27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-1125
DUCTED WIND TURBINES: TECHNICAL FEASIBILITY STUDY IN WIND ENERGY GENERATION IN RIO GRANDE DO NORTE

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Abstract. *Traditional wind energy generation using large wind turbines has limitations. Due to this, this study focuses on researching a Ducted Wind Turbine (DWT) system, known as INVELOX, designed to enhance the efficiency of wind energy generation and mitigate its impacts. The aim of this study is to evaluate the technical and economic feasibility of wind energy generation by ducted wind turbines in the state of Rio Grande do Norte, Brazil. For this, the study compares the INVELOX system with conventional wind towers through simulations in the HOMER software, considering a microgeneration energy scenario. The results show that INVELOX generated, on average, 280% more energy compared to conventional wind towers under the same conditions. However, due to the high initial cost of INVELOX, the savings generated by the increased energy production do not make its application economically viable at the residential level in Rio Grande do Norte. Yet, looking at the rural energy context, INVELOX can be a promising solution. It offers the opportunity to boost energy self-sufficiency and reduce environmental impacts, potentially being a beneficial solution for communities with difficult or no access to the electrical grid that seek a reliable and sustainable energy source.*

Keywords: *Wind energy, ducted turbines, technical feasibility, INVELOX.*

1. INTRODUCTION

Currently, although energy production through wind turbines is well-established and brings positive impacts, it is important to also consider the negative impacts associated with this form of energy generation. Conventional Horizontal Axis Wind Turbines (CHAWT) consist of long and heavy components, leading to challenges in terms of manufacturing, logistics, installation, maintenance, and cost (Allaei et al., 2015). Other negative factors include harm to wildlife, excessive noise, visual nuisances, and interference with radar or television reception due to the magnetic forces generated by these structures (Saidur et al., 2011).

Thus, there is a recognized need to explore alternative models of wind energy generation, which is why this work focuses its research on a Ducted Wind Turbine (DWT) system model, the INVELOX. According to Al-bahadly and Petersen (2011), the ducted turbine has the ability to increase airflow velocity by directing it through a converging inlet, resulting in an increase in the power that can be extracted from this airflow, thereby maximizing energy production.

The INVELOX is a system that captures wind using a funnel and directs it through a conical passage to a wind generator located at the narrowing of the channel. Due to the Venturi effect, the captured wind is accelerated, thereby increasing the efficiency of wind energy generation compared to traditional wind turbine designs. Additionally, INVELOX captures wind flow through an omnidirectional inlet, meaning there is no need for yaw control to orient the wind turbine (Narendrabhai and Desmukh, 2018).

This new technology offers solutions to the major issues associated with the current wind industry, reducing environmental impacts and boasting greater reliability, as it lessens the unpredictability of wind energy generation caused by fluctuations in wind speed (Allaei and Andreopoulos, 2014). Moreover, due to the turbine-generator system being installed at ground level, significant cost savings are realized both in terms of installation and maintenance over its lifespan (Narendrabhai and Desmukh, 2018).

A prototype of the INVELOX system, constructed in the Chaska industrial park, was used for testing between the years 2012 and 2013. According to Allaei and Andreopoulos (2014), field measurements revealed that INVELOX can significantly enhance daily energy production. The results showed that the INVELOX produced 80% to 560% more electrical energy than traditional methods during the studied period. Based on an experimental study conducted by Allaei et al. (2015), it was found that the power generated by INVELOX can be amplified as more turbines are added, producing 52% more energy in a system with two turbines and 72% with three turbines.

Numerical flow simulations through the INVELOX Wind Turbine System conducted by Narendrabhai and Desmukh (2018) demonstrated that the system can produce about 6 to 8 times more energy than a traditional wind turbine of the same turbine size. This performance increase remained consistent across a wide range of wind speeds, varying from 1m/s to 14 m/s. Upon detailed analysis, it was found that the wind speed is intensified in virtually all directions, except in a narrow band between angles of 135° and 225°. Specifically, the most substantial increments in wind speed were achieved for angles of approximately 45° and 315° (Narendrabhai and Desmukh, 2018).

In addition to wind direction and speed, other parameters can influence the efficiency of INVELOX. Anbarsooz et al. (2017), in his numerical analyses, investigated how changes in geometry impact the performance of this structure. He examined the effects of the inlet area, the diameter of the Venturi section, and the height of the funnel on the increase in wind speed in the Venturi section. As a result, the relationship between the dimensions that would provide maximum efficiency for the DWT was identified, resulting in speed increments of up to 1.9 for winds at 9 m/s.

Moreover, a comparative study between the ducted INVELOX wind turbine and the conventional wind turbine was conducted in Iran, aiming to evaluate its viability. Meratizaman and Nateqi (2021) demonstrated that, under similar operating conditions, INVELOX has the potential to generate between 18% to 235% more energy compared to conventional turbines, considering the climatic conditions of Iran. On the other hand, the initial implementation cost of this system in that region is approximately 550% higher than that of conventional turbines.

According to Alkhalidi (2022), the wind acceleration factor in INVELOX decreases in stronger winds due to the losses in air flow direction. This directional shift causes a significant proportion of the captured wind to escape from the structure on the opposite side of the air inlet. As an approach to mitigate this challenge, Alkhalidi proposed a new design that maintained a consistent logarithmic relationship between wind speed and the acceleration factor when simulated. Thus, it prevented the air from escaping, even under stronger wind conditions, making INVELOX a more promising option.

Considering the context of micro-generation of energy, the INVELOX ducted turbine system is significant. This is justified by the ability of these turbines to substantially reduce the noise and undesirable visual effects generated by rotating blades, enabling their installation in urban and rural areas close to residential centers. Furthermore, their ability to operate efficiently in locations with lower wind speeds broadens their application possibilities.

Given this, the purpose of this study is to conduct an assessment of the technical and economic feasibility of wind energy generation using ducted wind turbines in the state of Rio Grande do Norte, Brazil. The focus of this work is to make a comparison between the system based on conventional Wind Generating Towers and the INVELOX system, considering the context of micro-generation of energy in the current Brazilian scenario.

2. LITERATURE REVIEW

2.1 Wind Energy

Based on Burton et al. (2001), the stimulus for investment in energy production through wind turbines increased in the mid-twentieth century, due to the increase in oil prices and concerns about limited fossil fuel resources. But right now, the biggest driver is wind energy's potential to help limit climate change. With the growing concern about global warming and the need to reduce greenhouse gas emissions, wind energy stands out as a renewable source.

Wind energy is defined as kinetic energy contained in the mass of air in motion, that is, in the wind. To take advantage of this energy, wind turbines are used, which convert the translational kinetic energy of the wind into rotational kinetic energy, which is then used to generate electricity (ANEEL, 2008).

According to Hau (2013), the power that can be extracted from an air mass moving at a velocity can be expressed mathematically as:

$$P = \frac{1}{2}\rho v^3 A \tag{1}$$

Where ρ is the density of air, v is the wind speed and A is the cross-sectional area, which the wind is crossing.

To determine the amount of electrical energy that a wind turbine can generate in a given period of time, it is necessary to know its efficiency, which, according to Fadigas (2011), can be measured through the power coefficient *Cp* that expresses the relationship between the mechanical power of the turbine converter and the power of the wind entering the turbine (undisturbed wind). This coefficient depends on the ratio between the wind input speed and the speed after energy extraction, this relationship can be seen in Eq. (2).

$$C_p = \frac{\left(1 + \frac{v_2}{v_1}\right)\left[1 - \left(\frac{v_2}{v_1}\right)^2\right]}{2} \tag{2}$$

Where v_1 is the undisturbed wind speed and v_2 is the wind speed after mechanical energy extraction.

From Eq. (1) and (2), the power of the wind turbine is obtained, Eq. (3), which refers to the mechanical power extracted from the air flow by the wind turbine rotor (Fadigas, 2011). It is observed that the power extracted is proportional to the cube of wind speed (El-Sharkaw, 2016). Since the wind resource varies both geographically and temporally, the study of wind speed is fundamental to all aspects of wind energy implementation, from identifying suitable sites to assessing the economic viability of wind turbine projects, along with understanding their impact on electricity distribution networks and consumers (Burton et al., 2001).

$$P = \frac{1}{2}\rho A v^3 C_p \quad (3)$$

Where ρ is the air density, A is the area swept by the wind turbine blades, v is the wind speed and Cp is the power coefficient.

2.2 Ducted Wind Turbines (DWT)

The history of Ducted Wind Turbines (DWT) is relatively recent and still in development, the first reference we have about canalization of wind devices is from 1977, by George Webster. Based on Webster's (1977) description, his device uses airflow through a curved duct to rotate a vertical axis and generate wind energy. on this axis there is a set of blades that were designed to capture the kinetic energy of the wind and convert it into mechanical energy. According to Krüger (2016), this mechanism can be classified as a vertical Ducted Wind Turbine.

Unlike conventional wind turbines, the vertical DWT was specifically developed with the aim of integrating wind energy into the built environment, such as buildings and urban structures, because they bring advantages in terms of safety, power and size. They are safer because wrapping the blades in the duct minimizes the occurrence of unwanted blades coming off. As for power, with the duct there is a greater capture of energy compared to conventional turbines, due to greater differences in pressure and speeds in the rotor. And in terms of size, they were designed to be compact and closed (Grant and Beng, 2004).

In 2011, Al-Bahadly and Petersen explored horizontal Ducted Wind Turbines, which consisted of a wind turbine arranged inside a converging duct. Following the Venturi principle, as air flows through a converging duct, its velocity increases. This increases the power that can be extracted from the air, expanding the possibilities of energy use (Al-Bahadly and Peterson, 2011).

The Venturi principle exemplifies the application of conservation of mass during the flow of incompressible gas in a converging tube (Venturi tube). The mass flow into a control volume is equal to the flow out, so for an incompressible fluid, if the cross-sectional area decreases, its velocity increases. In the DWT developed by Al-Bahad and Peterson, the wind turbine was located in the narrowing area of the Venturi tube, which contributed to the increase in turbine efficiency (Al-Bahadly and Peterson, 2011; Çengel and Cimbala, 2012).

The research conducted by Al-Bahadly and Petersen was essential for the advancement and development of DWT devices. Currently, this technology is capable of capturing the wind with a funnel and directing it through a converging duct, where the air flow is accelerated and the generator is activated. The main parts of this system are shown in Figure 1 and they are: 1 - input for capturing the wind; 2 - accelerated wind transport; 3 - Venturi tube; 4 - wind turbine; and 5 - diffuser to help direct the airflow after passing through the wind turbine (Allaei and Andreopoulos, 2014; Allaei et al., 2015).

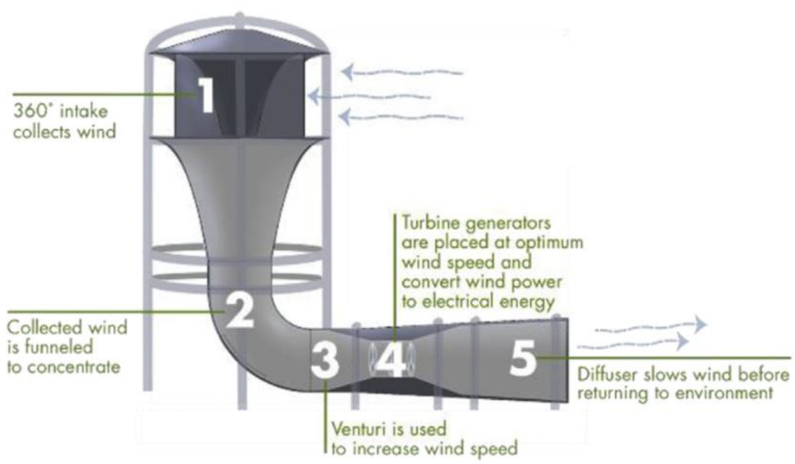

Figure 1. Current DWT System. Source: Adapted from Allaei et al., 2015.

According to Allaei et al. (2015), the power extracted by DWT, Eq. (4), is calculated through control volume analysis, using the principles of mass conservation, axial and angular momentum, and fluid energy conservation. From this, it was obtained that the power of a DWT is equal to the power of a traditional wind turbine (Eq. 3) multiplied by a wind acceleration factor.

$$P = \eta A S_r (1 - C_{pb} - K_b) \rho v^3 \quad (4)$$

Where P is the power, η is the efficiency of the turbine, A is the cross-sectional area, S_r is speed ratio and is obtained from the division between the accelerated wind speed and the input speed, C_{pb} is the pressure coefficient, K_b is the ratio between the kinetic energy of the accelerated wind and that of the wind entering the system, P is the air density and v is the speed of the wind entering the DWT.

The DWT system is capable of extracting a greater amount of energy compared to the conventional system due to the wind acceleration factor $S_r(1 - C_{pb} - K_b)$ which is always greater than 1 (Allaei et al., 2015).

2.3 Power microgeneration system

Microgeneration of wind power in Brazil is regulated by ANEEL Normative Resolution No. 1059/2023. This standard establishes the conditions for the connection of distributed microgeneration and minigeneration systems to the low voltage electrical grid. According to the resolution, the classification of microgeneration is an electric power generating plant with installed power less than or equal to 75 kW, as for minigeneration, it is a power generating plant with an installed power greater than 75 kW and less than or equal to 5 MW.

In the case of wind energy, microgeneration occurs through the installation of small wind turbines, such as low-power wind turbines, in different locations, such as homes, commercial establishments, rural properties, among others. It presents the advantages of providing users with the possibility of using renewable energy from the wind, reducing dependence on the conventional electrical grid and potentially obtaining financial benefits.

This own generation system with a wind turbine connected to the distribution grid is as follows: firstly, the mechanical energy captured by the wind turbine from wind energy is converted into electrical energy by means of a generator coupled to the turbine rotor; then this generated electrical energy passes through an inverter, which has the function of converting the direct current produced by the generator into alternating current, suitable for use in conventional electrical systems. And to monitor the flow of energy, a meter is used to record both the energy consumed by the residence and the excess energy generated by the wind turbine and injected into the electrical grid (Araújo and Bezerra, 2015). If the amount of energy generated by the wind turbine is greater than the amount of energy consumed by the place where it is installed, a credit is generated for the owner or user, defined by ANEEL Resolution No. 1059/2023.

3. METHODS

With the objective of comparing the microgeneration of energy between a traditional wind turbine and a channeled wind turbine in the state of Rio Grande do Norte (BR), the HOMER software was used as the main tool, since it is widely used to model simulations and perform analyzes of renewable energy systems. Its simulation process is summarized in the calculation of the energy balance of all hours of a year, comparing the electrical demand with the energy that the system under analysis can offer in each hour (Silva and Beluco, 2012). Thus, HOMER performs these calculations for each model configured by the user.

After simulating the configured model, the software verifies the viability of the system through the index called Net Present Cost (NPC). This index is calculated from cost and revenue data that occur throughout the life of the system as annualized cost and discount rates, and also considers the useful life of the wind turbine. With this, HOMER performs a filter and shows the simulations that have the greatest potential (Silva and Beluco, 2012).

To conduct the simulation and address the micro-generation perspective in the state of Rio Grande do Norte comprehensively, it was decided to evaluate the performance of wind turbines in contexts of different power ratings, costs, and dimensions. For this purpose, two micro wind turbines were selected: the Notus 138, a suitable option for homes in urban settings due to its compact dimensions; and the SkyStream 3.7, a small-scale wind turbine model designed for low-power applications in rural environments, both residential and commercial.

The simulation was conducted considering two distinct scenarios: the first involves energy generation using a conventional wind turbine, while the second scenario addresses the use of the wind turbine situated within the ducted INVELOX wind turbine. Each of these scenarios was analyzed separately for both wind turbines selected in this study.

In scenario 1, for the SkyStream 3.7, the technical specifications, shown in Table 1, and the power curve, Figure 2, were obtained from the Windtest GmbH (2009) test report. The installation cost was $22,605.11, and the maintenance cost was $70.64 per year. These figures are based on costs obtained for the installation of this wind turbine in Brazil from the study by Krüger (2016). To obtain a more precise cost for 2023, the Broad Consumer Price Index (IPCA) was used to account for inflation and update the value. For the Notus 138, its technical sheet, shown in Table 1, and its power curve in Figure 3, were obtained through supplier Enersud. The total wind turbine cost calculation was based on the price provided by the manufacturer, added to the inverter costs and the expense associated with installation at a height of 10 meters, which included the tower foundation, labor, and acquisition of materials, totaling about $2483.56.

Table 1. Technical specifications of the wind turbines under study.

Properties	**SkyStream 3.7**	**Notus 138**
Rated Power	2,400 W	420W
Rotor diameter	4 m	1.38 m
Cut-in	3.5 m/s	2.2 m/s
Survival wind speed	63 m/s	38.05 m/s
Useful life	20 years	20 years

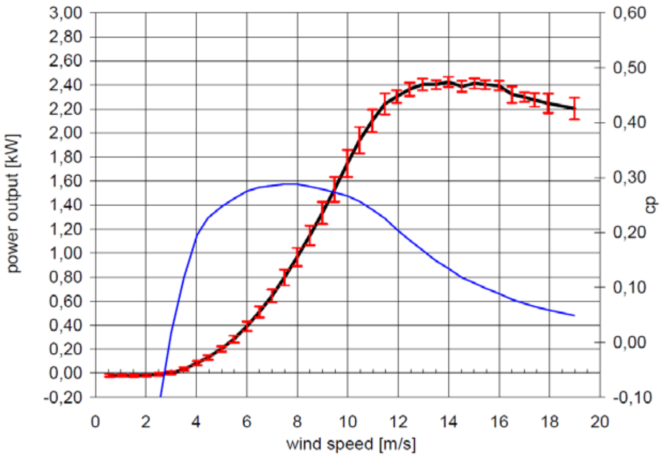

Figure 2. SkyStream 3.7 wind turbine power curve from Windtest GmbH (2009).

In scenario 2, the cost associated with using INVELOX in conjunction with the SkyStream 3.7 was $24,606.23, and maintenance costs totaled $70.64 per year. These figures were derived from the study conducted by Krüger (2016), which considers that the cost of the DWT system encompasses not only the device itself but also the foundations that require on-site construction, as well as associated installation expenses. Regarding the use of INVELOX with the Notus 138, the cost encompassed the price of the wind turbine and the inverter, and also included an estimate of on-site construction costs based on a market analysis and the study of the cost of a DWT in Brazil, estimated by Krüger (2016). The total cost for this configuration was $5,265.14. It's important to note that all costs were initially calculated in Brazilian reais and subsequently converted to dollars and the exchange rate used was R$4.76.

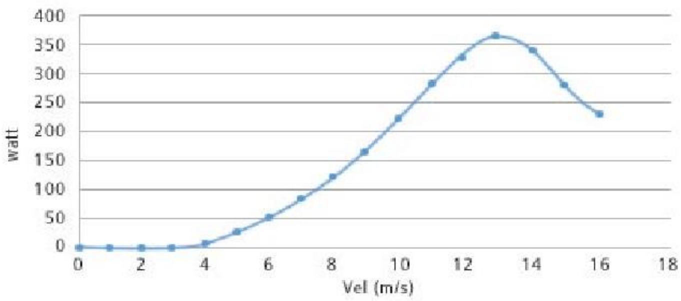

Figure 3. Notus 138 wind turbine power curve from Enersud supplier

To conduct the simulation in Scenario 2, it was necessary to establish an appropriate acceleration factor for the wind conditions in Rio Grande do Norte to ensure accurate energy generation estimates. For this, the study by Anbarsooz et al (2019) was used as a basis, which conducted a numerical simulation of an INVELOX considering the turbulence in the air flow during wind flow through the ducts. Four mathematical turbulence models were simulated, and the results of the wind acceleration factor as a function of the captured wind speed are presented in Figure 4.

The input data in HOMER to carry out the simulations were installation cost, maintenance cost, system lifetime, power curve, wind speed per hour for one year, grid power price, grid sellback price, electric load of the hypothetical residence simulated and the discount rate used in the calculation of the NPC.

Wind speed data for Rio Grande do Norte in the year 2022 were collected on the website of the National Institute of Meteorology of the Ministry of Agriculture and Livestock. The price of energy from the network was taken from the table of electricity tariffs made available by Energy Company of Rio Grande do Norte (COSERN), and taxes (PIS, COFINS AND ICMS) were applied, resulting in the value of 0.19 ($/kWh). From a field survey, it was estimated that the selling price of the surplus energy produced is around 0.16 ($/kWh). To determine the electrical load, the average residential energy consumption in the Rio Grande do Norte was used as a basis, which is approximately 143 (kWh/month) according to the 2023 statistical yearbook of electrical energy. Finally, the discount rate translated by SELIC is 13.75%.

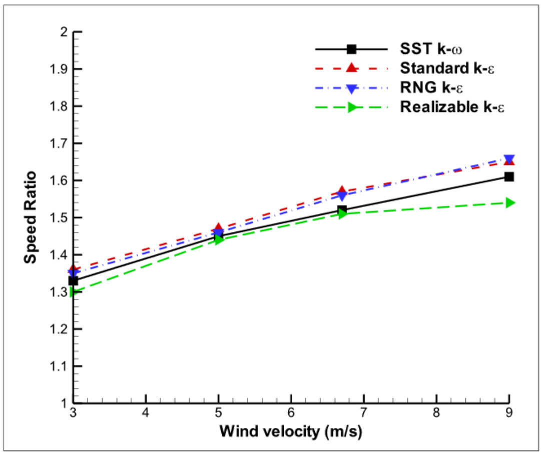

Figure 4. Numerical results for the speed ratio from Anbarsooz and Rashidi (2019).

4. RESULTS AND DISCUSSION

After entering the data regarding the average wind speed (m/s) for all hours of 2022 in the HOMER software, the program generated graphs representing the monthly wind speed profile, which can be seen in Figure 5, together with a table containing the monthly average speeds, from which it was possible to calculate the annual average speed, which corresponds to 3.78 m/s. These velocity data refer to those used in the first simulated scenario, in the second scenario, The wind speed data was multiplied by the acceleration factor, which, as shown in Figure 4, for a speed of 3.78 m/s, the speed ratio would be on average 1.35. Thus, the wind speed would increase by 35%, resulting in an annual average speed of 5.103 m/s.

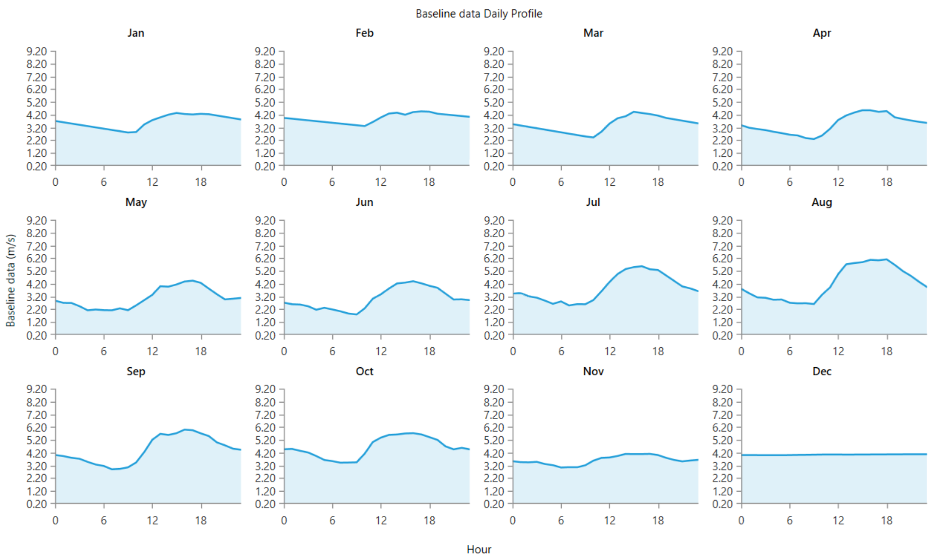

Figure 5. Wind speed profile in Rio Grande do Norte for a height of 10 m, Brazil, in 2022.

At the end of the simulations for both microgeneration systems, the results obtained included the NPC values, the nominal production capacity of the system per year (kWh/year), the amount of energy required from the electrical grid during the year (kWh), the energy credits generated and the levelized cost of energy (COE), which is the average cost per kWh of usable electrical energy produced by the system. In addition, the HOMER software calculated these data for a third scenario where there is no microgeneration system, only the residence connected to the electricity grid. With this, Table 2 was generated, for the comparative analysis.

Table 2. Results of simulations in HOMER software.

Electricity sources	**Initial Cost ($)**	**NPC ($)**	**COE ($/kWh)**	**Production (kWh/yr)**	**Energy purchased (kWh)**	**Energy sold (kWh)**
GRID	$0.00	$1,734	$0.19	-	1,741	-
SkyStream 3.7	$22,605.11	$24,199	$1.71	1,004	1,089	302
DWT with SkyStream 3.7	$24,606.23	$24,047	$1.07	2,920	463	1,496
Notus 138	$2,483.56	$4,633	$0.38	130	1,618	7
DWT with Notus 138	$5,265.14	$7,130	$0.58	356	1,405	20

From Table 2, it is evident that the ducted turbine system INVELOX exhibited a significantly higher nominal power than the conventional system for both wind turbines studied, given the same climatic conditions. The DWT paired with SkyStream 3.7 generated 290% more energy, and the DWT with Notus 138 produced 274% more than their respective wind turbines mounted on wind towers at a height of 10 meters. Therefore, on average, INVELOX generated 280% more energy than the wind tower.

However, for the low-powered Notus 138 wind turbine, the surge in energy production provided by the DWT impacted the total annual consumption modestly, contributing to only 20% of the residence's total energy. In stark contrast, the SkyStream wind turbine paired with the DWT supplied 73.4% of the total energy consumed, compared to a mere 37.44% without the INVELOX.

Considering the total energy output, accounting for the energy from both the wind turbine and the power grid, it is evident that systems with a ducted wind turbine generated a substantial energy surplus, which could be credited or sold. This cumulative energy generation is depicted in Figure 6. In the INVELOX paired with SkyStream scenario, the generated energy accounts for 86% of the total, compared to 48% without the DWT. This resulted in a 495% increase in surplus energy. Notably, with this surplus magnitude, the DWT with SkyStream produced a staggering 167% more energy than what the residence consumed annually. In the case of Notus 138, the contribution from INVELOX was 20.21%, whereas without the DWT it would only account for 7.43% and the surplus generated is 285.7% greater.

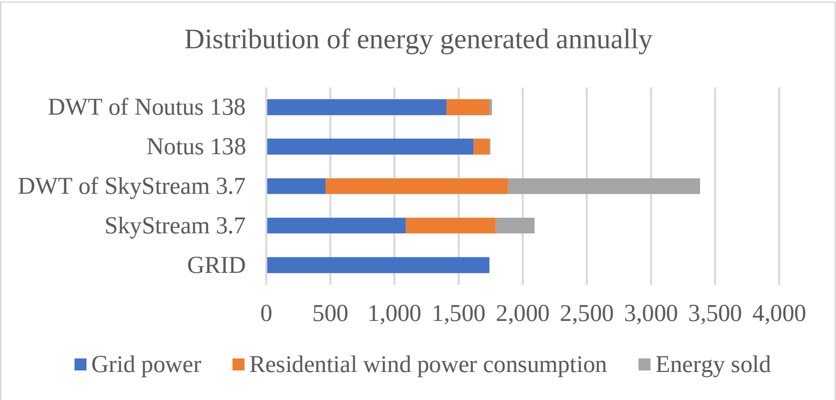

Figure 6. Total electricity generated annually.

Regarding the Net Present Cost (NPC), which represents the present value of all project costs and benefits over its useful life, the smaller it is, the more economically viable the generation system becomes. The union of the DWT system with SkyStream 3.7 culminated in a lower NPC compared to the standalone SkyStream 3.7. This integration of INVELOX curtailed the overall costs associated with electricity generation, making this amalgamation a more economically sound investment. This deduction is further illuminated by the COE (Cost of Energy) value, marking a 37.42% reduction with INVELOX.

In the context of Notus 138, it's significant to note that incorporating the ducted turbine escalated the initial cost, compared to implementing just the wind turbine. This surge in initial costs translated into a 153.9% increase in the project's NPC. Further, a 152% increment in the COE of the DWT system with Notus 138 was observed when analyzing the cost per kilowatt-hour. Hence, while the DWT system with Notus 138 boasts a superior electricity generation capacity, this spike wasn't enough to justify the increased kilowatt-hour cost.

Evaluating both NPC and COE results across all scenarios, it's evident that the traditional electric grid remains the economically superior choice. Yet, examining the INVELOX System's technical feasibility, the DWT configuration paired with SkyStream 3.7 showcased impressive energy potential. Therefore, the choice between these two hinges on striking a balance between economic efficiency and energy generation capability, considering the objectives and available resources.

Another pivotal economic factor encompasses the operational costs of each system, which includes maintenance, power grid consumption, and the potential sale of surplus energy. These components pave the way to compute the annual operating costs, as shown in Table 3. Using these values, the Net Operating Saving can be derived, reflecting the net financial savings from a particular project or investment.

This analytical approach illuminated the financial return of each system. It was discerned that the INVELOX system, when paired with the SkyStream 3.7 wind turbine, yielded a net savings 405% higher than a wind tower equipped with an identical turbine. Similarly, the INVELOX system with Notus 138 documented a 279% higher savings compared to using only the wind turbine. Yet, comparing the savings over 20 years, it becomes clear that the savings falls short of the initial investment, as seen in Table 2. Even in the most promising scenario, where DWT paired with SkyStream 3.7 demonstrated superior savings, the savings only accounted for a third of the entire investment, necessitating more than the system's lifespan to offset the initial amount.

Table 3. Cost and savings table by system.

Electricity sources	**Operating cost ($/yr)**	**Net operating savings ($/yr)**	**Net operating savings ($/20yr)**
GRID	$330.80	$0.00	$0.00
SkyStream 3.7	$229.19	$101.61	$2,032.2
DWT of SkyStream 3.7	- $80.79	$411.59	$8,231.8
Notus 138	$306.80	$24.00	$480.00
DWT of Notus 138	$263.75	$67,05	$1,341.00

Analyzing the total cost outcomes, the conventional electrical grid's cost for average residential consumption in Rio Grande do Norte is markedly lower over a span of 20 years, as depicted in Figure 7. However, broadening the analysis to incorporate the vast realm of microgeneration, especially in rural terrains, reveals a different narrative. According to the 2023 Statistical Yearbook of Electric Energy, rural areas report an average annual consumption of 7,800 kWh. Thus, projecting this over 20 years, the grid's cost would mount to $29,640. Therefore, even factoring in the potential variations in wind speed and costs for these rural terrains in contrast to urban data, the potential viability remains intact, however, this statement requires a more in-depth and specific analysis for the region in question.

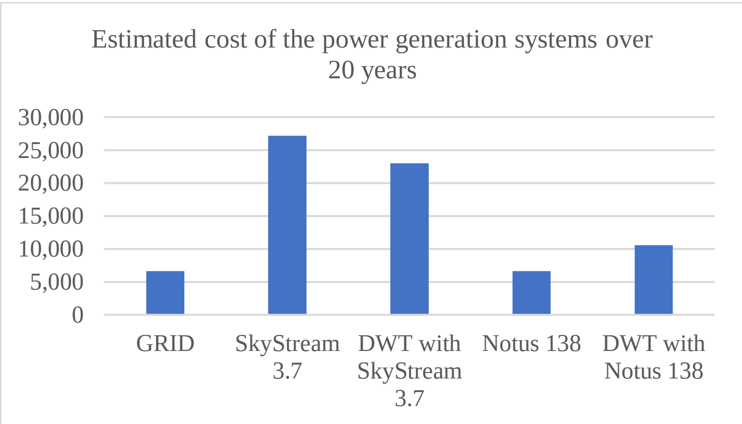

Figure 7. Estimated cost of the power generation systems over 20 years.

5. CONCLUSION

This article proposes to evaluate the technical and economic viability of implementing Ducted Wind Turbines in the state of Rio Grande do Norte, Brazil. For this, the wind conditions in the region, the installation and maintenance costs, the energy efficiency of these devices were analyzed, and these data were compared to those of the conventional method of Wind Generating Towers. This approach allowed a more precise understanding of the performance of each technology and its specific characteristics.

The analysis of the results highlighted that a wind turbine, when combined with the INVELOX system, possesses a superior energy potential compared to the same turbine operating under identical conditions. Yet, the high initial cost of

INVELOX means the additional energy produced doesn't offset the expenditure, rendering its application economically impractical for residential use in Rio Grande do Norte. It was also noted that the system's viability is closely tied to the wind turbine's power. As the power of the turbine increases, so do its dimensions, which makes it unsuitable for urban settings.

Broadening the scope to encompass the wider context of microgeneration, INVELOX shows promise in regions with greater energy demands and abundant space, typical of rural areas. Implementing INVELOX can be more economically beneficial than extending the electric grid to distant regions, a venture that often incurs high costs. Additionally, DWTs address some environmental challenges of traditional wind energy. They curtail potential wildlife hazards, reducing collisions with birds and bats. From a community perspective, DWTs create a less noisy environment, offsetting the disturbances from conventional turbines and enhancing the quality of life for nearby residents.

In essence, while DWTs like the INVELOX system might not be the go-to solution for urban areas connected to the traditional grid, especially considering Rio Grande do Norte's unique wind patterns and financial considerations, they could be ideal for remote regions. Particularly in areas without grid access, INVELOX could promote energy self-sufficiency and play a pivotal role in advancing energy sustainability.

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