Hybrid Electrical Generation for Grid Independent Oil and Gas Well Fields

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ABSTRACT

In Perú today, fossil fuels including petroleum, diesel fuel and natural gas are used to produce electrical energy for oil field extraction purposes. Due to their remote geographic locations, oil and gas fields are not linked to the national interconnected electricity system (Sistema Eléctrico Interconectado Nacional or SEIN). Therefore, high investment costs are required to produce electricity in their remote locations.

Wind power generation is a mature technology used worldwide. Perú has a substantial potential to produce electricity using wind turbine generators. Evidence of this includes the county's 164 MW of installed capacity, distributed among four operating wind farms that provide power to the electricity market. In 2018, three additional wind parks are expected to be commissioned. They will add another 162 MW of pollution-free energy, in total representing 3.8% of the power supplied to Perú's national power grid. The purpose of this article is to present the research that assessed the implementation of a hybrid wind-thermal natural gas system to provide electrical power for the Block X-Talara oil field and estimate the reductions in fuel consumption and CO_2 gas emissions.

USING WIND POWER FOR OIL AND GAS PRODUCTION IN PERU

The subject of this article is an oil field (Block X) located in the El Alto district, province of Talara, region of Piura in northwestern Perú. The El Alto Thermal Plant (TP) operates independently from SEIN and produces 8.3 MW of electricity using nine single cycle generating sets. These use internal combustion engines fired by natural gas produced in the oil field at a charging factor of roughly 50%.

According to studies developed by the Ministry of Energy and Mines of Perú (MEM, Spanish acronym for Ministerio de Energía y Minas), Piura has a total wind potential of 17,628 MW with 7,554 MW usable. This research considers the design of a hybrid wind and thermal natural gas system for electricity generation. An optimally sized wind park would be connected to the power grid of the oil field with a possible interconnection to SEIN, enabling excess electricity to be sold. This wind park will operate together with the El Alto TP. The available power resources (both wind and natural gas) in the oil and gas field can be optimized, thus reducing the cost of electricity, fuel gas consumption, and CO_2 emissions. It will effectively provide the electricity needed for the oil field.

Using the oil field electricity demand requirements (5.0 MW peak demand / 4.2 MW average demand), its distribution of electric charges, the current architecture of the oil field's power grid and DIgSILENT software, scenarios with different combinations of power supply were developed for the El Alto TP (as base charge) and wind power (as backup source). These scenarios were analyzed by means of electrical transient stability and reliability studies. The results confirmed that a hybrid wind-thermal system with a maximum penetration of wind power of 14.3% with a minimum of 3.75 m/s (12.3 feet/second), offers the stability and reliability required for the power supply of the Block X field. The data used for the hybrid system assessment included the wind data 4.88-7.01 m/s (16-23 feet/second) for the oil field's zone, the electricity demand requirements, the maximum wind power penetration of 14.3%, the current electricity production costs (0.139 U.S.$/kWh, including fuel gas), the total investment (U.S. $3.96 million), and the projected operation and maintenance costs of the wind systems. The optimal configuration of the hybrid system yielded a reduction of 11.2% in electricity production costs, a 36.4% reduction in CO_2 emissions (equivalent to 6,633 tons of CO_2/year) and a 24.2% reduction in fuel gas usage.

The results indicated that the hybrid wind-thermal system as proposed is an alternative for electricity generation for the onshore oil and gas field on the northwest side of Perú. The economics of developing electricity generation infrastructure in the country using wind technologies are encouraging.

RESEARCH GOAL AND OBJECTIVES

Research Goal

My goals were to assess the implementation of a hybrid wind-thermal natural gas system to supply electrical power for the Block X-Talara oil field (Figure 1), and to reduce natural gas consumption and CO_2 emissions.

Objectives

- To assess the present condition of natural gas consumption for the generation of electricity and the number and duration of the interruptions in the power supply of the Block X oil field.
- To determine the optimal operation of Block X oil field's power system with the implementation of a hybrid wind-thermal system. For this, the hybrid optimization model for electric renewables (HOMER) software was used.
- To assess Block X's power system stability with the implementation of a hybrid wind-thermal system. For this, DIgSILENT Power Factory software was used.
- To assess the reliability of Block X's power system with the implementation of a hybrid wind-thermal system. For this, the DIgSILENT Power Factory software was used.
- To show the reduction of natural-gas consumption as fuel gas, of CO_2 gas-emission production from power generation and the interruptions (outages) in the power supply.
- To show that it is possible to achieve an equivalent cost reduction of auto-production of electricity (U.S.$/kWh) using wind power as an alternative source for electricity generation.

APPROACH AND FORMULATION OF THE PROBLEM

The main electric charges of the Block X oil field are asynchronous three-phase electric motors with variable power between 5 to 75 hp. An electrical supply of 460 volts is used to activate the beam pumping unit for more than 2,100 producing wells located throughout the oil field in an area of more than 47,000 hectares (470 km^2) that form small and medium charge groups of roughly 80 kVA. This oil field continuously produces 11,000 barrels of petroleum and 15.5 million of standard cubic feet of natural gas each day. Nevertheless, the field's beam pumping units have been adversely affected by interruptions in the power supplied by its El Alto TP.

Due to increased drilling activities, the addition of new producing wells (many of them remote from the existing wells), and the volume of fluids being processed, the consumption of natural gas to produce electrical energy has increased. This increased consumption by natural gas-fired generating sets with internal combustion engines has reduced the volume of natural gas available for sale to third parties.

Interruptions in the electricity supply have increased due to the theft of electric copper cables, periodic voltage drops and power losses within the distribution system. The extensive length of the distribution networks (214 km) continues to expand as producing wells are added to the system.

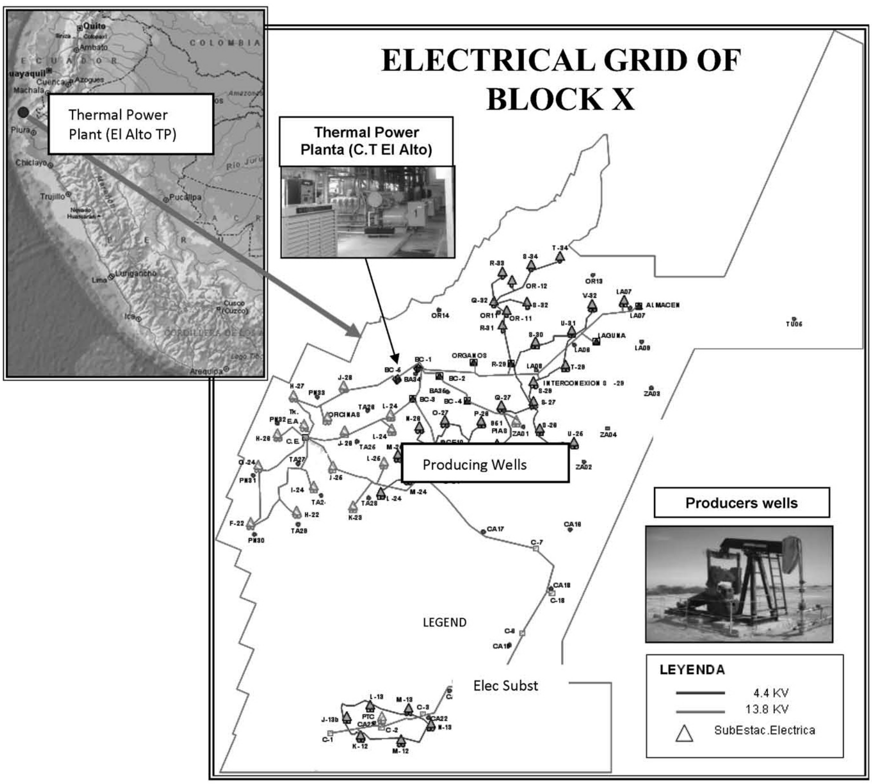


Figure 1. Geographical location of Block X oilfield (study zone).

HYPOTHESIS

General Hypothesis

The implementation of a hybrid wind-thermal natural-gas system in the Block X-Talara oil field will enable a reduction in the amount of fuel gas required for the supply of electrical power.

Specific Hypotheses

H1: The present consumption of natural gas for electricity generation is significant and the number and duration of interruptions exceeds the normal conditions.

H2: The optimal operation of the power system with the implementation of the hybrid wind-thermal system promotes reduced natural-gas consumption.

H3: The assessment of the stability of the electrical power system with the implementation of the hybrid wind-thermal system indicates that the system is stable over time and recovers quickly before fault conditions.

H4: The assessment of the reliability of the power system with the implementation of the hybrid wind-thermal system ensures reduced electrical power outages.

THEORETICAL FRAMEWORK OF THE RESEARCH

Hybrid Energy Systems

The increasing demand for energy and its associated environmental concerns have awakened interest in the development of hybrid renewable energy systems for electricity generation. Wind and solar energy generation potentials are dependent on the weather conditions. There is no single renewable energy source available in the region capable of supplying energy economically and reliably. Combining multiple energy sources can be a viable way to achieve reliable and marketable solutions [1]. With the combination of various energy sources it is possible that power fluctuations will occur. To mitigate or possibly eliminate these fluctuations, energy storage systems such as batteries can be used [2].

Hybrid renewable energy systems are widely used for electricity generation in locations not connected to power grids. This is due to improvements in renewable energy technologies and the higher cost of petroleum fuels delivered to remote locations. An electricity generation system that uses a combination of different sources has the advantage of electrical supply balance and stability [3]. Typical hybrid renewable energy systems might include combinations of solar, wind energy and hydropower. Hybrid systems might also combine energy sources such as wind-diesel, diesel-battery-wind, photovoltaic-diesel-wind, photovoltaic-diesel-battery, photovoltaic-diesel or photovoltaic-diesel-battery [4].

Numerous publications describe the optimization of systems using one type of renewable energy source. Systems with solar energy and thermal energy storage with photovoltaic systems are one example [5]. Complex hybrid energy systems are optimized (simulated) by means of computer programs due to availability and improvements in computer software.

Computer modeling allows the optimization of various economic and engineering parameters that are considered in order to plan, design and construct a hybrid energy system. In particular, computer simulations can be used to perform feasibility studies of new systems. These simulations can also be used to diagnose problems that might occur during system operation. Research on the use of computer modeling has been performed [6,7].

A detailed analysis of Saudi Arabian wind data was performed to assess wind energy potential in five coastal locations. Rehman et al. estimated the cost of energy generation in 20 locations in Saudi Arabia by assessing their net present values [8]. Rehman and Halawani presented statistical characteristics of wind speed and daytime variations [9]. Autocorrelation coefficients that allow matching the actual daytime variation of the hourly average wind speeds were determined. They also calculated the Weibull parameters (a continuous probability distribution) for 10 locations and found that the wind speed was well represented by the distribution function.

Rehman et al. conducted an economic feasibility study of an existing electric grid for remote location of 750 inhabitants which used a diesel thermal plant—adding wind turbines reduced diesel consumption and environmental pollution [4]. The Hybrid Optimization Model for Electric Renewables (HOMER) model was used as a dimensioning and optimization tool. This software contains a series of energy components and evaluates the appropriate options based on price and availability of energy resources.

Electrical system reliability is important. Reliability is defined as "the probability that a device carries out its purpose properly for a period of time under the foreseen operating conditions" [10]. Several reliability indexes are introduced in the literature [11,12]. Some of the most common indexes used in assessing the reliability of generation systems are the loss of load expected (LOLE), the loss of energy expected (LOEE), the expected energy not supplied (EENS), the loss of power supply probability (LPSP) and the equivalent loss factor (ELF). The ELF is considered as the primary index of reliability. The ELF index is the ratio of effective hours of load interruption for the total number of operating hours. It contains information on the number and magnitude of outages. In rural areas and stand-alone installations, an ELF <0.01 is considered acceptable.

APPLIED RESEARCH METHODOLOGY

The research performed is analytical and considers the descriptive, explanatory and co-relational levels. It uses 2011 and 2012 data for the analysis period using the following units of analysis:

- Present electrical system of the Block X oil field located in Talara.
- Natural gas electrical generators which are located in El Alto TP of Block X.
- Availability of natural gas in the oil field for electricity generation.
- Electrical motors (loads) that activate the beam pumping units (for extraction of petroleum and gas).
- Wind resources available in the study area of Talara.
- Previous electrical studies (stability, reliability, load flow, shortcut, harmonics, among others).
- Wind technology available in the market.
- Historical record of the number and duration of interruptions in the present electrical system.
- The structure of the scientific research model used (see Figure 2).

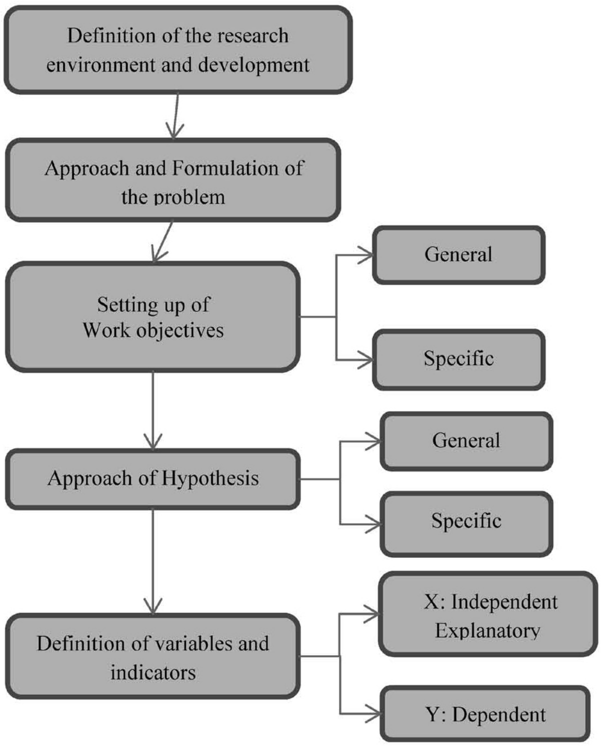


Figure 2. Structure of the research methodology.

The independent or explanatory variable (*X*) is the "implementation of a hybrid wind-thermal system." Its indicators are:

X1 Wind potential available in the study area

X2 Dimensioning of the hybrid wind-thermal system

X3 Optimal location of the wind generators

X4 Investment, operation and maintenance cost of the hybrid wind-thermal system

X5 Stability of the electrical system with the commissioning of the hybrid wind-thermal system

The dependent variable (*Y*) is the "reduction of the natural gas consumption for the electricity generation and reduction of the interruptions in the power supply of Block X oil field." Its indicators are:

Y1 Reduction in natural-gas consumption for electricity generation.

Y2 Reduction in operating costs (operating hours) of the gas generating sets (thermal generation)

Y3 Increase in the reserve margin available in the electrical system

Y4 Reduction in the number and duration of interruptions in the power grids (operational reliability)

TOOLS USED

Table 1. Tools and techniques used in the study.

Name	Type	Description
DIgSILENT PowerFactory	Software	Software for electrical power systems applicable to generation, transmission, distribution and industrial-system studies. Used in this work for the development of the following electrical studies: • Transient stability analysis • Electrical reliability analysis
HOMER (Hybrid Optimization Model for Electric Renewables)	Software	Most used optimization models for the design, modeling, optimization and feasibility analysis of hybrid electrical systems based on renewable energies, developed by the National Renewable Energy Laboratory. Its algorithm is based on three main tasks: • Simulation • Optimization • Sensitivity Analysis
Database of wind measurements in Talara (CORPAC S.A).	Field research	From the weather station of CORPAC, installed on Air Base Talara.
Database and technical documentation of Petrobras Energia Perú, S.A (CNPC Perú, S.A at present)	Documentary investigation	Monthly production reports. Monthly electrical autogeneration reports Records of natural-gas consumptions Records of electrical energy consumption Electrical faults statistics Electrical faults reports Operation daybooks
Delphi technique (Questionnaires and interviews)	Field research	Judgment of author Judgment of technicians and researchers of Universidad Nacional de Ingeniería

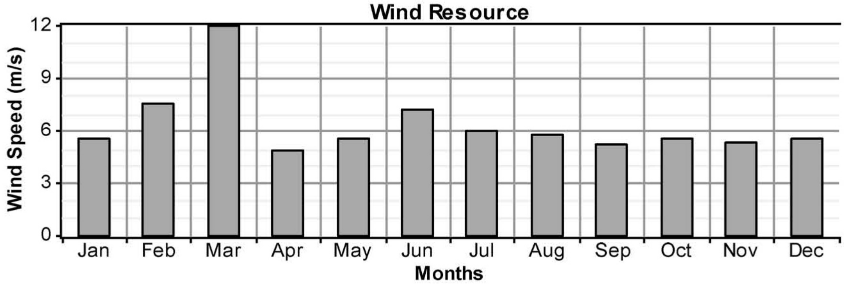
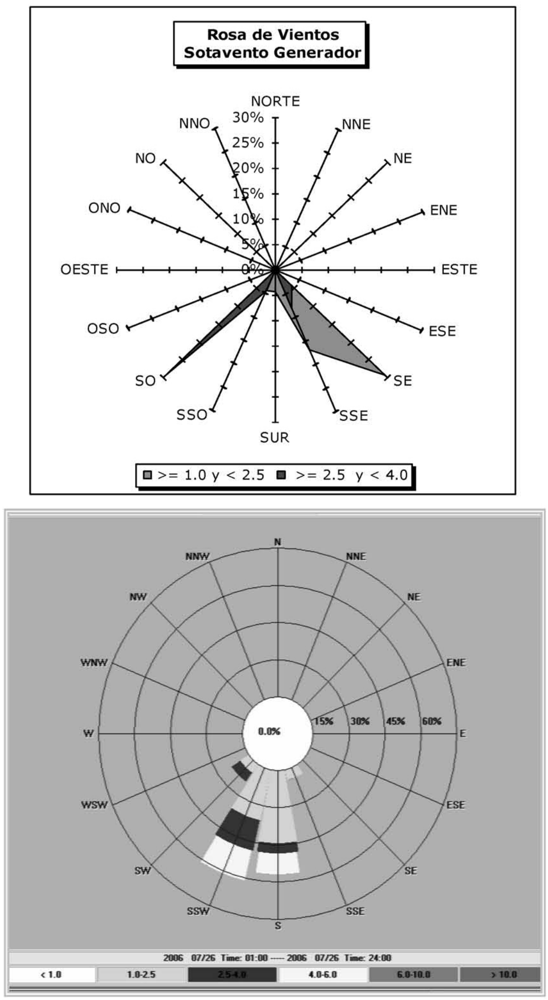


Figure 3A. Typical wind speed average availability in Talara (study zone).

Figure 3B. Wind rose for Talara Airport showing wind speed distribution and direction.



ANALYSIS OF OUTCOMES

From the technical and economic perspectives, a hybrid wind-thermal natural-gas system is required for a more reliable supply of electricity (Table 2). Since there is no excess electrical energy, battery banks or converters are unnecessary. System components include:

a) Two wind generators Vestas model V100-1.8 MW or similar, which consist of an upwind rotor equipped with three blades plus control and low-voltage connection equipment. Each wind generator provides 500 kW at an average wind speed of 6 m/s (19.7 feet/second). For both, 1,000 kW of electricity is supplied by the wind park.

b) Four 1,028 kW gas generating sets, Cummins model 1250GQNA.

c) Two 428 kW gas generating sets, Caterpillar model 3516LE.

As a result of the transient stability study, the most feasible scenarios from the point of view of stability are sub-scenarios 3.1 and 4.1. A maximum wind energy penetration of 14.3% is established in the electrical system of the reservoir. These sub-scenarios present frequency and voltage values slightly out of the tolerable range during and after the disturbance. Nevertheless, for the restoring status there are sustained oscillations which are neither damped nor stabilized, thus a power stabilizer or power system stabilizer (PPS) is required in the synchronous generators. The proposed model is the PSS-IEEEST.

Table 2. Generation supply (sub-scenario 3.1).

Effective Power of the hybrid system in kW	Number of effective 450 kW wind generators at 6 m/s.	Wind generation total kW	Supply of thermal natural-gas generators
Wind generation covering 14.3 % of the demand of the power plant in kW.	02	900	5,396 kW (one gas generating set at 1,028 kW plus three at 427.9 kW)
Total Power (kW)		**6,296**	

The rotor angle of all the synchronous generators increases when the fault on the entry 1 bar (Figure 4) is produced and oscillates during the first two seconds after a disturbance and are stabilized subsequently allowing the machines to be synchronized. It can be concluded that the angle of the rotors of the synchronous generators present acceptable values for system stability.

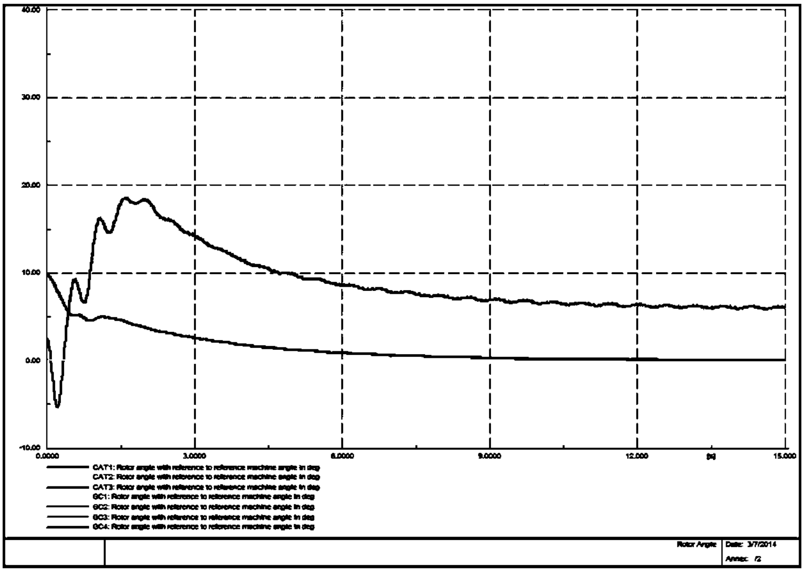


Figure 4. Rotor angle of each synchronous generator (Sub-scenario 3.1).

From the technical and economic analysis developed using HOMER, a reduction in the average energy cost (COE, acronym for costo promedio de energia) was 11.2 %. Including the cost of the fuel gas, the COE was 0.139 U.S. $/kWh for the base scenario and 0.125 U.S. $/kWh for sub-scenarios 3.1 and 4.1 (Figure 5).

From the historical records (2004-2013) of system operation and using the DIgSILENT software, reliability indexes (Table 3) of the electrical system were determined. These included the system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), customer average interruption duration index (CAIDI), average service availability index (ASAI) and the energy not supplied (ENS) to the system.

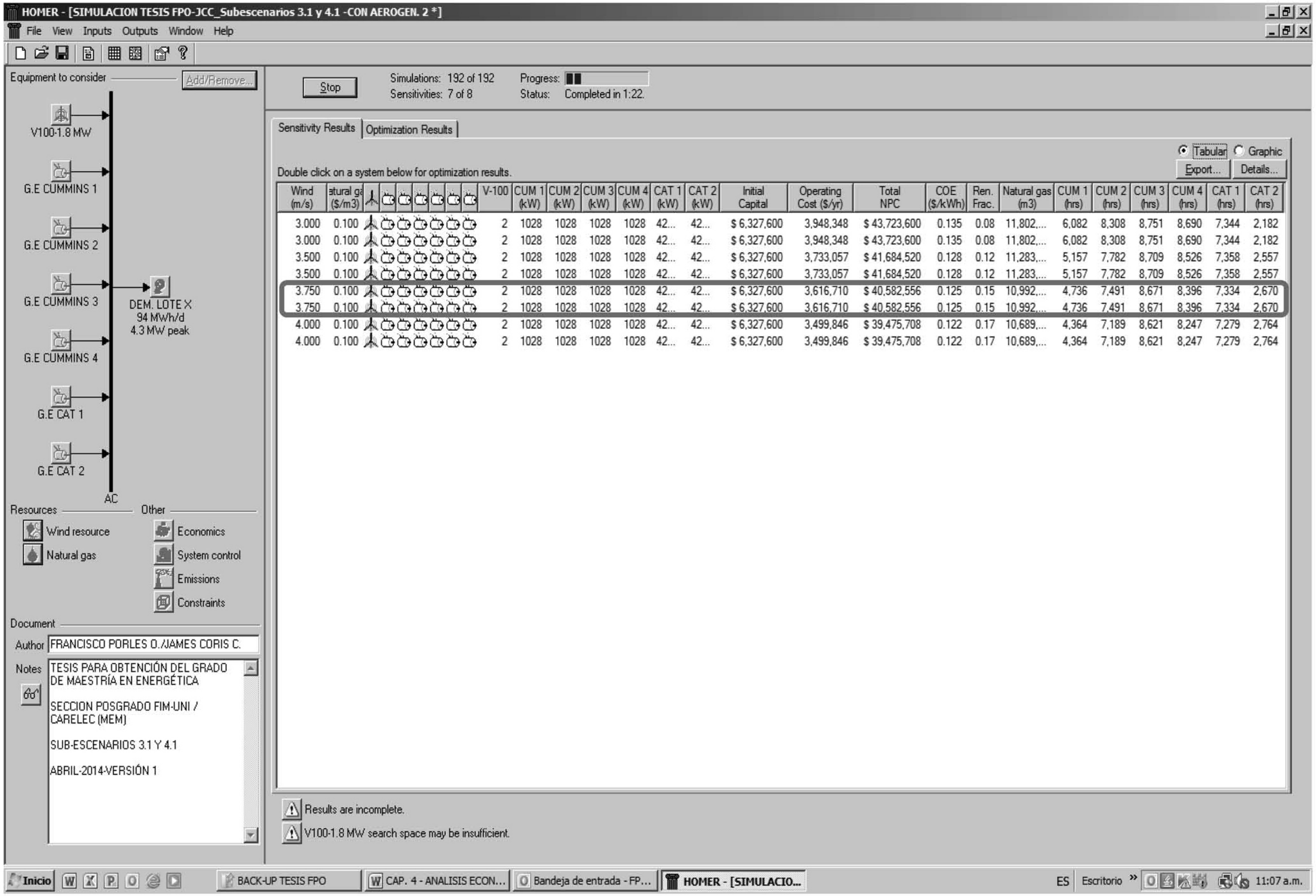


Figure 5. Final sensitivity outcome with HOMER for Sub-scenarios 3.1 and 4.1, for wind speeds between 3 and 4 m/s, a natural gas price of 0.1 U.S. $/m³ with a stability of 14.3%.

Table 3. Comparative table of reliability indexes of the simulated scenarios.

DESCRIPTION	INDEX	UNIT	BASE SCENARIO	SUB-SCENARIO 3.1	SUB-SCENARIO 3.2	SUB-SCENARIO 3.3	SUB-SCENARIO 4.1	SUB-SCENARIO 4.2	SUB-SCENARIO 4.3
System average Interruption Frequency Index	SAIFI	1/a	31.927	38.889	38.889	38.889	36.938	34.246	33.307
System Average Interruption Duration Index	SAIDI	h/a	97.818	114.116	114.116	114.116	104.543	90.628	85.866
Customer Average Interruption Duration Index	CAIDI	H	3.064	2.934	2.934	2.934	2.83	2.646	2.578
Average Service Availability Index	ASAI	-	0.989	0.987	0.987	0.987	0.988	0.990	0.990
Energy Not Supplied	ENS	MWh/a	627.541	746.33	746.328	746.328	676.626	576.085	541.453

The following conclusions were derived from a comparative analysis of the simulated scenarios:

- Sub-scenario 4.3 offers the lowest values of SAIFI, SAIDI, CAIDI, ENS indexes and has higher values for the ASAI index. According to the transient stability study, this scenario is not feasible due to the sustained voltage and frequency oscillations after large disturbances. This sub-scenario presents one fault every 263 hours.
- Sub-scenario 4.2 offers the best reliability indexes for the system and represents the wind generation distributed with 35.7% of the electrical demand. According to the transient stability study it is not a feasible option. This sub-scenario presents one fault every 256 hours.
- Sub-scenario 4.1 offers the best reliability indexes and represents the wind generation distributed with 14.3% of the electrical demand. According to transient stability, it represents the most feasible option. This sub-scenario presents one fault every 237 hours.

According to the reliability indexes of the network topology, sub-scenario 4.1 does not significantly affect the present network topology. Using 14.3% of wind generation distributed by zones in the present system will not affect system operation. It is recommended sub-scenario 4.1 be implemented with wind generation.

High Impact Indicators

High impact indicators were obtained considering a 10-year project useful life, equivalent to the remaining concession period for the Block X oil field. These indicators are shown in Table 4 (pages 54-55).

CONCLUSIONS

The electrical grid for the Block X oil field has always been based on fossil fuels. Renewable energy now provides a viable alternative. A hybrid wind-thermal system is proposed to generate electrical energy for oil field operations in northwestern Perú where oil wells are distant from thermal plants. The progress of renewable energy technologies and the high cost of natural gas generated electricity in Talara provide opportunities to improve the electrical supply system for the oil fields.

Table 4a. Table of high-impact indicators obtained.

General Objective	Specific Objectives	Impact Indicator	Type of Indicator	Description of the impact obtained
To assess the implementation of a hybrid Wind-Thermal (natural gas) system for the power supply of the oilfield Block X of Talara.	To reduce the own natural-gas consumption used for electricity autogeneration.	Reduced natural-gas volume (in MMm^3 or MMpc)	Energy	1.71 million m^3 (equivalent to 110.3 million $feet^3$).
				Equivalent to a reduction of 24.6% of the natural-gas consumption.
	To assess wind energy penetration in the energy grid of the oilfield for the electrical energy autoproduction.	Maximum Penetration of wind energy (%), regarding the maximum electricity demand of the oilfield.	Energy	14.3%
	To reduce the electricity auto production cost.	U.S.$/kWh	Economic	From 0.139 U.S.$/kWh the cost was reduced to 0.125 U.S.$/kWh.
				Equivalent to a reduction of 11.2% of the electricity cost (including fuel gas).
				It represents an economic saving in electricity of annual 551.9 M U.S.$
	Level of investment.	Required investment	Economic	3,960,000 U.S.$
		VAN	Economic	4,686,321 U.S.$
		Pay-out	Economic	5.28 years

Table 4b. Table of high-impact indicators obtained.

General Objective	Specific Objectives	Impact Indicator	Type of Indicator	Description of the impact obtained
To assess the implementation of a hybrid Wind-Thermal (natural gas) system for the power supply of the oilfield Block X of Talara.	To reduce the number and duration of electrical power outages in the electrical networks of the oilfield.	System Average Interruption Frequency Index (SAIFI) (#faults/year)	Operational	An acceptable value of 36.9 is obtained.
		Customer Average Interruption Duration Index (CAIDI) (in h/year)	Operational	It is reduced from 3,064 to 2.83.
	To determine the most optimal configuration and dimensioning of the hybrid wind-thermal to be implemented.	Number of wind generators to be installed	Operational	2 units VESTA 1.8MW
		Total usable power (kW) of the wind generators	Operational	900 KW
	To reduce the level of CO_2 emissions generated with the present thermal plant.	t CO_2e reduced/year	Environmental	6,633 tons CO_2/year
				Equivalent to a reduction of 36.4% of CO_2 emissions.

Accounting for the outcomes obtained in both the transient stability study and the reliability study, a power supply system with hybrid (wind and thermal) generation, dimensioned to a renewable energy penetration of 14.3%, offers the power supply stability and reliability required by oil fields such as those located in northwestern Perú. With the area's available wind data, it is concluded that a hybrid energy system can be planned, modeled and designed.

The most technically and economically feasible scenarios for system stability are:

- Sub-scenario 3.1—Centralized wind generation providing (from El Alto TP) up to 14.3% of electricity demand.
- Sub-scenario 4.1—Wind generation providing up to 14.3% of the electricity demand, but distributed strategically to better use the region's dominant winds, reduce unbalancing and improve electrical system instability.

It is clear that wind speeds are the thermodynamic determinant variable for the configuration of the hybrid systems studied when considering the natural potential energy in Talara. The average wind speed available in the region is from 5 to 6 m/s (16.4-19.7 feet/second). To meet the restriction of 14.3% of maximum wind energy penetration (MWEP), a minimum of 3.75 m/s (12.3 feet/second) is required. It is fully covered by the average speed available in the zone.

The economic aspects of wind technologies in Perú are sufficiently promising to continue the development of wind powered electrical generation capacity in the county's northwest regions. The outcomes obtained in February 2016 in the fourth auction for electricity generation with renewable energy resources by Osinergmin offer proof. The minimum price offered for the wind technology dropped 42.3% compared to the minimum price in the first auction in 2010 and the maximum price offered was reduced by 26%.

References

[1] Jahanbani, F. and Riahy, G. (2001). Optimum design of a hybrid renewable energy system. Intech, page 233.

[2] Wang, L. and Singh, C. (2009). Multicriteria design of hybrid power generation system based on a modified particle swarm optimization algorithm. IEE, pages 24, 163-72.

[3] Ding, J. and Buckeridge, J. (2000). Design considerations for a sustainable hybrid energy system. UNITEC Institute of Technology, Auckland University, New Zealand. Pages 1-2.

[4] Rehman, S., El-Amin I., Ahmad, F., Shaahid, S., Al-Shehria, A., Bakhashwain, J. and Shash, A. (2005). Feasibility study of hybrid retrofit to an isolated off-grid diesel power plant. Elsevier, page 642.
[5] Vries, H. and Francken, J. (1980). Simulation of a solar energy system by means of electrical resistance. *Solar Energy*, pages 25, 275-81.
[6] Barnard, J. and Wendell, L. (1997).
[7] Simmons, A. (1996). Grid-connected amorphous silicon photovoltaic array. Progress in *Photovoltaics: Research and Applications*, 4, pages 381-388.
[8] Rehman, S., Halawani, T. and Mohandes, M. (2003). Use of radial basis functions for estimating monthly mean daily solar radiation. *Solar Energy*, pages 161-168.
[9] Rehman, S. and Halawani, T. (1994). Weibull parameters for wind speed distribution in Saudí Arabia. *Solar Energy*, pages 473-479.
[10] Billinton, R. and Allan, R. (1992). Power system realiability and its assesment: part 1—background and generating capacity. *Power Engineering Journal*, pages 191-196.
[11] Billinton, R. (1994). Reliability assesment of electrical power system using Monte Carlo methods. Plenon Publishing, pages 936-941.
[12] Xu, D., Kang, L. and Cao, B. (2005). The elitist non-dominated sorting GA for multiobjective optimization of standalone hybrid wind/PV power system. *Journal of Applied Science*, page 6.

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