Small wind turbines for on grid and off grid applications

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Abstract. Electricity production must shift towards carbon neutral sources such as wind power to mitigate the impacts of climate change. Wind energy today accounts 18.8% of total installed power generation capacity in Europe, with a total installed capacity of 189 GW (170 GW onshore and 19 GW offshore wind farms), taking the second largest form of power generation capacity, closely approaching gas installed capacity. The progress of wind turbine technology over the last 20 years is important and is also the main reason for the rapid development of the wind power globally. In addition, the nominal capacity of onshore wind turbines has increased to more than 3 MW and more than 5 MW for offshore wind turbines. Despite the tendency for larger wind turbines there is a significant potential for small wind turbines for the urban environment as well as for off grid applications. The objective of this work is to provide a spherical knowledge of the technology of small wind turbines in the range of some kW up to 50kW nominal capacity, their market, costs, as well as their possible applications in urban and in off grid environment. Parameters such as, performance, noise issues, and visual disturbance is also discussed in this paper.

1. Introduction
The development of Renewable Energy Sources (RES) and the increase of their share in the total energy production is a priority in the European Union's (EU) Policy Agenda to tackle climate change and reduce greenhouse gas emissions. The share of energy from renewable energy sources in the EU's energy mix is still rising and, according to today's figures, is well on track to reach the 20% target by 2020. In continuation to these efforts, the Paris Climate Change Agreement, reached in 2015, aims to limit the rise in global warming and to decouple national economies from fossil fuels. The EU’s nationally determined contribution (NDC) under the Paris Agreement is to reduce greenhouse gas emissions by at least 40% by 2030 compared to 1990, under its wider 2030 climate and energy framework.

As a necessity of the above issues all the countries have to increase the contribution of Renewable Energy Sources (RES) to their total power production. Figure 1 presents the contribution of RES to the total power production capacity in EU countries from 2008 to 2018 [1]. As shown, wind energy is one of the most important power producer and contributor to tackle climate change, with a significant share in total energy production at the European level, which in 2018 reached the 362 TWh, energy generated from 189 GW installed wind farms, enough electricity to meet 14% of the EU’s electricity
demand\(^1\) [1]. According to Figure 1, wind energy is the second largest form of power generation capacity in the European Union and, is likely, to overtake natural gas capacity in 2019.

![Figure 1. Total power production capacity in EU from 2008 to 2018.](image)

Furthermore, Figure 2 presents the average annual electricity demand per country covered by wind energy in EU28 [1]. The figures represent the average of the share of wind in final electricity demand\(^2\).

![Figure 2. Percentage of the average annual electricity demand covered by wind 2018.](image)

Moreover, according to the World Wind Energy Association (WWEA) statistics for 2018, the overall capacity of the wind turbines installed worldwide reached 600 Gigawatt (GW), with around 54 GW being added in 2018. The rapid development of wind power is mainly due to the significant progress of wind turbine technology over the past 20 years. Additionally, the nominal capacity of

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\(^1\) IEA note: generation data for Luxemburg, Croatia and Malta was not available (their combined demand represent less than 1% of EU demand)

\(^2\) IEA note: Data is not available from all European countries.
Onshore wind turbines has increased from less than 50 kW in the 1980s, to more than 3 MW today. In general, in new wind farms the rated power of wind turbines ranges from 2 MW to 3.5 MW with a tower height of 80-130 m limiting the number of WTs required for a specific wind farm power capacity.

Despite the tendency of the increase of wind turbines size there is a significant market for small wind turbines for on grid and off grid (decentralized stand alone or mini grid) applications, in majority installations at homes, farms, sailing boats, small industries and offshore applications (Figure 3, 4). According to the World Wind Energy Association (WWEA), at the end of 2015, one of the most challenging years for the small wind industry in the recent years, a cumulative total of at least 990.000 small wind turbines, with a cumulative capacity of 945 MW were installed all over the world [2]. In 2017 the total global installed cumulative small wind capacity was estimated at more than 1.0 GW with China, U.S., U.K. and Italy to be the market leaders in terms of installed units (see Table 1) [3].

Table 1. Indicative worldwide SWT installations.

| Country | Cumulative MW Installations |
|---------|-----------------------------|
| China   | 532.81                      |
| Italy   | 189.43                      |
| U.K.    | 140.60                      |
| U.S.    | 148.0                       |
| Germany | 30.75                       |
| Denmark | 21.88                       |
| Canada  | 13.47                       |
| Japan   | 8.43                        |

Small wind turbines (SWTs) can play a significant role to the power supply in many countries of the world. SWTs have traditionally been used for off grid applications in remote areas, in developed and developing world. Off grid applications include rural residential electrification, telecommunication stations, water pumping and treatment, and hybrid systems with solar photovoltaics and diesel gensets. Energy storage systems, such as batteries are necessary in off grid systems to store energy for the time that the renewable energy sources are not available. Energy storage such as batteries increase the initial investment cost however in stand-alone systems is a cost that cannot avoid.

In recent years, the concept of Zero Energy Buildings is gaining ground as a major tool for achieving sustainable development. Small wind turbines, specially adapted for operation on buildings are an important tool to achieve local scale energy production. In general, the potential market for on grid small wind turbines accelerate the development of their technology as the expected large scale production justifies the higher financial investment required for the development of the technology. These issues lead to the necessity of the application of international standards and certification schemes for small wind turbines to ensure the quality of products, to improve the level of the technology and to certify that small wind turbine industry can be developed accurately. This technology and market growth is expected to decrease the cost of SWTs which is still high, especially for wind turbines with nominal capacity in the order of 10 kW and more. The policy and mostly the
incentives (e.g., tax credits, grants, net metering, FITs) followed by each country, play an important role in the development of SWTs, (see Table 2-data available from WWEA). An example is Italy, where SWTs (<200 kW) received easier permitting and better market conditions, leading to a total of 2000 operated turbines at the end of 2015, with a total capacity of 50 MW [4].

Table 2. Indicative FITs worldwide, (2017 update).

| Country Name   | Size limit (kW) | EUR/kWh |
|----------------|-----------------|---------|
| Denmark        | <10             | 0.330   |
| Greece         | <50             | 0.250   |
| Italy          | <1000           | 0.300   |
| Japan          | <20             | 0.464   |
|                | ≥20             | 0.185   |
| China Taipei   | 1-20            | 0.237   |
|                | >20             | 0.078   |
| USA            | Hawai           | 0.198   |
| Vermont        | <15             | 0.200   |

The forthcoming development of grid small wind turbines will rely greatly on the reliability of the technology, on economic factors, and on privileges granted by the governments of the countries concerned to the sale of the energy produced in the grid. It is obvious that harmonized technical standards and governments favourable policies will encourage further the development of SWT in on grid and off grid applications.

Figure 3. Installation of a 20 kW HAWT.  
Figure 4. Layout of a typical off-grid system. [14]

3 Law 3851/2010, article 5, as amendment of Law 3468/2006, sets the tariff of 250 €/kWh for SWT < 50kW. In 2013, Law 4203/2013, article 4, defines that the installation of SWT connected to the grid is done solely within the framework of the Special SWT Development Program, prepared by decision of the Minister of Environment, Energy & Climate Change. In December 2018 a public consultation of the ministerial decision was launched regarding the definition of the permitting process, as well as any other necessary detail, for the installation and connection to the distribution network of SWT≤ 60 kW. Among others, the MD will replace FIT scheme with the Operating Support Contract (FiP) scheme through competitive bidding for independent producers (Law 4414/2016). For auto-producers the net metering scheme will be applied.
2. Technology

Technically, there are several definitions of small wind turbines. The International Electrotechnical Commission (IEC) in standard IEC 61400-2 defines as small wind turbine the one having a rotor swept area of less than 200 m², corresponding to a rated power of approximately 50 kW generating at a voltage below 1000 Vac or 1500 Vdc. Moreover in U.K. small wind turbines are subdivided further into three categories: micro wind turbines (0-1.5kW), small wind turbines (1.5-15kW) and small medium wind turbines (15-100kW).

In general a small wind turbine converts the kinetic energy of the wind from mechanical energy collected by the rotor to electrical energy through the generator. The energy produced by a small wind turbine, as for large wind turbines, depends on the annual average wind speed at the site – higher wind speeds produce more energy. Therefore the accurate prediction of the wind speed is essential to calculate the electricity output of a small wind generator, representing the basis for its economic performance. For small wind turbines a sufficient wind potential should exceed the 4.5-5 m/s mean annual wind speed. For example a 1kW nominal power wind turbine with a rotor diameter of 3m and annual mean wind speed 5m/sec at the site of installation, and maximum capacity factor (cp) of 40% is estimated that could produce 2000 kWh per year. A 5.0 kW wind turbine with a rotor diameter of 5.5 m at 5.0 m/sec annual mean wind speed can produce 9167 kWh/year, while the same turbine at a site with annual mean wind speed 7.0 m/s can have an annual production of more than 17,000 kWh. Moreover, a 10 kW wind turbine on a windy site may generate 25,000 kWh annually, enough amount to cover the electricity needs of a domestic residence, while a 50 kW wind turbine with an estimated production of 217,000 kWh with annual mean wind speed of 7.0 m/s, is capable to cover the needs of a small village.

The main components of a SWT is the rotor, the generator/alternator and the tower, (see Figure 5, 6). [5] Most small turbines are oriented upwind and most of these use a tail to keep the turbine pointed into the wind and to enable furling or folding at high rotational speed. Common tower types include guyed and monopole (tubular). Rotor blades are made of a variety of materials depending on the design (e.g. plastic, wood, and aluminum), with glass reinforced plastic being the prevailing material. The most common generator technology for SWTs is the direct drive permanent magnet which produces alternating current (AC) or variable frequency and voltage electricity, which must be converted through an inverter. Another configuration is a turbine rotor connected to a gearbox for driving a high speed generator. Induction generators produce AC electricity, so power conversion is not required. Typically, a gearbox is used to increase the rotational speed (rpm) of the rotor to the synchronius speed of the generator. Usually is used in SWTs with nominal power of more than 50 kW. Only few market available SWT in the range of 5 to 50 kW nominal power use a gearbox of any type.

For permanent-magnet alternators or wound-field synchronous generators, the turbine’s output, is variable voltage, variable frequency alternating current (AC) (usually three phase). The power must then be conditioned through an inverter before being fed to the utility grid. Several inverters are now available to directly interface with a SWT’s controller and synchronize with utility voltage and frequency with very little conversion losses.

Turbines control rotor overspeed by various methods, which are often used in conjunction with each other for redundant safety measures. Primary overspeed controls include furling or tilting up out of the wind, active or passive blade pitching, and fixed-pitch stall regulating. As a redundancy, most turbines have either mechanical or electrodynamic brakes or manual furling capabilities (see Table 3).

The two main designs of small wind turbines are the horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) [6, 7]. The horizontal axis SWT is a proven technology which usually uses permanent magnet generators and direct drive technology. They present a higher performance than VAWTs and they continue to dominate the small wind turbine market. Vertical axis wind turbines VAWTs are typically developed only for urban utilization (Figure 8). The average rated capacity of VAWTs is estimated to be 7.5 kW. However in recent years few larger VAWT, of more than 10kW, are available in the market. Although the cost of vertical turbines is much higher than the horizontal ones, VAWT are very popular in the urban area and the rooftop of buildings, as they need...
less space for the installation and emit lower noise than HAWT. Additionally, other innovative horizontal or vertical axis designs are being proposed for use mainly in urban environments (see Figure 7).

![Figure 5. Configuration of HAWT.](image)

![Figure 6. Configuration of VAWT.](image)

VAWT does not need to be positioned into the wind direction; however, their overall efficiency in producing electricity is lower than HAWTs. Because urban wind turbines (UWT) are available in many different shapes and sizes and each one operates best under different conditions, the choice of UWT model for a potential installation site should be studied carefully, [8]. Table 2 presents technical characteristics of market available SWT (indicative list), [9, 10]. Based on the literature, a number of obstacles for VAWT in urban environment exist and further improvement is required mainly on their efficiency, noise emission, vibrations and safety.

![Figure 7. View of an innovative HAWT design.](image)

![Figure 8. View of a VAWT.](image)

A special attention is required on the siting of urban wind turbines since in many cases are placed at unsuitable locations such as behind obstacles or at high rooftops. Installation of wind turbines in built environment is a complicate issue since several factors have to be identified. The placement on buildings, space availability for extra equipment (e.g. inverter), cables installation, maintenance access to the turbine, visual impact, shadow effect, and neighbor’s acceptance are some of the issues that have to be taken in consideration. Moreover, rooftop and complex terrain sites are the most challenging because of high turbulence, wind shear, vertical velocity and the influence of atmospheric stability. Based on that, in October 2018 the first edition of a report on recommended practices for the micro-siting of SWT for highly turbulent sites is issued by IEA Wind [11]. The report provides practical guidance to owners, site assessors, installers, regulators, permitting authorities and
policymakers developing incentive policy programs. Additionally, wind turbines’ reliability and safety is mainly ensured with the certification existence. In the next paragraphs the value of the certification of small wind turbines is presented.

Table 3. Technical characteristics of market available HAWT and VAWT small wind turbines – indicative.

| Name of the company | Ampair U.K. | Ropatec S.p.a Italy | Fortis Montana The Netherlands | OY Windside Production L.t.d. Finland | Aircon OY Windside Production L.t.d. Finland | Eurowind U.K. | Endurance Wind power (E-3120), U.K. |
|---------------------|-------------|---------------------|-------------------------------|---------------------------------------|-------------------------------------------|-------------|----------------------------------|
| Type                | HAWT        | VAWT                | HAWT                          | VAWT                                  | HAWT                                      | HAWT        | HAWT                             |
| **Power Unit**      |             |                     |                               |                                       |                                           |             |                                  |
| Rated power, kW     | 0.3         | 3                   | 5.6                           | 8                                     | 10                                        | 19          | 50                               |
| Rated wind speed m/s| 12.6        | 14                  | 17                            | 20                                    | 11                                        | 12          | 9.5                              |
| Cut-in wind speed m/s| 3           | 2                   | 2.5                           | 2                                     | 2.5                                       | 3-4         | 3.5                              |
| Cut-out wind speed, m/s | -       | -                   | -                             | -                                     | 32                                        | 28-32      | 25                               |
| Surveillance wind speed km/h | 180 | >150 | 60 | 216 | 190 | 255 | 52 |
| **Dimensions**      |             |                     |                               |                                       |                                           |             |                                  |
| Rotor weight, kg    | 12          | ~430                | 170                           | 3000                                  | 144                                       | -           | -                                |
| Rotor diameter, m   | 1.2         | 3.3                 | 5                             | 2                                     | 7.1                                       | 8.25        | 19.2                             |
| Rotor height for VAWT, m | - | 2.2 | - | 6 | - | 8 | - |
| Swept area, m²      | 1.13        | 7.26                | 19.6                          | 12                                    | 39.6                                      | 66          | 290                              |
| Height of the mast m| variable    | not relevant        | 18                            | not relevant                          | 12/18/24/30                               | site dependent | tubular 24,8/36,6 |
| **Other information**|             |                     |                               |                                       |                                           |             |                                  |
| Gearbox             | gearless    | gearless            | gearless                      | gearless                              | gearless                                  | Yes         |                                  |
| Number of blades    | 3           | 2                   | 3                             | 2                                     | 3                                         | 3           | 3                                |
| Blades material     | glass/filled polypropylene | aluminium | composite fibre glass | aluminium | composite fibre glass | composite fibre glass | fiberglass/polyester |
| Output voltage V    | 12/24/48 or on grid | 0-220 | 24-400 | 0-200 | 400 | 24 – 240 | 400-480 |
Acoustic levels at a distance 20m at nacelle, 5m/s), DB
Use of asynchronous generator
Yaw control system
Lifetime

| Acoustic levels at a distance 20m at nacelle, 5m/s), DB | not audible | <60 | 0 | <40 | - | 40 dB(A) at 120 m at wind speed 6m/s |
|--------------------------------------------------------|-------------|-----|---|-----|---|-----------------------------------|
| Use of asynchronous generator                            | No          | No  | No| Yes | No | No                                |
|Yaw control system                                        | wind vane, free yaw | independent of wind direction | wind vane | not needed | azimuth motor | not necessary | yaw damper|
|Lifetime Year                                             | 10          | 15/20 | 20 | 100 | >20 | 20 | 20                                |

3. Application
Today, common applications of SWTs include residential commercial and industrial use, fishery and sailing boats, hybrid systems, farms and remote villages, water pumping and water treatment, remote monitoring, telecom base stations, off shore stations and research and education. Despite the market tendency of using small wind system on grid and urban environment, off grid (stand-alone or mini grid) applications continue to play an important role in remote areas of developed and developing countries. Over 80% of the SWT manufacturers produce SWT for off grid applications. In China, where million households still lack electricity, off grid units comprised more than 85% of the market.

4. Certification
The tendency for grid connected small wind turbines leads to a further need for the harmonization of quality infrastructures for small wind turbines. The international community has worked hard on this, initially through an International Energy Agency (IEA) Recommended Practice, then as an informative annex to the International Electrotechnical Commission (IEC) standard IEC 61400-2 as a Consumer Label.

The IEC standards form the basis for the national standards by the American Wind Energy Association (AWEA); RenewableUK, previously British Wind Energy Association (BWEA); Japan Small Wind Turbine Association (JSWTA). The International Standard IEC 61400-2 Wind turbines – Part 2: Small wind turbines, 3rd edition, issued in 2013 deals with safety philosophy, quality assurance, and engineering integrity and specify requirements for the safety of small wind turbines including design, installation, maintenance and operation under specified external conditions. The purpose of the standard is to provide the appropriate level of protection against damage from hazards during their planned lifetime, including all subsystems of SWTs, such as protection mechanisms, internal electrical systems, mechanical systems, support structures, foundations and the electrical interconnection with the load. The third revision of 61400-2 has an informative annex on consumer labelling, which is similar to the Consumer Label developed under IEA Task 27 Recommended Practice [12, 13].

The IEA Consumer Label includes information on annual energy production estimates based on power performance testing per IEC 61400-12-1,2 sound information based on acoustics testing and analysis per IEC 61400-11 (and possibly IEC 61400-14), and occasionally design classification or turbine test class as specified in IEC 61400-2. Table 3 summarizes the relevant IEC standards for SWTs. Meeting all of these standards is not currently required by certification bodies. However, due to the high cost of the accredited system tests and certification procedure, which may exceed the 60.000 € for a SWT model, a significant number of SWTs still do not have certificates.
Table 4. IEC small wind turbine suite of standards.

| IEC standard | Standard title                                                                 | Status                        |
|--------------|--------------------------------------------------------------------------------|-------------------------------|
| IEC 61400-2  | Wind turbine – Part 2: Small wind turbines                                     | 1st Revision 1995             |
|              |                                                                               | 2nd Revision 2006             |
|              |                                                                               | 3rd Revision 2013             |
| IEC 61400-11 | Wind turbine generator systems – Part 11: Acoustics noise measurement techniques | 2006                          |
| IEC 61400-12-1| Wind turbines – Part 12-1: Power performance measurements of electricity-producing wind turbines | 2006                          |
| IEC TS 6140013| Wind turbines – Part 13: Measurement of mechanical loads                      | 2001-06                      |
| IEC 61400-14 | Wind turbines – Part 14: Declaration of apparent sound power level and tonality values | 2005                          |
| IEC 61400-22 | Wind turbines – Part 22: Conformity testing and certification                 | 2010                          |

5. Market
More than 500 models of HAWT and VAWT are available at the market worldwide. Around 80% of the small wind industry provides HAWT while the rest provides VAWT or both. Based on the world distribution of turbine manufacturers, the production of SWTs remains concentrated in few world regions: in China, in North America and in several European countries. Five countries (Canada, China, Germany, U.K. and U.S.) account for over 50% of the small wind manufacturers. Developing countries continue to play a minor role in small wind manufacturing.

6. Economics
The capital cost of small wind turbines is high and ranges from 2500 to 6500 €/kW while the annually operational and maintenance costs are considered at around 1-3% of the initial investment. For example the initial investment of a 20 kW wind turbine can reach the 100,000 € while the annually operational and maintenance cost is estimated at around 2000 €.

The economic benefits of small wind turbine depend mainly on wind turbine’s capacity factor, the annual mean wind speed of the site and on the existence of incentives or not. Moreover, system’s reliability and appropriate siting of the wind turbine ensures that the operational and maintenance costs will be predictable and according to the initial expectations.

The levelized cost of energy (LCOE), which represents the present value of all anticipated project costs (initial and O&M) over the project’s expected lifetime energy production, for SWT ranges from around 10 c/kWh to 2 €/kWh depending on the factors mentioned above. Figure 9 presents the results of a study computed giving the LCOE versus annual average wind speed, at different specific investment values, while the household energy purchasing prices in EU are also presented as references [14].
7. Conclusions
The increasing demand for clean and affordable energy all over the world will lead to an increasing demand for small wind applications. The application of small wind turbines in urban and decentralized areas in combination also with other renewables, such as solar energy, can enable the electricity production without harming the environment, and contribute to the economic and social development of the area and its citizens. Small wind turbines in decentralized areas are important for their development, displacing of diesel generation, and for improving quality of life, especially in developing countries. The existing challenges such as the high cost, safety and certification issues, energy efficiency, current policies and social acceptance should be examined and rapidly solved. The forthcoming development of on grid small wind turbines will rely greatly on the credibility of the technology, on economic factors (initial cost and O&M costs), and on privileges granted by the governments of the countries concerned to the sale of the energy produced in the grid.

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