Small-scale Urban Venturi Wind Turbine: Direct-Drive Generator

J.J.H. Paulides, L. Encica, J.W. Jansen, E.A. Lomonova
Electromechanics and Power Electronics
Eindhoven University of Technology
P.O. box 513, 5600 MB Eindhoven, The Netherlands
Email: j.j.h.paulides@tue.nl

D. van Wijck
Home Energy BV
Buys Ballotstraat 9, 4507 DA
Schoondijke, The Netherlands
Email: d.van.wijck@homeenergy.nl

Abstract—**There is a growing interest for the use of small-scale wind turbines at buildings. In most situations the deployment of existing (small $\leq$ 5kW) wind turbines will not be very successful due to the fact that they are not adapted to the complex wind environment. Several novel wind turbines have been developed to be able to extract a large amount of energy from these urban environments. This paper concerns a new horizontal Venturi wind turbine (2.0m diameter), which has a comparable power per rotor cross-sectional area in respect to various other wind turbines, due to its direct-drive generator. This direct-drive external rotor permanent magnet brushless generator system has been selected for this application due to its power density, where a total system efficiency of $\geq$80% has been achieved over a large speed range.**

I. INTRODUCTION

In a strategy document submitted by the American Wind Energy Association small wind turbine committee chaired by [1], a projected total of 75,000 MW wind power capacity by 2020 is provided by small to medium scale systems. Of this amount some 15,000 MW is foreseen at locations that are suitable for rooftop mounting of wind turbines. Further, a potential market of similar extent as in the USA is foreseen for the EU, hence a worldwide market of millions of units, provided that the cost targets with respect to cost of electricity are met. It should be taken into account that the targeted cost for urban wind turbine electricity can exceed the domestic purchasing price of electricity, mainly due to the transportation costs (typically two to four times higher in North West Europe).

Since the European renewable energy directive set the target for 22.1% of electricity generation to be supplied by renewable sources by 2010, there has been increased interest in using renewable energy technologies in the urban environment [2]. The most common technologies considered are solar thermal installations and solar photovoltaics. Nevertheless, in the last few years, a number of manufacturers have developed small wind turbines specially designed for the urban environment. These small scale renewable energy technologies generate clean and renewable energy, while reducing CO_2 emissions. Like photovoltaics, urban turbines generate electricity on site, avoiding transmission losses. Urban turbines also provide a visual statement for sustainable energy, hence highlight the promotion of a green image. As such, there is an increasing amount of support and interest from politicians, industry, local authorities and the public alike for small wind technologies. These urban wind applications especially cover various kinds of small wind installations in urban or built up areas. Previously wind turbines were not considered in urban areas and were mainly used in remote areas together with photovoltaics to provide local power, however an emerging market is existing for small wind turbines and the associated technologies. However, there is still relatively limited experience with the installation and grid connection of these products. Therefore, numerous projects have been initiated to gather the information on the development of small wind energy in urban areas covering a wide variety of technical, economic, planning and administrative aspects. In Europe large expectations are placed on the European "Urban wind turbine cities network" which is realizing a sustainable and effective knowledge network between European cities and knowledge institutes in the period 2007-2013 [3].

Fig. 1. Venturi wind turbine installed at Schiphol airport Amsterdam, The Netherlands.

II. URBAN WIND TURBINES

The popularity of small wind turbines in Europe is growing and there is increasing interest from home owners and businesses to install small wind turbines on their homes and buildings [4]. Considering the urban wind regime, two main characteristics appear: lower annual mean wind speeds and more turbulent flow. The reduced mean wind speeds are caused by the presence of buildings, etc., which reduce the wind

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speeds at higher altitudes, where turbulences are resulting from the interaction of the wind with the same buildings and other obstacles. Especially, turbulent flow provides a design challenge due to the rapidly changing wind direction, e.g., the turbine needs to quickly react to the changing wind directions. This clearly highlights the challenges of urban wind energy systems compared to stand-alone turbines. As such, turbulence will significantly reduce the output power and increase stress for turbines not designed to operate in these conditions. Additionally also the society demands that the turbine integrates smoothly to the building both structurally and visually with minimized maintenance and noise especially in highly dense populated areas. Thus, the challenge is to find turbine topologies that can cope well with turbulence, or find the least turbulent areas of the urban environment. Of the latter, building-tops could show a great deal of promise, partly because the wind flow there could be substantially greater as it gets concentrated by passing around, through or over buildings. Other less turbulent areas are open areas on the ground such as parks, sport fields or flood defences.

The output of the wind turbine is limited by Betz law [5], although that recently small-scale stand alone are approaching this limit, turbines integrated or in close proximity of buildings are often well below this. This Betz limit is often used to estimate the maximum efficiency of such turbines when designing wind farms, defined as the ratio of the turbine power to the power of the unconstrained uniform flow through the turbine area. These calculations are based on the momentum rate change and the Bernoulli relations for the fluid flowing through the turbine and consequently an efficiency limit of 59.3 percent was obtained. Recently, additional models of vertical-axis wind turbine with straight vertical wings are developed with the aim to study the upper limit of one-dimensional Betz theory with respect to turbines when two-dimensional effects are included. One of these models illustrated the potential of exceeding the Betz limit [6], since it does not take into account the two-dimensional flow effects and the velocity of the rotating wind turbine. By including these effects, more optimistic results for the performance of vertical-axis wind turbines (see Section III-B) could be obtained.

III. HORIZONTAL OR VERTICAL WIND TURBINES

Many different types of wind turbines exist for the urban environment and they can be divided into two groups of turbines depending on the orientation of their axis of rotation, namely HAWTs and vertical axis wind turbines (VAWTs). The general public associates wind turbines with HAWTs and are unaware of the several other technologies based on the VAWT. The recent attention that VAWTs have received in several journals arouses an interest in making comparative studies between HAWTs and VAWTs (e.g., [7], [8], [9]). Although that many wind turbine configurations have been analyzed one important variant has not been mentioned, namely the HVAWT Venturi wind turbine that tries to combine the advantages of the HAWT and VAWT in a single wind turbine, as shown in Fig. 1.


(a) (b)

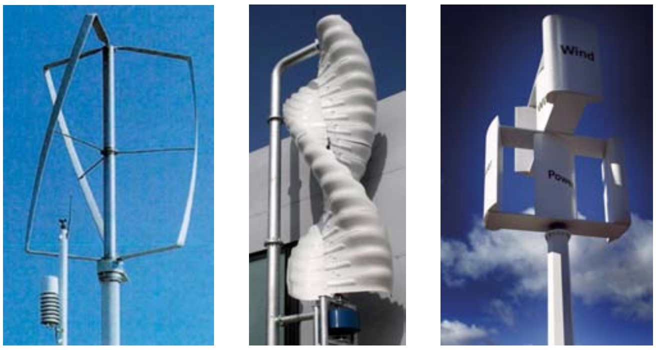
Fig. 2. Small scale horizontal axis wind turbines: (a) airdolphin from Semplice Energy (b) Montana from Fortis Wind Energy.

A. Horizontal axis wind turbine

At present, the type of wind turbine that is most widely associated with wind power is the three-bladed horizontal axis wind turbine (HAWT), as shown in Figure 2. The propeller-type rotor is mounted on a horizontal axis. The rotor needs to be positioned into the wind direction by means of a tail or active yawing by a yaw motor. HAWTs are sensitive to the changes in wind direction and turbulence which have a negative effect on performance due to the required repositioning of the turbine into the wind flow. The best locations for HAWTs are open areas with smooth air flow and few obstacles, hence not that suitable for mostly turbulent urban environments. Further, in general, small wind turbines are designed with a high tip speed ratio comparable with large wind turbines, hence, the angular velocity becomes very high. Considering that most small wind turbines have fixed pitch type blades, while their rotational surface can be furled upward or side wards to prevent the over-rotation, these turbines are usually noisy which is a very undesirable feature in urban environments.

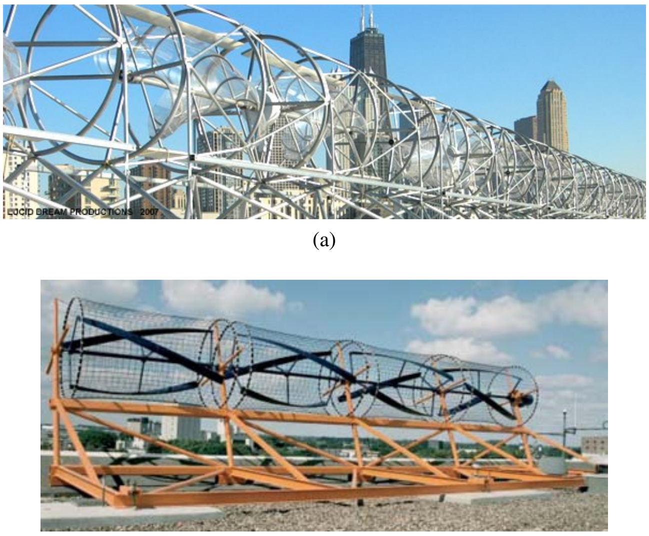
B. Vertical axis wind turbine

Vertical axis wind turbines are typically developed only for the urban deployment. Changes in wind direction have fewer negative effects on this type of turbine because it does not need to be positioned into the wind direction. However, the overall efficiency of these turbines in producing electricity is lower than HAWTs. Historically, these turbines are categorized as Savonius or Darrieus types, according to the principle used to capture the wind flow, where the oldest VAWT is the Savonius rotor [10]. For this type, the wind pushes the blades, which implies that the rotation speed is always lower than the wind speed. Contrary to that, the shape of the rotor of the Darrieus type makes it possible for the rotor to spin faster than the wind speed. The Darrieus type is powered by wings attached to a vertical tower at the upper and lower ends, where the curved wings has a barreled or eggbeater



(a) (b) (c)

Fig. 3. Small scale vertical axis wind turbines: (a) Turby from Turby (b) S594 Wind Turbine from Helixwind (c) Double vertical from Ropatec.



(a)

(b)

Fig. 4. Fixed position small scale horizontal vertical axis wind turbines: (a) Aeroturbine from Aerotecture International (b) Windwall from Windwall.

shape (eliminates bending loads) with a number of straight or curved-in plane airfoil blades and a shaft that is perpendicular to the air flow. This VAWT has more advantages besides its independence on the wind direction. It runs silently compared to the horizontal machine and allows for the generator to be placed on the ground. However, in the past, the Darrieus turbine has not received wide practical applications, mostly due to the pulsating torques during the rotation when blades change angles of attack traveling along the circular path, since the turbine vibration often leads to the early fatigue failure of its parts and joints. Skewing the blades can minimize this, where skewed VAWTs are usually implemented for the operation of VAWTs in the built-up environment. Further, recent experimental thrust results for the urban environment have shown that thrust can increase with skew (i.e. to 30°-40°) [11]. Examples of skewed VAWT are: Turby, WindSide, Helix wind, Ropatec (some of which are shown in Figure 3).

C. Horizontal vertical axis wind turbine

Figures 4 and 5 show examples of innovative horizontal axis turbines, e.g., Aeroturbine, Windwall and Energy Ball. Aerotech and Windwall are examples of a horizontal/vertical axis turbine, where the axis is fixed to the roof so that it can catch the wind from just one direction. This makes it suitable for locations were the wind from one direction strongly prevails.

On the contrary, the Energy Ball (also named Venturi, Fig. 5) [12], is an example of a horizontal/vertical axis turbine with a tail but with an innovative rotor construction: six half-circular blades forming a spherical construction. In general, wind turbine concepts only bring about a force in the direction of wind flow, where no more energy can be extracted than the amount that is supplied perpendicular to the rotor plane. However, in theory, if the flow converges upstream of the wind turbine rotor and diverges downstream, the rotor is capable of extracting more energy from the flow (similar to the VAWTs in Section III-B). This enables the Venturi turbine to generate electricity from turbulent flows allready at very low wind speeds. The development of an operational concept is attractive, because suitable efficiencies can be realized compared to the conventional concept wind turbines in urban environments. This allows the design of small wind turbines which can function cost-effective at typical urban locations [13].

The blades of the small HAWT Venturi turbine are attached to the hub on both ends. When rotating, a sphere is described. Because of this aerodynamic behavior, Venturi turbines create a wind flow-pattern that generates a low-pressure area within the sphere which attracts the air in front of the rotor towards the sphere. After the rotor has absorbed energy from the air, the energy-poor air is swung radically outwards through the Venturi planes and is carried away by the surrounding airflow. This enables additional power to be extracted from the wind for a relatively small wind turbine, however, it needs noting that for a Venturi type design the wind turbine probably draws air from a larger area than the projected frontal area of the rotor.

The various components of the Energy Ball are illustrated in Fig. 5, which shows the spherical blades, the yaw system, the mechanical support, the post and the position of the direct-drive generator. This machine is build directly within the turbine to minimize the frictional losses. Using a direct-drive generator means the ability to run with variable speed without an electrical contact element between stator and rotor, which is favorable from the aspect of maintenance and noise.

The efficiency of wind turbines is most commonly measured in terms of cost-effectiveness, i.e. in cost per kWh of the produced electricity. In a technical context, in order to determine the revenue generating potential, the efficiency would be expressed by yield measured as the number of kilowatt-hours produced per square meter of rotor area. A summary of the yield for various wind turbines is given in Table I. This table illustrates that VAWT or HVAWT have comparable power outputs per frontal area, however, individual differences between the various turbines still exist, i.e. the noise production, maximum operating speed, wind turbine swept

TABLE I
PERFORMANCE VALUES AT A WIND SPEED OF 12 M/S

Type	Pout	Area	Spec P/A
	(kW)	(m^2)	(kW/m^2)
Wes Tulipo [15]	2.60	19.6	0.17
Montana [14]	3.90	19.6	0.20
Turby [16]	1.25[1]	5.30	0.24
Ropatec [17]	1.90[2]	6.60	0.23
Energy Ball V100 [13]	0.18	0.95	0.18
Energy Ball V200 [13]	0.75	3.14	0.24

[1] assumed AC-DC-AC efficiency of 81 %

[2] assumed DC-AC efficiency of 90 %

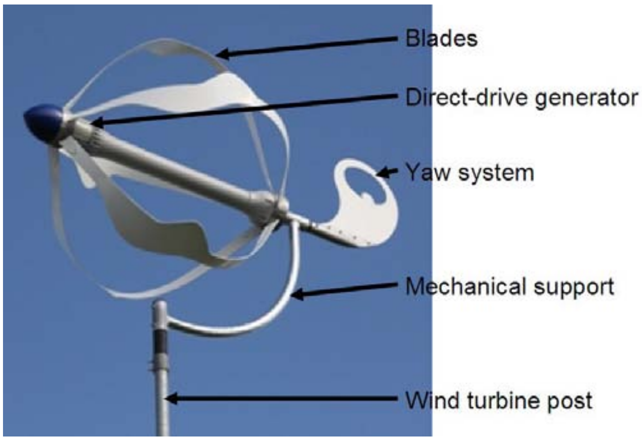


Fig. 5. Horizontal vertical axis Venturi wind turbine with component explanation.

area, used generator type, etc. The data in this table is surely not complete, since numerous systems exist, and is directly derived from manufacturers data (only the 12 m/s point of the performance characteristic is taken). Hence, comparison tests should be undertaken to illustrate to which extend the provided data is correct, e.g. [4]. However, in these tests, undertaken by independent institutes, not only the output data should be provided, but also the means to check whether the provided information is correct, e.g., by giving the equipment that is used to measure the output power, power output over time, average measured wind speeds, etc.

IV. DIRECT-DRIVE GENERATOR

The main advantage of the Venturi concept is the possibility to keep the structure simple, where the rotor does not require any pitch regulation and, therefore, has few movable parts. Further, using a direct drive system the gearbox is excluded from the system, which is much more efficient and will react faster to changes in the wind than a generator with a gearbox. Based upon the dimensions of the Energy Ball V200: 2 m diameter, a power level of 2.25 kW was found to be an optimum. For these power levels of-the-shelf generators and converters could have been selected. However, these components are in general not application optimized, and therefore less efficient. For the connection to the grid, a six-pulse rectifier and a single phase inverter have been selected.

Fig. 6. External permanent magnet rotor with one of two rows magnets glued to the mildsteel back-iron.

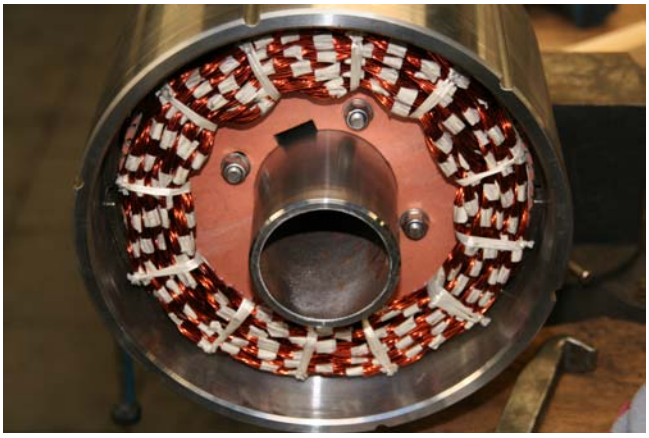


Fig. 7. Wound armature prototype with a distributed winding configuration inserted in the external rotor.

The main challenge for the design of the direct-drive generator is to achieve a high efficiency over an extended speed range, since the turbines will turn at 2 m/s and start generating electricity already at 3 m/s (Beaufort scale 2-3). At 19 m/s (Beaufort scale 8) the wind turbine delivers its maximum power of 2250 W to the grid and the maximum survival speed for the wind turbine is 40 m/s (> Beaufort scale 11). For optimal integration and simplicity of the total design the generator is designed with an external rotor, where the outer part is the rotor with the permanent magnets. The magnets are positioned straight within the rotor, where the slots are skewed to minimize cogging torque, DC-link voltage and power ripple, see Figs. 6 and 7. This is also clear from Fig. 5, where the wind turbine blades are directly attached to the external rotor configuration. This eases start-up of the wind turbine in low winds, hence, allows for even small gusts to be utilized. Further also the generator size and weight have been minimized in the next section, since, besides having few moveable parts, also the size and mass of supplementary wind

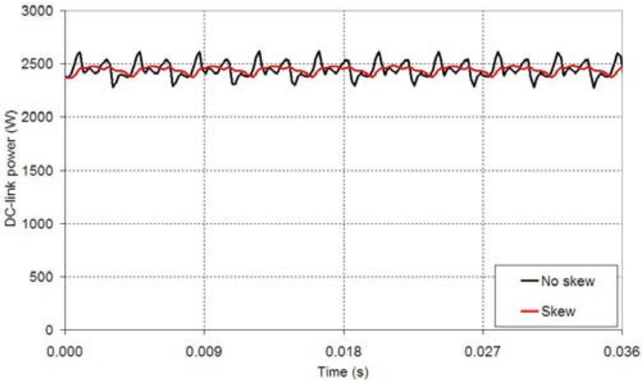


Fig. 8. Simulated DC-link power by finite element analysis with and without stator skewing.

turbine components reduces, hence their costs. The direct-drive solution is used, since it is expected that this will result in a reduction of the total cost of ownership during the complete lifetime, and therefore, will promote the use of small wind turbines in urban environments turbulent wind speed regions.

V. PROTOTYPE GENERATOR

The 12-pole, 72-slot external rotor brushless permanent magnet generator has been specially designed using analytical equations that provided the various relations between dimensions and parameters, and verified using finite element analysis. Using these parameters, for each turbine operating point (depending on wind speed), the generator losses and power supplied into a rectifier are calculated. The design approach included the selection of a large number of dimensional and performance parameters, e.g., slot number, pole-arc, slot opening, coil-pitch, back-emf waveform, losses and other principal dimensions. A finite element model has been created to accurately provide the back-emf and cogging force. The surface mounted magnets taken into consideration are NdFeB type with a remanent flux-density of 1.15 T and coercivity field-strength of 836 kA/m as typical values. The magnets are glued on a ferromagnetic hub being alternatively magnetized, where Fig. 6 shows the first (out of two) magnet row that has been glued to the mildsteel solid rotor back-iron. Each magnet has to cover the magnetization of the airgap and to compensate the field due to the armature reaction, even at short circuit circumstances which are sometimes used to bring the turbine to a standstill.

In order to minimize the cogging torque and smooth the back-emf waveform skew has been applied to the stator laminations, which also reduced the DC-link power ripple as shown in Fig. 8. In this generator design a distributed winding topology is chosen, shown in Fig. 7, to achieve a high winding factor and a winding that locates the phases in individual slots to enable ease of automatic winding.

The realized prototype brushless generator (active volume of $2.95\ 10^{-3}\ m^2$), as shown in Fig. 9, delivers the maximum torque at maximum speed where the nominal electrical power into the grid is 2250 W at 430 rpm for which a total of 2750 W is necessary from the wind, as shown in Fig. 11. It needs noting that the maximum power is limited by the current power electronics and that the voltage will continue to rise with increased turbine speeds. This increased voltage level has to be considered by the selection of rectifying components. Fig. 11 also provides the total efficiency of the generator system including the power electronic converter to be approximately 80 %.

Fig. 9. Prototype direct-drive external rotor brushless permanent magnet generator on the test bench for initial measurements.

The cogging in this direct-drive generator has been minimized to <1 % of rated torque (1.3 Nm without skew and 0.1 Nm with skew) to enable the wind turbine to start rotating at very low speeds. Additionally, also the thermal capabilities of the wind turbine have been measured on the setup to be 88 °C within the winding at full power and steady state thermal conditions, on the test setup of shown in Fig. 10. Further, the maximum short circuit current that can be allowed for by the magnets to prevent partial demagnetization has been investigated and approximated to be 150A within the winding. However, this is a worse case physical limit if the generator runs at 430rpm and an imminent short circuit would occur. Considering the average cable length between generator and rectifier (approximated to be 10m), 2.5 mm^2 cable and assuming ideal copper and no temperature rise, the resistance of this cable is given by 67 $m\Omega$, respectively. This combined with the phase resistance and synchronous reactance, gives that in every phase an effective resistance of approximately $84 m\Omega$ is apparent, which further reduces the short circuit currents. However, a disadvantage of these relatively long cables is the influences on the operational efficiency of 80 % (already included). It needs noting that the bearing friction should be as low as possible to allow the wind turbine to start at very low wind speeds and minimize the losses.

VI. DISCUSSION

Currently, the diversity of technical wind turbine solutions for the urban environment means that different types of turbine perform optimally under different conditions and that a solution can be found for most locations and specific wind

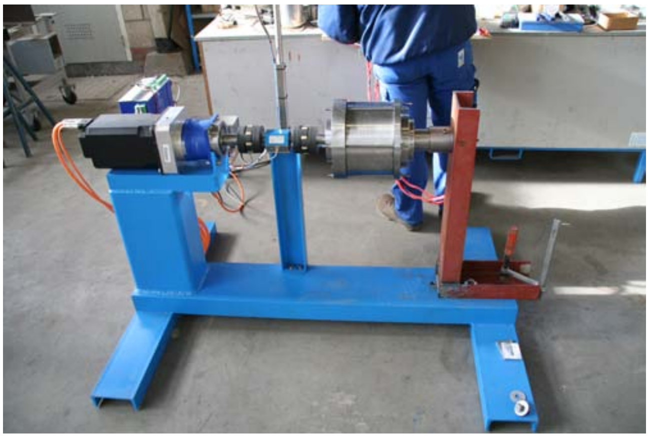


Fig. 10. Direct-drive external rotor brushless permanent magnet generator attached to a servo machine for power measurements.

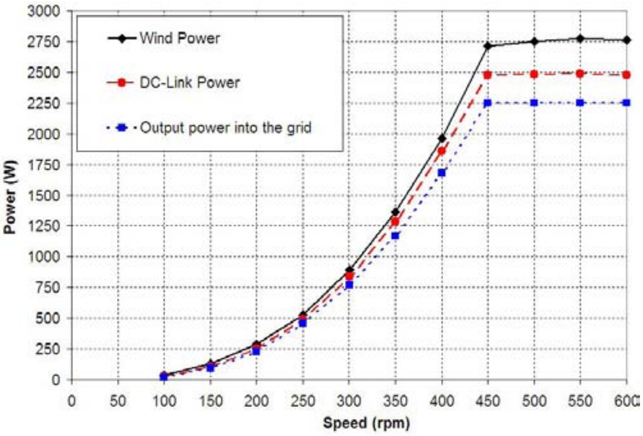


Fig. 11. Output power measurements at various turbine speeds

regimes. However, in general, urban turbines are not fully developed, mature technologies. Hence, the electricity yield is still too low and the costs are out of proportion to the benefits of installing a wind turbine. Further, the generally available information regarding the urban wind turbines is insufficient and has almost never been technically verified by independent institutions (e.g. KEMA, TÜV, etc), where also information on existing installations is very limited.

VII. CONCLUSION

This paper has shown that a low noise small-scale wind turbine for the urban environment of 2.25 kW into the grid is feasible using the Venturi principle with a diameter of 2 m. The main advantages are the low noise and that the turbine draws a larger amount of air from a bigger area than the projected frontal area of the rotor. This wind turbine is equipped with a direct-drive permanent magnet generator with a relatively high efficiency and power density at minimum costs.

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