind turbines:** The cost of a SWT is presently on average 5450 EUR/kW (investment cost) both in the US and the UK [45, 46]. One can expect that building-mounted turbines will have a higher cost of installation than a ground-mounted turbine. Literature about that aspect being scarce, we will study the cost variation in the sensitivity analysis. Finally, no economies of scale were considered for the wind turbines.

**Results:** The step in the PV curve (Fig. 5, at a rooftop surface of 240 m$^2$) shows the result of a decreasing price of PV panels. The turbine curves remain flat because no cost reduction was considered.

The LCOE for PV panels varies between 0.19 EUR/kWh for rooftops smaller than 240 m$^2$ to 0.14 EUR/kWh for larger rooftops, which is in agreement with the EU report [43]. For small turbines, it is difficult to find relevant references to compare the results of our study as the number of rooftop-mounted wind turbines is very small. However, the LCOE values from Fig. 5 are comparable to ground-based references (0.13 to 0.31 EUR/kWh, 0.04 to 0.39 EUR/kWh) [47, 46].

The comparison between the two energy systems indicates that PV panels are generally cheaper per kWh than the turbines. For a good mean wind speed (above 5 m/s), only the 10 kW turbine shows better results than the PV panels. However, its suitability for a rooftop installation should still be investigated. Only for small rooftop surfaces and a mean wind speed above 6 m/s, the SWT can compete with PV panels.
3.4.2 Internal rate of return

The cash flows are estimated based on the costs and the revenues [48, 24]. We will only assume investment cost and OM costs since they represent the highest expenditures for photovoltaic and wind turbine projects [49]. The magnitudes of these costs were given in Sec. 3.4.1. The revenues cover the energy saved, the different incentives and the salvage value. This study does not consider the systems end-of-life, therefore the salvage value is taken as zero. The different revenues are discussed in what follows:

Saved expenses: The energy produced by the rooftop reduces the amount of energy required from the grid. In this model, we assume that all energy produced by the system is consumed by the producer. The saved expenses ($CF_{AEP}$) are calculated as follows:

$$CF_{AEP} = E_n C_e (1 - TR), \quad (11)$$

where ($C_e$) is the price of energy and $TR$ is the tax rate in Brussels.

Incentives: In Brussels, the incentives are either granted by the Federal level (Belgium) or the Brussels Region. As of 2018, four incentives exist to promote renewable energy for companies: the fiscal depreciation, the super deductibility, the green certificates and the environmental investment support.

1. The first federal incentive is the fiscal depreciation ($CF_F$). It represents the spread of a cost over the estimated duration of use:

$$CF_F = \frac{I_0}{T_{dep}} TR, \quad (12)$$

where $I_0$ is the cost of investment and $T_{dep}$ is the depreciation period (Table 2).

2. The second federal incentive is a tax advantage for companies investing in improvements of the energy use [50]. This advantage is a profit exemption that corresponds to a percentage of the cost of investment of the project:

$$CF_{TA} = TA I_0 TR, \quad (13)$$

where $TA$ is the tax advantage (Table 2).

3. The first regional (Brussels) incentive is the green certificates ($GC$). Green certificates are used in several countries to promote green energy. In Europe, the most used mechanism are the feed-in tariffs (FIT) (and feed-in premiums) and the green certificates [51]. The number of green certificates is calculated with:

$$CF_{GC} = N_{GC} P_{GC} (1 - TR), \quad (14)$$

where $N_{GC}$ is the number of green certificates and $P_{GC}$ is the selling price for one green certificate (see Table 2).

4. The second regional support is for any company willing to invest in a ‘green’ project. It is calculated as a percentage of the total investment cost and varies depending on the size of the company (in this study 30% of investment cost, given in year 2).
Table 2: Values for the main economic variables used in the case study.

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<th>Parameters</th>
<th>Value</th>
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<tr>
<td>$I^\text{PV}_0$ [EUR/kWp]</td>
<td>varying (Sec. 3.4.1)</td>
<td>[43, 44]</td>
</tr>
<tr>
<td>$I^\text{WT}_0$ [EUR/kW]</td>
<td>5450</td>
<td>[45, 46]</td>
</tr>
<tr>
<td>$r$ [%]</td>
<td>3</td>
<td>[25]</td>
</tr>
<tr>
<td>$C_{OM}$ [%]</td>
<td>2</td>
<td>[25]</td>
</tr>
<tr>
<td>N [years]</td>
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</tr>
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<td>$C_{el}$ [EUR/kWh]</td>
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</tr>
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</tr>
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<td>$N_{GC}$ [#/MWh]</td>
<td>2.4 (PV), 1.81 (SWT)</td>
<td>[52]</td>
</tr>
<tr>
<td>$P_{GC}$ [EUR/N_{GC}]</td>
<td>83</td>
<td>[52]</td>
</tr>
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</table>

Figure 6: IRR comparison between PV panels and wind turbines at several wind speeds. The three graphs correspond to 3 turbines (left to right: 3.2, 5.2 and 10 kW rated power). The rooftop has an aspect ratio of 3 and has an increasing surface. The average surface of the tallest rooftops in Brussels is represented by the black dotted line.

Results: Fig. 6 shows an IRR ranging between 12 and 19 % for a photovoltaic installation (these results are in accordance with [53]). For appropriate wind speeds, the wind turbines have an IRR between 5 % (for the 5.2 kW turbine at 5 m/s wind speed) and 23 % (for the 10 kW turbine at 6 m/s).

The PV curve increases rapidly for increasing rooftop surfaces up to 240 m$^2$. This is the result of the decreasing cost of the PV, as explained above.

Comparing the two energy systems and the three turbines, similar conclusions as for the LCOE can be drawn. The 5.2 kW turbine shows lower IRR than the 3.2 kW turbine for the same wind speeds ($\leq$ 6 m/s). For wind speeds below 6 m/s, the PV panels have generally a higher IRR than these two turbines. The 10 kW turbine shows again interesting results with an IRR higher than 23 % for a 6 m/s wind speed, which is better than the PV installation, for any rooftop size.
Variability of renewable resources has a major impact on the viability of RES projects, both at the local and the global scale [27, 54]. Tall buildings have a large energy consumption [55] and it is likely that the instant energy production will always remain lower than the instant energy consumption. Nevertheless, to cover all possibilities, the impact of varying self-consumption on the economic indicators is addressed in the next paragraphs.

In Brussels, buildings with a RES need to install an electricity meter that measures the electricity injected into the grid as well as the consumption. On a daily basis, the energy supplier receives the data and can therefore charge the customer accordingly. If the self-consumption (i.e. the percentage of electricity production that is actually consumed) is lower than 100 %, this separate metering has a significant impact on the revenues collected from the saved expenses, because 1 kWh self-consumed is worth more than 1 kWh injected into the grid. Regarding the economic indicators studied in this paper, only the IRR will be impacted, as it is the only indicator that takes into account the yearly revenues (Sec. 3.4.2).

Fig. 7 shows the impact of self-consumption on the IRR for a rooftop of 1280 m$^2$ and an AR of 3, and installed with PV panels or SWT. We observe that taking the self-consumption into account can strongly affect the economic performance of the RES. To increase the economic value of the project, one should choose the energy system that fits the demand as much as possible. Deciding which system (PV panels or SWT) is the most relevant is therefore case-dependent and should be based on time series analyses of energy production and consumption.

4 Sensitivity analysis

Using three metrics, the previous section provides a comparison between PV panels and SWT. The results of these metrics strongly depend on the chosen values of each parameter. Therefore, a sensitivity analysis has been performed, for the 3.2 kW turbine at an average wind speed of 5 m/s, to observe the variation of the economic metrics under different scenarios (drop of turbines cost, impact of incentives and variation of aspect ratios)
Figure 8: IRR variation as a function of the turbine’s cost (WT = blue and PV = orange). The two energy systems have the same IRR when the turbine’s cost reaches 2700 EUR/kWp. The current cost of a ground-mounted SWT is represented with the black dotted line.

4.1 Cost of the wind turbine

This analysis is performed to simulate the higher cost of a roof installation as well as a possible cost reduction caused by a growing market. It also expresses the current cost uncertainty of SWT [45, 46].

In Fig. 8, the variation of IRR is shown as a function of the wind turbine cost. The simulation is performed for a rooftop surface of 1280 m$^2$ (mean/median rooftop surface for the 31 tallest buildings in Brussels) and a wind speed of 5 m/s. The other parameters are the same as in section 3.

What is observed is that for turbine investment cost below 2600 EUR/kWp (current 5450 EUR/kWp), the IRR of a turbine installation becomes higher than for PV panels. We observed a large IRR variation ranging from -3 to 21 %. The little drop at 5200 EUR/kWp is caused by the environmental investment cash flow and the way it is granted by the region. As of now, predictions on future competitiveness between both systems remain difficult and will mainly depend on the turbine cost of installation. A very high cost of installation could completely annihilate the viability of a 3.2 kW rooftop-mounted turbine.

4.2 Incentives

In Sec. 3.4.2, the various federal and regional incentives that a company can claim were introduced. These incentives are not permanent and can be modified or revoked. For instance, between 2015 and 2016, the Brussels Region removed an incentive to purchase and install PV panels and wind turbines. This incentive granted a maximum of 25 and 30 % of the total cost of the installation, for the turbines [56] and photovoltaic panels [57] respectively. In the future, other incentives might be stopped.

Three scenarios are shown in Fig. 9. The scenario 2015 expresses the IRR before that the incentive was removed. The 2019 scenario represents the current situation. The ‘no incentives’ scenario excludes all incentives. We observe a difference of 3 and 7.5 % between the 2015 and today’s scenarios, for wind turbines and PV panels respectively. Although the ‘no incentives’ scenario shows that the PV panels keep a positive IRR, such a low IRR would not attract many
investors. In contrast, the turbines are no longer profitable without any incentives.

This figure raises the question of inequity of incentives between PV panels and SWT in the Brussels Region. In Belgium, 1 GC is delivered for every MWh of energy produced. This number of green certificates is multiplied by a coefficient that depends on the energy system used to produce that energy. In particular, PV arrays larger than 5 kWp have a coefficient of 2.4, while wind turbines have a coefficient of 1.81 \[52\].

4.3 Aspect ratios

As mentioned in the methodology, this study does not consider the orientation of the building. However, by varying the aspect ratio of the rooftop, one can simulate a very good orientation (longer edge of the roof facing south for PV panels) or a bad orientation (longer edge facing west for PV panels). The same applies for the wind turbines. Figs. 10 and 11 show the impact of different aspect ratios on the AEP.

Fig. 10 displays the AEP for 5 aspect ratios (1/9, 1/5, 1, 5 and 9). An aspect ratio larger than 1 means that the longer edge of the rooftop faces south. Each line has a sawtooth pattern. The longer the edge facing south, the higher the jump in the AEP whenever a row is added while increasing the area.

Fig. 11 displays the AEP of the 3.2 kW turbine as a function of the aspect ratio. In this case, a higher aspect ratio (longer edge of the roof facing south-west) produces more electricity. This is caused by the different turbine spacing requirements for different wind directions. For the same rooftop surface, more wind turbines can be installed if the longer edge faces the optimal wind direction (because turbines’ spacing is smaller when SWT face the optimal wind direction, see Sec. 2.2).
Figure 10: Annual energy production of PV panels for an increasing rooftop surface. The graph displays the AEP for 5 aspect ratios (1/9, 1/5, 1, 5 and 9). An aspect ratio larger than 1 means that the longer edge of the rooftop faces south.

5 Conclusions

In this work, we propose a methodology that allows to compare rooftop-mounted photovoltaic panels with small wind turbines on the basis of three metrics: the annual energy production, the levelised cost of energy and the internal rate of return. The methodology was tested on a case study, the Brussels Region, adopting its economic and weather conditions. To ensure a fair comparison, both systems were considered to be installed in the most favourable condition, i.e. optimally inclined and oriented on tall buildings with good wind conditions (5 to 6 m/s annual mean wind speed). This study considers the rooftops to be free of other installations. The considered PV panels were of the crystalline type (216 Wp, 1.6 m$^2$) and three SWT of 3.2, 5.2 and 10 kW rated power were studied.

The techno-economic comparison shows that the 3.2 and 5.2 kW turbines can compete with PV panels, but only in terms of their energy production. In good wind conditions (5 m/s) and for rooftop surfaces < 550 m$^2$ and < 600 m$^2$ (for the 3.2 and the 5.2 kW turbines respectively), more energy is produced by the wind turbines than by a PV array. Only the 10 kW turbine can compete with PV panels in terms of economic metrics for winds averaging 5-6 m/s. However, the suitability of such turbines for rooftop applications requires further investigation, in particular their effect on the structural integrity of the building.

If one considers the available space for each of the 31 tallest buildings in Brussels, the wind turbine solution generally produces more energy annually than the PV panels solution. This is because the positioning of PV panels is more strongly affected by the presence of other rooftop installations.

A sensitivity analysis was conducted for three parameters: cost of the SWT, incentives and aspect ratios of the rooftops. In Belgium, the profitability of both RES significantly depends on the incentives. Moreover, a high cost of installation could adversely affect the viability of a rooftop-mounted turbine. Finally, the building geometry has a larger impact on the AEP of the wind turbines than for PV panels, because of the inter-turbine spacing requirements.
Figure 11: Annual energy production of wind turbines for an increasing rooftop surface. The graph displays the AEP for 5 aspect ratios (1/9, 1/5, 1, 5 and 9). An aspect ratio larger than 1 means that the longer edge of the rooftop faces south-west.

Acknowledgement

This research was partially funded by the research project Wintegrate in the context of the Innoviris Strategic Research Platform 2012 ‘Brussels Retrofit XL’ (www.brusselsretrofitxl.be).

References


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