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Economics of Small Wind Power Plants in Urban Settings: An Empirical Investigation for Germany

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ABSTRACT

In this paper we investigate the location-specific attractiveness of small wind turbines (SWT) for private households. In order to assess the economic viability of an investment in SWT, we analyze a set of scenarios that incorporate different types of SWT, various storage system options, support schemes, and specific urban surroundings for the case of Germany. As urban structures substantially influence local wind speeds, and hence the potential energy yield of a turbine, the potential location of the SWT in the urban area is crucial for the economic feasibility. We find that SWT today are only profitable under very favorable conditions, the most important parameters being prevailing wind speeds and the location’s degree of urbanization. In most cases, the coupling of the SWT to a storage system is crucial for cost-effectiveness. A feed-in tariff system specifically adapted to the SWT technology is found to be an important driver of diffusion. Further research needs are identified in the field of long-term performance and yield projections for SWT. Based on the findings from our study, significant SWT diffusion can be expected, if at all, only in coastal suburban and rural areas.

Key words: small wind turbine; energy storage; urban environment; feed-in tariffs
JEL Classification: Q42; Q48; O18

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I. INTRODUCTION

In the context of the political debate on global climate change, in 2007 the German federal government set ambitious energy and climate goals. Establishing Germany as a global forerunner and technology leader in the field of climate protection, until 2020 40% of the CO₂ emissions (compared to the level of 1990) need to be saved. Compared to the climate goals of the EU, which aim at reducing emissions in the same period by 30%, the German climate goals are even more ambitious. A pivotal measure to reach the climate goals is the extensive support of renewable energy sources (RES). In particular, this includes the stepwise increase of the share of RES in primary energy generation to 35%. In the year 2011, this share was already at about 20% (AfEE, 2011). Despite increasing shares of RES, technical, economic, environmental as well as social acceptance problems are more and more slowing down the energy transition in Germany. These particularly refer to the cost of the grid expansion and restructuring, the integration of off-shore wind farms, both from a technical and environmental perspective, and a decreasing social acceptance of RES, such as on-shore wind power. However, tackling the complex challenge of meeting climate goals requires the consideration and contribution of various renewable energy technologies.

From the perspective of large-scale investors, mature renewable energy technologies, such as on- and off-shore wind power, solar (thermal) power plants, hydro power and biomass plants are the most important investment options. Due to the feed-in tariffs provided by the EEG support scheme (EEG, 2012) and the associated feed-in guarantee for the generated electricity, these technologies are often attractive long-term investments.

But also small investors, such as private households, can play an important role regarding the energy transition in Germany. Firstly, the environmental awareness increases, as households are interested in a sustainable and CO₂-free electricity supply which is also reflected in the willingness-to-pay for sustainable energy technologies (Mattes, 2012). Secondly, private households are financially contributing to the expansion of RES through a fixed rate per kWh, which implies increasing long-term costs that have to be paid for the energy transition. Therefore, actively supporting climate protection and decreasing the own electricity bill are valid incentives for investments in RES (Halbhuber, 2010). So far, however, in the private household sector in Germany, only investments in photovoltaics (PV) and to some extent in biomass plants turned out to be economically feasible.

Besides PV and biomass facilities, barely considered investment options for households to generate electricity are small wind turbines (SWT). SWT are characterized by a small installed capacity (typically around 1 – 10 kW) as well as a hub height of up to around 30 m, and can either be free-standing or roof-mounted. Roof-mounted SWT in particular could be an investment option for private households in urban areas.

1 In this case RES essentially contain relatively mature energy technologies, such as on- and off-shore wind power, solar (thermal) power, hydro power and biomass power plants.
2 Since October 2012 the levy imposed on households is € 5.3 ct/kWh (BEE, 2012), raised from the previous level of € 3.6 ct/kWh. In 2012, the burden imposed on electricity consumers was around €20 bn.
The market for SWT is still small, but steadily growing. The German Federal SWT Association (Bundesverband Kleinwindanlagen, BVKW) expects an increase of the number of installed SWT of up to 700,000 units in Germany until 2020 (Frey, 2009). In comparison, the number of installed SWT in the UK is expected to increase to about 600,000 units in the same period of time (Renewable UK, 2011). The World Wind Energy Association (WWEA) published the first worldwide market study of SWT in 2012. China was identified as the country with the largest number of SWT (450,000 units), followed by the United States with around 140,000 units. Most of these SWT are not grid-connected but running in off-grid (island) systems, particularly in rural areas of China, where SWT have been used for local electricity generation or water pumps since the early 1980s. According to the WWEA study, there were around 520,000 units installed in 2009 worldwide, a number which grew in 2010 by 26% to about 650,000 (WWEA, 2012). Increasing importance of SWT is also expected for developing countries in the context of rural electrification projects (Rolland, 2013).

SWT exhibit several advantages. SWT offer the possibility of an independent electricity supply, or alternatively receiving feed-in payments from feeding the generated electricity into the grid. Transport costs are negligible due to the spatial proximity between supplier and consumer. From a technical perspective, the manufacturing processes of SWT are well-known and proven. Therefore, SWT are characterized by a high degree of reliability, which is advantageous regarding supply and planning reliability (Kühn, 2010a). Despite some similarities between large-scale turbines and SWT, there are considerable differences with respect to the economic feasibility, which calls for a separate investigation of SWT economics (Halbhuber, 2010). The development potential of this technology is still impaired by the lack of technological standards, intransparent regulatory frameworks and the lack of reliable wind power prediction tools, particularly with respect to the economic feasibility.

Recent literature on SWT is still particularly focused on technical aspects of this energy technology. This includes the assessment of life-cycle costs (Celik et al., 2007), energy-related amortization calculations and the evaluation of the CO$_2$-saving potential (Philips et al, 2007). Other publications investigate the optimal installation position of roof-mounted turbines by means of wind tunnel tests (Blackmore, 2008) or the change of wind speeds in areas with higher building density (Heath et al, 2007). First attempts to estimate yield expectations for SWT are conducted by Kühn (2010b), Richter (2010) and Sunderland and Conlon (2010) among others. Reference studies or long-term field tests on the performance of SWT in urban areas are very limited in numbers. The Warwick Wind Trials study, conducted in the UK in 2007 and 2008, provides some results on SWT performance in urban areas, indicating that an increase in the degree of building density leads to a decrease in the generated energy yield (Encraft, 2009). More recently, Abohela et al. (2013) specifically investigated the effect of roof shape, wind direction, buildings height and surrounding urban environment on the energy yield and positioning of roof-mounted SWT.

In this paper, we investigate the potential investment in SWT for private households dependent on the location under varying urban conditions. The economic feasibility of a SWT

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3 SWT have a high degree of reliability compared to large-scale, multi-MW wind turbines.
and, therefore, the investment decision of households in this technology essentially depends on three factors: (1) the technical design of the turbine with regard to size and type; (2) the economic and regulatory framework with respect to the support scheme; and (3) spatial aspects, such as the wind speed in the context of the urbanization level, particularly with regard to building heights and density. Especially the potential location of the SWT in the urban area is crucial for the economic feasibility evaluation, as urban structures substantially influence local wind speeds, and, therefore, the potential energy yield of a turbine. In order to assess the profitability of an investment in this technology from the perspective of a private household, we model various investment scenarios that incorporate different types of SWT, various storage system option that can be coupled, support schemes, bank loans, and in particular the specific characteristics of urban locations. In addition, we investigate the impact of the introduction of a modified feed-in tariff system that is better adapted to SWT than the existing tariffs for large wind turbines. However, the main focus of this empirical study is the assessment of definite investment decisions in SWT in view of varying conditions caused by different urban settings.

Since, to our knowledge, there is no comprehensive economic feasibility evaluation for SWT under urban conditions available yet, this paper aims at providing a better empirical understanding of the economic potentials of the SWT technology, also trying to identify key factors for the private household’s investment decisions. Additional merit is created through specifically investigating the economic feasibility in respect of the support scheme in place.

The remainder of this paper is structured as follows. In section II, we introduce the three SWT reference plants considered and some peculiarities of SWT. Section III introduces the methodology and the parameters considered for the prediction of yields and revenues. The procedure is then applied to selected locations as an illustration. Subsequently, the economic viability is assessed by means of the net present value (NPV) criterion. The results obtained are provided in Section IV, and checked for their robustness by means of a sensitivity analysis. Section V discusses the results in a broader context and derives some policy recommendations, particularly regarding the role of support schemes and storage options. Finally, section VI summarizes the study, provides some conclusions and points out some future research needs.

**II. REFERENCE PLANTS CONSIDERED**

In order to investigate the economic profitability under different urban conditions, we chose three representative and commercially available plant types. In the following, they are briefly introduced, and compared with each other according to their technical characteristics.

*Skystream 3.7*

The Skystream 3.7 turbine, a product of Southwest Windpower, is produced in Broomfield, Colorado, and globally sold. According to BWE (2011), about 6,500 wind turbines of this type are installed worldwide, most of these in the USA. Compared to technically comparable turbine
types regarding nominal capacity, the Skystream 3.7 shows the highest sales figures worldwide (Southwest Windpower, 2012).

The horizontal axis wind turbine (HAWT) Skystream 3.7 produces electricity from cut-in wind speeds of about 3 m/s and gains the nominal capacity of 2.4 kW at wind speeds of 10.3 m/s. The main advantages of this turbine type are the flexibility regarding its utilization, either roof-mounted or free-standing, and the relatively high availability at various hub heights. Initial installation costs account for about € 12,000 (Southwest Windpower, 2012) and maintenance costs for about € 300 per year (or 0.5% of the installation costs), respectively.

**Aventa AV-7**

The second reference plant considered is the Swiss-made SWT Aventa AV-7. This turbine is also a HAWT and specifically developed for sites with low wind speeds. The Aventa AV-7 produces electricity already at wind speeds of 2 m/s and gains the nominal capacity of 6.4 kW at wind speeds of just 6 m/s (Aventa, 2012). Compared to the Skystream 3.7, the Aventa AV-7 needs lower cut-in speeds and reaches its full output capacity earlier. Technical field tests of this plant type already attested the specific applicability for locations with low wind speeds (Twele, 2007).

Since 2009, Aventa is cooperating with the Italian company Tozzi Nord in order to access new markets and decrease the still very high production costs and sales price (Kirchweger, 2009).

**Envento ENV-M**

Compared to the HAWTs Skystream 3.7 and Aventa AV-7, respectively, the Envento ENV-M is a vertical axis wind turbine (VAWT), designed as an H-rotor. The plant is developed and produced by the German company Envento Windenergie GmbH in Bergen (Chiemgau, Bavaria). Envento is also involved in a research cooperation with the Fraunhofer IWES institute in order to optimize the blade design of SWT (Envento Windenergie, 2013a).

The cut-in speeds of the ENV-M is about 3 m/s, with a nominal capacity of 3 kW that is reached at wind speeds of 14 m/s (Envento Windenergie GmbH, 2013a). Plant-specific advantages are a silently operating rotor with low vibrations. Furthermore, because of the VAWT design, it is not necessary to yaw the turbine according to wind direction. The so-called pitch system adapts the blade angle, depending on the actual wind speed, in order to increase the output of the turbine especially under gusty conditions (Envento Windenergie, 2013b).

Table 1 provides a summary of the technical parameters.

---

4 In Italy, the Aventa AV-7 is sold as TN-7.
### Table 1
Comparison of technical characteristics of the three SWT reference plants studied

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Skystream 3.7</th>
<th>Aventa AV-7</th>
<th>Envento ENV-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>HAWT&lt;sup&gt;a&lt;/sup&gt;</td>
<td>HAWT&lt;sup&gt;a&lt;/sup&gt;</td>
<td>VAWT&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Rotor diameter [m]</td>
<td>3.7</td>
<td>12.9</td>
<td>3</td>
</tr>
<tr>
<td>Rotor surface $A$ [m$^2$]</td>
<td>20.86</td>
<td>129</td>
<td>15</td>
</tr>
<tr>
<td>Nominal capacity $P_{nom}$ [kW]</td>
<td>2.4</td>
<td>6.5</td>
<td>3</td>
</tr>
<tr>
<td>Wind speed at nominal capacity $v_{nom}$ [m/s]</td>
<td>10.3</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Cut-in speed $v_{in}$ [m/s]</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Turn-off speed $v_{off}$ [m/s]</td>
<td>-</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>Specific plant output $\theta$ [W/m$^2$]</td>
<td>221</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>Installation costs [€]</td>
<td>12,000</td>
<td>93,000</td>
<td>19,500</td>
</tr>
<tr>
<td>Operation &amp; maintenance costs p.a. [€]</td>
<td>300</td>
<td>2,325</td>
<td>488</td>
</tr>
<tr>
<td>Yawing control</td>
<td>passive</td>
<td>active</td>
<td>-</td>
</tr>
<tr>
<td>Connection type</td>
<td>grid-connected</td>
<td>isolated operation / grid-connected</td>
<td>grid-connected</td>
</tr>
<tr>
<td>Set-up</td>
<td>roof-mounted / freestanding</td>
<td>freestanding</td>
<td>roof-mounted / freestanding</td>
</tr>
</tbody>
</table>

Notes: <sup>a</sup> HAWT = horizontal axis wind turbine; <sup>b</sup> VAWT = vertical axis wind turbine
Source: Own illustration, based on data from BWE (2011), Southwest Windpower (2012), Aventa (2012), and Envento Windenergie (2013a)

### Performance curves

All three reference plants have particular (dis-)advantages and are, therefore, differently suitable for utilization in varying urban settings. In the case of locations in urban areas, predominantly the cut-in speeds, the nominal capacity and the specific plant output $\theta$ are the most important parameters. Particularly, the specific plant output $\theta$ indicates the applicability for locations with low and high wind speeds, respectively (Twele, 2007).

Most noticeably, the plant types differ substantially with respect to their specific plant output $\theta$, their rotor surfaces $A$ and their costs. Due to the large differences in size (rotor diameter and surface), the Aventa AV-7 has only a very low specific plant output $\theta$ (50 W/m$^2$), as compared to the Skystream 3.7 (221 W/m$^2$) or the Envento ENV-M (200 W/m$^2$), respectively.

Figure 1 illustrates the performance curves of the reference plants based on the values given in Table 1. The performance curve for each plant type is compared to the maximum wind energy and the limit according to Betz law (Betz, 1926), i.e. the difference between the performance curves and the theoretical limit. This difference is small at low wind speeds but grows with increasing wind speed conditions. The green curve indicates the capacity of the turbines in dependence of the wind speed. Besides the different output levels already mentioned above, the cut-in timings of the turbines can vary substantially.
FIGURE 1
Performance curves of the three SWT reference plants considered
Source: Own illustration, based on Southwest Windpower (2012), Aventa (2012), and Envento Windenergie (2013a)

Note that the performance curves are solely based on manufacturer's data and could not be independently verified. Most often, the performance parameter values are measured under optimal settings in wind tunnel tests or are even only calculated (BWE, 2011). In this context, performance studies for VAWTs are most often conducted under steady, and artificial, wind conditions, leading to a still poor understanding of turbine aerodynamics under unsteady (urban) real-world wind conditions (Scheurich and Brown, 2013).

In summary, the consideration of different plant types (HAWT vs. VAWT), each with specific characteristics, will allow for a more comprehensive picture on profitability requirements, dependent on the conditions in varying urban settings. Most commonly VAWT seem to be the preferred plant type particularly for densely populated urban areas due to their independence from wind speed directions (Tschätsch, 2011).

III. MODELING AND ECONOMIC ANALYSIS

The profitability of the various investment options is evaluated based on the NPV criterion given by

\[
NPV = -I_0 + \sum_{t=0}^{T} \frac{CF_t}{(1+i)^t},
\]

where \(-I_0\) are the investment costs at \(t=0\), \(CF_t\) is the cash flow at time \(t\) and \(i\) is the interest rate, which is initially assumed to be 3% p.a. The time span for the NPV is 20 years due to the guaranteed feed-in tariffs under the German EEG regime (see subsection ‘Feed-in tariff systems’ below).

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5 This particularly applies to the Envento ENV-M turbine.
There are various techniques in order to evaluate investment decisions in renewable energy technologies, such as discounted cash flow methods (e.g. NPV) or the Internal Rate of Return (IRR) (Packey and Holt, 1995). Each assessment technique has particular disadvantages. Directly comparing the IRR and NPV method, the IRR method is characterized by a more complex assessment procedure as it provides multiple solutions, follows the assumption of cash-flow reinvestments, and there may occur inconsistencies with respect to the NPV rankings (Brealey and Myers, 2003). In general, NPV is the most frequently used and thus in practice preferred method (Bhattacharyya, 2011; Brealey and Myers, 2003). The most important limitations of the NPV method is the omission of investment flexibility, particularly regarding the timing of investment (Brealey and Myers, 2003; Dixit and Pindyck, 1994; Mun, 2006).

In order to evaluate the profitability potential of investments in SWT in different urban locations, given guaranteed feed-in tariffs in Germany for fed-in electricity from renewable energies (see section ‘Feed-in tariff systems’ below), the NPV criterion appears to be an appropriate assessment method for providing an understanding of the unexploited market potential of this technology, particularly in urban areas.

The following sections provide an overview of the input factors and parameters that enter the NPV calculations.

**Plant-specific factors**

All three reference plants are characterized by specific parameters which affect the economic feasibility. The NPV calculations consider the performance curves, the overall investment costs of installing the system \( I_{0,\text{total}} \) (consisting of the investment costs of the plant and the costs for the optional use of an energy storage system) and the respective operation costs, \( C_{op} \). According to this, \( I_{0,\text{total}} \) is given by

\[
I_{0,\text{total}} = I_{0,\text{plant}} + \Delta_{SP} \times P_{stor},
\]

where the energy storage capacity (kWh) is given by \( P_{stor} \) and \( \Delta_{SP} \) are specific storage costs (€/kWh) (see Figure 3). The operation costs consist of the overall investment costs, \( I_{0,\text{total}} \), and an operation and maintenance factor, \( \alpha_0 \):

\[
C_{op} = \alpha_0 \times I_{0,\text{total}},
\]

where \( \alpha_0 \) takes the value 0.5%, according to Kirchweger (2009).

The option to make use of a bank loan is an important aspect of financing the investment in SWT for private use. The KfW banking group, a German government-owned development bank, focuses on the promotion of renewable energy technologies and offers bank loans for private households at moderate rates, depending on the creditworthiness, security, and loan period. The basic model offers a credit level of 70% of the total investment, with a loan period of 10 years. Assuming a moderate creditworthiness and security level, the fixed rate for the whole period is 1.71% p.a. (KfW, 2012).
Feed-in tariff systems

The Act on Granting Priority to Renewable Energy Sources (Renewable Energies Act – EEG) was introduced as the successor of the Stromeinspeise-Gesetz (StrEG) in 2000, amended in 2004, 2009, and 2012 (EEG, 2000, 2004, 2009, 2012). The current version of the EEG support scheme entered into force in January 2012. The feed-in tariffs provided depend on the source of energy (e.g. wind, solar) and are guaranteed for 20 years. The payment period starts at the end of the year in which the plant first fed electricity into the grid.

The basic tariff for feeding-in electricity produced by wind power plants is € 4.83 ct/kWh, and in the first five years of operation even € 8.93 ct/kWh. An additional bonus of € 0.48 ct/kWh is granted if the generated electricity meets the technical requirements of the bylaw SDLWindV (SDLWindV, 2009, §2). In the case that the plant’s yield falls short of a plant-specific reference level, the payment period of the increased tariff can be extended. In order to decrease the costs of the plant operators, SWT are assumed to reach only 60% of the reference level, so that, in total, the increased tariff can be paid for 16 years and 8 months. In this paper, we assume that the technical requirements given by the SDLWindV are fulfilled at each location. Accounting for that, the average feed-in tariff over the 20 year’s payment period is € 8.55 ct/kWh.

According to Liersch (2010), the EEG feed-in tariff scheme for SWT in Germany, which is mainly adapted from the scheme for large-scale wind power plants, is not economically feasible in any location in Germany. Therefore, Liersch (2010) developed a modified tariff scheme for SWT that provides three tariff classes, dependent on the nominal capacity of the plant. The support scheme is illustrated in Figure 2. The proposed tariff scheme offers fixed payments for the first two classes (I, II) and variable tariffs for the third class (III). The first class contains all plants up to 5 kW nominal capacity and grants € 25 ct/kWh. Plant class II applies to the plants with capacities between 5 and 30 kW, for which a tariff of € 20 ct/kWh is designated. The tariff for the third class is linearly declining from € 15 ct/kWh at 30 kW to € 10 ct/kWh at 100 kW nominal capacity.

![Figure 2](image)

**Figure 2**
The SWT support scheme according to Liersch
Source: Own illustration, based on Liersch (2010)
Some European countries already provide tariff systems particularly adapted for SWT. Especially the UK offers special incentives for private investors. An important advantage of the UK is the large coastal area with exposed wind location (Troen, 1990). The UK feed-in tariff system (DECC, 2010) grants about € 30 ct/kWh for SWT with capacities of between 1.5 and 15 kW, which are guaranteed for 20 years. SWT owners are allowed to apply for the support scheme if the plant is certificated by the Microgeneration Certification Scheme (MCS, 2012). Among the three SWT reference plants considered in our study, the only MCS-certified SWT is the Skystream 3.7.

**Modeling of the electricity price**

The average household’s\(^6\) benefit for the produced electricity is given by eq. (4):

\[
B_{\text{elec}} = \alpha_1 \times P_{\text{elec}} + (1 - \alpha_1) \times B_{\text{feed-in}}
\]

where \(P_{\text{elec}}\) is the price of electricity (€ 26.4 ct/kWh, according to AfEE (2012)), \(B_{\text{feed-in}}\) indicates the revenue from feeding the produced electricity into the grid, and \(\alpha_1\) denotes the share of electricity produced that accounts for private consumption. Without any electricity storage option, the share of private electricity consumption is assumed to be 30%. In contrast, considering electricity storage, the share of produced electricity that accounts for private consumption is expected to be higher due to a better match of supply and demand compared to the situation without storage system. Indeed, recent field tests conducted in Germany showed that linking storage facilities with intelligent load management to SWT increased this share substantially from about 30% to 65% (SWT Portal, 2012)\(^7\). This corresponds to a factor of \(\Delta_{pc} = 716 \text{kWh/kW}\). The upper limit of the share of private consumption is assumed to be 70%. In addition to it, both the prediction of yields \(\bar{R}\) and the storage efficiency \(\eta_{stor}\) enter this calculation. The share of private consumption of the produced electricity \(\alpha_1\) is, therefore, given by:

\[
\alpha_1 = 0.3 \text{ if } P_{\text{stor}} = 0; \text{ otherwise: } \alpha_1 = \frac{\bar{R} \times 0.3 + \Delta_{pc} \times P_{\text{stor}} \times \eta_{stor}}{\bar{R}}, \quad \alpha_1 < 0.7;
\]

\[
0.7, \quad \alpha_1 \geq 0.
\]

**Storage systems**

In order to influence the own electricity bill, a possible strategy for a private household could be the maximization of the share of private consumption by minimizing the feed-in of electricity. In this context, energy storage systems are an option worth considering for increasing the use of

\(^6\) We consider an average three-person household with an electricity consumption of 3,908 kWh per year (EnergieAgentur.NRW, 2006).

the generated power. Therefore, according to market relevance and technical availability, we take three types of storage system options into account: the redox flow, the lithium ion, and lead acid battery (see Mahnke and Mühlenhoff, 2012).

The most recent major development in the field of electro-chemical storage systems is the redox flow technology, which has been commercially available for about four years. The specific advantages of this technology are the variable scalability, the high efficiency (70-80%) and the enablement of fast access to stored electricity (Radgen, 2007). Actual prices are varying between € 100 and € 1,000 per kWh, whereas large-scale production and associated scale effects are expected to substantially reduce costs in the future (Mahnke and Mühlenhoff, 2012).

Compared to redox flow systems, lithium ion accumulators are quite mature storage systems, as they have been used in cell phones or laptops for many years. Lithium ion accumulators are characterized by low weight, very high efficiency (ca. 90%) and fast rechargeability (Radgen, 2007). Particularly, because of the current development of the E-mobility sector, prices are expected to further decline in the coming years. Today, prices vary between € 800 and € 1,500 per kWh (Mahnke and Mühlenhoff, 2012).

Lead acid batteries have been used in various industry sectors for many decades (e.g. automotive sector), which makes the technology the most mature technology of those considered these days (Hannig et al, 2009). Its advantages are the long life-cycles (around 12 years) and the low price of between € 25 and € 250 per kWh. The efficiency level of lead acid systems is usually between 65% and 90%. Due to the toxicity of lead and sulphur acid, maintenance is a critical issue (Mahnke and Mühlenhoff, 2012).

Figure 3 shows the storage efficiency of the technologies discussed, plotted against the investment cost in € per kWh$^8$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{storage_efficiency.png}
\caption{Storage efficiency and specific costs}
\label{fig:storage_efficiency}
\end{figure}

\textbf{Source: Own illustration, based on Mahnke and Mühlenhoff (2012)}

$^8$ For the calculations we assume an average efficiency value for each storage option. Thus, the storage efficiency for the redox flow storage is 77.5%, for the lithium ion storage 92.5% and for the lead acid storage 70%.
Adaptation of wind speeds to urban surroundings

The evaluation of the profitability of SWT under urban conditions crucially depends on a reliable prediction of yields. Compared to the planning procedure of large-scale wind energy projects, the investment in SWT commonly takes place without a detailed ex-ante feasibility assessment that accounts for the specific urban conditions, mostly due to the high costs compared to the total investment costs (Twele, 2011). Equipment for wind speed measurement for private use is available in most electronics DIY stores at a price of about € 400. However, according to Kirchweger the difference in results between professional wind speed assessments and measurements conducted with equipment for private use can account for up to about 60% (Kirchweger, 2009).

In order to account for the specific wind conditions in various urban areas, this study applies an approximation procedure which is based on high resolution wind speed maps provided by the German Meteorological Service (Deutscher Wetterdienst, DWD). Figure 4 shows the average annual wind speeds for Germany at a height of 10 m in a raster of 1 x 1 km. The DWD (2013) wind speed data are provided by 218 measurement stations and provides detailed values for the whole of Germany. These measuring stations are substantially differing regarding the land use

![FIGURE 4](image)

**FIGURE 4**
Distribution of wind speeds in Germany at a height of 10 m and selected locations
Source: Own illustration, based on DWD (2013)
patterns in their surrounding area. Therefore, locational characteristics (i.e. urban or rural area) and the associated local topography and development are implicitly captured in the measured wind speed values. Nonetheless, as the incorporation of locational information is rather crude and random, an adaption to specific locations has to be made.

An early study investigating the performance of SWT in urban areas, particularly focusing on methodologies to predict wind yields, was undertaken by Philips et al. (2007). The authors investigated the correlation between typical urban scenarios and the yield of two generic SWT in different mounting positions. Furthermore, they identified the CO₂ payback time⁹ of SWT to be likely short, except in areas with very low wind speeds (Philips et al., 2007).

Sunderland and Conlon (2010) also focus on the evaluation of wind yield predictions in urban areas and identify key parameters for an urban wind yield prediction approach. According to that, the main uncertainty related to wind yield predictions is the dependence of wind speeds on the local surface character, temperature influences, and environmental dynamics. All these factors will likely cause a reduction of expected wind yields (Sunderland and Conlon, 2010).

The dynamics of air flow in the surrounding of buildings are also a research topic in the field of aerodynamics. Heath et al. (2007) provided a review of studies and, additionally, developed a wind profile for building proximity. Figure 5 shows a logarithmic and exponential wind profile in relation to the building height $H$ (in m) in the surrounding. Here, the ordinate gives the quotient of hub $h_{hub}$ and building height $H$, whereas the abscissa depicts the wind speed at hub height $v(h_{hub})$ in relation to the wind speed at building height $v(H)$.

\[ \frac{h_{hub}}{H} \]

\[ \frac{v(h_{hub})}{v(H)} \]

**Figure 5**
Normalized urban wind profile
Source: Heath et al. (2007)

---

⁹ Though a wind turbine generates electricity without emitting CO₂, the manufacturing process of this turbine creates CO₂ emissions. Thus, the operation time needed to pay back its ‘CO₂ debt’, i.e. the CO₂ emissions incurred during production of the turbine, is called “CO₂ payback time”.

[13]
According to this, a formal relationship between the adjusted reference wind speed \( v(h_{\text{hub}}) \) at hub height \( h_{\text{hub}} \) and the wind speed derived from the wind speed map \( v_{\text{map}} \) at map height (10 m) \( h_{\text{map}} \) can be determined. Furthermore, important parameters are the canopy of the urban area \( z_0 \) [in m] and the canopy of the underlying map \( z_{0,\text{map}} \), the zero-plant displacement \( d_0 \)\(^{10} \), the average height of the objects in the surrounding (e.g. buildings, trees, etc.) \( h_{\text{surround}} \), the height of the boundary layer \( \delta_b \) [in m] and the distance to the periphery \( x \) [in m] (Heath et al, 2007). According to Heath et al., \( d_0, \delta_b \) and the adjusted urban wind speed \( v_{\text{adj}} \) is given by:

\[
d_0 = 0.64 \times h_{\text{surround}} \tag{6}
\]

\[
\delta_b = 0.75 \times z_0 \times \left( \frac{x}{z_0} \right)^{0.8} \tag{7}
\]

\[
v_{\text{adj}} = \frac{\ln \left( \frac{h_{\text{hub}} - d_0}{z_0} \right)}{\ln \left( \frac{\delta_b}{z_{0,\text{map}}} \right)} \times \frac{\ln \left( \frac{\delta_b - d_0}{z_0} \right)}{\ln \left( \frac{h_{\text{map}}}{z_{0,\text{map}}} \right)} \times v_{\text{map}} \tag{8}
\]

Applying the introduced urban wind speed adjustment approach, we are able to adapt the general wind speed data provided in DWD (2013) to the specific conditions of the different selected urban locations. The urban locations considered in this study are introduced in detail in the section ‘Locations’ further below.

**Weibull distribution**

The distribution of wind speed is modeled by means of a Weibull function. The rate of the occurrence of the particular wind speeds, based on an average annual wind speed, is determined by the probability density function:

\[
f(v_{\text{adj}}) = \frac{k}{s} \left( \frac{v_{\text{adj}}}{s} \right)^{k-1} \times e^{-\left( \frac{v_{\text{adj}}}{s} \right)^k}. \tag{9}
\]

The shape of the distribution is defined by the scaling parameter \( s \) and a shape parameter \( k \). Commonly, \( k \) takes the value 2\(^{12} \) and \( s \) can be calculated by (Heier, 2009):

\[
s = \frac{2}{\sqrt{\pi}} \times v(h_{\text{hub}}) \tag{10}
\]

---

\(^{10}\) \( d_0 \) describes the height above the ground at which the wind speed is 0.

\(^{11}\) This approximation goes back to Cowan (1968).

\(^{12}\) In this special case the Weibull distribution becomes a Rayleigh distribution. For further information, see Heier (2009).


**Determination of the yield prediction and modeling of the payment streams**

The predicted annual yield $\tilde{R}$, considering the values according to the Weibull distribution $f(v)$, multiplied by the capacity $P_i$ at $v$ (see Figure 1) of the SWT and the number of hours per year $t_{\text{year}}$, can be calculated by:

$$\tilde{R} = t_{\text{year}} \times \sum f(v) \times P_i . \quad (11)$$

Applying eqs. (2) to (11), the cash flows $CF_t$ at time $t$ are determined by:

$$CF_t = \tilde{R} \times B_{\text{electr}} - C_{\text{op}} . \quad (12)$$

**Additional influencing factors**

Besides the already mentioned location-specific and urban factors to be considered in the profitability calculation, we have to be aware of additional influencing factors which are significant for the planning and positioning of a SWT. Evidence of the crucial role of the positioning of roof-mounted SWT was proved by Blackmore (2008) in wind tunnel tests. Dependent on the type and angle of the roof, wind speeds can vary by about 70% according to the positioning above or below the roof ridge (Blackmore, 2008). As the wind-speed-reducing turbulences are mainly caused by the characteristics of the roof, SWT should generally be installed on the highest spot of the roof (Blackmore, 2008). An example for the resulting turbulences is the vortex that mainly appears at the roof edges. Air streams impinge on the building wall and cause a so-called ‘separation bubble’ above the roof edge. This region of the roof is characterized by low wind speeds and should be avoided from the positioning of the turbine (Twele, 2011). Hence, the ideal location of a roof-mounted turbine in an urban array crucially depends on the hub height (Millward-Hopkins et al., 2012).

Figure 6 illustrates a separation bubble on top of a rectangular-shaped building. The size and shape of the bubble varies with the particular roof type. In this context, case studies revealed a great potential for SWT mounted on office buildings with flat roofs. Measurements taken in some regions above the separation bubble showed 20% higher wind speeds compared to the region around the building with free air flow (these regions are colored red in Figure 6(a)) (Sàenz-Diez Muro et al., 2010; Mertens, 2002; Simiu and Scanlan, 1996). If the exact height and position of the bubble can be identified (Figure 6(b)), then it will be possible to exploit this further potential. In this particular case, urban locations could exhibit an increased wind potential (Sàenz-Diez Muro et al., 2010).
Locations

In order to describe the heterogeneous urban wind conditions, we specified urban locations, each representing different characteristics. In particular, the varying degree of urbanization at different locations, from large cities to rural areas, is captured in six location settings. Furthermore, the settings correspond to locations in Germany (indicated in Figure 4).  

The first location, *Urban I*, is characterized by a high building density of large-scale buildings and a great distance to the periphery, therefore matching the characteristics of a metropolis. According to the urban wind speed adaption procedure, the adjusted urban wind speed at this location is 3.28 m/s. In Germany, these conditions apply to eastern Berlin.

*Urban II*, the second location, represents a small town. The urban area is characterized by single-family homes and rather flat office buildings. Due to the smaller size of the city compared to location *Urban I*, building heights are smaller and the distance to the periphery is shorter. The adjusted urban wind speed in this location is 4.15 m/s. A German city correspondent to these conditions is the city of Baden-Baden (Baden-Württemberg).

The third location, *Suburban I*, exhibits the typical characteristics of a suburb located near to a medium-sized city. An example for this location could be a suburb of the city of Aachen in the west of Germany. The dominant types of buildings are single family- and duplex houses, so that building heights are similarly low as in rural areas. The estimated adjusted urban wind speed is 2.85 m/s.

---

13 The selection of locations in Germany correspondent to the location settings is merely illustrative (see Figure 4).

14 The term “periphery” is equivalent to the city limits. Therefore, the values for the distance to the periphery, indicated in Table 2, measure the distance from the center of the considered city, town or village to its areal limits.
The location *Suburban II* is comparable to the location *Suburban I* regarding most of the parameters as a suburb near to a medium-sized city. The major difference is the high reference and also adjusted wind speed of 5 m/s due to the coastal location. The corresponding location could be a suburb near Kiel in northern Germany.

A fifth location (*Semi-Urban*) is characteristic for a semi-urban location sited in the transition area between an urban and a rural area and, therefore, with a short distance to the periphery and the next rural settlements. The location is mainly characterized by a higher share of flat office buildings and row houses. The adjusted average urban wind speed in this location is 4.34 m/s, which applies for instance to the area at the urban fringe of Hannover close to the airport.

The sixth and last location (*Rural*) is sited in a rural area, mainly characterized by a small-sized and sprawled agglomeration of farms. The degree of urbanization corresponds to that of a small village. This location enjoys the highest adjusted wind speed of 5.2 m/s. We can find these conditions in the region near to the city of Kempten (Allgäu, Bavaria).

Due to the adjustment procedure according to eq. (8) and the local attributes reported in Figure 4, it occurs that in some locations the adjusted urban wind speed exceeds, and in other locations falls below, the reference wind speed. Table 2 gives an overview of the locations and their characteristics.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Hub height [in m] $h_{hub}$</td>
<td>55</td>
<td>18</td>
<td>13</td>
<td>18</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>Average heights of objects in the surrounding [in m] $h_{surround}$</td>
<td>12</td>
<td>7.5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Distance to periphery [in m] $x$</td>
<td>2,500</td>
<td>400</td>
<td>250</td>
<td>200</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>Canopy factor [in m] $z_0$</td>
<td>1</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Average wind speed [in m/s] $v_{map}$</td>
<td>3.1</td>
<td>5</td>
<td>3.7</td>
<td>5.5</td>
<td>4.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Adj. urban wind speed [in m/s] $v_{adj}$</td>
<td>3.28</td>
<td>4.15</td>
<td>2.85</td>
<td>5</td>
<td>4.34</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Source: Own calculation and assumptions, based on Heath et al. (2007) and Sàenz-Diez Muro et al. (2010).

Notes: The parameter values provided in this table were used to adapt the reference wind speed, based on the map of DWD (2013), to the considered locations and to calculate the adjusted wind speed. The values for the hub heights are based on the average building heights in the considered locations and the manufacturer’s data for the technically possible heights of roof-mounted or freestanding installations.
IV. RESULTS

Figure 7 provides an overview of the results obtained from the NPV calculations regarding the different selected settings. Therefore, Figure 7 shows the NPV over the period of 20 years for the different types of SWT and storage options dependent on the six locations. The basic setting considers the operation of a SWT without the coupling to a storage system.

Regarding the results for the Skystream 3.7 (Figure 7(a)), in only two of the six locations the calculations yield positive NPVs over the 20 years’ operation period. In the locations Suburban II and Rural, the Skystream 3.7 turbine can be operated profitably, note that the combination to a storage system turns out to be crucial for the profitability. The investment in the Skystream 3.7 turbine without storage yields a negative NPV. Overall, the lead acid storage system performs best in all cases in combination with the Skystream 3.7. In contrast, Urban I and Suburban I are the least favorable locations for an investment in SWT, irrespective of the storage options.

Compared to the Skystream 3.7, the NPV calculations for the Aventa AV-7 yield similar results (Figure 7(b)). Also for this type of turbine the locations Suburban II and Rural are the most favorable ones regarding the profitability prospects over the 20-years’ period. Nevertheless, note that the expected NPVs obtained are substantially higher than those for the Skystream 3.7. Again, combining the turbine with a storage system is more attractive than without. One major difference compared to the Skystream 3.7 is that the Aventa AV-7 operates most profitably when coupled to a redox flow battery. But also in combination to a lead acid or a lithium ion system, the investment in the Aventa AV-7 yields a positive NPV.

According to the results illustrated in Figure 7(c), the Envento ENV-M, which is the only VAWT among the considered turbines, cannot be operated profitably across all settings. Although, the results for the locations Suburban II and Rural are again better than those obtained for the other locations, the NPVs are still highly negative. A possible explanation for the poor performance of the Envento ENV-M is the high wind speed (14 m/s) that is necessary to reach the maximum capacity level. In contrast, the two HAWTs reach the maximum output much earlier (see Figure 1).
Results of the NPV calculation

Source: Own calculations

Note: Since the Aventa AV-7 cannot be roof-mounted, it is the only turbine which is not suitable for the settings of location Urban I. Therefore, Urban I is not included in Figure 7(b).
FIGURE 8
NPV for all SWT considered in combination with the different battery storage options

Source: Own calculations

Note: Repayment of the bank loan is assumed to start in period 3 and to end after period 10, which is also reflected in the shape of the NPV trends.
Figure 8 shows the evolution of the NPV of the three turbines for selected locations. Figure 8(a) provides a comparison of the NPV trends of the three turbines over the 20 years’ operation period in the setting Urban II. In all three cases a redox flow storage system is coupled to the plant. Although there are considerable differences in the NPVs of the three turbines, all values remain negative until the end of the plants’ lifetime.

In contrast, the setting of location Suburban II provides better conditions regarding a profitable operation of SWT (Figure 8(b)). In this setting, the turbines are coupled with a lead acid storage system. The Skystream 3.7 and in particular the Aventa AV-7 gain positive NPVs over the operation time, whereas the Aventa AV-7 performs best (€ 22,295.83). Both plants feature a payback period of 16 years of operation.

The Rural setting in Figure 8(c) shows a NPV development similar to the Suburban II location. In this setting, all three SWT are linked to lithium ion storage systems. Again the Aventa AV-7 performs best (€ 26,784.18) and is even more profitable than in the setting before. The payback period of the Skystream 3.7 is 18 years and the NPV is at a lower level compared to the Suburban II setting.

Figure 9 illustrates the NPVs for the three SWT given the feed-in tariff system proposed by Liersch (2010) (see Figure 2). The basic setting (blue bar) represents the standard setting for each turbine without storage system and with feed-in tariffs according to the current German support system (EEG, 2012). The setting “Feed-in tariff (Liersch, 2010)” (green bar) incorporates the proposed tariff system adjustment, but still without considering a storage system. The last setting (red bar) incorporates the adjusted tariffs and also the coupling with a storage system. The considered storage system in the figure varies according to the turbines, choosing the best performing combination between turbine and storage system on the basis of the results obtained in Figure 7. Thus, the Skystream 3.7 and the Envento ENV-M are coupled with a lead acid battery and the Aventa AV-7 to a redox flow battery.

According to the results depicted in Figure 9(a), without the linkage to a storage system, the Skystream 3.7 turns out to be unprofitable in all locations. Introducing the adjusted tariff system according to Liersch (2010), but still without battery system, the Skystream 3.7 gains positive NPVs in the location Suburban II and Rural. The NPVs can also be increased for this location with the inclusion of a lead acid storage device. In this case, considering the adjusted support scheme and the storage system, the Skystream 3.7 also gains a positive NPV in the Semi-Urban setting.

In the case of the Aventa AV-7 (Figure 9(b)), the positive impact of the support scheme adjustment becomes even more evident. The Aventa AV-7 cannot be operated profitably under the current support scheme and without the linkage to a storage system. Introducing the tariffs according to Liersch, the turbine yields positive NPVs in location Suburban II and Rural. In addition to it, coupling the turbine to a redox flow storage, the Aventa AV-7 allows to make profit in all locations, except for the Suburban I setting. The introduction of the adjusted feed-in

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15 NPV trends for the other locations (Urban I, Suburban I, and Semi-Urban) are provided in the Appendix (Figure A1). The storage system for each location example was chosen randomly, ensuring that each storage option has been considered twice.
tariff system (and the combination with a storage system) has a substantial influence on the profitability of the turbine.

**Figure 9**

NPV at feed-in tariffs according to the ones proposed by Liersch (2010)

Source: Own calculations
In contrast, the introduction of a modified feed-in tariff system for SWT with or without storage system coupling has no significant impact on the economic performance of the Envento ENV-M turbine (Figure 9(c)). The support system according to Liersch (2010) increases the NPV, but a positive NPV cannot be expected in any location.

_Sensitivity analysis_

In order to test the robustness of our results and to obtain a more detailed understanding of the most important factors influencing the profitability of an investment in SWT, we shock key parameters in our NPV model by means of a sensitivity analysis. For this purpose, we vary the height of the installed turbine \( h_{\text{hub}} \), the adjusted urban wind speed \( v_{\text{adj}} \), the energy storage capacity \( P_{\text{stor}} \), and, in particular, the degree of urbanity – through the parameters \( x \) (distance to the periphery), \( h_{\text{surround}} \) (average height of the objects in the surrounding) and \( z_0 \) (canopy of the urban area). Each parameter is varied individually, _ceteris paribus_, where we choose a variation of +/- 10% in steps of 2.5%.

The sensitivity analysis on the key parameters is conducted for all considered turbine types in all location settings. Again, the type of storage battery that is combined with the particular turbine type is chosen according to the results obtained in Figure 7. Thus, the best-performing combinations between SWT and storage are used for the sensitivity analysis (i.e. Skystream 3.7 + lead acid; Aventa AV-7 + redox flow; Envento ENV-M + lead acid).

The results of the sensitivity analysis are illustrated in Figures 10 and 11. Overall, the variation of the key parameters within this analysis yields consistent results regarding their sensitivity and their impact on the NPV, proving the robustness of the model. Due to the wide scope of the sensitivity analysis and space limitations, we only present the results for two location settings (Suburban II and Semi-Urban) as representative examples.\(^\text{16}\)

Comparing the impact of the key parameter variations on the NPV for location setting Suburban II (Figure 10), we find similar effects across the considered turbines. As expected, varying the adjusted urban wind speed \( v_{\text{adj}} \) by +/- 10% has the greatest impact on the NPV. Accordingly, a decrease in the average urban wind speed by 10% (i.e. from 5 to 4.5 m/s) decreases the NPV e.g. from about € 2,989 to € -923 in the case of the Skystream 3.7 and from € 23,801 to € 6,461 in the case of the Aventa AV-7, respectively. Conversely, a 10% increase of the average urban wind speed causes a substantial rise of the NPV.

The increase of the hub height also has a positive influence on the NPV. In the case of location setting Suburban II, increasing the hub height by about 1.8 m (i.e. +10%) yields additional € 2,015 (Skystream 3.7) and € 6,485 (Aventa AV-7), respectively, or decreases the overall loss by about € 1,043 in the case of Envento ENV-M. _Vice versa_, a 10% lower hub height decreases the NPV about € 1,959 (Skystream 3.7), € 8,031 (Aventa AV-7) and € 1,100 (Envento ENV-M), respectively.

\(^{16}\) Further sensitivity results can be obtained from the authors upon request.
Figure 10
Sensitivity analysis for location setting Suburban II
Source: Own calculations

SKYSTREAM 3.7

AVENTA AV-7

ENVENTO ENV-M

NPV [in €]

90% 92.5% 95% 97.5% 100% 102.5% 105% 107.5% 110%

NPV [in €]

90% 92.5% 95% 97.5% 100% 102.5% 105% 107.5% 110%

NPV [in €]

90% 92.5% 95% 97.5% 100% 102.5% 105% 107.5% 110%

$\text{h}_{hub}$ $\nu_{adj}$ $P_{ste}$ Urbanity ($\nu_{surround}$ $\nu_{adj}$)

-16,000 -14,500 -13,000 -11,500 -10,000

-16,000 -14,500 -13,000 -11,500 -10,000

-16,000 -14,500 -13,000 -11,500 -10,000
Varying the energy storage capacity $P_{\text{stor}}$ has no substantial influence on the development of the NPV in all cases. In addition to it, the NPV development resulting from the $P_{\text{stor}}$ variation is non-linear. Note that, due to eq. (5), the share of private consumption in the produced electricity $\alpha_1$ cannot exceed 70%, which is reached in each location by increasing $P_{\text{stor}}$. Hence, the increase in the energy storage capacity $P_{\text{stor}}$ just leads to rising total costs without increasing the NPV. In general, we can assume that the storage capacity of 3 kWh seems to be appropriate for the electricity demand of the considered type and size of private household.

The degree of urbanity turns out to be negatively related to the expected NPV. A 10% higher degree of urbanity, which comprises a greater distance to the periphery, higher building heights in the surrounding and a higher value of the canopy, reduces the NPV by about € 1,296 in the case of the Skystream 3.7, € 5,122 when considering the Aventa AV-7, and € 722 in the case of the Envento ENV-M. In contrast, reducing the degree of urbanity by 10%, i.e. shifting to the periphery with lower heights of the surrounding development, will increase the NPV considerably (Skystream 3.7: + € 1,507; Aventa AV-7 + € 4,913; Envento ENV-M: + € 769).

The sensitivity analysis for the second example, the location setting Semi-Urban, provided comparable results regarding the impact of the key parameters on the NPVs (Figure 11). Nevertheless, as this location turned out to be a less favorable location for SWT investment according to the NPV results provided in Figure 7, varying the key parameters alters the overall valuation of this location and in some cases the NPV even changes from negative to positive.

Again, shocking the adjusted urban wind speed parameter shows the greatest impact on the NPV, where an increase of about 0.43 m/s (i.e. +10%) yields an additional € 3,224 for the Skystream 3.7, € 15,932 for the Aventa AV-7, and € 1,758 in the case of the Envento ENV-M. In the case of Skystream 3.7 the NPV changes from negative to positive at an average wind speed of about 4.6 m/s (i.e. +6%), for the Aventa AV-7 a positive NPV can be expected even at 4.38 m/s (i.e. +1%).

Higher hub heights are also positively correlated to the NPV. Thus, increasing the height of the installed turbine by about 2 m (i.e. +10%) results in an additional € 1,294 in the case of the Skystream 3.7, € 6,804 for the Aventa AV-7, and € 511 considering the Envento ENV-M. Only for the Aventa AV-7 the increase of the hub height changes the NPV from negative to positive. According to that, an additional hub height of about 0.2 m (i.e. +1%) turns the sign of the NPV from negative to positive.

The variation of the parameter $P_{\text{stor}}$, the energy storage capacity, has similar results compared to the Suburban II setting (Figure 10). Again, the variation in the boundaries of +/-10% has no significant impact on the NPV of the considered wind turbines. While reducing the energy storage capacity yields slightly smaller NPVs in all cases, the increase had no impact due to the private consumption limit of 70%, which is directly reached by increasing $P_{\text{stor}}$.

As in the example before, the degree of urbanity is negatively correlated with the NPV for the different turbines. Thus, a turbine site near the city center (i.e. increasing the urbanity parameters by 10%) reduces the NPV by about € 884 in the case of the Skystream 3.7, € 5,010 for the Aventa AV-7, and € 281 when considering the Envento ENV-M.
**SKYSTREAM 3.7**

![Graph of SKYSTREAM 3.7 NPV vs Urbanity](image)

**AVENTA AV-7**

![Graph of AVENTA AV-7 NPV vs Urbanity](image)

**ENVENTO ENV-M**

![Graph of ENVENTO ENV-M NPV vs Urbanity](image)

**Figure 11**
Sensitivity analysis for location setting *Semi-Urban*
Source: Own calculations
V. POLICY RECOMMENDATIONS

Despite the increasing number of commercially available turbine types and the steadily growing market for SWT in terms of worldwide sales figures and also in Germany in particular, the SWT is still a niche technology compared to other energy technologies (e.g. solar PV) used in the private household sector. Main impediments regarding faster market diffusion are diverse and predominantly encompass a lack of technological standards and also an intransparent regulatory framework with respect to planning and building laws as well as support schemes.

Regarding technological standards, the efforts of the SWT industry still could not establish a dominant technological design, particularly for the operation in urban areas. Compared to large-scale wind power plants, where a dominant design (horizontal, three-bladed rotor) emerged and rapidly penetrated the market (Bergek and Jacobsson, 2003), there are a variety of technical designs, such as HAWT or VAWT and their variants. Due to the early development stage of SWT technology, there are still significant discrepancies between the different commercially available turbines types (Simic et al. 2013). Also, more research and series of tests are still needed in order to find suitable technical solutions for the operation of SWT under the specific conditions in urban areas. Research activities in this field should mainly tackle the optimization of the starting behavior of the turbine and the minimization of wind speeds required to yield the maximum energy output, as cut-in wind speeds are often low and wind conditions in densely built-up areas characterized by strong turbulences. Performance data and reference parameters of today’s available SWT are mostly based on computer simulations provided by manufacturers only and can therefore not easily be verified. In this context, a consistent certification system for SWT could provide more transparency regarding the potential performance of the different turbine types and associated with that, a more reliable basis for investment decision-making. From the private household’s perspective, this would also enhance the visibility regarding the possibilities of private utilization of the SWT technology.

For niche technologies, such as SWT, energy policies should essentially address the provision of suitable incentives for innovation and entrepreneurship (Ross et al., 2012). In this respect, the regulatory framework for SWT in Germany involves two main challenges. Firstly, the urban planning and building law, both for freestanding and roof-mounted facilities, is inconsistently regulated across the German federal states. The integration of SWT utilization for private households in a coherent regulatory framework based on the existing urban building law would certainly promote the development prospects of SWT. Secondly, as the German feed-in tariff system predominantly considers large-scale wind power plants, the support scheme provided through the EEG does not provide an appropriate incentive program to effectively foster additional investments in SWT. Compared to the UK or USA, which already have specifically adapted feed-in tariffs for SWT, the current German support grant is significantly lower. Although a straightforward increase of tariffs is no panacea, an adapted and differentiated tariff system, scaled according to the nominal capacity of a turbine, could likely improve the future diffusion prospects of the technology. The tariff system suggested by Liersch (2010) could be a viable approach, not predominantly from the perspective of economic efficiency, but to foster
market diffusion of this technology. This would also contribute to the goal of current energy policies to promote a decentralized energy supply, where private households become ‘prosumers’ by simultaneously acting as producers and consumers of electricity.

VI. CONCLUSION

This paper focused on investigating the economic potential of SWT under different urban location settings, and accounting for the most important parameters for investment decision-making. We find that investments of private household in a SWT in Germany today are only economically feasible in exposed areas with minimum average wind speeds of about 4 to 4.5 m/s.

Besides the average wind speeds in the considered areas, the degree of urbanity (including the average heights of the surrounding development, the canopy of the area, as well as the distance to the periphery) plays an important role regarding the economic viability of SWT investments. Accordingly, the proximity to the city center and the characteristics of a densely built-up area affect the profitability prospects of such an investment negatively. We also can conclude that under the current EEG support regime in Germany, SWT can only be operated profitably in suburban or rural areas with a relatively low building density.

Regarding the considered turbine types available, the chosen HAWTs performed better in an urban environment compared to a VAWT. This might be due to the relative maturity of the HAWT design, which is adapted from the large-scale wind turbines. The VAWT was found to be inefficient with respect to the starting behavior and the wind speeds required to reach maximum energy output. Furthermore, we found evidence for the necessity of coupling SWT to a storage system. The inclusion of an energy storage system increased the NPV of the SWT investment in all cases. This is an interesting finding, given that storage systems are relatively expensive but at the same time considered as pivotal for the transition to a more decentralized and increasingly renewables-based power supply.

The feed-in tariff system does also play a crucial role for the investment decision of private households. The current German support scheme, however, does not provide a sufficient basis for fostering private investment efforts. The feed-in tariff scheme proposed by Liersch (2010) could be a solution to promote SWT. According to the results obtained, the Liersch scheme markedly improves the profitability of SWT due to higher grants offered and expands in consequence the areas in Germany in which SWT can be operated profitably.

The sensitivity analysis revealed strong wind speed, urbanity and hub height sensitivity of the model and results. Slightly varying the wind speed in the urban locations substantially affected the expected NPVs and thus also the investment decision. In the context of different wind conditions, also the hub height of the installation was found to be an important parameter. The same applies to the degree of urbanity, where distance to the city center or the average heights of the surrounding buildings are key parameters regarding economic feasibility.

Future research in the economics of SWT should also consider commercial and public buildings in urban areas, as these also offer a substantial potential for the utilization of SWT
regarding the building characteristics (mostly large buildings with flat roofs). Furthermore, different economic aspects of energy storage should be considered, such as the integration of SWT and storage systems into smart grid solutions, or the consideration of battery (dis-) charging behavior in charging cycles. Overall, precise and reliable economic prediction tools are essential in order to further assess the economic potential of SWT and market prospects, particularly of investments by private households.

REFERENCES


[30]


[31]


APPENDIX

(a) URBAN I
LITHIUM ION STORAGE

(b) SUBURBAN I
REDOX FLOW STORAGE

(c) SEMI-URBAN
LEAD ACID STORAGE

Figure A1
NPV for all SWT considered in combination with the different battery storage options
Source: Own calculations
Note: Repayment of the bank loan is assumed to start in period 3 and to end after period 10, which is also reflected in the shape of the NPV trends.

[33]
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