Energy 69 (2014) 336–344

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

INVELOX: Description of a new concept in wind power and its performance evaluation

Daryoush Allaei [a], Yiannis Andreopoulos [b], *

[a] SheerWind, Inc. Chaska, MN 55318-2342, USA
[b] Department of Mechanical Engineering, City College of New York, New York, NY 10031, USA

A R T I C L E I N F O

Article history:
Received 23 September 2013
Received in revised form
4 March 2014
Accepted 6 March 2014
Available online 8 April 2014

Keywords:
Wind energy
Sustainable energy
Wind turbines
Ducted turbines

A B S T R A C T

A new concept in wind power harnessing is described which significantly outperforms traditional wind turbines of the same diameter and aerodynamic characteristics under the same wind conditions and it delivers significantly higher output, at reduced cost. Its first innovative feature is the elimination of tower-mounted turbines. These large, mechanically complex turbines, and the enormous towers used to hoist them into the sky, are the hallmark of today's wind power industry. They are also expensive, unwieldy, inefficient, and hazardous to people and wildlife. The second innovative feature of INVELOX is that it captures wind flow through an omnidirectional intake and thereby there is no need for a passive or active yaw control. Third, it accelerates the flow within a shrouded *Venturi* section which is subsequently expanded and released into the ambient environment through a diffuser. In addition, INVELOX provides solutions to all the major problems that have so far undermined the wind industry, such as low turbine reliability, intermittency issues and adverse environmental and radar impact. Simulating the performance of this wind delivery system is quite challenging because of the complexity of the wind delivery system and its interaction with wind at the front end and with a turbine at the back end. The objectives of the present work are to model and understand the flow field inside the INVELOX where the actual wind turbine is located as well the external flow field which not only provides the intake flow but also has to match the exhaust flow of the system. The present computations involved cases with different incoming wind directions and changes in the intake geometry. The results show that it is possible to capture, accelerate and concentrate the wind. Increased wind velocities result in significant improvement in the power output. These results led to the design of a demonstration facility which has provided actual data which verified the significantly increased power expectations.

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).

1. Introduction

Wind energy conversion systems have existed for more than 3000 years. Since the appearance of the ancient Persian vertical-axis windmills 3000 years ago, many different types of windmills have been invented. Initially, wind energy was used to induce a function, such as moving boats using sail, cooling houses by circulating outside air, running machinery in farms, and even small production facilities. In late 1800s and early 1900s, conversion of wind energy to electrical power marked a turning point for the wind power generation industry. The review in Ref. [1] provides a very good description of its historical development. Due to energy crises and changes in the political and social climates, wind turbines started to rapidly spread across the globe in the last three decades. However, wind power is far from reaching its full potential.

Manufacturers have incrementally improved conventional wind turbines in the last two decades – but the greatest energy output gains have come from building turbines with ever-larger blades, perched on ever-taller towers, built at ever increasing expense and with ever increasing areas of land required. As the size and height of turbines and towers increase, often reaching beyond 100 m – wide enough to allow one or two 747 aircrafts to fit within the sweep area of the blades – the cost of wind-generated power continues to exceed the cost of power generated by hydropower plants, coal and natural gas. Turbines are often subjected to excessive downtime, and failure and repair costs are high. Moreover, complaints of harm to wildlife continue to plague the industry, as do complaints of harm to human health from high-decibel low-frequency sound waves from wind turbines, propeller noise and flickering of light through

---

* Corresponding author.
E-mail address: andre@ccny.cuny.edu (Y. Andreopoulos).

http://dx.doi.org/10.1016/j.energy.2014.03.021
0360-5442/© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).

rotating turbines. The visual nuisances of large wind farms are another cause of complaints.

Conversion of wind power to electrical energy is controlled by the free stream wind speed and blade shape, orientation and radius. Because of these design parameters, the tower height and blade sizes in conventional systems have grown to sizes that are considered excessive. In terms of manufacturing, logistics, installation and maintenance challenges and costs, the heights of the towers and size of the blades are reaching to very challenging limits.

Innovators across [2–19] the globe have developed approaches showing promise for certain applications. For example, airborne units have been developed with turbines at 300–500 m above the ground. A variety of single and multiple array ducted turbines [2–4,20–23] have also been developed. The single-ducted turbines have been shown to be effective and economical for small wind applications. Attempts have been made to scale up the single-ducted turbines for utility scale applications. However, due to size, and the required speed increase, they have been proven to be uneconomical. Even though an array of ducted turbines can generate more electrical energy, they suffer from complexity in actual implementation at utility scale. As a result, the industry has remained on the same track – using turbines mounted on the top of towers – for almost a century.

A recently developed technology [5–14], INVELOX (increased velocity), has shown promise. The patented [15,16] INVELOX is simply a wind capturing and delivery system that allows more engineering control than ever before. While conventional wind turbines use massive turbine-generator systems mounted on top of a tower, INVELOX, by contrast, funnels wind energy to ground-based generators. Instead of snatching bits of energy from the wind as it passes through the blades of a rotor, the INVELOX technology captures wind with a funnel and directs it through a tapering passageway that passively and naturally accelerates its flow. This stream of wind energy then drives a generator that is installed safely and economically at ground or sub-ground levels.

In this paper, both computational and test results measured from a fielded unit are reported. The performance of the system was validated by recent measured field data. It has been shown that the increase in wind speed was maintained even when a turbine was installed inside INVELOX and thereby the daily energy production was significantly improved. This measured data is shown to be consistent with that obtained through laboratory and wind tunnel tests, and full-scale computational fluid dynamics models.

1.1. *Description of the INVELOX delivery system*

The five key parts of INVELOX are shown in Fig. 1. These key parts are (1) intake, (2) pipe carrying and accelerating wind, (3) boosting wind speed by a Venturi, (4) wind energy conversions system, and (5) a diffuser.

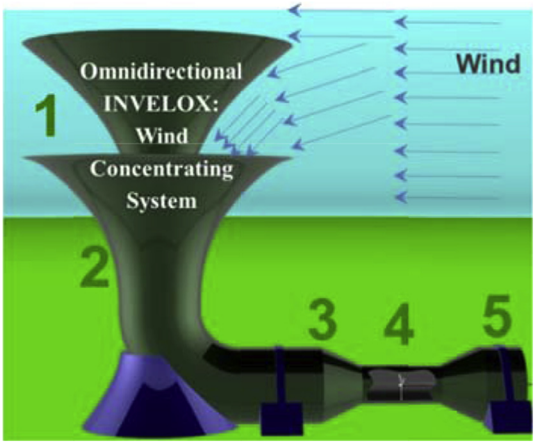

Fig. 1. Schematic of the INVELOX wind delivery system with its key components, (1) intake, (2) channeling wind, (3) wind concentrator, (4) *Venturi* plus wind power conversion system, (5) diffuser returning wind to nature.

Control volume analysis for conservation of mass, axial and angular momentum balances, and energy conservation for inviscid, incompressible axisymmetric flows yields [6]:

$$\oint_A \rho\mathbf{V}\cdot d\mathbf{A} = 0;\ \oint_A u_x\rho\mathbf{V}\cdot d\mathbf{A} = T - \oint_A p\, d\mathbf{A}\cdot\mathbf{e}_x;\ \oint_A r u_\theta \rho\mathbf{V}\cdot d\mathbf{A} = Q;\ \oint_A \left[\frac{p}{\rho}+\frac{1}{2}\|V^2\|\right]\rho\mathbf{V}\cdot d\mathbf{A} = P$$

where $\mathbf{V} = (u_x, u_r, u_\theta)$ is the velocity vector in the axial, radial, and azimuthal direction, respectively; r is the radius; ρ is the density of air; $\mathbf{A}$ denotes the outward-pointing area vector of the control surface; $\mathbf{e}_x$ is the unit vector in the x direction; p is the pressure; T is the axial force (thrust) acting on the rotor; Q is the torque; and P is the power extracted from the rotor.

It is obvious from the above relation that the extracted wind power P can increase by increasing the mass flow rate $\oint_A \rho\mathbf{V}\cdot d\mathbf{A}$ or the total energy drop $[(p/\rho)+(1/2)\|V^2\|]^{\text{in}}_{\text{out}}$ across the turbine.

The fundamental characteristic of the INVELOX system is that it captures a large portion of free stream air flow and can do so in nearly any free stream locations with flow greater than 1 m/s. This increased mass flow rate carries energy per unit mass from the free stream given by $e = [(p/\rho)+(1/2)V^2]$ which for inviscid fluids remains unchanged till it interacts with the turbine in the *Venturi* section.

INVELOX passively converts the existing kinetic and potential/pressure energy of wind to higher kinetic energy $1/2\|V^2\|$ that can more effectively be converted to mechanical rotation of a turbine. Along any part of the INVELOX tower of constant cross-section the velocity remains the same and therefore there is no kinetic energy drop across the turbine. Thus, the extracted power is given by $P = \oint(p/\rho)\rho\mathbf{V}\cdot d\mathbf{A}$ which can be approximated by the $P = \eta\dot{Q}\Delta p$ where $\dot{Q}$ is the increased volumetric flow rate, Δp is the pressure drop across the turbine and η is its efficiency.

In contrast to older designs of ducted turbines, INVELOX separates the location of the shroud and turbine-generator system; the intake is on the top while the turbine-generator is placed at the ground level inside the ducted pipe carrying captured wind towards the turbine. This unique feature allows the engineers to size the intake wind delivery system for any speed increase required without increasing the turbine size. The size of an intake depends on local wind speeds and other environmental conditions. In short, the turbine size may be selected based on the ability of the INVELOX to increase wind speed/mass flow rate.

The turbine-generator system is installed at ground level and inside the optimum location of the horizontal section of INVELOX resulting in significant cost savings at the time of installation, and during operation and maintenance for the life of the system.

Because there is no moving component on the top of the tower, most adverse environmental impacts are eliminated or minimized. Moreover, radar interference and optical flickering are no longer issues. The absence of a large rotating turbine on the top allows INVELOX towers to be installed closer to each other, reducing required land requirements.

Turbines inside INVELOX, or any ducted turbine, have a higher power coefficient than those installed in an open-flow

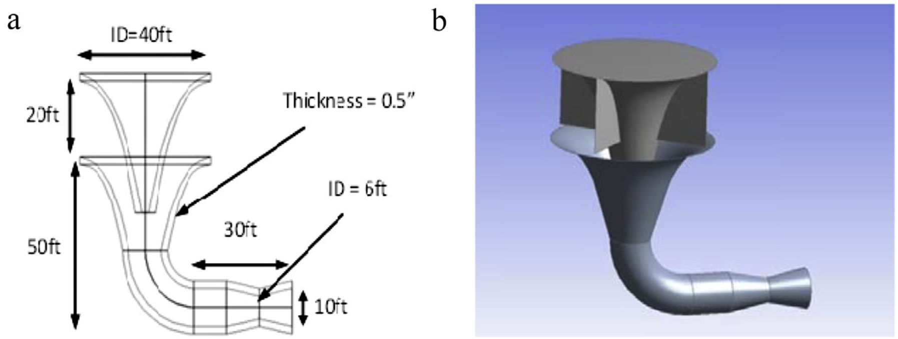

Fig. 2. (a) detailed dimensions and geometry of omnidirectional INVELOX; (b) configuration with four fins oriented at 45° to flow direction.

environment. Standard horizontal or vertical turbines can be installed inside INVELOX and generate significantly more energy when compared with open-flow systems.

INVELOX allows a much lower cut-in speed because it can increase wind speed at the location of the turbine. For example, if INVELOX is designed to increase free stream wind speed by a factor of 4 at the turbine location, and it uses a traditional turbine that has a cut-in speed of 4 m/s, the cut-in speed of the INVELOX-turbine system will be 1 m/s. Having a low cut-in speed is one of the most important features offered by INVELOX. This feature not only allows an increase in annual energy production and capacity factor but also increases wind power availability. It allows installation of INVELOX in wind class 1 and 2 areas. It also allows INVELOX to be installed nearer the end user, thereby significantly reducing transmission losses and added costs. INVELOX does not require the huge upfront capital cost of traditional wind technology, and nor does it leave a negative environmental impact.

In all, INVELOX has the potential to reduce the net cost of utility scale wind power generation by reducing installation, O&M, turbine, and land costs while improving energy production and environmental impacts.

In the first glance, INVELOX appears to be another ducted turbine. In fact the ducted turbine has been traced to the work conducted in Finland in 1930s. The subject of ducted turbines has resurfaced in every decade since 1930s. Without exception, in all the ducted turbines that have been tried to date, the turbine location and the intake are strongly coupled. In other words, if one wishes to scale up the system to utility scale, not only the blade increases in size but also the duct structure increases in size and impacts the cost substantially. There are various examples of failed ducted turbine products because they were not financially viable. There is also no other savings to compensate for the huge cost of the additional structures that needed to align the structure with the wind direction. The industry learned from this experience and thereby most of the ducted turbine companies in USA and Europe, Japan, and China have limited their product lines to small wind power (below 50 kW). The most successful ones are those that limited the power below 5 kW.

The similarities, however, between INVELOX and the traditional ducted or shrouded turbines end here. It is true that INVELOX falls under general area of ducted turbines. But it has distinct differences that make it financially viable and performance wise superior to the other ducted turbines and traditional horizontal axis wind turbines. Key features of INVELOX are:

1) The intake and turbine are decoupled. This means the intake size may be adjusted while keeping the turbine as small as necessary depending on the required speed ratio and environmental conditions.
2) The above decoupling of intake and turbine location allows the WTG (Wind Turbine Generator) be mounted at the ground level and thereby reduce O&M.
3) Decoupling of the intake and Venturi, where the turbine is installed, allows designing INVELOX with speed ratio of 6 or higher. This allows operating at high wind speeds and thus generating a lot more power with smaller blades while utilizing a much more efficient generators operating at higher speeds.
4) Smaller blades operating at higher wind speeds results in 85% smaller blades that results in cost savings in material, manufacturing, transportation, and installation.
5) The intake designed to be omnidirectional and thus no need for huge bearing and motors to turn the intake in the direction of wind.
6) INVELOX can be designed with a power rating of 500 W to 25 MW. All that matter is how much air is captured.

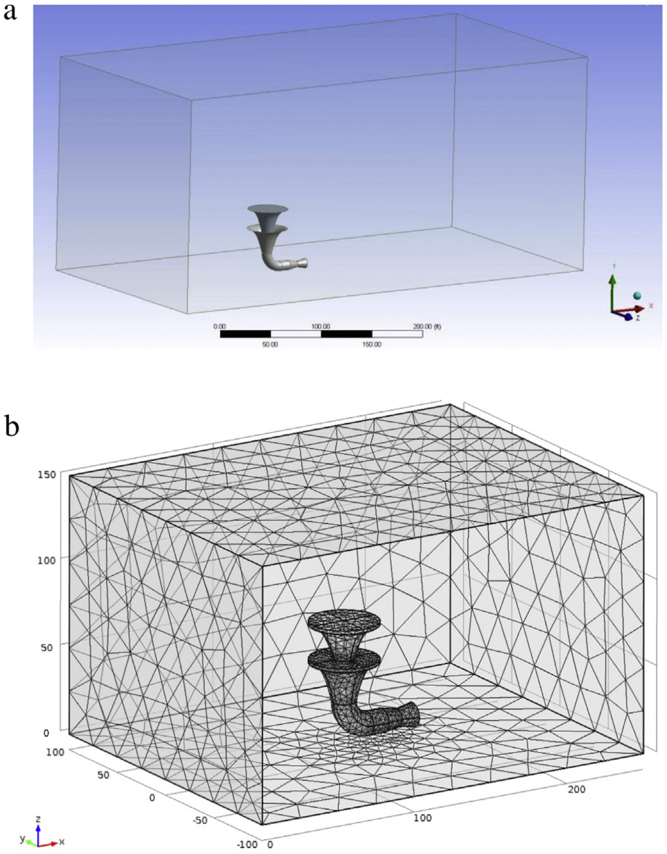

Fig. 3. Computational domains used in (a) ANSYS and (b) COMSOL.

7) The decoupling of the intake and turbine allows multiple intake be connected to increase mass flow and thus power output.

2. CFD (Computational Fluid Dynamics) models

Fig. 2a shows the dimensions and geometry of omnidirectional INVELOX modeled. This model (INVELOX-12-02) uses double nested cone concept with 360° wind intake capability. This unit is scaled to fit a 1.8 m (6 ft) diameter wind turbine at the *Venturi* location, and to be erected to a height of 18 m (60 ft). Because INVELOX has no rotor/hub on the top, the height of the tower is measured from the center of the intake to the ground level. The speed ratio of the velocity at the *Venturi* U_i over that of the external free stream U_e, $S_R = U_i/U_o$, an important design factor, is designed to be about 2. If the free stream wind speed is 6 m/s, the speed at the location of the turbine (*Venturi*) will be equal to 12 m/s. The intake is composed of two nested cones. The top cone is the guide directing wind into the lower cone. The intake of the INVELOX tower was also fitted with four fins oriented at 45° angle to flow direction as shown in Fig. 2b. These fins contribute to further enhance intake's performance in capturing free stream flow rate.

This unit was modeled using the commercially available packages ANSYS and COMSOL. The two models were developed independently with the objective to compare the results. Fig. 3 shows a typical flow domain used in the computations. The computational domain used in the ANSYS computations had a size of 120 m (400 ft) length, 72 m (240 ft) width and 67.2 m (224 ft) height. A slightly smaller domain was used in the COMSOL computations which had dimensions of 60 m (200 ft) × 90 m (300 ft) × 45 m (150 ft). The outer diameter of upper funnel at the tip of its lowest vertical position is 6 ft while the inner diameter of the lower part of the funnel at the same height is 16 ft.

The flow domain was discretized with a mesh of tetrahedral elements. Mesh sizes from 120,000 to 3,680,000 were used for

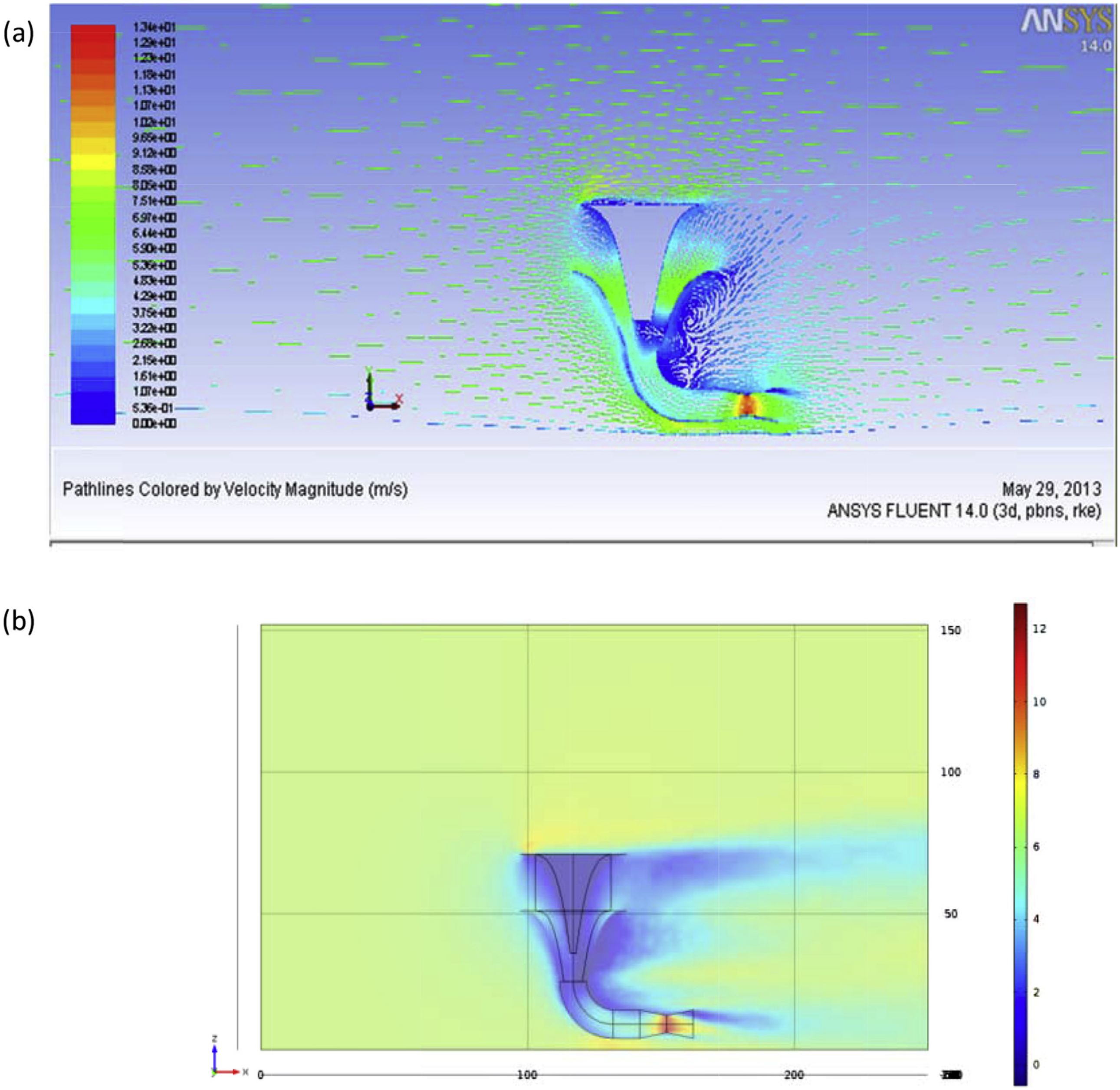

Fig. 4. Velocity profile in cutaway slice on the plane of symmetry: (a) ANSYS model; (b) COMSOL model.

solution convergence tests in the ANSYS and COMSOL computations. In both cases, the three-dimensional Reynolds-Averaged Navier–Stokes (RAN-S) equations were solved numerically with a second-order accuracy upwind schemes and standard or realizable *k*–epsilon turbulence model closures with standard wall functions. For the inlet air source, 5% turbulence intensity was used in either of the two computations while a length scale of turbulence 0.01 m and 1.0 m were used in the COMSOL and ANSYS computations, respectively. No boundary layer elements were used in the COMSOL model. Higher mesh resolution was used near the wall regions in the ANSYS computations. “Extra Fine” mesh was used in the *Venturi* duct sections. A constant input velocity field, representing the free stream wind, was assigned to the entire frontal plane of the flow domain. The magnitude of the velocity was set at 6.7 m/s (15 mph). In the case of COMSOL simulations, all other five wall boundaries were considered slip walls with the exception of the exit plane in which the pressure outlet boundary condition was assigned. In the case of ANSYS simulations, the ground was considered as wall with no-slip conditions. The reference pressure was assumed to be the atmospheric pressure throughout the domain.

3. Comparison of models

The CFD results are based on a steady-state formulation and therefore the model does not include the unsteady motion of the INVELOX system or turbine. Furthermore, these simulations did not involve any rotating turbine. The only meaningful comparison between CFD and experiments (i.e. field data) are the velocity distributions, speed ratios, and mass flow rates in the absence of the turbine.

Fig. 4a and b shows the velocity magnitude distribution simulated in ANSYS and COMSOL platforms, respectively, on the symmetry plane of the tower. The captured air flow is diverted by the intake downwards into the piping system of the tower and after taking a 90° turn reaches the *Venturi* section where it is accelerated as shown in both simulations. These data were integrated over the cross-section of the *Venturi* and at two other locations, one upstream and one downstream at the exit of the flow to provide the average velocity and volumetric and mass flow rates through the system. The velocity distributions shown in Fig. 4 appear to be similar. Both indicate that the maximum velocity takes place within the *Venturi*. ANSYS predictions show some asymmetries within the *Venturi* cross-section which are due to the turning of the flow at the 90° corner where centrifugal forces have different effects along the radius of curvature direction.

The intake captures the free stream flow in rather complex way. As shown in the plot of velocity vectors in Fig. 5, part of the incoming flow impinges on the wall of the front quadrant of the intake formed by the four partitioning baffles and is diverted downwards inside the delivery system. Another part of the incoming free stream is deflected to the sides of the intake and it separates at the tip of the two fins. The flow inside the funnels appears to be non-uniform and there is separation zone in the aft section. Overall, the intake captures a substantial amount of free stream flow despite the flow separation which is also associated with a small portion of flow exiting the system at its aft.

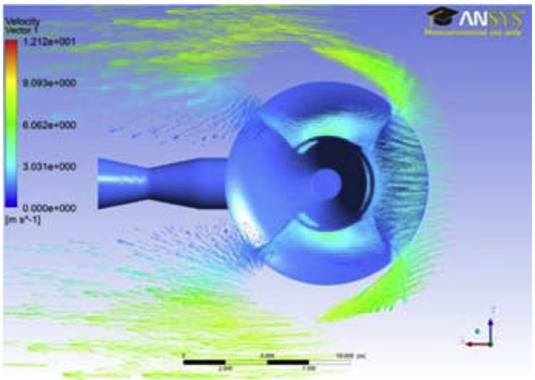

Fig. 5. Top view velocity vectors predicted by ANSYS on a horizontal plane perpendicular to the axis of symmetry of the intake.

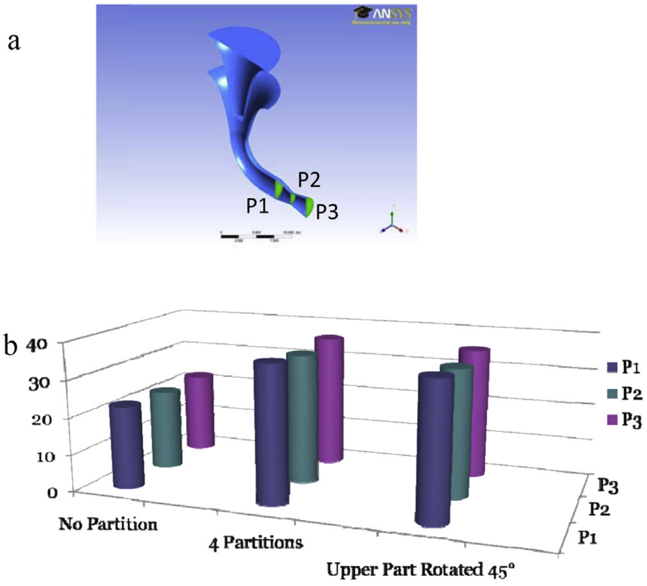

Fig. 6. (a) Locations along the Venturi section where mass flow rate was computed. (b) Comparison of captured mass flow rate (kg/s) by different intake configurations.

The performance output of the present system depends strongly on the captured mass flow rate by the intake. Of interest is the question which of the three different intake configurations simulated in the present work captures the maximum flow rate. The first configuration contains no partitions/baffles; the second one contains four partitions symmetrically positioned at 90°, 180°, 270°, and 360° about the vertical axis of the axisymmetric intake with their baffle orientation parallel or perpendicular to the free steam velocity direction. In the third configuration, the partitions are at 45° to the flow direction. The mass flow rate was computed at three locations along the pipe one upstream of the *Venturi* section one at the *Venturi* section and the third downstream of it. These positions are designated as P_1, P_2, and P_3 in Fig. 6a. The results shown in Fig. 6b indicate that the presence of partitions improves the performance of the intake substantially and that their orientation does not increase the captured mass flow rate.

The average and maximum wind speeds inside the *Venturi* are shown in Tables 1 and 2. In addition, the volumetric and mass flow rates are also calculated inside the *Venturi* as shown in Table 1. The results generated from the two models are in satisfactory agreement. In Table 2, the free stream and *Venturi* wind speeds and speed

Table 1
Comparison of velocities and flow.

Model	Mesh size	*Venturi* velocity [m/s]		Flow [m^3/s], [kg/s]	
		Average	Maximum	Volumetric	Mass
ANSYS	Fine	10.6	12.1	28.2	34.5
COMSOL	Normal	10.6	12.1	29.6	36.3
	Fine	11.7	13.1	30.5	37.4

Table 2
Comparison of velocities and speed ratios (SR).

Model	Mesh size	Free stream [m/s]	*Venturi* velocity [m/s]		Speed ratio (SR)	
			Average	Max	Average	Max
ANSYS	Fine	6.71	10.6	12.1	1.58	1.80
COMSOL	Normal	6.71	10.6	12.1	1.58	1.80
	Fine	6.71	11.7	13.1	1.74	1.95

ratios are compared. It is noted that the free wind speed is constant at 6.71 m/s. The predicted average speeds across the *Venturi* and speed ratios based on the maximum wind speeds inside *Venturi* are in agreement between the ANSYS and COMSOL models.

One parameter, which indicates the ability of the omnidirectional intake to capture flow, is the area in the free upstream where the captured flow is originated. This area is given by the relation $A_0 = \dot{m}/\rho U_0$ where U_0 is the free stream velocity. For the value of $\dot{m} = 36$ kg/s the area is $A_0 = 4.4$ m^2. A similar expression can be obtained for the Venturi cross-sectional area A_v and its velocity U_v, i.e. $A_v = \dot{m}/\rho U_v$. Thus the area ratio is $A_0/A_v{}^\circ{=}^\circ U_v/U_0{}^\circ{=}^\circ S_R$, where S_R is the velocity amplification, i.e. the speed ratio. In the present case, $S_R{}^\circ{>}^\circ 1$ and therefore $A_0/A_v{}^\circ{>}^\circ 1$, which means that there is a substantial reduction of the area where energy is drawn from. If A_0 is referred to as an effective area at the inlet of the intake A_{intake} defined as $A_{\text{intake}} = (D_o - D_i)H/2 = 18$ m^2 the $A_0/A_{\text{intake}} = 0.244$.

Additional computations, not reported here, have shown that S_R can be increased by a factor of 3 by increasing the diameter of the intake while keeping the turbine diameter unchanged.

4. Field demos and measured data

4.1. INVELOX with no turbine

Fig. 7 shows one of the two fielded demos of the INELOX delivery system tested in Chaska, Minnesota in 2012 and 2013. Pressure and velocity were measured at free stream and right before the turbine inside the *Venturi*. Five cup anemometers were installed: one was used to measure free stream wind speed at 8 ft above the top of the tower, and the other four were used to measure the wind speed right at the intake (see Fig. 7). Four hotwire anemometers were used at the turn of the pipe and three were used at entrance, middle, and exit plane of the *Venturi*. This set up provided wind speed data before and after the turbine. At the same location as the wire anemometers, pressure sensors were installed. The diffuser faces north. The INVELOX system was constructed in the Chaska industrial park and is surrounded by buildings. The unit has been tested with four different turbines installed inside the *Venturi* in 2012 and two more were tested in 2013. A load bank is used to dissipate the generated energy. The results presented in this paper are from a three-bladed turbine with power rating of 600 W at 12.5 m/s. In this paper, a small sample of the results is presented here.

Fig. 7. Fielded INVELOX demo (right) and conventional turbine-tower system (left) under evaluation in Chaska, Minnesota.

Table 3
System specifications.

Item		Traditional tower	INVELOX
Model		Sunforce 600	Sunforce 600
Rotor diameter [m]		1.31	1.31
Rated free stream wind speed [m/s]		12.5	6.25
Rated power [W]		600	600
Voltage [V]		24	24
Rated load current [A], maximum		35	35
Generator		3-Phase	3-Phase
Free stream wind speed [m/s]	Cut-in	2.0	1.0
	Survival	70.0	35.0
Number of blades		3	3
Blade material		Fiber glass	Fiber glass
Resistive load bank [ohms]		10	10
Tower height [m]		10	18.3
Over-speed braking [rpm]		1400	1400

Table 3 shows the specification of the two systems. As it was pointed out, the turbine, generator, control panel, load bank, all sensors (current, velocity, speed) are all the same for the turbine on the traditional tower and turbine inside INVELOX.

In order to compare the field data with those generated by the CFD models, we collected wind speed data when the turbine was not placed inside the *Venturi* section of INVELOX.

Fig. 8a shows the measured free stream and *Venturi* wind speeds for 24 data sets with Sunforce turbine inside the *Venturi* section of INVELOX. It is very interesting to observe the high degree of correlation between the measured wind speeds as it expected. The instantaneous speed ratio (SR) and average SR are also displayed. It is noted that SR varies from 1.5 to 2.1 with an average value of about 1.8. The SR values are in satisfactory agreement with those predicted by the CFD models and reported in Table 2.

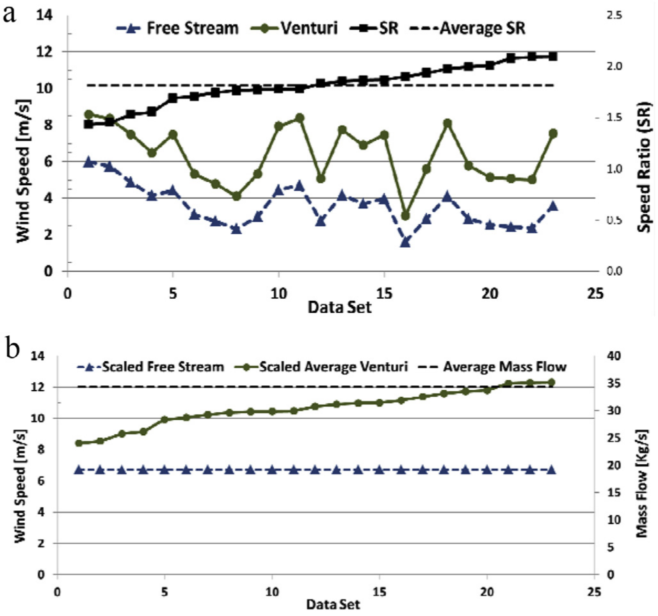

Fig. 8. (a) Raw field data and speed ratios for 24 data sets. (b) Scaled field data based on constant free stream wind speed at 6.71 m/s and mass flow rate for 24 data sets.

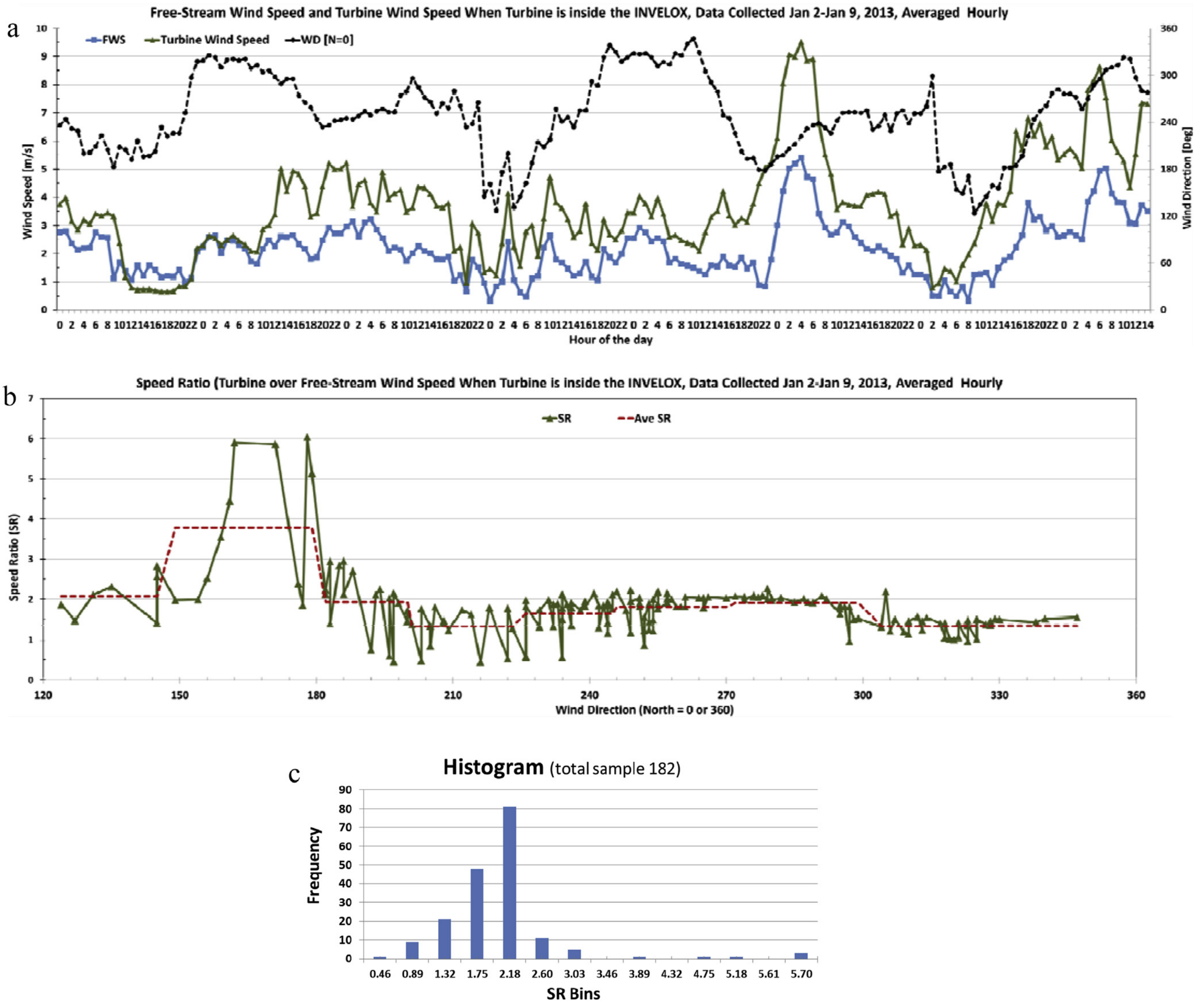

Fig. 9. (a) Free stream and turbine wind speed and wind direction for data measured over 8 days. (b) Speed ratio (turbine over free stream wind speed) versus wind direction for data measured over 8 days. (c) Histogram/frequency of appearance analysis of speed ratio SR data shown in Fig. 9a and b, average value of SR is 1.81 and most probable value is 2.18.

Fig. 8b shows the scaled version of the data presented in Fig. 8a. In order to compare the result with those predicted by the CFD models, the data was scaled based on a constant free stream wind speed of 6.71 m/s. It is noted that the *Venturi* wind speed follows the same trend as the instantaneous SR shown in Fig. 8a. The average mass flow was determined to be about 34.30 kg/s; this value is in satisfactory agreement with those predicted by the CFD models in Table 1.

4.2. INVELOX with turbine

In order to make meaningful comparisons with traditional turbines, additional measurements were carried out by placing the same turbine used in the INVELOX, on top a conventional turbine-tower system as shown in Fig. 7 (left). The same electrical conversion system and same load bank were used as in the case of INVELOX. Thus, the performance of this set up with the turbine placed on the top of a traditional tower in the same location could be directly compared with the INVELOX data.

Fig. 9a and b shows that higher wind speeds were maintained even when a turbine was placed inside the *Venturi* section of INVELOX. In addition, while recorded data shows that the intake is indeed omnidirectional; the system performs well in all wind directions, due to structures and tress around the intake, the wind speed inside the Venturi is dependent on the wind direction. Furthermore, Chaska, Minnesota is generally considered a class 1 or 2 wind area which is verified by free stream wind speeds recorded as shown in the figure. However, wind speeds recorded inside the *Venturi* section of INVELOX show that winds are converted to class 3.

The interpretation of the field data shown here should be always considered in the context of the location of the present facility in reference to the pre-existing structures and terrain surrounding the intake. There is a 25 ft tall building on the west side of the INVELOX tower located about 30 ft away. There is also, a 100 ft tall cell tower and a very large water tower (135 ft tall) located 50 ft and 150 ft away in the north east direction with respect to the INVELOX tower, respectively. Trees of 50–60 ft in the south, east, and north east directions are close enough so that leaves and branches fall inside INVELOX when there is enough wind in the right direction. The omnidirectional intake, the orientation of the four baffles with respect the orientation of the diffuser, and orientation of the diffuser, and the surrounding structures make the performance of

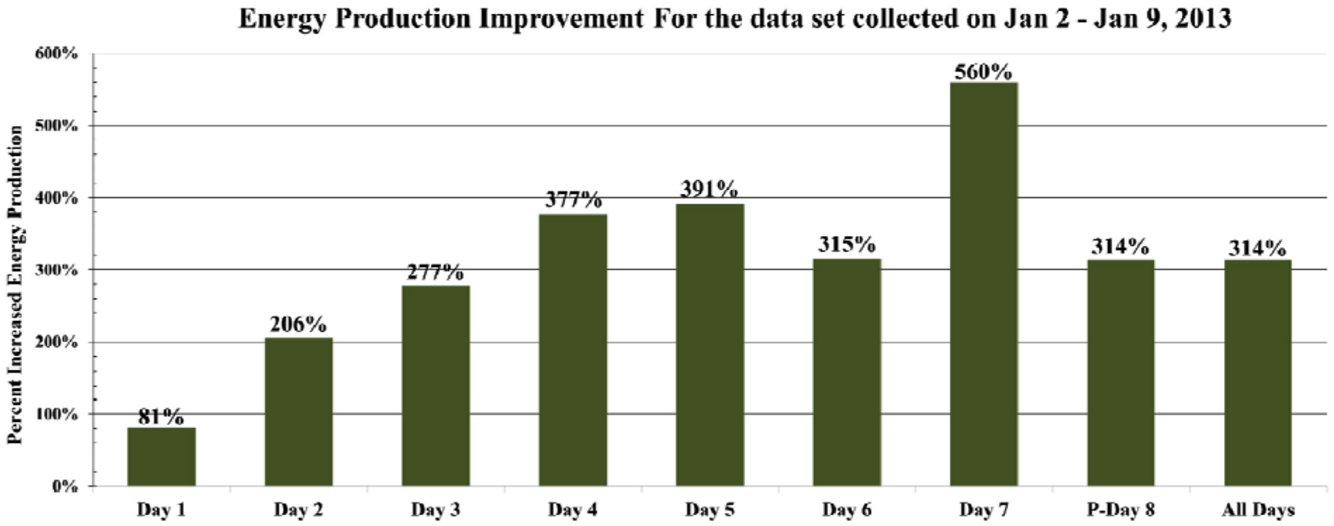

Fig. 10. Daily energy production improvements – the INVELOX with respect to traditional turbine-tower systems.

the present tower dependent strongly on the wind direction as shown in Fig. 9a and b.

Further statistical analysis of the speed ratio data S_R plotted in Fig. 9a and b has been carried out to generate the frequency of appearance/histogram information shown in Fig. 9c. The bulk of observations are in the range of S_R between 1 and 2.6 while there are events with values well above 2.6 as well as events with $S_R < 1$. The mean value of the S_R data is 1.81 while the most probable value is 2.18. Less than 10% of the data, however, fall in the range $S_R > 2.6$ or $S_R < 1$.

Fig. 10 shows the daily energy production improvements of INVELOX with respect to the traditional WTG system. The results show INVELOX generated 80–560% more electrical energy than the traditional WTGs. P-Day 8 means partial data was collected on the eighth day. The total average energy production improvement of INVELOX over 8 days is about 314%.

5. Conclusions

It was shown that INVELOX can be designed to capture and accelerate air using an omnidirectional intake. The system has low sensitivity with respect to wind direction. A comparison between INVELOX and a traditional wind turbine has been attempted under virtually similar conditions. It is always difficult to design a meaningful good comparison between two different systems. Such a comparison is always dependent on the input parameters, i.e. independent variables used to affect the two systems and the selection of the dependent variable or constraint as a criterion to monitor a given function. Ideally one should expect only one independent variable to change at a time while detecting the change in the dependent variable output. In the present work, we selected the diameter of the turbine to be the same and vary the wind speed while monitoring the output power. Such a comparison was based on field measurements which indicated that the INVELOX-turbine system generated significantly more energy than the tower-turbine systems with the same turbine size. INVELOX has a strong potential and is worthy of further development.

Along with all new technologies come strong skeptics with opposite views on their viability. A reason to be skeptical of INVELOX is the fact that in the past-ducted turbines have not made any significant headway in the industry due to questions related to technical implementation and financial viability, even though positive performance was in general demonstrated. One technical issue, for instance, which has been insurmountable to address is the implementation of a mechanism design which will allow for self-alignment of large-scale ducted turbines with the wind direction. In addition, ducted turbines still need to be placed at a certain height which increases the technical complexity as well as the cost. INVELOX eliminates the need for self-alignment with the wind because its intake is omnidirectional and all rotating parts are on the ground which simplifies the operation and maintenance.

It is also reasonable to question whether, once a turbine is placed inside an INVELOX system, the increase in resistance will reduce the output making the promise of superior performance no longer valid. It should be noted, however, that the same is true for traditional open-flow systems. The free stream wind reduces its speed as it approaches the blades due to the induced velocity field by the vortex system shed in the wake of the turbine; this reduction could be up to half or to two-thirds, depending on the environmental and blade profile factors. In the case of ducted turbines like the present one inside INVELOX, mass conservation requires that the area-averaged velocity remains constant upstream and downstream of the turbine along a constant cross-section duct. It appears that the vortex sheets shed by the rotating blades are mostly affecting the wake flow more than the upstream flow. There is a small decrease of the incoming velocity in some parts of the upstream flow as it approaches stagnation particularly directly upstream of the blades, but at the same time other parts of the flow are accelerating to satisfy mass conservation.

The last issue to be discussed is the scalability problem which is pertinent to all engineering devices. Our CFD work has indicated that INVELOX as delivery system only, i.e. excluding the wind turbine increases the mass flow rate and the air velocity in the Venturi section in an upward scalable way. The turbine-generator subsystem has been proven to be scalable and therefore the whole INVELOX system is scalable.

Acknowledgments

The support of this work was provided by SheerWind and CCNY.

References

[1] Sørensen JN. Aerodynamic aspects of wind Energy conversion. Annu Rev Fluid Mech 2011;43:427–48. http://dx.doi.org/10.1146/annurev-fluid-122109-160801.

[2] Grant A, Kelly, N. The development of a ducted wind turbine simulation model. In: Eighth international IBPSA conference, Eindhoven, Netherlands; 2003.

[3] First installation of a wind tamer wind turbine in Europe; 2011. Available from: http://aristapower.com/2011/08/first-installation-of-a-windtamer-wind-turbine-in-europe/.

[4] Al-Bahadly IH, Petersen AFT. A ducted horizontal wind turbine for efficient generation. InTechOpen; 2011, ISBN 978-953-307-221-0. Available from: www.intechopen.com.

[5] Allaei D, Gonzalez JE, Sadegh AS, Andreopoulos Y, Tarnowski D, INVELOX – bringing noise & vibration issues to the ground level. In: Second international conference on wind turbine noise & vibration, Hamburg, Germany; November 2013.

[6] Allaei D, Schwartz L. INVELOX – making wind a reliable source of electrical energy for China. In: 2013 China wind power, Beijing, China; October 2013.

[7] Allaei D, Andreopoulos Y. INVELOX: a new concept in wind energy harvesting. In: ASME 2013 7th international conference on energy sustainability & 11th fuel cell science, engineering and technology conference ES-fuel cell, Minneapolis, MN, USA; July 14–19, 2013.

[8] Allaei D, Schwartz L. INVELOX – a promising new renewable energy solution for China. In: China power & clean energy expo China, Beijing, China; July 2013.

[9] Allaei D, Gonzalez JE, Sadegh AS, Andreopoulos Y, Tarnowski D. INVELOX – affordable wind power for anyone anywhere. WindTech International; March 2013.

[10] Allaei D. Game changing wind power technologies. Invited Speaker. Phoenix, AZ: Clean Tech Connect; March 2013.

[11] Allaei D. Using CFD to predict the performance of innovative wind power generators. In: Proceedings of the 2012 COMCOL conference in Boston; 2012.

[12] Allaei D. Review of alternative wind power generation technologies. In: Second new energy wind energy forum, Guangzhou, China; October 2012.

[13] Allaei D. Wind power generation technologies. In: 2012 Energy issues summit, MN; August 2012.

[14] Allaei D. Affordable clean power solutions for buildings anywhere. USGBC Minnesota's first annual IMPACT conference, Minneapolis, MN; September 2012.

[15] Allaei D. Turbine-intake tower for wind energy conversion systems. US patent no. 7,811,048; 2010.

[16] Allaei D. Power generating skin structure and power generation system thereof. US patent no. 7,812,472; 2010.

[17] Shen X, Zhu X, Du Z. Wind turbine aerodynamics and loads control in wind shear flow. Energy 2011;36:1424–34.

[18] Lin WM, Hong CM. Intelligent approach to maximum power point tracking control strategy for variable-speed wind turbine generation system. Energy 2010;35:2440–7.

[19] Mabel MC, Raj RE, Fernandez E. Adequacy evaluation of wind power generation systems. Energy 2010;35:5217–22.

[20] Lawn CJ. Optimization of the power output from ducted turbines. In: Proceedings of Institution of Mechanical Engineers, vol. 217 [J Power Energy].

[21] Politis GK, Koras AD. A performance prediction method for ducted medium loaded horizontal axis wind turbines. Wind Eng 1995;19(5):273–88.

[22] Georgalas CG, Koras AD, Raptis SN. Parameterization of the power enhancement calculated for ducted rotors with large tip clearance. Wind Eng 1991;15(3):128–36.

[23] Frankovic B, Vrsalovic I. New high portable wind turbines. Renew Energy; 2001:491–9.