Issues associated with the implementation of wind energy power generation in isolated and non-interconnected rural areas – case study

FRANCISCO D. MOYA CH.
School of Engineering, University of Santiago de Cali
Calle 5 # 62-00 Cali, COLOMBIA
francisco.moya00@usc.edu.co
Efrain Bernal[A], Jairo Montoya[B], José Luis Rubiano[C], Fabián Salazar[D], Andres Garzon[E],
School of Engineering, University of La Salle
Carrera 2 # 10-70 Cali, COLOMBIA
(A) ebernalal@unisalle.edu.co, (B) jamontoya@unisalle.edu.co, (C) jorubiano@unisalle.edu.co,
(D) fsalazar2186@gmail.com, (E) aogarzonp@gmail.com

Abstract: - Analysis of difficulties and issues related to the design, construction, transportation, installation and operation of two single-blade wind turbines type as part of a hybrid project to supply electrical energy to an isolated rural community in northern of Colombia are discussed in this paper. This study modeling aerodynamic forces, as well as the analysis the materials used in the construction stage, welding analysis and control systems. This investigation indicates the difficulty to provide stability of civil and mechanical structures of wind turbines without a complete assurance of installation. Most significant issues associated to the development this case including the lack of plan strategy and deficient supervision during construction stages.

Key-Words: - Electrical Renewable Energy Source, Polygeneration, Wind Energy, Wind Turbines, Rural Electrification, Wind Systems Modeling.

1 Introduction

Energy is clearly the key of the social progress in developing countries and a fundamental resource for the human well-being. For isolated and electrically non-interconnected rural communities, development is adversely affected by the lack of this vital service, thereby limiting improvements in quality of life, education, and human dignity. Providing electricity in isolated areas requires a local energy source which offers a stable, reliable, and economically viable supply. Renewable energy projects provides alternatives to improve life conditions through efficient use of natural resources and reduction of greenhouse gas emissions.

Sustainable power generation projects based on renewable energy is a promising option for populations who are not able to connect to the National Interconnected System (NIS) [1]. However, implementation, operation, and maintenance of renewable energy systems faces several challenges, for instance: a) concept design, b) engineering constraints regarding special installation and operation of the equipment, c) high costs and slow return on investment, and e) requirement to operate highly complex equipment. Problems associated with rural electrification in developing countries [2], suggests a need for better national coordination between the institutions involved in the development and implementation phases.

A case study of a hybrid project is presented in [3], which was undertaken to install a variety of technologies used for supplying electricity to an isolated population in northern Colombia. Despite the efforts, installation of two single-bladed turbines was unsuccessful as a result of several different causes. The fundamental problems are described in this article as an analysis in design, transport, assembly, construction and operation stages. In section 2, a brief description of the current state of Conventional Energy Sources (CES) in Colombia is provided. In section 3, the current situation of Non-Interconnected Areas (NIA) in Colombia is described. In section 4, the case study is detailed. In section 5, the problems resulting from the implementation of the project are described. In section 6, a structural and mechanical analysis of wind turbines is illustrated. In section 7, the results obtained are described. Finally, in section 8, the conclusions of the case study are presented.

2 Non-conventional energy sources in Colombia (NCES)

According to the, the recent approval of Colombian Law 1715 on May 13, 2014, regarding the regulation of for renewable energy integration to the National Electrical System (NES) [4], it referred to deployment of low carbon technologies in Colombia. The former law describes benefits derived from unconventional energy projects, such as reduction of greenhouse gas emissions, new jobs, promotion of scientific and technological development and research, and gradually reduction of the dependence on fossil fuel sources, and maximizing the country's sustainable development [5].

In Colombia, Energy Mining Planning Unit (UPME in Spanish) and Institute of Planning and Promotion of Energy Solutions (IPSE in Spanish), are government agencies which oversee the fulfillment of energy policies. One of important responsibilities of the mentioned agencies is proposing and incentivizing the use of renewable energy to provide energy solutions in No Interconnected Zones (NIZ). Similarly, the implementation of Renewable Energy Program (PROURE in Spanish) is expected to increase the participation NCES over a medium-to-long term timeframe compared to the total consumption of energy in Colombia (Table 1).

Tabla 1. NCES estimation 2015 and 2020

Participation	2015 (%)	2020 (%)
in NIS	3,5	6,5
in NIZ	20	30

Participation of renewable sources is around 4.4% of its total capacity in the NIS (14,559.05 MW), as shown in Table 2 [6]. Currently, the NCES diagnosis in Colombia is scarce and incomplete, since in many cases there are insufficient technical tools, budgets, or engineering labor. Therefore, more incentive and development are required of the regulatory framework concerning each type of technology. Taking into account that Colombia provides significant natural resources which could be potentially used in NCES projects, an adequate analysis is required to allow investors to deploy renewable energy projects in the country. Particularly in isolated zones of Colombia, the renewable energy projects development is very scarce.

Tabla 2. NCES in NIS, December 31 of 2013

Participation	MW	(%)
Small Hydroelectric Plant (SHP)	560	3,84
Cogeneration	66	0,45
Eolic	18	0,12

3 Isolated zones in Colombia

The electrical energy zones in Colombia have been divided into two types of areas: interconnected zones (IZs) and NIZ; the IZs are those have access to electricity services provided by the NIS, and the isolated zones are those without access to electricity services provided by the NIS [7]. These areas have, in general, high ecological importance, as they are characterized by their wealth of natural resources and great biodiversity; the largest percentage of all reserves and natural parks are found there. Public services are scarce and poor. There is a general lack of basic services like electrical energy, water, and sewage, and these areas have limited access to education services, health, potable water, and communication. The NIZs comprise approximately 66% of the country's area, including 17 departments, five departmental capitals, 54 municipal heads, and 1,262 municipal towns [8]. The highest percentage of NIZs with electrical energy are in the departmental and municipal centers, which generally have diesel generators and, in some cases, small amounts of hydropower; 96.3% of the generating capacity is from diesel [9]. In NIZ, electrical energy is expensive; in general, the price is twice that of the national average cost per kWh, and, low service hours are received; 99% of the rural areas have services for less than 6 hours a day. The cost of electricity varies from region to region and reaches up to 866 COP $ / kWh (referred to 2017) in San Andres Island and 786 COP $ / kWh in Leticia [10].

Most currency energizing projects proposed by the national government are focused on urban areas, therefore for these small population centers is necessary to find electrical energy solutions. The current energy management for NIZs based on large interconnection projects and the implementation of fossil fuels for local generation is not adequate and has serious environmental and social impacts. Interconnection projects result in huge damage to ecosystems, in addition to causing fragmentation and creating dependency on the NIS; moreover, these solutions are not efficient, due the large amount of energy lost on transmission processes. The generation of energy from fossil fuels causes major environmental impacts in the generation and transportation phases, and creates dependence on fuel supply.

4 Case study: Nazareth

Colombia has an estimated potential of 21 GW wind power only in La Guajira state. The use of wind power is appropriate in this region due the average annual density of wind energy, which is valued between 1000-1331 W/m2, being the highest in the country [11]. However, Colombia only has 19.5 MW wind power installed with an efficiency of 28%, therefore, only 0.4% of its theoretical wind energy potential is used [12]. Nazareth is a rural area of La Guajira with an average population of 2,000, including colonists and indigenous Wayuu people [13]. There is no accessible potable water, and electricity is supplied only from 5:00 pm to 10:00 pm, from a diesel fuel power plant. In cases when the fuel is depleted, power can be unsupplied for several days. To improve the Wayuu life conditions, the government, along with the support of international institutions, implants rural electrification projects, using the natural resources available in the region. The Polygeneration Park in Nazareth (PPN) [14], use different energy sources (solar, wind and thermal) to supply electricity to Wayuu people. Moreover, this project will help mitigate the environmental impact by reducing carbon emissions [15]. Since 2008 the government and the National Energy Finance (NEF), began the PPN implementation with initial investment of $ 1,350,000 USD in September 2009 [16]. In PPN two single-bladed wind turbines with oscillating movement (first prototypes installed in the world) were installed. PPN have two three-phase wind turbines of 100 kW and 45% efficiency, a height of 20 m and a raceway 25 m each one. PPN has also photovoltaic systems composed by eight two-axis solar trackers, each generating 12.5 kW (the solar panel peak power is 220 W per module that could generate 120/208 volts of electricity with three-phase voltage, an efficiency of approximately 25%), generators with fuel liquefied petroleum gas (LPG), and diesel. Furthermore, demand management, energy management system, system balancing, battery banks and accessory synchronization were implemented, to ensure continuous service 24 hours per day. PPN is a center of innovation, which would be used to evaluate different electric generator technologies, and also the performance of low voltage network with twisted pair cabling, lighting, connections, prepayment meters, and internal installations in town of the Nazareth rural area.

The installation of wind turbines to produce electricity in very isolated regions is a god solution, but single-bladed wind turbines do not perform well, and also supply only 100 kW each. To increase the watts, is necessary to incorporate several wind turbines, which create a major capital expenditure. These pilot technologies has high-risk of failure and high cost of implementation, taking into account that the success or failure of this kind of projects depends on government policies and the way that the technology is delivered to users [17]. The report in [18], identifies factors that can affect the success or failure of renewable energy projects, specifying that the development of renewable energy technologies requires support from research, until the creation of a strong and competitive renewable energy industry has been established.

5 Problems in PPN implementation

In 2010, additional work was carried out related to the transport, installation, commissioning, and testing for the civil construction, electrical installation, software, and control systems required to start up the wind turbines. During the month of April 2011, the project started the testing process, where certain failures in both the Polygeneration system integration and operation of the wind turbines were found. In January 2012, the IPSE received a pilot project report from the contractor; this included a summary of evident complications of civil and mechanical nature. Thus there was a need for technical and economic evaluation of the damages found, information that would allow the IPSE to define required action to protect against any possible claim to the contractors responsible for implementing the project. An expert assessment of this would include specific laboratory tests that allow economical assessment of the damages. The IPSE hired the University of La Salle (ULS), located in the city of Bogotá (Colombia), to perform such work, based on one of the acclaimed functions of the university to provide "cooperate, technical, administrative and financial support to strengthen the research for the development of projects in areas related to renewable energy and implementation of energy solutions, researching in the area of Generation, Transmission, Distribution and Marketing of energy in the country". Thus, the ULS supported, from a technical point of view, the following activities: technical checks of civil and mechanical damages caused during the execution of the PPN, estimating the value of such damages. In order to accomplish this, the ULS met a group of electrical, mechanical, civil and automation engineers to perform the following tasks:

Task 1: wind turbine mechanical structure analysis:

1. Check the structural design and layout of the original armor, and other as-built layouts available, to confirm that the thickness and quality of the concrete, along with existing armor, match or exceed the stress and deformation requirements and expected functionality.
2. Review the current loads in detail and compare with design loads.
3. Identify and determine civil and mechanical damage in existing wind turbines.
4. Perform static and dynamic stability analysis of mechanical and civil systems, from the information and results of tests carried out.

Task 2: wind turbine base and rotation track analysis:

1. Review the current state of the construction of civil works.
2. Take soil samples and perform laboratory tests to determine if the sedimentation requirements of the work are met.
3. Analyze the plasticity index of the material base support structures to determine compliance with the requirements.
4. Analyze the slopes generated during construction, to evaluate its stability.
5. Analyze rainfall patterns and historical runoff to verify the effectiveness of drains constructed.
6. Perform nondestructive testing to determine the presence of internal voids and fissures and the depth of penetration of visible fissures on the surface.
7. Carry out tests to determine the resistance of existing concrete.

The presence of fissures in the wind turbine structures led to a thorough evaluation of the mechanical design, to determine the root causes and consequences of the damage. To perform this analysis and comply with the tasks described, it was necessary to perform some of the following technical activities: aerodynamic force calculations, material analysis, structural finite element analysis, welding analysis, assembly analysis, in addition to and structure imaging and hydraulic circuit analysis for required control and power calculations. The following paragraphs illustrate some of the results of these studies.

6 Structural and mechanical analysis of single-blade wind turbines

Single-blade wind turbine motion consists of the following elements: supporting structure, nacelle, blade, slow shaft, gear box multiplier, pendulum, three phase electric AC generator, measurement system (anemometer and wind vane), and (hydraulic and electronic) control system, as illustrated in Figure 1. The wind turbine transforms wind energy into electricity by capturing the wind kinetic energy through the blade and transforming it into mechanical energy [19].

6.1 Study and modeling of aerodynamic forces

The aerodynamic forces analysis exerted on wind turbines and to the determination of the strength requirements and functionality of the equipment, a theory of wind flows was used, to calculate the energy stored in a fluid per unit volume as expressed in Equation 1.

$$E_k = \frac{1}{2}\rho V^2$$

Equation 1

Where ρ is the fluid density (kg/m3) and V is the fluid speed (m/s). The power [W] available in the wind before passing through the turbine (see Figure 2) is represented by Equation 2, as follows:

$$P_v = \frac{1}{2}\rho A V^3$$

Equation 2

Where A is the rotor swept area (m2).

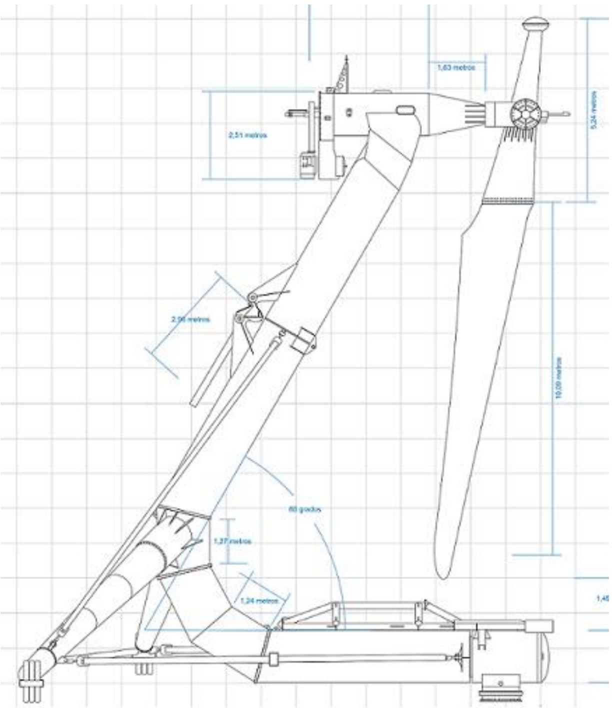

Fig. 1. Single-Blade Wind Turbine.

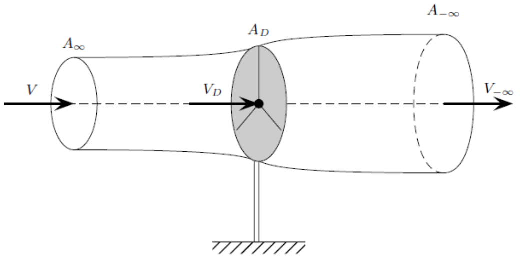

Fig. 2. Flow in a wind turbine (Momentum Theory) [19].

For mass conservation, the input and output of flows must be the same. Additionally, a differential pressure is immediately generated before and after the blade. With these concepts, and applying the Bernoulli energy equation, it is possible to obtain Equations 3 and 4, with which the force (FD) and power (PD) generated by the wind on the blade are calculated.

$$F_D = 2\rho A_D V^2 a(1-a) \qquad \text{Equation 3}$$

$$P_D = F_D V_D = 2\rho A_D V^3 a(1-a) \qquad \text{Equation 4}$$

Where ρ is the air density, AD is the blade swept area, V is the upstream wind speed and ɑ is the wind speed loss coefficient. Using the Betz coefficient (Cp) and maximizing its value, ɑ is obtained to equal 0.33. With this value, the Betz coefficient magnitude is 0.59, that only a part of the available force is used for power generation, is obtained:

FD = 11,5 kN
PD = 100,02 kW

This power value calculated using the above procedure is a metric of the wind turbine's design capacity. A prototype of the single-blade wind turbine implemented in this case study has a structure made of a central tubular body with wall thickness of 10 mm that supports the entire upper assembly rotation, two supporting legs for the central body, and everything bounded by five stability straps, as illustrated in Figure 1. To achieve the wind turbine model and strength study, it was necessary to carry out the characterization of the materials used in the structure. Because of the lack of knowledge about the construction materials of the structure, physical samples were taken and analyzed through X-ray diffraction that identified the steel used in the building structure .The composition is shown in Table 3.

The high chromium and nickel found values demonstrated that the construction material corresponds to an austenitic stainless steel, which has the mechanical properties shown in Table 4.

Table 3. Materials composition results.

Element	Percentage
Aluminum, Al	<= 0.20 %
Carbon, C	<= 0.050 %
Chromo, Cr	19.5 - 23.5 %
Copper, Cu	1.50 - 3.0 %
Iron, Fe	>= 22.0 %
Manganese, Mn	<= 1.0 %
Molybdenum, Mo	2.50 - 3.50 %
Nickel, Ni	38.0 - 46.0 %
Silicon, Si	<= 0.50 %
Sulfur, S	<= 0.030 %
Titanium, Ti	0.60 - 1.20 %

Table 4. Austenitic Stainless Steel mechanical properties

Strength, Ultimate	590 MPa a 550 °C.
Yield strength	220 MPa.
Elongation at break	45% a 550 °C.

The study evidenced material brittleness owing to the elongations caused by weight bearing. Thereby, it was necessary to perform a wind turbines structural analysis by developing a 3D model in SolidWorks, which is illustrated in Figure 4. This model was exported to the ANSYS-V11 software, where a refined meshing was modeled, Figure 5, to conduct a stress and strain analysis using finite elements, accounting for the structural component weights and forces generated by the wind (Equations 3 and 4). Figure 6 illustrates the force resulting from the weight vector related to the structural elements and the force wind vector, where the gondola was located (generator and blade housing). In this case, it had a value of 70 kN and a vertical deviation of 5.7°. Figure 7 shows the maximum stress point location, which was located on the outside elbow, with a value of 432 MPa. Figure 8 illustrates the structure stress values under full load conditions. The resulting maximum strain caused by the applied forces in the structure was 0.084 m in a vertical plane and was present at the top of the structure. Regarding the structure safety factor, the simulation results showed a value less than one in the internal and external elbow area, reaching a minimum value of 0.577 as shown in Figure 9. This indicates that the applied load was greater than the yield strength of the material, meaning that it was subject to plastic deformation. In a mechanical structure, curved areas are high stress concentration regions. The elbow revealed three fissures, showing that such high stress concentration regions were not considered in the design. Maintenance or replacement of affected parts was not sufficient to ensure proper operation of the wind turbines because the structural damage and inadequate generator performance was not only related to the occurrence of fissures.

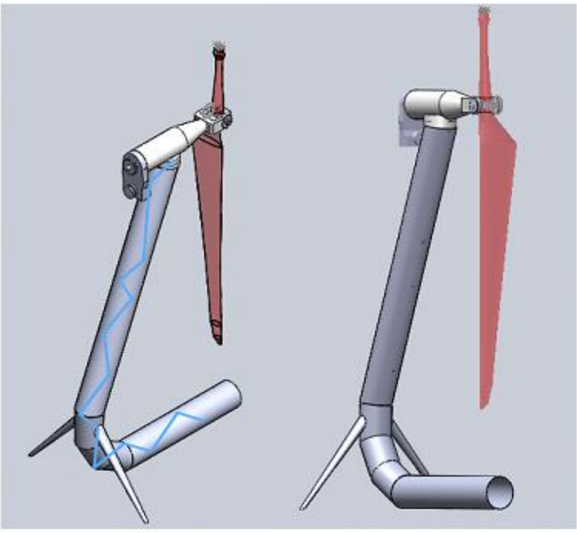

Fig. 4. SolidWorks 3D model.

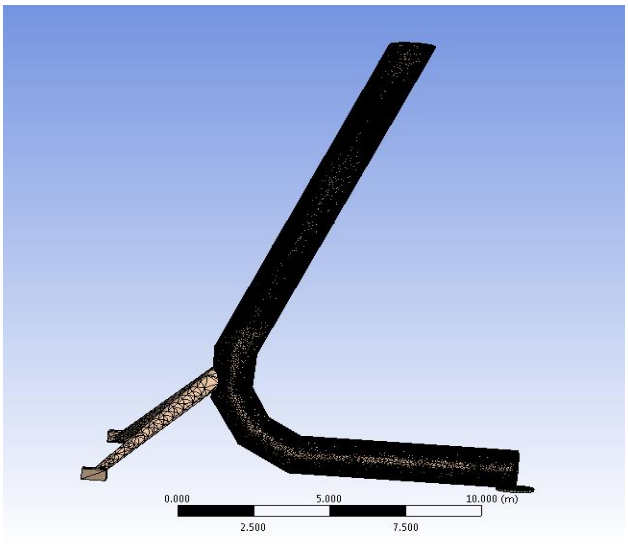

Fig. 5. Refined meshing model.

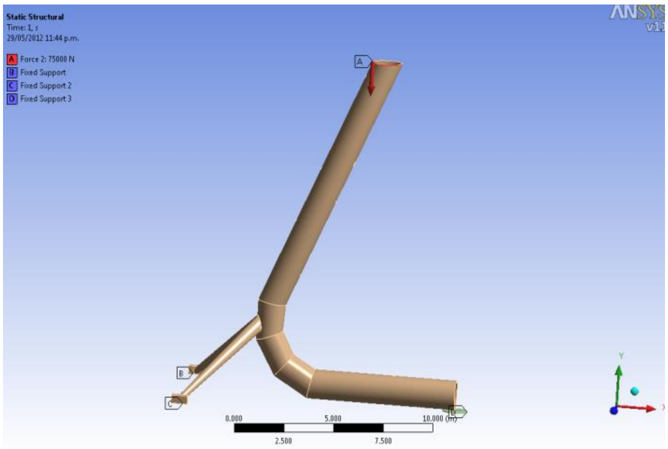

Fig. 6. Resultant force on the structure.

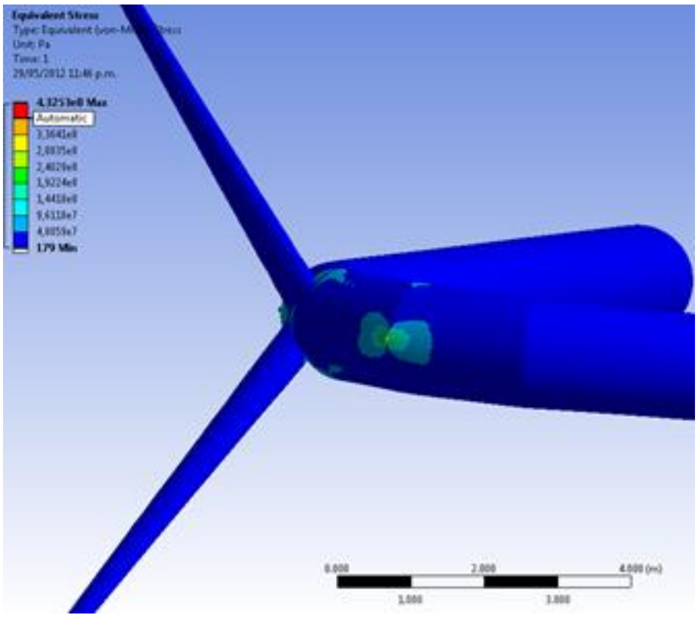

Fig. 7. Location of maximum stress point.

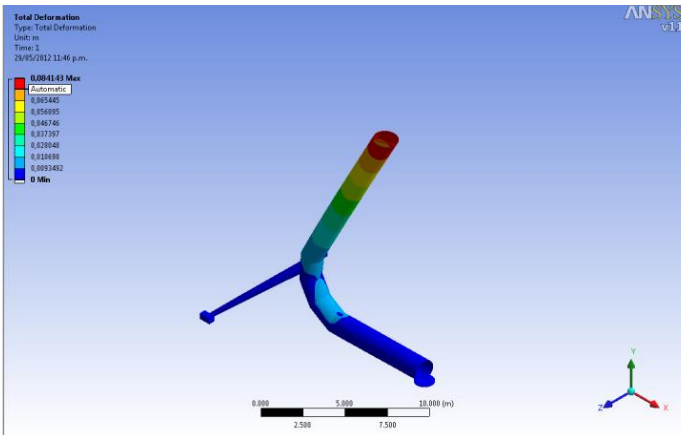

Fig. 8. Structure strain.

6.2 Welding analysis of wind turbine structure

Visual inspections showed flaws in the wind turbines manifested as fissures on both sides of the structure and on the outer elbow region. The welding filler material broke on the inner elbow region. Conducting a detailed weld inspection of the whole generator assembly identified deficiencies in the welding application procedures, evidenced by splashing in the junction areas, thickness irregularities in the welding beads, lack of weld penetration due to a deficiency in the applied current, and failures in the welded joint. The evidence of these fissures was the main reason to stop the wind turbines operation, these generators have not powered beyond the initial testing. This task provided strong evidence about the severity of the structure damages. Figure 10 illustrates large-sized fissures, showing that the material used in building the structure (austenitic steel) was clearly not the right choice for the wind turbines.

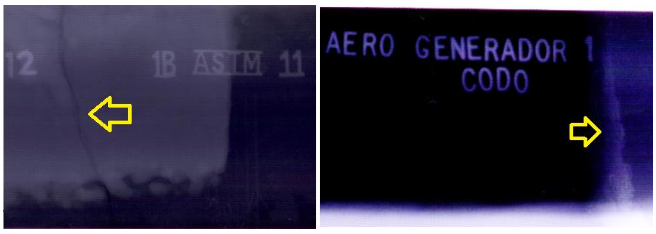

Fig. 10. X ray samples performed in the wind turbines structure.

6.3 Wind turbine assembly

Non-conventional energy sources systems projects is a promising alternative to supply power to isolated communities, however, several aspects should be taken into account in order to reduce possible negative impacts to equipment in transportation from Spain (origin) to isolated locations in the north of Colombia. Furthermore, throughout the investigation of the assembly, there were several incidents (some based on readings from logbooks of the project), which could make evident the lack of experience of the project staff. In order to illustrate about the incidents during installation. In addition, mistakes in hydraulic system installation were found include valves, actuators, and accumulators being located in series (together), thereby increasing the risk of fire, electrical, and mechanical failures.

6.4 Image analysis

This situation required use of footage from the security cameras to analyze the wind turbine operation and movement. It was evidenced through the videos that the blade movement generated an oscillating motion of the whole wind turbine structure, creating a horizontal displacement and strong vibrations. It was necessary to process all recorded images using "VISION" software from National Instruments. Image processing allowed estimation of the average horizontal displacement to be 0.42 m. This was caused by the dynamic loads generated by the wind speed variability and the structure design, whose curved shape facilitated the oscillation movements.

6.5 Wind turbine control system

The control system must be capable of repositioning and braking the turbine blade when the wind velocity exceeds the design speed. This system is composed of an electronic part and a hydraulic actuation part. The latter consists of 4 sub-systems that control the wind turbine movements. These include the pitch circuit for adjusting the blade position with air speed changes, the blade-break

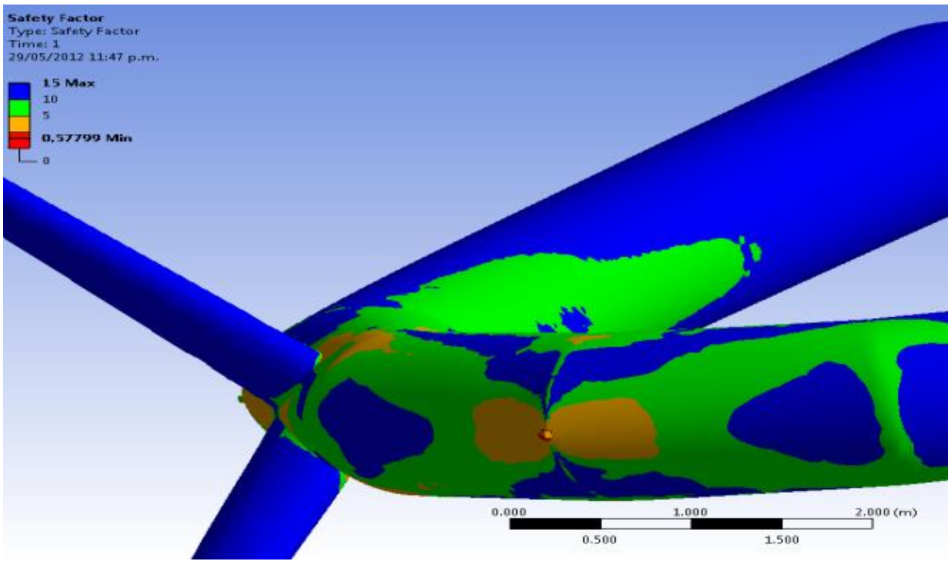

Fig. 9. Structure security factor.

circuit, the tilting circuit for the gondola and blade maintaining, and the steering circuit for positioning the wind turbine optimally based on the wind direction. Evaluation of this control system revealed some problems, the most important listed below:

The recorded ambient temperature indicated normal operating conditions; however, the high temperatures inside the wind turbines at certain times of day and year in the PPN represent a risk for the appropriate operating temperature of the hydraulic fluid and its viscosity.

a) The fuel storage tank volume (100 L capacity) fell short of the appropriate oil storage requirement by at least 50 L.

b) Improper installation in which valves, accumulators, and actuators were located in series was found. Encountered support accessories were incapable of bearing the element loads and providing the required degree of motion. Devices to support those elements did not provide the necessary security for the hydraulics system. The risk of fire, electrical failure, or mechanical failure was high under these circumstances.

c) The hydraulic control system that should automatically work through the programmable logic controller (PLC), never worked appropriately, thereby presenting constant failures in the electronic and communication systems.

7 Results analysis

The developed study, found several mistakes in the PPN wind turbines project, listing the major ones below:

- The lack of experience and staff professionalism responsible for the wind turbines assembly, led to: welds poorly done, errors in moving the equipment to the PPN and assembly were factors that contributed to the presence of structural flaws in the wind turbines
- The material thickness of the structure, identified as austenitic stainless steel, had yield strength of 220 MPa, which was not adequate to bear the maximum real stresses. The calculated safety factor is 0.50, which was too low for expected operating conditions.
- The wind turbine design caused a reciprocating oscillatory movement of the entire structure, generating a gondola horizontal displacement up to 0.42 meters. This movement also generated strong vibrations throughout the structure, threatening its stability and posing a constant risk of destruction due to resonance.
- The electronic control system worked improperly, thereby hindering the wind turbine optimal position with respect to wind flow and reducing the wind turbine efficiency. Additionally, the hydraulic system storage tank did not have the proper size for their functions.
- Although the civil engineering studies are not described in this paper, they can be summed up as follows: soil samples showed that they did not fulfill the sedimentation requirements, nor it has the appropriate plasticity index for the wind turbines base support material during the turbines operation forces. Furthermore, it was found that the concrete bases of the turbines do meet neither the current standards nor the slopes generated during construction threatening the stability of the equipment. Also were found flaws in the drains design and construction. Non-destructive tests conducted on the concrete structure that holds the turbines determined its poor mechanical resistance, and this explained the presence of visible fissures on the construction surface.

8 Conclusions

Since 1994, the right to access to basic public services has been constitutionally established with Laws 142 and 143, where Article 3 of Law 143 elaborates on this as “achieving coverage of electricity services to the country’s different regions and sectors in order to ensure the basic needs of the low-income users in rural areas, through various public and private provide of this service”. However, there are still approximately two million people living in NIZs that are still waiting for continuous power supply 24 hours a day (almost half a million of them without any power supply), and in good technical quality terms legally established in accordance with the relevant regulations. Cases such as the one analyzed in this paper illustrate the severe factors that may arise in attempting to enforce such laws, which seek to improve the adverse living conditions of thousands of people including the Wayuu. Below are listed the most important mistakes in the PPN implementation:

1) There was an evident a lack of research prior to project execution, including the absence of detailed planning by the entities engaged in the project, which triggered a combination of factors that led to failure in effectively providing wind energy based electricity supply to the region.

2) The inappropriate selection of technology was evident since equipment still under development is not the best choice to be implemented in isolated regions, where the improvement process becomes highly expensive and extremely slow because of the

drawbacks from traveling vast distances across aggressive geography.
3) Premature purchasing technology "turnkey" (turn-key agreement) by the Colombian government was revealed, showing the desire to disperse public funds.
4) There was a clear lack of auditing by qualified staff in different areas to track and support the project in all phases, from initial research through the processes of design, demonstration, construction, transportation, installation, operation, and maintenance.
Taken into account all the factors described in this study, the ULS manifested that is not possible to ensure the wind turbine structure stability during operation, primarily indicating a potentially catastrophic elbow fracture and consequential total destruction of turbines resulting from the stress concentration and reduced safety factors. Therefore, the IPSE was advised against starting up these generators, thereby leaving them useless, doomed to oblivion and oxidation, exposed to extreme weather and salinity, sandstorms, and the relentless sun.

The Colombian government must engage through the IPSE and other relevant entities, to take legal actions against with contractors involved in the project. The costs that the IPSE may have to incur in the event that they have to perform the work again, considering the effects of civil and mechanical additional costs such as total value of the contract settlement initially carried at present value, demolition of buildings, removal of turbines, transportation of debris and non-recoverable materials, disposal of debris and non-recoverable material, amongst others could easily exceed twice the initial investment.

Unfortunately, only the community is affected for these mistakes. At the beginning of the project, the Colombian government announced with great fanfare the power supply for 24 hours a day, and Wayuu natives look with hope to the fulfillment of this promise when they are passing by front of wind turbines in the middle of a forgotten region. Unfortunately, Nazareth continues to maintain high indicators of extreme poverty, while remaining confronted by factors that worsen their situation such as the recent heat waves and high temperatures that result from the current climate changes.

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