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Research Article

Assessment of locally manufactured small wind turbines as an appropriate technology for the electrification of the Caribbean Coast of Nicaragua

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Abstract: This article presents an assessment of the challenges facing the use of small locally manufactured wind turbines as a rural electrification solution for the Caribbean Coast of Nicaragua. Strongly based on the authors work experience at the non-profit, non-governmental organization blueEnergy, this assessment makes an objective analysis of the technical, social, economic and organizational challenges faced by blueEnergy when using small wind turbines for rural electrification. The article provides detail on the challenges faced and puts forward methodologies and technologies to overcome or to detect and avoid these. Based on the challenges faced, a set of key factors that are essential for the success of small wind turbines in other contexts is proposed, together with two methodologies for a preliminary feasibility assessment.

Keywords: small wind power; rural electrification; multidisciplinary analysis; implementation challenges

1. Introduction

1.1. Small wind turbines for rural electrification

Energy enables people to light households, irrigate fields, refrigerate vaccines and opens the possibility to more [1]. Decentralized energy technologies have been put forward as the solution for providing access to modern energy services in remote areas where grid connection is impractical [2,3]. Small-scale renewable energy solutions such as wind, solar and hydro can offer the opportunity to generate electricity from sustainable resources to many of the 1.3 billion people in the world currently without access to electricity, either as stand-alone household systems or as part of a mini-grid [4,5].

The successful dissemination of small wind turbines (SWTs) in Inner Mongolia has shown that in the right context, SWTs can provide a cost-effective and reliable solution to rural electrification [6,7].

The recent development and publication of open source designs has empowered organizations around the world to manufacture SWTs to electrify communities in their local area [8,9]. This decentralized manufacturing has the advantage of enabling the technology to be adapted to suit the local availability of skills and materials, as well as the local environment [10]. By using local labor and materials, a greater proportion of the value chain is shifted into the local area helping to create jobs. Due to the mechanical nature of the technology and its constant exposure to the weather, maintenance is one of the biggest challenges facing small wind [11]. However, by building local capacity and a solid supply chain for manufacture and installation, the infrastructure required for maintenance is already in place [12].

Hugh Piggott's open-source design for a SWT [13] is currently the most widely used in development projects around the world due to its simplicity, as well as the support offered by Piggott himself. A growing community of users also provides support and has been formally connected via the Wind Empowerment association.

1.2. blueEnergy

blueEnergy is a non-profit, non-governmental organisation (NGO) founded in 2003 and working on the Southern Caribbean Coast of Nicaragua or Región Autónoma Atlantico Sur *(*RAAS*)*. The initial vision of the organization was to provide clean water through an ultra violet radiation purification system powered by locally manufactured SWTs. In order to reduce technical and operational risk, by the time the organization commenced operations in Nicaragua in May 2004, the water purification component was dropped and the vision was to focus on the electrification of schools and health centers and finally on the electrification of individual homes. In 2011 blueEnergy stopped using SWTs as part of its rural electrification strategy. The decision was taken based upon the numerous challenges faced when using SWTs for rural electrification in the RAAS and on the increasingly favorable conditions of the global solar energy market. This article elaborates on these challenges and establishes a set of criteria according to which other organizations may assess the feasibility of their SWT based rural electrification initiatives.

blueEnergy's SWT projects were carried out by a team of local and international technicians on contracts ranging from several weeks to several years. The experience blueEnergy gained on SWTs was intermittently recorded by technicians in several internal documents. Furthermore, a great deal of knowledge was transferred orally between technicians. The tacit knowledge gained from experience in the workshop, as well as participating in installations and community trips added greatly to the knowledge recorded in these documents. blueEnergy also organized two SWT design conferences inviting Hugh Piggott—the inventor of the open source design of SWT employed by blueEnergy [13], Otherpower—an organization championing the development of SWTs in the USA [14]—and local stakeholders, such as universities and other NGOs. The SWT installations performed by blueEnergy are presented in Table 1 and Figure 1.

Table 1. Status of SWTs installations performed by blueEnergy.

Community	Installation year	Status/Comments	Purpose
Bangkukuk Taik	2005	Uninstalled in 2007	School electrification
Monkey Point	2007	Working intermittently	Community electrification
Bluefields (Three turbines)	2004	Uninstalled	School electrification
	2006	Uninstalled	Workshop electrification
	2007	Uninstalled in 2011	Test
Pearl Lagoon	2006	Uninstalled	School electrification
Kahkabila (Two turbines)	2007	Not working	School electrification
	2008	Uninstalled in 2011	Health center electrification
Set Net Point	2007	Uninstalled in 2009	School electrification
Cuajinicuil	2010	Working	Community electrification

The initial aim of blueEnergy's SWT based projects in the RAAS was to support education and health related activities by electrifying schools and health centers. In Set Net Point a church was also electrified. In Monkey Point the project evolved to a mini grid system providing electricity to a communal house and two businesses: a battery charging center and a shop with refrigerator. Both businesses were operated by individual community members or families, the shop with refrigerator having initially been operated by a cooperative. In Bluefields the turbines were installed at a local educational institution, providing energy to classrooms, office spaces and a workshop. Furthermore, one of the towers doubled as a test bench. The project in Cuajinicuil—a collaboration with NGO AsoFenix—was designed to power a mini grid system delivering energy to households and to a well.

1.3. Technical Specifications of the blueEnergy SWT

The SWT used by blueEnergy is an evolution of Hugh Piggott's [13] open source Axial Flux Permanent Magnet design. Figure 2 portrays the wind turbine used by blueEnergy and the technical terms used throughout the article. Figure 3 displays the power curve of the wind turbine and Table 2 summarizes its technical specifications. Table 3 summarizes the price of the SWT without the improvements described in chapter 2.

The protection system used on blueEnergy's SWT was a furling tail. The system hinges the tail to the body of the SWT, in a way that the force and momentum generated at high wind speeds sways the turbine away from the wind preventing damage to it. The wind speed for which the protection system engages can be calibrated by modifying the weight of the tail.

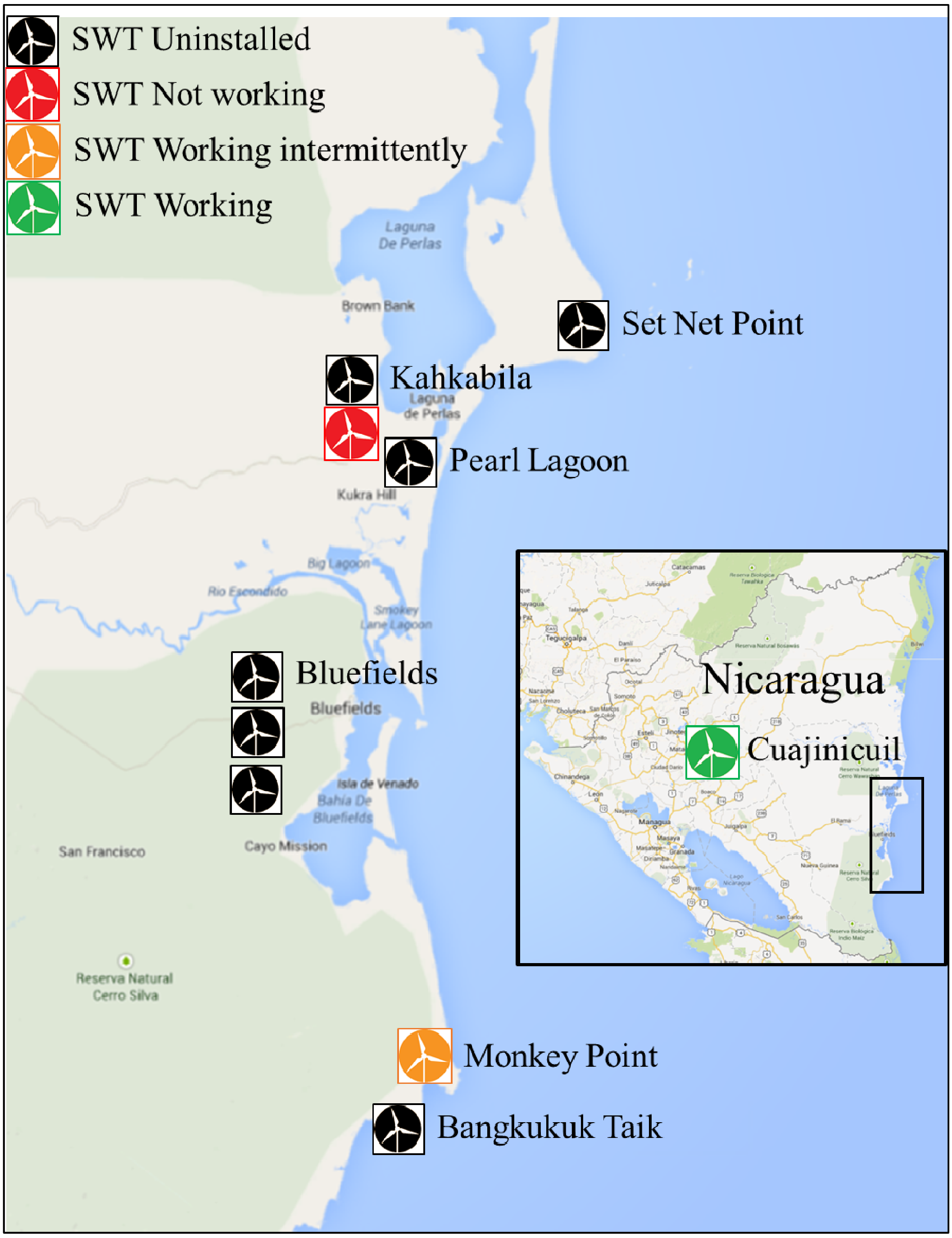

Figure 1. Map of blueEnergy's SWTs installations (Image source: Google Maps).

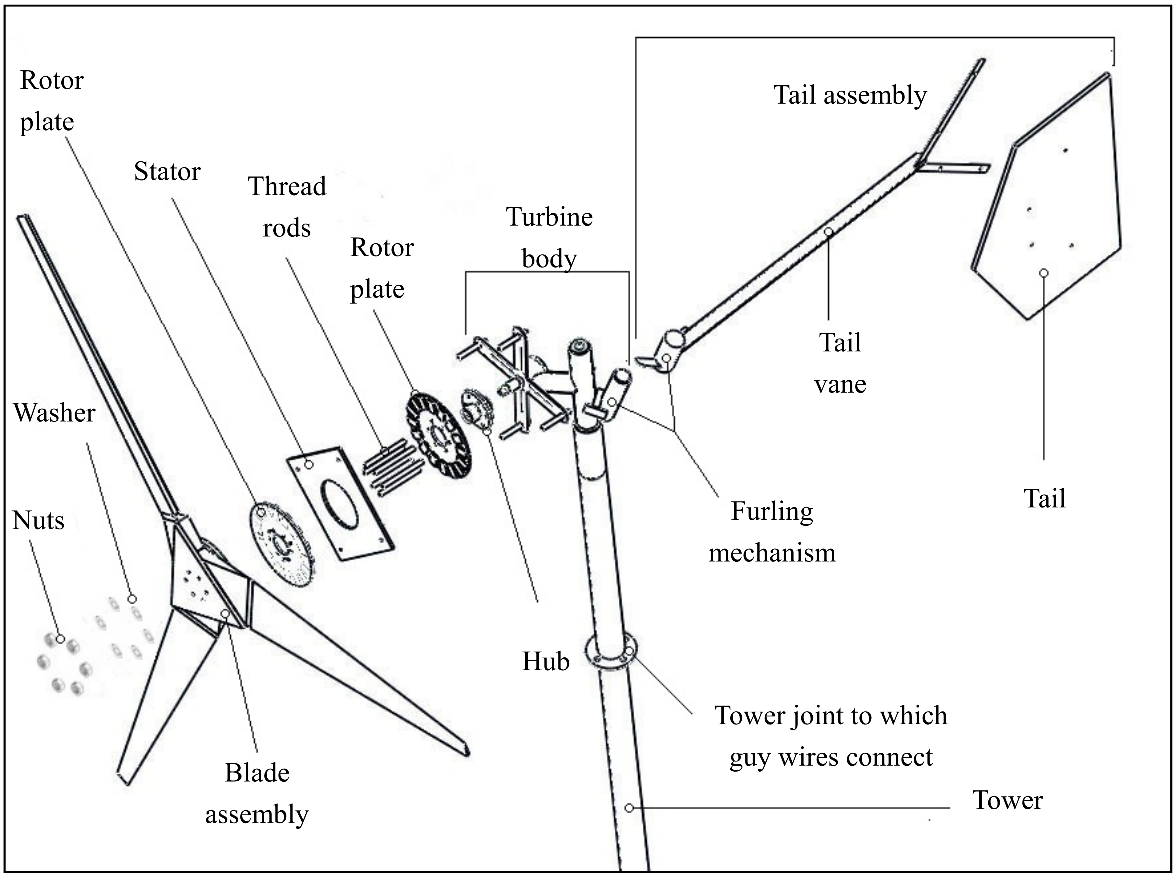

Figure 2. Diagram of blueEnergy's wind turbine.

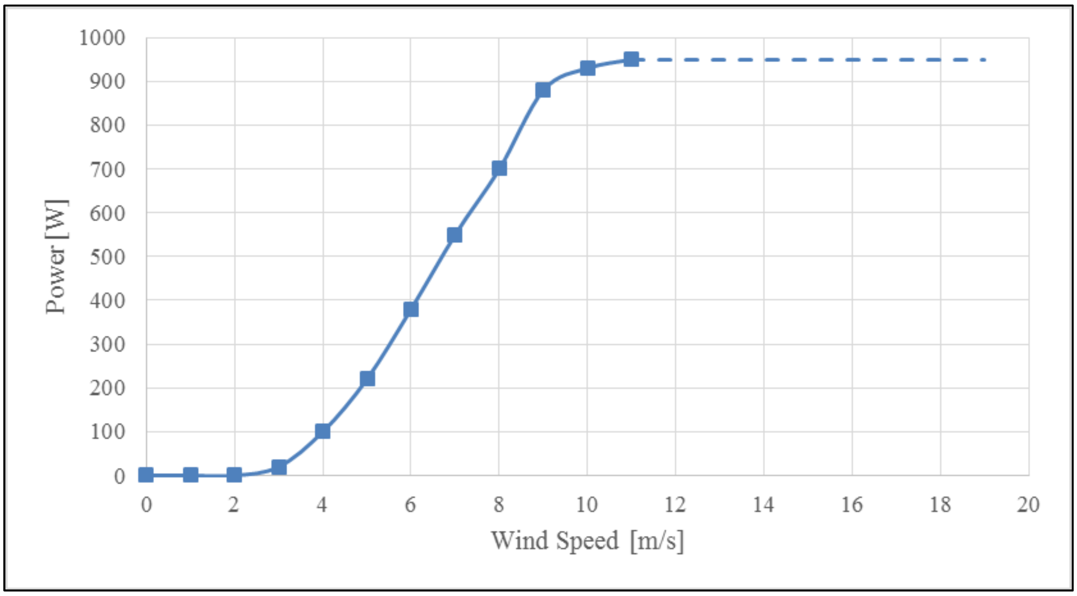

Figure 3. Power curve of blueEnergy's SWT—Full line, measured power production; Dashed line, extrapolated power production after engagement of protection system [15].

Table 2. Technical specifications of blueEnergy's wind turbine.

Characteristic	Specification
Diameter [m]	3.6
Rated power @ 11 m/s [W]	950
Annual energy production in Monkey Point [kWh/year]	1455
Rated annual energy yield [kWh/year at 5m/s AMWS Rayleigh distribution]	2696
Protection system	Furling tail
Protection system engagement wind speed [m/s]	8-11
Control system	PWM charge controller
System voltage [V]	24
Generator topology	Axial flux

Table 3. Component cost of the SWT employed by blueEnergy before improvements.

Component	Cost (USD$)
Stator	167
Rotor plates	505
Body	356
Blades	325
Tail	64
Assembly	174
Import duties	597
Guy wires and accessories	449
Total of SWT (without guy wires and accessories)	2188

1.4. Methodology

The experience of blueEnergy shows that employing locally manufactured SWTs as part of a rural electrification strategy is likely to face a variety of challenges, which are categorized in Table 4.

Each challenge was then assessed in detail with regards to its effect on the technical, economic, organizational and social viability of the local manufacture of SWTs as a solution for rural electrification. Where appropriate, the following methodologies were employed to provide evidence for each of these assessments:

- Review of blueEnergy's SWT installation and maintenance reports.
- Participant observation as members of the blueEnergy technical and social teams including participation in daily community life.
- Follow-up of SWTs by blueEnergy technical and social teams through surveys, community

meetings and informal discussions.

- Modelling of Monkey Point's Wind-Solar hybrid system using MS Excel and HOMER [16] based on energy resources—wind and solar—and energy consumption.
- Breakdown of additional costs of each modification required to adapt the SWT to the RAAS.

Based on the challenges of Table 4 a set of critical success factors is created, together with a set of guidelines for the assessment of the viability of SWTs projects in other contexts.

Table 4. Challenges faced by blueEnergy when implementing SWT projects.

Nature of challenge	Challenge
Technical	Wind resource
	Corrosion
	Water induced damage
	Lightning strikes
	Maintenance and repair
	Development process
Economic	Manufacturing costs
	Installation costs
	Operation and maintenance costs
	Cost of power produced
	Development costs
Organizational	Local knowledge
	Knowledge transfer
	Technicians motivation
Social	Assessment of communities
	Funding maintenance
	Community involvement

2. Challenges

This section analyses each of the challenges faced by blueEnergy during its implementation of SWTs based rural electrification projects in the RAAS.

2.1. Technical

The majority of the technical challenges are related to the environment in which the SWT is installed and can therefore be mitigated through the adaptation of the technology and improvements in the manufacturing process. However, as is the case on the Caribbean Coast of Nicaragua, if many challenges are faced in any particular context, the high cost of these adaptations is likely to render the turbine economically unviable. The following subsection presents a techno-economic analysis of each challenge, evaluating the costs of overcoming the challenge with respect to the basic component costs of Table 3.

2.1.1. Wind resource

2.1.1.1 Average wind speed

As discussed in both the "Small Wind Turbine Conference" in Dakar, February 2011 and the "First International Symposium of Wind Energy" in Lima, December 2011, a rule of thumb commonly employed by SWT experts is that the average annual mean wind speed (AMWS) at the hub height of a SWT should be at least 4.5 m/s in order for the turbine to be economically viable, given the other energy sources typically available (solar, hydro, diesel). The resource itself is particularly important for wind power, as power production is proportional to the cube of the wind speed, whereas for solar power, it is directly proportional. According to the wind atlas provided by NREL [17] and ENCO [18] for the locations where blueEnergy has installed SWTs, the wind resource potential is marginal for hub heights of 50 and 30 m. For the hub height of blueEnergy turbines—24 m—the potential of the wind resource will be equally marginal. Furthermore, at such low heights topology and surrounding vegetation is further detrimental to the quality of the wind resource.

The macro wind atlases of Figure 4 and Figure 5 are a combination of weather station measurements and satellite data. They do not account for the effects of local topography and of vegetation, and as a consequence they should be used only as a guide and must be validated with

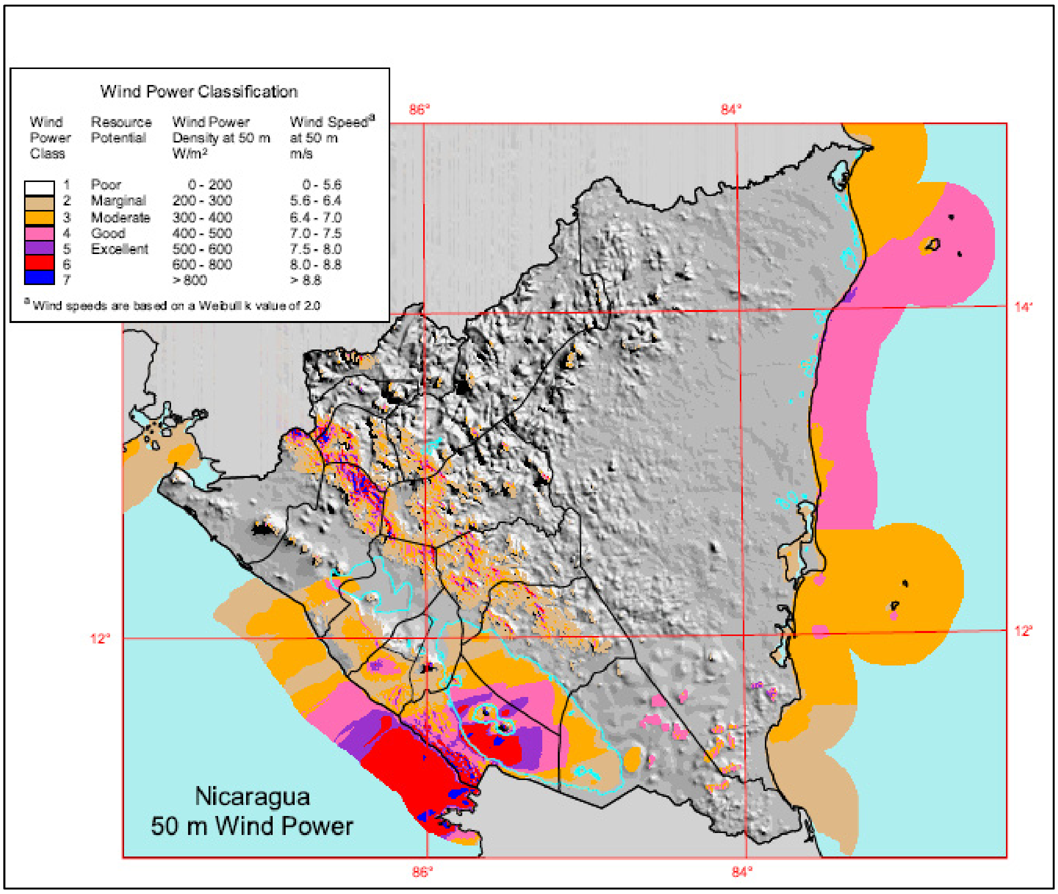

Figure 4. Wind atlas of Nicaragua at 50 m—Wind resource map developed by NREL with data from AWS TruePower [17].

local measurements at the sites where SWTs have been installed. blueEnery has performed AMWS measurements in Monkey Point and Bangkukuk Taik, showing that the AMWS is below 4 m/s at a height of 18m. Measurements performed in Bluefields show the same and are consistent with measurements from the meteorological station at the airport [19]. These measurements were performed using simple data loggers coupled with an anemometer and wind vane. Measurements were taken between 2004 and 2011. Due to logistic difficulties the data is not consistent and contains some gaps. The data was processed statistically using a custom made Matlab application. The data showed significant yearly and monthly variation due to the tropical storm season and the varying proximity of outlying storms.

Design modifications such as an optimized blade chord variation from root to tip, for increased power production, were performed to increase performance at lower wind speeds. A 14' diameter SWT was also built to increase energy yields, however, the 14' model was only experimental and as a consequence there is no field data to assess the increase in power production on the field. The Improvements on the generator enable the 14' to produce more energy at lower wind speeds when compared to the 12'. However, these same improvements penalize energy production at higher wind speeds due to higher generator loses [20].

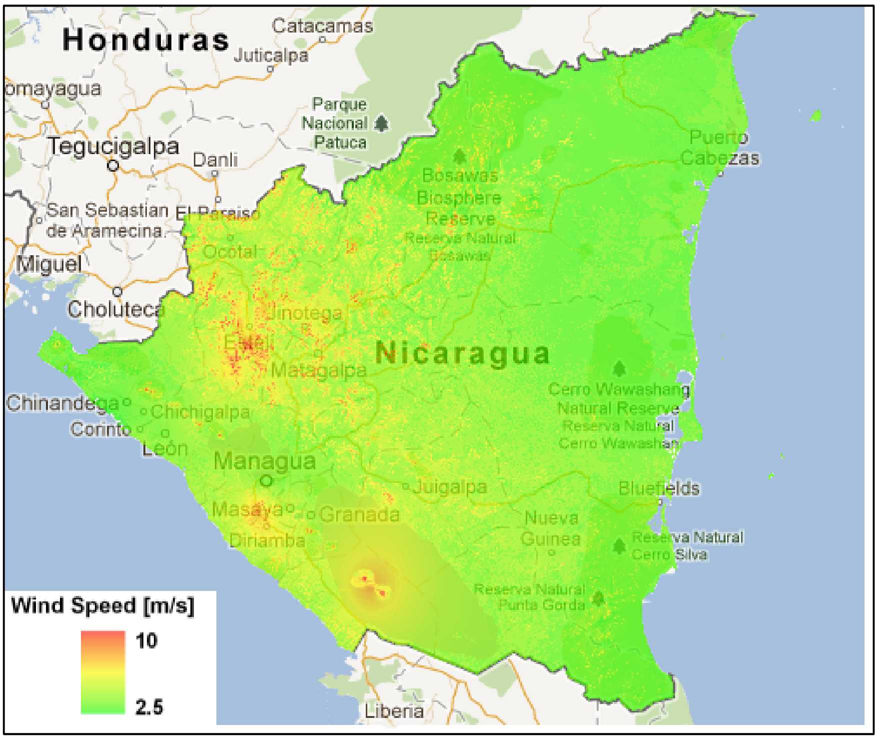

Figure 5. Wind Map of Nicaragua (c) Meteotest (www.meteotest.ch) [18].

Figure 6 portrays the relative increase in performance of the 14' over the 12' based on a test bench and on an expected annual energy production calculated using the software HOMER.

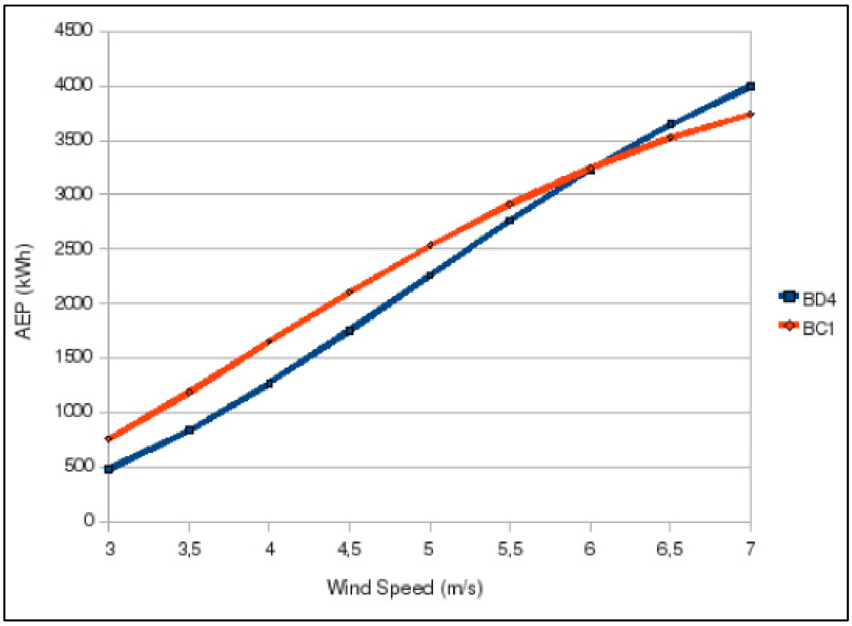

Figure 6. Expected Annual Energy Production of 14' turbine (bC1) vs. 12' turbine (bD4) [20].

2.1.1.2 Turbulence

Turbulence affects the quality of the wind resource and decreases both the performance and the lifetime of the SWT. In order to reduce the likelihood of turbulence, SWTs should be located at least 10m above any obstacle in a 100m radius [14]. Some authors such as Hugh Piggot [13] mention that the rule of thumb is that the turbine should be placed at twice the high of the obstacle and at a distance of ten times its height down wind. The sites of the SWTs in Kahkabila, Pearl Lagoon and Monkey Point do not conform to these guidelines as they are on the wake of obstacles such as trees or houses. The turbines were located this way in order to decrease the electrical loses from wind turbine to the control systems and because of community infrastructure constraints such as the location of the buildings—schools and health centers—to be electrified.

2.1.2. Corrosion

The environmental conditions on the coast of the RAAS are characterized by high salinity, high humidity, high heat and frequent rainfall. The combined effect of these environmental conditions drastically increases the rate of corrosion of the metallic components of the turbine. The following subsections detail the different components affected by corrosion and the proposed solutions for these problems.

2.1.2.1 Turbine body and rotor plates

The turbine body and the rotor plates are made of carbon steel, which without treatment will quickly corrode. Initially the turbine was covered in two layers of ordinary anti-corrosive paint, a solution that proved insufficient. The improved solution was to clean the carbon steel with a sand blaster or a metal brush, and to paint the metal with two layers of anti-corrosive epoxy primer and polyurethane finish. The use of specialized paints increases costs—USD$ 185 for a gallon of primer and a gallon of finish—as well as manufacturing time. Using specialized paints increased the cost of the turbine body in 26% and of the rotor in 17%, representing a global increase of 8% on the total cost of the turbine. Despite this treatment, the body of the turbine and the rotors generally began to exhibit signs of corrosion, particularly at the welding seams, two years after installation. Transportation and handling of the turbine during maintenance is likely to damage the protective layer of paint and facilitate corrosion.

A solution for corrosion at the turbine body would be to use stainless steel. However, this solution would increase the price of the turbine due to the higher cost of materials, the increased complexity of welding and the absence of a local supplier of stainless steel.

2.1.2.2 Guy wires

The guy wires support the SWT tower and are particularly vulnerable to the effects of corrosion. There have been two instances of guy wires failure, one of them less than a year after installation. Several solutions have been employed to mitigate this problem and are listed on Table 5 for guy wires with a diameter of 5/16". Table 6 lists the price of the guy wires necessary for a tower with a height of 24 m according to different combinations of solutions from table Table 5.

Table 5. Prices of different 5/16" guy wire solutions.

Solution	Cost (USD$)
Fence wire	52
Galvanized steel	84
Galvanized steel plus lithium grease or linseed oil coating	115
Galvanized steel plus anti-corrosive paint coating	135
Galvanized steel plus plastic sleeve coating	150
High quality galvanized steel	137

The current solution uses high quality galvanized steel for the top guy wires. These have shown no signs of corrosion after two years. The cable size required for the lower guy wires is not available locally in high quality galvanized steel and would have to be imported with increased financial and logistical costs. As a consequence these were made with lower quality galvanized fence steel wires stranded together locally, however this process is complex and can lead to mistakes if carried out by inexperienced workers. Using this solution slightly reduced the cost of the guy wires and of the guy wires and accessories component in less than 1%.

Table 6. Prices of different guy wire solutions for the tower.

Solution	Type	Cost (USD$)
High quality galvanized steel	3/8”	138
	5/16” imported	137
	Total	**275**
Fence wire plus high quality galvanized steel for top guy wires (current solution)	3/8” High quality	138
	AWG 10 (4 strands per guy wire)	52
	Total	**190**
Galvanized steel	3/8”	109
	5/16”	84
	Total	**193**

2.1.2.3 Magnets

The first magnets on the rotor were made of rare-earth neodymium covered with three layers of anti-corrosive protection. This protection proved insufficient, as the protective layers would chip after some time, exposing the neodymium powder to water, leading to corrosion which would make the magnets swell. Stator failure would ensue due to rubbing between stator and rotor.

Magnets with an additional protection layer—epoxy—were the improved solution. However, it was found that transportation to Nicaragua—from China via the USA—caused the fourth protection layer to chip away. Ultimately this leads to the above listed corrosion problems.

A possible solution would be to revert back to the ferrite magnets, which were the standard ten years ago, since they are less prone to corrosion. However, this would require a redesign of the generator, as they are significantly less powerful than their neodymium counterparts.

2.1.2.4 Balancing weights

It is crucial for the assembly—rotor, stator and blades—to be as balanced as possible, in order to avoid excessive vibration and the associated damage. The assembly is balanced by fastening lead weights to the blades using screws. These screws—be it carpentry or galvanized steel—are prone to corrosion, which will result in the balancing weights detaching, causing the turbine to vibrate until failure if not lowered for maintenance. The difference between the materials is simply the amount of time before the screws need to be replaced. A possible solution would be to use stainless steel screws.

2.1.3. Water induced damage

The climate of the RAAS is characterized by a 6 month rainy season from May to November with very high relative humidity. This leads to water related failure of different components.

2.1.3.1 Tail vane

The model of SWT manufactured by blueEnergy uses a furling system to protect the SWT against high winds. At a certain wind speed when the generator starts to become in danger of overheating, the blades begin to fold up beside the tail vane, turning them out of the wind. The wind velocity at which this occurs is governed by, among other factors, the weight of the tail vane.

Initially the tail vane was made out of plywood, a material prone to absorb water. As the tail vane absorbs water, its weight increases, disrupting the furling mechanism and causing stators to overheat. Different solutions were attempted with different cost increases. The most recent solution is a fiberglass tail vane, which does not absorb water, thus keeping the furling system functional. Using the fiberglass solution increased the cost of the tail vane in 57%. However, this corresponds to a global increase of 2% on the total cost of the turbine.

Table 7. Prices of different tail vane solutions.

Solution	Cost (USD$)
Plywood coated in polyester resin (original solution)	35
Marine grade plywood	45
Fiberglass (current solution)	77

2.1.3.2 Blade assembly

The blade assembly—see Figure 2—was originally made out of plywood, which would rot due to rain. The loss of rigidity at the blade assembly would loosen the blades causing the system to become unbalanced. This problem was solved by using solid hard wood for the blade fixtures and using an epoxy resin coating—USD$ 148 for the resin and curing agent—to protect the wood not only of the blade assembly but also of the blades themselves. Using the epoxy resin increased the cost of blades component in 67%. This stark increase corresponds to a global increase of 6% on the total cost of the turbine.

However, it was later found that this solution delays the problem but does not solve it. A possible solution would be to use a blade assembly made of stainless steel. This would increase the financial cost—the cost is estimated at USD$ 150—and would be logistically challenging due to the limited local availability of stainless steel.

2.1.3.3 Blade leading edge

The leading edges of the blades are prone to erosion, which allows water to enter the wood causing them to expand. The solution is to repair the blades by sanding down the damage, filling with filler paste, repainting and rebalancing. This operation may need to be performed annually or in some cases biannually.

An alternative would be to cover the leading edges with a special tape to avoid erosion. This solution would increase the cost of the turbine—the leading edge tape roll costs USD$ 35—and would also pose logistical challenges as the tape needs to be imported. Other solutions would be to manufacture the blade out of a composite material such as fiberglass or carbon fiber, as employed in similar projects in Peru and Sri Lanka [21]. However these solutions would further increase the cost of the turbine.

Figure 7. Different damages to SWT—Clockwise from upper left corner: Corrosion of body, corrosion of guy wires, tail vane water absorption and blade assembly damaged by water.

2.1.4. Lightning strikes

Figure 8 shows that the Atlantic coast of Nicaragua receives about 100 thunderstorms a year, with lightning striking 8−10 times a year in each km^2 [22]. Due to the high prevalence of lightning strikes in the region there have been several instances of lightning strike damage.

2.1.4.1 Safety

SWTs are usually installed atop a metallic tower with heights ranging from 6 to 24 m. By design, these towers are the highest point of elevation within a radius of 500 meters—in order to position them way from obstacles than can affect the wind—making them attractive to lightning strikes. As a consequence the following guidelines should be followed [23]:

- No buildings or people in a vicinity of 10m from a wind turbine tower and its anchors.
- Locate the turbines 1.5 times the height of the tower away from buildings or power lines.

- In case of lightning or possibility of lightning e.g: during intense rain storms, the turbine area must be cleared.

However, blueEnergy's guidelines state that end users must lower down the turbine in case of a tropical storm or hurricane. Furthermore, the turbine also needs to be frequently lowered down for maintenance. These guidelines clash with the reality of the RAAS, as there are often day or week long rain showers as well as tropical storms in the region.

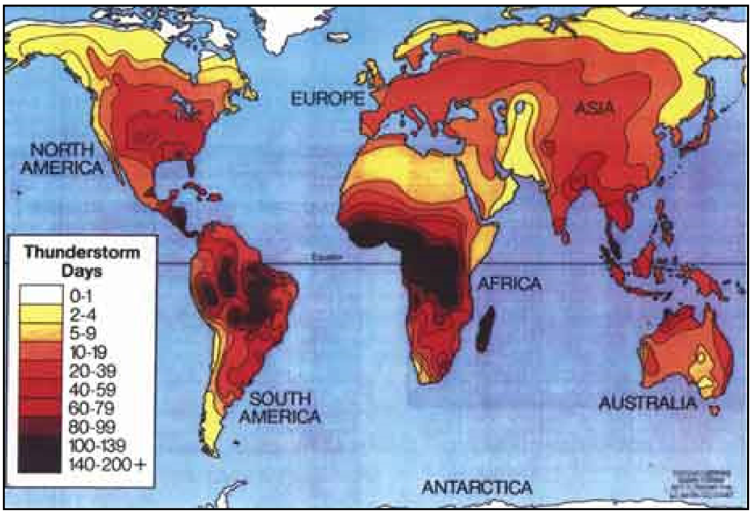

Figure 8. Average thunderstorm days per year from the National Lightning Safety Institute [22].

2.1.4.2 Lightning strike damage

A lightning strike on the turbine endangers the electrical components associated with the turbine system such as rectifiers, charge controllers and inverter, which is likely to lead to damage in the order of hundreds of dollars per incident. Table 8 summarizes the lightning strike events that have occurred in blueEnergy installations.

Lightning has on average struck one installation once per year and the average damage of each event has been USD$ 500 in spare parts. The total cost of the repair would have to include the costs of the repair trip and the operational costs of procuring the spare pats. These are significant costs, which are not easy for the remote communities of the RAAS to manage every year. As a consequence blueEnergy has covered all the costs of lightning strike damage, with the exception of the 2010 event in Monkey Point in which the community provided USD$ 500. However, even this sum was raised over several years through a mechanism facilitated in part by blueEnergy and it is therefore very unlikely that such sums can be raised every year. Repeated lightning events in the community of Monkey Point, together with recurrent maintenance problems, have also made community members question the use of SWT technology in their community.

2.1.4.3 Solutions

In an attempt to prevent further lightning strike damage, the following grounding procedures were employed:

- Grounding of tower and guy wires: Connecting the excess wire from the guy wires of each anchor to a copper clad grounding rod connected to the foundation of the respective anchor. For the tower a wire can be connected to a cooper clad grounding rod, welded to a buried metallic mass in order to improve the grounding electrical potential. The material cost for this solution is USD$ 130, including cooper clad grounding rods and the radiator to be buried.
- Lightning arrestors both for the DC side and for the AC side, with a total cost of USD$ 90.

Other techniques that can help prevent lightning strikes and/or mitigate their damage have been studied but not implemented due to high financial costs or difficult execution, including:

- Installing a "ground net" made of 1" or 1–1/2" copper strap between the tower ground rod and the ground rods at the guy wires, burying the strap at a depth of 2.5 m. This solution would cost USD$ 578 using cooper straps and USD$ 344 using copper wire.
- Using a combined 10/350 μs and 8/20 μs lightning arrestor for 3-phase systems attached to the cables coming out of the rectifier. The price without import duties or shipping costs of the combined lightning arrestor system described above is of USD$ 300.
- Weld circular disk of metal to the bottom of the tower pipe—with the same diameter and an opening for electrical cables—so as to make the tower the closest possible to a Faraday cage.

Table 8. History of lightning strike events, with damages and their costs.

Year	Location	Damage	Cost (USD$)
2006	Rama Cay	Data logger	400
2007	Rama Cay	Wind vane	200
2007	Bluefields	Rectifier, Anemometer, Charge controller	800
2008	Monkey Point	Inverter logic card	300
2010	Monkey Point	Inverter logic card, charge controllers	700

2.1.5. Maintenance and repair

The SWTs used by blueEnergy were manufactured locally in Bluefields. While this means that it was possible to repair the turbines and if necessary, produce replacement components, it also made difficult to ensure adequate quality control in the manufacturing and assembly processes. This led to the turbines being more prone to failure and requiring frequent maintenance. Given the high cost of transport in the region—due to the long distances that must be travelled by boat—this added significantly to the operating costs of the turbines.

Hugh Piggott lists a number of failures that are likely to occur during the life time of the turbine, all of which require further investments:

- Failure of diodes.
- Wear of the turbine hub bearings.

- Corrosion of the rotor plates or magnets.

On average, Piggott estimates that SWTs will incur one failure per year [13]. In blueEnergy's experience, these problems occurred at a higher frequency because of the environmental conditions along on the RAAS and quality control deficiencies. As a consequence the maintenance costs for the SWTs installed by blueEnergy were very high. This is illustrated by the maintenance activities performed on blueEnergy's SWT installations which are listed in Table 9. It should be noted that the installation in Cuajinicuil—a collaboration with NGO AsoFenix—showed significantly fewer maintenance issues.

As a result of the above maintenance issues, the SWTs spent long periods out of service, as illustrated by Table 10. The extended periods of downtime are also a consequence of the lack of reliable communication links between Bluefields and the communities, resulting in difficulties in relaying the status of the SWT system from the community to blueEnergy, as well as the logistical difficulties of organizing maintenance trips.

Table 9. Maintenance history of blueEnergy's SWT systems.

Community	Year	Maintenance issue
Set Net Point	2007- 2009	Corrosion; Stator failure (twice); Charge controller failure (twice); Rotor failure; Replacement of turbine body, stator and guy wires. Guy wire failure
Kahkabila (School)	2007-2008	Blades replaced
	2009-2010	Stator and rotor repaired; Turbine replaced; Guy wires replaced
Monkey Point	2007-2008	Stator failure (three times); Problem on hub; Tail vane repair
	2009-2011	Stator failure, Guy wires replaced; Lightning strike; Corrosion; Damaged bearings; Blade replacement
Cuajinicuil	2010-2011	Dump load failure; Stator failure

The uptime for Cuajinicuil is, when compared to the turbines installed by blueEnergy in the RAAS, better. This is attributed to more favorable environmental conditions—lower risk of corrosion and of lightning strikes—as well as higher levels of interest and involvement from the community and the ability of the community members to perform maintenance on the turbine independently. This is in part due to the fact that members of the community travelled to blueEnergy's workshop in Bluefields to participate in the manufacture of the turbine to be installed in Cuajinicuil. This provided an ideal opportunity for practical learning, essential for successful knowledge transfer in communities with low levels of formal education. The participation of community members of Cuajinicuil in the manufacturing of the turbine is considered a key factor for the SWT project in Cujinicuil and the subsequent elevated uptime of the SWT [24].

Table 10. Uptime of installed SWTs.

Green – SWT Working	2010												2011									Uptime (%)
Red – SWT Not working Orange – SWT working intermittently (50% uptime)	January	February	March	April	May	June	July	August	September	October	November	December	January	February	March	April	May	June	July	August	September	
Monkey Point, RAAS	Red	Red	Red	Green	Green	Green	Green	Green	Red	Red	Red	Green	Green	Green	Green	Green	Red	Red	Red	Green	Red	52
Kahkabila, Health Center, RAAS	Green	Red	Green	Red	Red	Red	Red	Red	Red	Red	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	20
Kahkabila, School, RAAS	Green	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Green	Red	Red	Red	Red	Red	Red	Red	Red	14
Pearl Lagoon, RAAS	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Red	Red	Red	Red	Red	-
Cuajinicuil,Boaco	White	White	White	White	Green	Green	Green	Green	Green	Green	Green	Orange	Orange	Orange	Orange	Orange	Green	Green	Green	Green	Green	85

2.1.6. Development process

The previous subsection shows that SWTs in the RAAS faced a constant stream of challenges. As a result this led to a constant redesign process. The 12' turbine was developed over four years, with several thousand dollars of direct investments, two design conferences with the pioneers of the SWT movement and previous work on an 8' turbine. Despite this significant investment, the turbine did not reach the end of its development.

The duration of the development process of the technology should be factored into projects using locally manufactured SWTs. Time frame and financial investment limits should be set, with regular progress evaluations, so as to avoid a continuous and unfruitful development process. The length of the development or adaptation process of SWTs to a context can also be seen as a sign of the suitability of the technology to the context. It should be noted that a technical solution that works in a context, may not work in another.

The Wind Empowerment association offers a centralised platform for sharing design evolutions of locally manufactured SWTs being developed around the world by other organisations analogous to blueEnergy. Such a platform facilitates knowledge sharing and collaboration, in order that the solutions found to specific problems in one context can be transferred to other contexts that face the same challenge. Thus contributing to the reduction of the lengthy and costly development time required to adapt the technology to each new context.

2.2. Economic

Using SWTs as part of a rural electrification strategy can pose economic challenges, which can be analyzed from different perspectives. Please note that the costs presented in the following section are only direct costs—the cost of materials. Indirect costs, such as time spent on meetings, installation or maintenance are not included.

2.2.1. Manufacturing costs

Building a SWT involves purchasing close to fifty different types of material, bringing the total material cost of a single turbine to USD$ 2462. The main cost drivers are epoxy resin, marine grade anticorrosive paint and neodymium magnets which cost USD$ 160, USD$ 184 and USD$ 539 respectively. The copper for the stator and the import duties—including shipping fees—for the magnets and hub are also significant cost drivers, USD$ 126 and USD$ 597 respectively. These prices are also sensitive to fluctuations in the raw material market, especially in the case of copper and neodymium. Furthermore, some materials need to be brought to the RAAS from Managua. The internal shipping cost is negligible when compared to importing materials from the USA. However, internal procurement and logistics require significant amounts of time and should not be underestimated.

Figure 9 summarizes the cost of the different components of the SWT used by blueEnergy, assuming that all the required materials are in stock. Some of the material, such as piping, cannot be bought in the exact quantity required but only in predefined quantities exceeding those required for a single turbine. Figure 10 illustrates the costs assuming that all materials must be purchased in stock sizes.

The cost of labor is not accounted for in the previous values. The best case scenario estimate for the manufacture of a 12’ small wind turbine is that 60 worker days are needed. Assuming a local worker is paid at the rate of USD$ 10 per day, then this would amount to USD$ 600. This labor cost includes the time spent in purchasing and handling the logistic of the materials and testing of the turbine generator on a test bench prior to installation [25].

2.2.2. Installation costs

The material costs of the tower, guy wires and material for the anchors are estimated to be USD$ 1687. This value may change as different terrain types may require different anchoring methods. The price quoted is for concrete block anchors, the most expensive. Preparing the materials required for the installation, such as the tower sections and control panel assembly requires a minimum of 25 worker days. Assuming a worker is paid at the local rate of USD$ 10 per day then the cost of installation is at least USD$ 250. The physical installation of the SWT system also requires labor which may vary depending on:

- Site accessibility—see Figure 14.
- Anchor method and soil conditions—USD$ 163 for the most adverse soil conditions.
- Community involvement—for each participating community member the installation costs are reduced by USD$ 20.

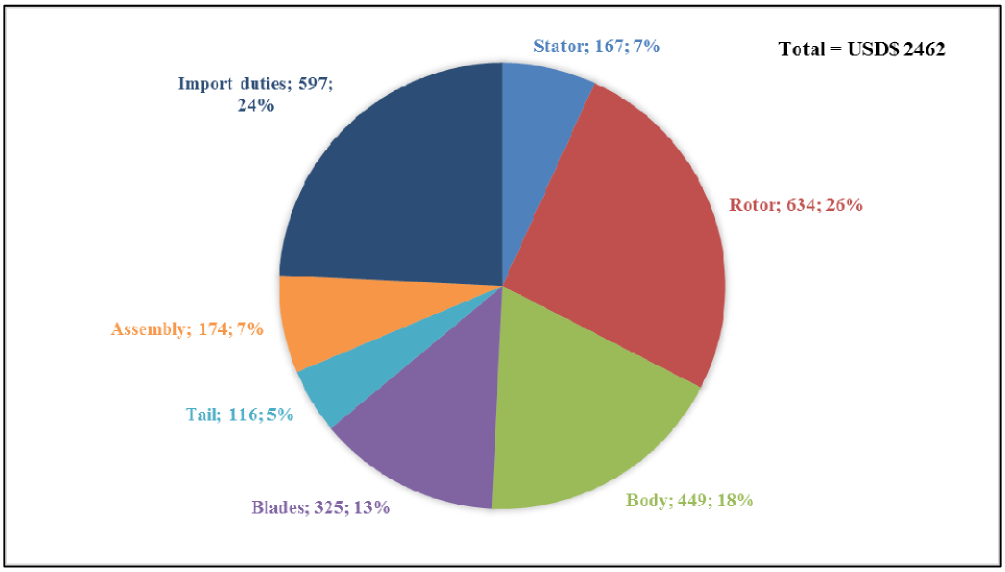

Figure 9. Component cost of the SWT employed by blueEnergy using materials in stock.

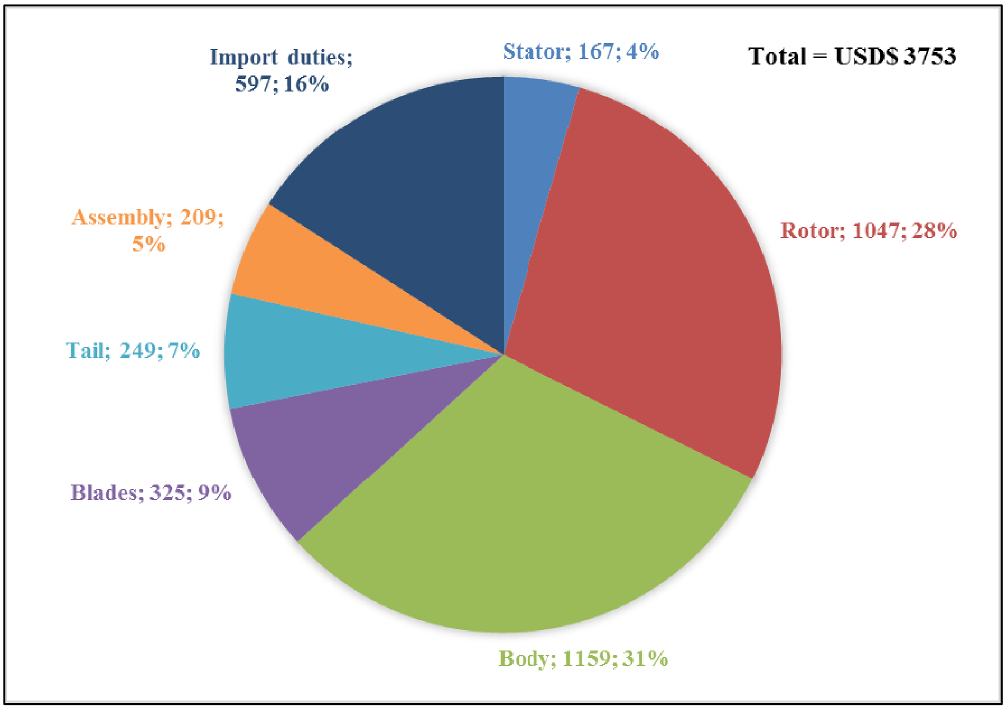

Figure 10. Component cost of the SWT employed by blueEnergy using newly purchased materials.

These costs are not included in the price of USD$ 2462 quoted in section 2.2.1, nor is the transportation, accommodation or food during the installation. The costs of organizing visits to the community to evaluate the ability of the community to manage the turbine and other preparatory meetings are also not included. Typically the cost of accommodation and food during a trip to a community is USD$ 20 per day and per participant. It is important to evaluate the costs associated with the installation of an SWT system in any new context as these are an early indicator of the suitability of the technology to that particular context.

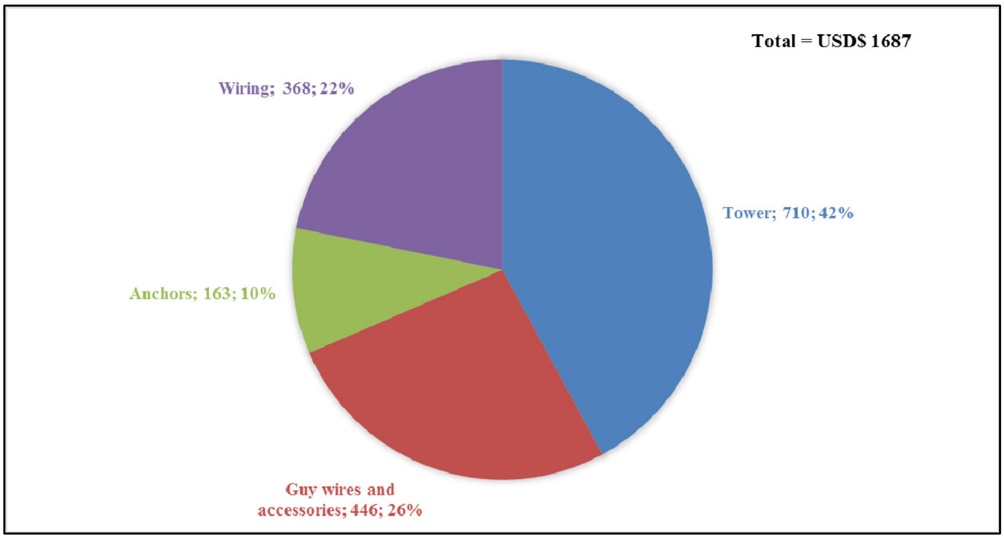

Figure 11. Material costs for installation with anchor cost for worst possible soil conditions.

2.2.3. Operation and maintenance costs

In the RAAS, the repair of a SWT involves a boat trip between Bluefields and the installation site. If the repair cannot be done on site, this must be done in two trips. Depending on the location of the community, the duration of the stay and the number of people participating, the full costs associated solely with the trip range between USD$ 200 and USD$ 500.

It should be noted that community trips are often multipurpose and as a consequence trip costs cannot normally be attributed solely to SWT maintenance. However, trips are made more frequently and are pushed forward in order to perform wind turbine maintenance. In addition to the trip costs there is the cost of the repair itself. The cost varies greatly depending on the part that needs to be serviced. Table 11 gives an overview of the costs of repairing the components that are more likely to fail within the lifetime of the system.

2.2.4. Cost of power produced

The uptime calculated in Table 10, together with the material costs of Table 9 and Table 11, the estimated maintenance costs from the combination of Table 9 and Table 11 extrapolated across the lifetime of the system, and an estimated Annual Energy Production (AEP) computed with the software HOMER using data from measurements performed in the community of Monkey Point - see Figure 12—allow the calculation of the Levelized Generating Cost (LGC). This calculation assumes a 15 year system lifetime (n) and considers a discount rate (r) of 10% [26]. A sensitivity analysis was performed for a discount rate between 5% and 15%, showing that the dependency between the LGC and the discount rate is under 20%.

Table 11. Cost of the repair of different components of the SWT system.

Component	Cost (USD$)
Stator	180
Blades	200
Bearings	50
Guy wires	500

This cost analysis assumes that the uptime is that of Table 10 for the entire lifetime of the turbine and that the maintenance needs of Table 9 are recurrent. It should be noted that this calculation only includes the upfront capital and maintenance costs for blueEnergy's SWT. Costs associated with logistics, installation and others are not included.

The cost of the batteries and other electrical components are not included in the material cost. Costs associated with the damages of a lighting strike are not included in the annual maintenance cost. The costs associated with lighting strike damage to electrical systems components have not been not included in the annual maintenance cost, as the electrical systems are not defined in this article as part of the SWT. However it should be noted that lightning damage to these components is significantly more likely in wind power systems than solar powered systems. This simplified approach enables a comparison of power sources strictly by the amount of produced energy feed into the system—see section 2.2.5. Including the maintenance costs induced by a lightning strike would double the annual maintenance cost and increase the LGC in 40%.

The LGC calculation is performed, using the abovementioned data and assumptions, according to the following equation:

$$LGC = \frac{\sum_0^n \frac{Upfront\ capital\ cost + Maintenance\ cost}{(1+r)^n}}{\sum_0^n \frac{Energy\ production * Uptime}{(1+r)^n}} \qquad (1)$$

Table 12. Calculated price of wind power in Monkey Point.

Power installed (W)	Energy production (kWh/year)	Uptime (%)	SWT Material Cost (USD $)	Annual Maintenance Cost (USD $/year)	LGC ($/kWh)
950	1455	52	4149	356	1.11

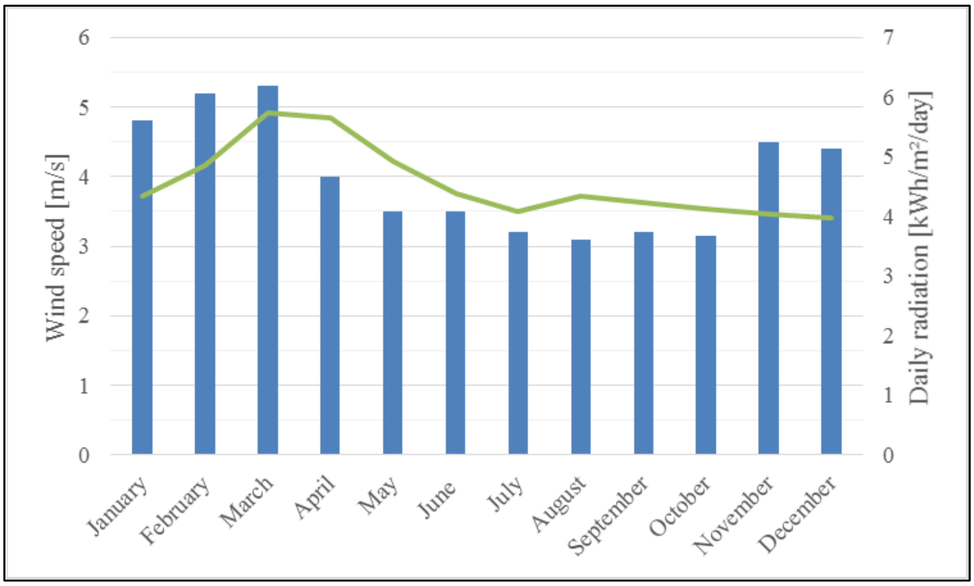

Figure 12. Wind and solar resource of Monkey Point 15.

2.2.5. Cost of alternative sources of electricity

The cost of wind power in Monkey Point can be put in perspective when compared with alternative technologies such as solar energy. The cost of solar energy for Monkey Point is calculated in subsection 2.2.5.1. As a reference, the estimated cost of energy generated in Nicaragua by small scale diesel generators is in the order of 0.60 $/kWh—varying greatly depending on the scale of the system, current diesel price and the load factor—and for grid generated electricity is in the order of 0.11$/kWh [11]. It should be noted that including the cost of the battery charging system which the assumptions in section 2.2.4 dismiss, and using as a term of comparison the energy supplied to meet demand instead of the energy generated, would increase the LGC of wind generated power. The same would apply in the solar energy LGC calculation of subsection 2.2.5.1.

2.2.5.1. Solar energy

For comparison, the cost of solar energy was calculated based on a 2011 quote from a local solar panel provider—including material costs for installation such as mounting and wiring, an extrapolated annual maintenance cost and the solar energy production simulated by software HOMER. The estimated uptime for the equivalent period of Table 10 is 95%. The maintenance costs correspond to cleaning the solar panels. The lifetime of the system (n) is taken to be 15 years and the discount rate (r) as 0.1 in order to allow for a fair comparison with the SWT. This allows for the comparison, within the scope of this cost analysis, of the prices of wind and solar energy. Once again additional costs regarding logistics, and others are not included. The cost of the batteries is not included for simplicity. Equation 1 is used for solar as on wind.

Taking into account strictly the costs of materials, for the case of Monkey Point, the electricity provided by the solar panels is cheaper than that provided by the SWT. If other costs such as installation, labor and logistical costs, participatory construction workshops and operator training sessions the cost balance is further tipped in favor of solar energy. It is also worth mentioning that the price of solar panels is decreasingly steadily [27]. At the same time, the cost of copper and neodymium, is fluctuating with periodic upward spikes [28]. This simple analysis serves to illustrate that for a SWT it is essential that environmental conditions are favorable in order to be as competitive as possible with other electrification technologies. In contexts with favorable conditions, locally manufactured SWTs can be the most appropriate solution for rural electrification as they may offer savings of up to 20% during the entire lifetime of a system when compared to commercially available SWTs [29].

Table 13. Calculated price of solar power in Monkey Point.

Power installed (W)	Simulated production (kWh/year)	Uptime (%)	Solar Panels Material Cost ($)	Maintenance Cost (USD $)	LGC ($/kWh)
1387	1871	95	4161	10	0.26

2.2.6. Seasonal variation in availability of power

The analysis of the previous subsection focusses on the individual annual energy generation of each power source. Figure 13 shows that power produced by the wind power system is more variable than the power produced by the solar system, due to the cubic dependence of power production on wind speed. Moreover, both resources are at their lowest in June and July, reducing the utility of a hybrid system.

For these reasons it is more useful to use the annual power production for the analysis of the previous subsection.

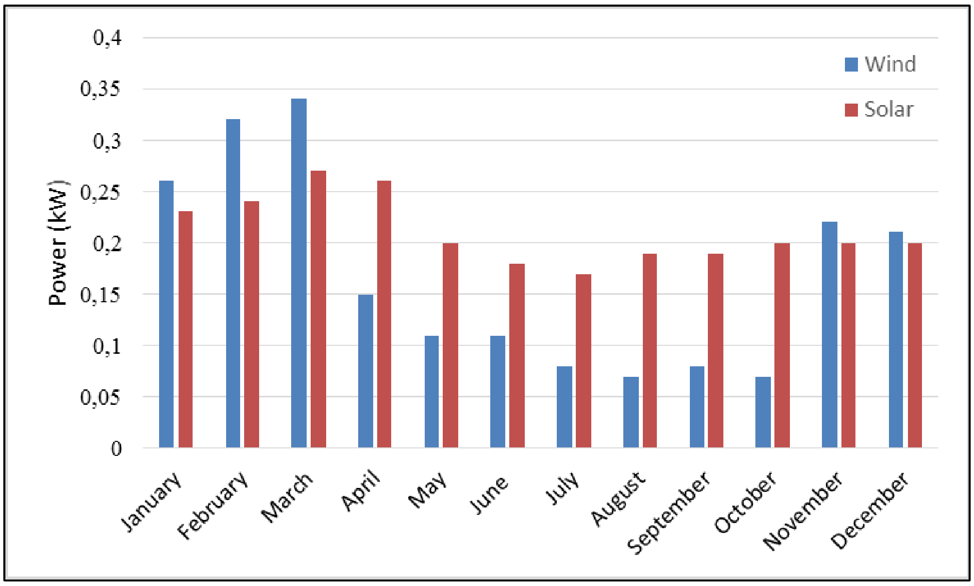

Figure 13. Power production in Monkey Point

2.2.7. Development costs

Since its inception blueEnergy has put significant effort into developing a reliable SWT. This effort, both in terms of financial and human resources costs has not been accurately documented. However a tentative estimate can be made assuming that one person has worked full time with wind turbines since the blueEnergy was founded. If it is considered that one person normally works roughly 2000 hours per year and that during periods of intense research, production or installation more people were involved with SWTs, then in terms of labor, the costs of development, can be put in the tens-of-thousands hours range. In the case of blueEnegy these costs were significantly reduced as most of the development labor was accomplished through voluntary work. Assuming this work was done by an engineer paid at the local rate of USD$ 20 per day, then this would amount to at least USD$ 25000.

Additional costs such as the rent of the workshop, the tools necessary for manufacture, training the workforce and material costs for the construction and testing of prototypes should also be factored in. These can be estimated between USD$ 15000 and USD $ 30000. These figures put locally manufactured SWTs at a significant disadvantage when compared to other more mature technologies. Only in large scale, long-term SWT based electrification projects such as that facilitated by the Inner Mongolia Science and Technology Commission (IMS&TC) [7], does it seem that development costs can ever be amortized.

2.3. Organizational

blueEnergy faced different organizational challenges while implementing SWT projects. Organizational challenges are often overlooked, but can have a significant impact on the outcome of rural electrification projects, particularly due to their influence on the effective utilization of human resources.

2.3.1. Local capacity

When blueEnergy started working with SWTs in the RAAS, local knowledge on the technology was non-existent. As a consequence, it was initially difficult to find local skilled technicians able to manufacture SWTs, and the technicians that built the initial turbines were international volunteers. Later blueEnergy tapped the potential of local workers skilled in carpentry, welding, metal and fiberglass and started to transfer SWT knowledge to them and begin to build up a local skill base. After some years local workers gained confidence and were able to build SWTs alone. In order to achieve this, it was necessary to put emphasis into translating SWT specific knowledge into local skills. The aforementioned illustrates the necessity of conducting an assessment of local universities and technological schools, existing related industries and businesses. This local capacity is essential for establishing an industry based upon the local manufacture of SWTs. If this base does not already exist, significant time and effort must be expended in order to develop it.

SWT related training activities in the RAAS had a positive educational impact, with regards to raising awareness of the technology. However the unreliability of the systems led to a discrediting of the technology, with the community of Monkey Point reportedly asking for the replacement of the SWT by solar panels.

This situation highlights the importance of using proven and established technologies in rural electrification projects, as well as conducting proper preliminary assessments, such as a market assessment or participatory community diagnostics when implementing SWT projects. Failure to do so is likely to lead to the discredit of the organization implementing the projects, in addition to a discrediting of the technology. It is very important that the technology itself is not discredited as it may lead to significant delays in subsequent projects using the same technology in the same community or region.

2.3.2. Knowledge transfer

In blueEnergy there was a high staff turnover among the technicians responsible for manufacturing, installing and maintaining the SWTs. As a consequence knowledge transfer between technicians both local and international was an significant organizational challenge. Knowledge transfer to the end user was also a challenge and is addressed in subsection 2.4.3.

Knowledge was transferred primarily though participation and demonstration, with more experienced technicians showing inexperienced ones how to perform the tasks associated with SWTs. This was a viable strategy for maintenance, as regular maintenance trips were made to the communities. However, for manufacturing and installation, due to the low number of SWTs manufactured and installed it was not possible for all technicians to learn all the details associated. This created a circle in which manufacturing mistakes were repeated cyclically. The lack of documentation regarding manufacturing processes or the development of improvements for the SWT further emphasized the problem. Later, this issue was addressed by writing experience documents on the manufacturing, installation, maintenance and development of the SWTs. Despite this, such documents do not fully replace practical experience and as a result, it is recommended that at least one technician with experience with SWTs should be employed by the implementing organization at any one time with a six month handover period if new staff are employed, in order to ensure continuous transfer of the tacit knowledge required to manufacture, install and maintain an SWT.

Simplified procedures for the manufacturing processes of the SWT were also developed to address this challenge. However their introduction proved slow, as technicians were often reluctant to adapt these procedures and would complain that these kept changing. This challenge highlights that it is as important to document the processes—manufacturing, installation and maintenance—as to implement them. The often tight time frames of the projects meant that there was little time for documentation. This is seen as an important factor in the success of SWT projects and must be taken into account in planning.

2.3.3. Technicians motivation

There are not many organizations implementing SWTs. As a consequence, and organization that does implement SWTs is, both from a funding as well as human resources perspective, an attractive organization. Such attractiveness generates a steady flow of technicians, which may have caused technicians to rotate more often than desired.

Implementing SWTs in the RAAS can be, due to the need of constant maintenance, frustrating. Often technicians were sent to the community to perform a repair only to discover in a few months or weeks that the SWT needed further maintenance. The recurrence of lightning strike damage is also a factor contributing to this weariness. This is felt not only by the technicians but also by community workers, as they needed to handle the frustrations of the communities regarding their SWT.

2.4. Social

The context of the RAAS is from a social point of view complex. The communities of the RAAS in which SWTs were installed are ethnically diverse, their inhabitants have a low level of formal educational and often live in situations of extreme poverty. Social challenges are important and those that can most severely influence the implementation of SWTs, be it in the RAAS or elsewhere.

2.4.1. Assessment of communities

The lack of electricity was often perceived as the main challenge for the development of the communities of the RAAS. As a consequence, electrification was the focus of many development projects in the region. Nevertheless it is important to confirm that perception with the inhabitants of the communities through participatory diagnostics. Establishing a relationship of trust between the community and social workers of the organization promoting development projects is essential in order to obtain valid results in these diagnostics.

blueEnergy has performed participatory diagnostics in 9 communities of the RAAS. These have revealed a low prioritizing of electrification in their development priorities [30]. The top priorities being reliable access to clean water, education and health services. It is suspected that the rationale behind a community wanting a SWT was often not for electrification or even for development, but instead as a status symbol. In community meetings in Kahkabila it was observed that the members of the community would often mention the aesthetics of the SWT as an argument to keep the turbine. The need for a SWT in a community must be thoroughly assessed as installing a SWT in a community that does not prioritize it or its outputs highly leads with upmost certainty to the failure of the project.

2.4.2. Funding maintenance

Assessing the ability of the community to raise funds to maintain a SWT is a strong preliminary indicator of the sustainability of SWTs. While there was no legal obligation for performing maintenance on the SWTs, blueEnergy did so because the communities were not able to generate enough funds for the maintenance of their SWT.

The inhabitants of communities along the coast of the RAAS frequently live in situations of extreme poverty. The situation poses a significant challenge to the availability of funds for the maintenance of SWTs. In the community of Monkey Point, several attempts to collect maintenance funds were implemented. These involved collecting a fee from each household, charging a fee for the usage of the health center and promoting the organization of activities to raise money for the maintenance of the SWT. These attempts had initial success, however they all then faded due to internal conflicts within the community. As a consequence, the majority, of the maintenance expenses in Monkey Point were covered by blueEnergy.

There are several possible interpretations for the behaviors described:

- The community does indeed have difficulty raising money for the maintenance.
- The community can raise the money for the maintenance but does not do so because:

- blueEnergy has historically paid for maintenance operations, thus fostering a dependency culture, already prevalent in the RAAS.
- The community does not place any value on having the SWT in operation.
- The community has other priorities, e.g.: In Kahkabila a fund raiser was organized for a football event, but not for maintaining the wind turbine.

Connecting the SWT system to an income generating activity that generates sufficient economic benefit for the end user to offset the maintenance costs can be a success enabling factor for a SWT project. In the cases where there are clear signs that the community is not able to fund the maintenance of a SWT it should not be eligible to have one.

2.4.3. Community involvement

A key to the success of a SWT is proper maintenance, both preventive and corrective. The relative isolation of the communities made maintenance done by Bluefields based technicians expensive. A possible solution is to have maintenance done by community members. Due to the low level of formal education in the communities it was initially thought that this would not be possible and as a result, the maintenance was historically done by Bluefields based technicians with little help from community members. This contributed to the community members seeing the SWT as belonging to blueEnergy and not the community, leading to a decrease sense of ownership of the SWT further complicating raising funds for maintenance.

The community of Cuajinicuil provides a different example. From the inception of the project, the community members were involved in the manufacturing and installation of the SWT. This contributed not only to the community members' sense of ownership, but also gave confidence to the community members in handling the SWT. In Cuajinicuil, community members are able to perform almost all maintenance operations—including completely disassembling and assembling the turbine. The participation of community members in maintenance operations can be seen as a gauge of the value that a community place on their SWT [31].

The challenges mentioned above can be mitigated in several ways:

- Community visits adapted to the realities of the community:
  - Longer trip times: One to two weeks instead of an average of 3–4 days to enable a deeper understanding of the issues within each community.
  - Reduced number of trip participants, avoiding bringing new visitors for consistency.
  - Means of transport: Using the same transportation as the community members to build up trust through common practices.
- Reinforcement and adaption of the informal knowledge base of community members for the maintenance of SWTs
- Inclusion of community members in every step of the process: manufacturing, installation and maintenance.

Despite bringing an additional cost to the project, these measures ensure that trust is built between the organization implementing the SWT project and the local community. The increased initial costs—longer community trips and more training sessions—are expected to be offset throughout the life time of the project, as the community members are able to perform maintenance on the turbine themselves, thus reducing the need for maintenance trips. The cost offset is particularly stark for communities with a low level of access as shown in Figure 14.

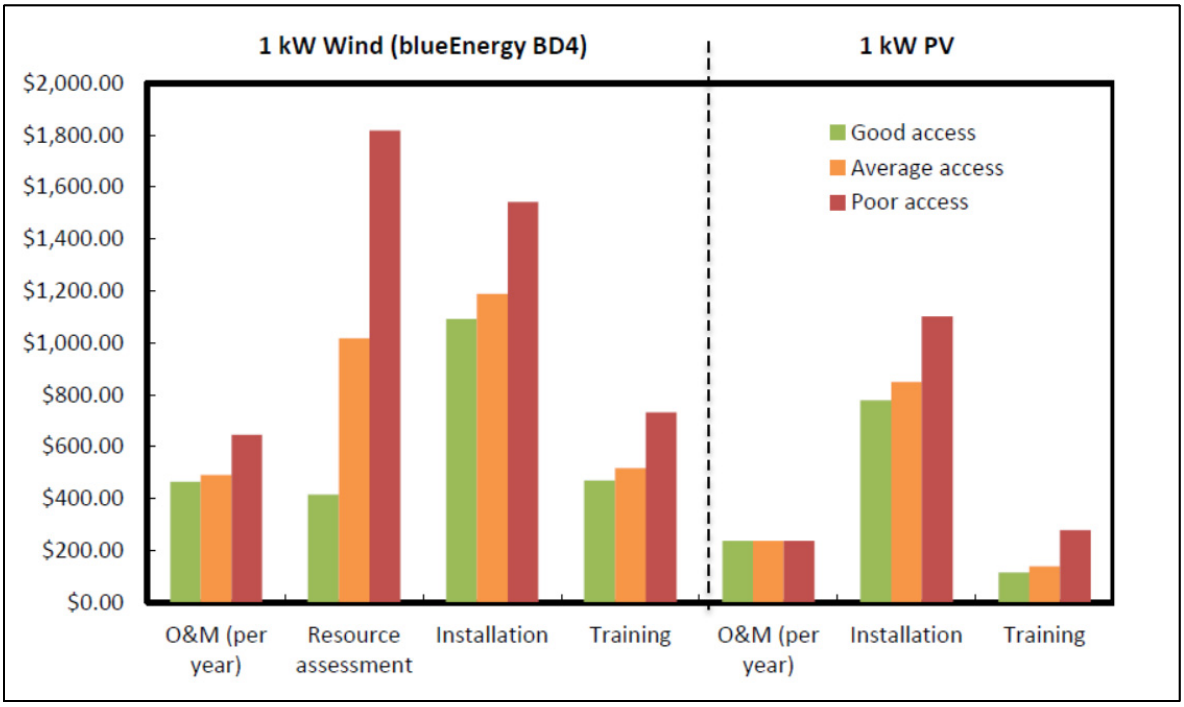

Figure 14. Influence of the level of access of a particular community on the transport dependent costs associated with a SWT system [11].

3. Results and discussion

The previous section highlighted the different challenges facing SWTs on the RAAS. Each challenge has a solution and the latter a cost. If the total cost of overcoming all challenges faced in a particular local context pushes the costs—both financially and socially—of generating electricity from SWTs above that of other viable options for power generation, then SWTs should not be employed.

On the RAAS it was not only the number of challenges facing SWTs, but also the multiplying effect of the interaction between challenges that made SWTs fail. Lightning strikes pose a hazard to SWTs independent of where they are installed. However, when the same SWT is installed in a difficult to access community, without a trained community technician then a long downtime is to expect. As a result the value that the community gains from the SWT is reduced, together with the community's willingness to raise funds for its repair. This will in turn lead to progressively longer downtimes and to the ultimate failure of the SWT project.

In contexts where only few of these challenges are faced—such as Scoraig [11] or Inner Mongolia [7]—the implementation of the solutions to the challenges can make SWTs be a viable solution for rural electrification. The following subchapters summarize the challenges and solutions presented in Chapter 2 and establishes a set of factors that influence the success or failure of SWTs in other contexts.

3.1. Technical

An Annual Mean Wind Speed (AMWS) of 4.5 m/s is regarded as the minimum threshold for the economic viability of SWTs. As a consequence, it is vitally important to correctly assess the AMWS at each installation site before introducing the technology. This assessment must take into account the effects of topography and vegetation, as these can improve or hinder the wind as well as diminishing the lifecycle life of the SWT. Flat and open environments with little vegetation should be favored over hilly, forested regions.

The environment in which the SWT is to be installed must not be corrosion prone. In temperate latitudes this is not a significant problem, even in salty and wet coastal environments such as Scoraig [11]. In the tropics, the added presence of heat and high relative humidity catalyzes corrosion.

The probability of a lightning strike hitting the wind turbine tower must be taken into account, as a direct strike will damage critical and expensive electronic equipment. Lightning strike safety guidelines must also be followed at all times and are to be taken as critical factors when choosing SWTs as a rural electrification technology.

The accessibility of the installation site must also be taken into account when assessing the feasibility of a SWT project. Transportation costs are associated with project activities such as installation and more importantly maintenance. An accessible project site not only leads to lower maintenance costs, but also foments more frequent maintenance, or a more frequent flow of system information towards the organization responsible for the SWT project. Conversely, a difficult to access installation site will impose high transportation costs which can make a project unsustainable and ultimately lead to a project failure.

Unsuccessful SWT pilot projects may lead to a loss of trust in the technology by the local population [32], which can lead to future difficulties introducing the technology in neighboring areas and even difficulties in introducing other technologies. This reinforces the need to correctly assess the feasibility of SWTs projects for the given implementation context.

3.2. Economic and organizational

Manufacturing, installation and maintenance costs of SWTs are highly dependent on the context, as is the available resource and as consequence the energy produced. A market assessment should be conducted to assess the influence of each of these factors and to compare SWTs against other viable options for power generation.

Consistency of manufacture is vital to the success of SWT systems. This consistency can be achieved by having well defined manufacturing procedures and requirements, together with a properly trained and motivated staff. Including staff on the decision process surrounding the manufacturing of the SWT contributes to staff motivation and often produces cost effective locally adapted solutions. Manufacturing in low volumes makes manufacturing equipment of consistent quality difficult due to the lack of knowledge transfer between employees and higher costs of materials.

Installing SWTs in clusters with an associated regional service center and local technician can have a positive impact as the added scale factor lowers the average maintenance costs and increases consistency of maintenance. Distance, and the associated cost, between the service center and the site should be taken into account. In some cases a network of service centers or a mobile service center might be the most appropriate solution.

The constant maintenance, both preventive and corrective, of SWTs is crucial to their success.

Maintenance must be performed periodically according to guidelines, using appropriate tools and equipment. These should be provided to end users. The end-users should be empowered by being trained as technicians, who are able to perform all maintenance procedures independently, unless the implementing organization's technicians have easy access to the site.

A functioning supply chain for the required manufacturing and maintenance materials is also an important factor. When necessary the supply chain should be created or strengthened, together with local partners in order to extend its benefits to other activity fields. These are aspects that a market assessment can evaluate.

3.3. Social

SWTs require a significant amount of maintenance. Successful implementation of the technology requires that the end users are able to generate enough revenue to pay for the maintenance of the system. If there is a real need and interest in the system, then allocating funds to the maintenance of the SWT system will not be an issue. Associating the wind turbine with an income generation activity for the end users also facilitates obtaining maintenance funds as there is a clear cost to benefit relationship.

The interest and potential of the end user to create and manage an income generating activity can be accessed through participatory diagnostics and discussions with the community. It is important to check if this interest and potential can be brought to fruition in the context of that community and region. This can be done by analyzing the supply chain and market required for the sustainability of the income generating activity within the community.

In order to be successful, SWT projects must be culturally appropriate, reflecting the reality of life within the context of the community and building upon existing skills, knowledge and practices. Organizations delivering the solution should adapt their practices to those of the community.

Even with favorable environmental climatic conditions and a reliable SWT, a rural electrification project will fail if the end users lack the need for and interest in the system. As a consequence the social interest and motivation is the most critical success factor for SWTs, alongside the creation of an income generating activity associated with the SWT.

4. Conclusion

Locally manufactured SWTs can, under certain circumstances, provide an appropriate and viable solution for rural electrification. However, due to the number and diversity of challenges facing the technology, an assessment of the viability in each new context prior to installation is essential.

Local environmental conditions, such as wind resource and climate should be assessed, together with the viability of other power generation technologies, an analysis of the technologies currently being used for electrification and the institutions engaged in their implementation. An assessment of local universities and technological schools, existing related industries and businesses, is also necessary as these form the base of the technological layer necessary to achieve consistency in the production of SWTs. Evaluating the current state of the supply chain for the manufacture and maintenance of SWTs is also an important step, as a strong supply chain can significantly improve the feasibility of a SWT project.

A participatory diagnostic of the community must first assess whether energy is a priority for the end users, if the community is able to generate the income necessary for the maintenance of the SWT and if there is the potential to create income generating activities associated with the SWT. The participatory diagnostic should also assess if the community has a deep interest on the SWT system as this can also lead to a sustainable system. A market assessment [33] covering all the aforementioned subjects should be conducted in any new region before any SWTs are installed. If both the market assessment and participatory diagnostic provide clear positive results, only then should a SWT based rural electrification project proceed. During the project execution, special emphasis should be given to communication between all stakeholders, and to documentation to ensure that knowledge is retained within the organization.

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Conflicts of Interest

Four of the article authors have worked or currently work for blueEnergy. The possibility of an active conflict of interest is however discarded as the organization is no longer using SWT in its projects.

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