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Design and analysis of hybrid energy systems: The Brazilian Antarctic Station case

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ABSTRACT

This paper presents the design and analysis of a hybrid energy system for an Antarctic Station. The research considered the constraints of the extreme climate, the logistics limitations and the technical assets of the Brazilian Antarctic Station. The thermal and electrical annual profiles of the Station, the spreadsheets of the organic solid waste, and the local measured data of wind and sun were investigated. The application of anaerobic digestion, combined heat and power generation, use of photovoltaic panels and wind turbines were analysed. In the renewables analyses, 25 years of local climatic data were assessed. The influences of air density, temperature and ground reflectance on the renewable generation were also investigated. In order to assess potentials hybrid energy systems for the Brazilian Antarctic Station, possible topologies were organized in groups and then analysed by consumption, performance and feasibility. The methodology supported the identification of an efficient and feasible energy system for the Brazilian Station. The proposed system reached 37% of fuel saves considering the original demand profile of the Station. This work adopted the liter of oil as a currency, thus in any future time the results can be used for financial studies.

1. Introduction

Antarctic research Stations resemble small isolated villages, requiring water, heating, waste treatment and power generation to ensure the human survival conditions [1]. In this scenario, one of the most disturbing elements related to the impact of the human activities is the use of fossil fuels for energy production. The emitted gases, the risks of spills, and the difficulty of logistics in Antarctica, make the use of fuels harmful and complex. The pollution can affect the researches and impact the local fauna and flora. The final cost of the fuel in Antarctica, is also a problem. Literature suggests that in some Stations, the difficult of transportation and handling of fuels makes the final cost more than seven times higher compared to the origin [2].

In this context, the integration of renewable energy in the Station's power plants has becoming the most adopted alternative to reduce the environmental impacts, extend the autonomy and minimize the energy costs [2–9]. However, design hybrid energy systems for the cold continent requires a thorough study of local constraints and energy resources for achieving robustness and autonomy required to the safe operation even in harsh conditions [2,5,10].

This paper presents the methodology applied on the research of renewable energy integration in the Brazilian Antarctic Station [9]. Scientific expeditions to Antarctica were made and a comprehensive energy investigation of Comandante Ferraz Antarctic Station (EACF, Portuguese acronym) was conducted. The energy consumption profiles and the local energy resources were assessed. Finally, several compositions of the hybrid energy systems were analysed and the most adequate to EACF, identified.

On February 25, 2012, due to a fuel leak, a severe fire consumed 70% of EACF [11]. This research addresses an ultimate and historical register of the EACF's complete operational profile. The indicators and methodology presented in this paper assisted the benchmark for new installations of EACF, which has the construction planned for 2015–2018 [12].

2. Material and methods

The research was conducted through scientific expeditions to Antarctica (2008–2011 summers), an energy audit of the EACF

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during the 2011 expedition, the estimation of the local energy resources and analyses of hybrid energy systems, subjected to the local logistic restrictions and worst climate characteristics. The statistical analysis was made in dedicated software, and the simulations were performed in HOMER (Hybrid Optimization of Multiple Energy Resources) software [13].

During the expeditions, were performed electrical measurements in the generators, in electrical panels and circuits, measurements of temperature on the external water pipes, copy of equipments documentation (generators, boilers and incinerator), copy of the annual spreadsheets of fuels consumption, interviews with the plant operators and the review of technical assets as built.

The annual electricity consumption profile of the EACF, was estimated based on the annual fuels spreadsheet, which was updated daily by the technicians of the Brazilian Navy. The 2011 generators daily fuel consumption were processed considering the efficiency curve of the diesel based generator, Cummins C200-D6-4, at 60% of load. For this load, 36% of the fuel is transformed in electricity. The diesel proprieties used to convert the daily fuel volumes in daily energy was the HOMER standard values (lower heating value of 43.2 MJ/kg, and density of 820 kg/m^3).

The annual thermal load profile of the Station, were also estimated based on the 2011 annual fuels spreadsheet and cited diesel proprieties. The fuel volumes registered in each boiler's tank supply (the boiler tanks were supplied only once or twice per week), were processed using a simple moving average (30 days period). The result was the daily average boiler consumption along one year. To estimate the thermal load, the daily fuel averages were finally processed considering a boiler efficiency of 90% and the diesel proprieties.

Three-phase voltage and currents of the grid were registered with an energy analyser, brand Embrasul, model RE6000, with integration time set to 100 ms. The measurements were made on the generator output, on all electrical panels and heating cables circuits. The electrical loads profile was obtained expressing the percentage of active power consumption per groups of loads, like: general loads; communication systems; laboratories; and heating.

The estimation of the amount of solid waste useful for energy production was made based on the monthly spreadsheets of the waste generated in the Station and on the EACF's waste classification presented by Woelffel et al. [14]. The organic solid waste was counted and the average generation per inhabitant were calculated. The estimation of possible biogas generation was made considering the conversion parameters and technologies presented by Reichert and Hessami et al. [15,16]. Was selected a Chinese digester technology for household organic waste, with 20 days of retention period and production of 31,1 m^3 of biogas per tonne. Was assumed a biogas calorific value of 20 MJ/m^3.

The estimation of cogeneration capacity was made considering the 2011 fuels spreadsheets, the diesel based generators energy flows diagrams presented by Lora & Nascimento and the generator Cummins C200-D6-4 efficiency curve [17]. According to these documents, was considered that in the generators, 36% of the consumed fuel was transformed in electricity, 40% in recoverable heat and 24% in losses.

To perform the solar energy resource estimation, the global horizontal radiation, the transparency index and the influence of ground reflection were assessed. For this was used the monthly solar data from NASA Surface Meteorology and Solar Energy programme (average of 1983–2005 from satellite measurements) [18]. The average ground reflectance was considered 70% based on Laine studies [19]. To evaluate the useful solar energy, a commercially available monocrystalline photovoltaic solar system (327 W of peak power, 20.1% of panel efficiency and a power temperature coefficient of −0.38%/°C) with MPPT (Maximum Power Point Tracking) was analysed in different fixed-tilt positions and tracking techniques, considering the influence of temperature and also and also overall losses of 20% (soiling of the panels, shading, snow cover and wiring losses). The estimation was performed using HOMER software.

In order to estimate the local wind energy resource, 25 years (monthly averages, 1986–2010) of local climatic data provided by the National Institute for Space Research from the Brazilian Antarctic Meteorology Project, were assessed [20]. The data was measured in a 10-m tower, installed at 16 m above sea level and situated about 100 m from the Station. The maximum and standard deviations of annual wind speeds were calculated using statistical software and the values were used later to specify the reliability limits of the wind energy estimation. The characterization of the wind resource was made through the histograms of wind speeds (3 h averages, 1994–2006), by the equivalent Weibull distribution functions (using maximum likelihood algorithm) and average air density for each month. The Wind Power Density (WPD) and the wind turbines energy production were estimated also considering air density. These investigations were performed in the WindoGrapher, dedicated software for wind data analysis [21].

The assessment of the advantages and disadvantages of each alternative in the Station's power plant was carried out by the simulation of several hybrid compositions, always with the diesel as base. Before the simulation of the hybrid systems the imputed data and assets parameters in HOMER were validated. The hybrid energy systems are assigned in three groups according to the relation between renewable potency and the mean electricity demand of the Station. The systems were compared in terms of annual fuel saves, performance, area required for the installation, complexity, advantages and logistic effort considering local restrictions, in accordance with the Antarctic Environmental Protocol [22]. Finally, was selected the hybrid energy system that best fit to all the cited conditions, with minimum equivalent payback (presumed based on the performance and in the amount of assets of each energy system).

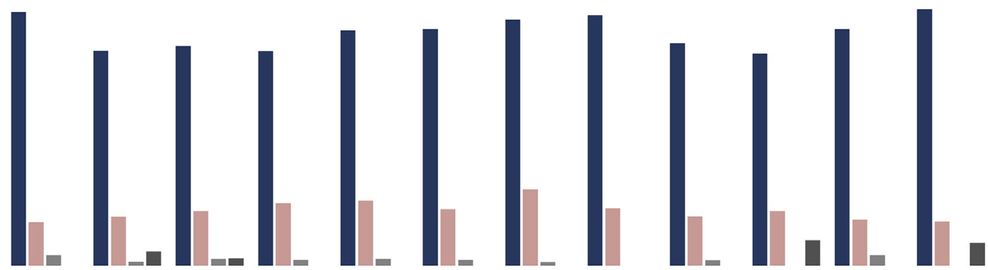
3. Results

The proposed methodology made possible the comprehension of the Station's energy system dynamics with the integration of renewable and cogeneration systems, and also the identification of the most adequate configuration for deployment in the EACF. The energy audit of the building, the local energy resources assessment, and finally, the analysis of the renewable integration, are shown as the elementary investigations.

3.1. Energy audit of the Station

The analysis of the power generation system and loads identified possibilities for energy efficiency actions, heat recovery and renewable energy integration. The buildings were completely dependent on diesel fuel, and the annual oil consumption in 2011, 358,985 L, was more than the local storage capacity, 300,000 L. To transfer all the oil from the ship to the Station, every summer, approximately 60 complex and risky trips with the oil-carrying vessel were required. For electricity generation, there were four generators Cummins C200-D6-4, of 240 kVA each, but the operation of only one was more than sufficient for the normal Station operation (without maintenance activities). One of the generators was only for emergency use. For heating the water and the Station's interior, two redundant diesel boilers, of 120,000 kcal/h each, were used on monthly alternation.

The energy audit of the EACF performed in 2011 quantified that 78% of fuel was consumed for electricity generation and 18% for heating the water and Station's interior. The diesel oil consumption for the generators was 21% higher in the summer and winter



	01/2011	02/2011	03/2011	04/2011	05/2011	06/2011	07/2011	08/2011	09/2011	10/2011	11/2011	12/2011
GENERATORS	25,450	21,560	22,010	21,540	23,636	23,739	24,655	25,145	22,325	21,270	23,730	25,758
BOILERS	4,360	4,880	5,410	6,260	6,480	5,620	7,660	5,720	4,885	5,400	4,580	4,435
INCINERATOR	1,030	370	650	570	650	580	300	0	500	0	1,000	0
OTHERS	0	1,390	700	0	0	0	0	0	0	2,500	0	2,237

a)

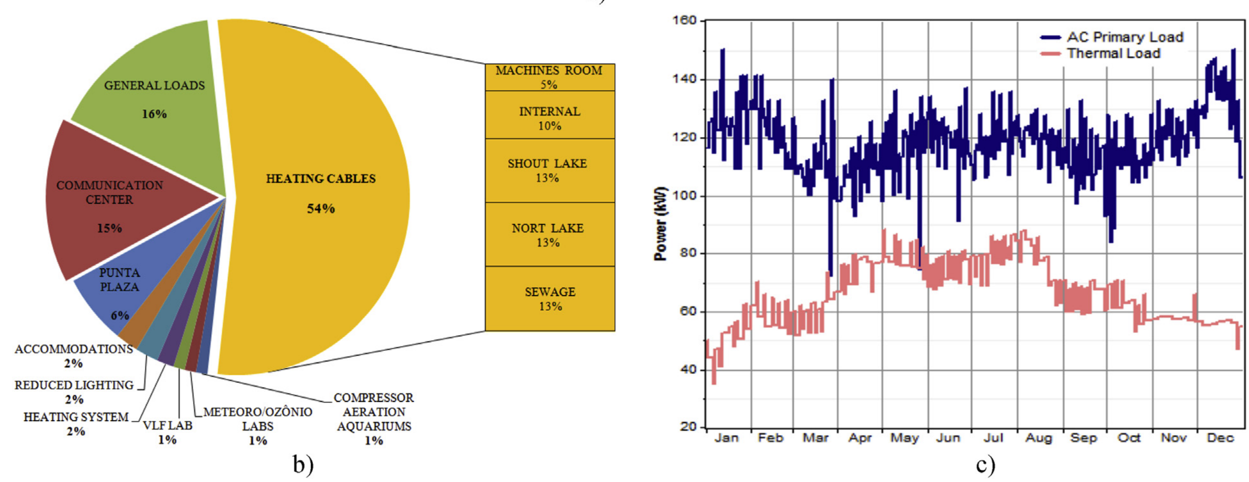


Fig. 1. a) EACF fuels consumption in 2011; b) EACF electric loads profile in 2011; c) EACF average daily demand of electric loads and the heating system demand along 2011.

months, when higher research activity occurs and there is greater need for heating of the water pipes and sewers (the EACF uses heating cables[1] to prevent freezing in the pipes). For the boilers, a 75% higher diesel oil consumption was observed in the winter, when the thermal compensation must be higher due to reduced external temperatures. Fig. 1a shows the consumption of diesel at the EACF throughout 2011. The category "Others" refer to vehicles and vessels. Fig. 1b shows the EACF's electric loads consumption per type. Fig. 1c shows the average daily demand of the electricity (AC primary loads[2]) and heating (thermal loads) in 2011.

Analysing the electric loads consumptions, per equipment type, surprisingly was detected that 54% of the electricity was needed only to supply the heating cables circuits. The measurements of pipes temperatures and the system audit, showed that the heating cables are heating the pipes over 15° than the necessary to freezing protection (5 °C) and that the system was always on even in the absence of risk of freezing. This fact raised a new point of attention towards the reduction of diesel consumption: the importance of the careful specification and fully automation of heating cable circuits to operate strictly in a real risk of frozen pipes.

[1] The heating cables are resistive electrical tapes installed around the pipes for thermal maintenance. The electric current is transformed into heat by the Joule effect.

[2] AC primary load is the electrical load must be served by alternating current that must be met immediately.

3.2. Local energy resources assessment

3.2.1. Organic solid waste

The solid waste, depending on their characteristics, could be incinerated or processed into an anaerobic digestion system, which consists of an organic matter conversion process with lack of oxygen [15].

In the EACF, 50% of the solid wastes are organic, and the remainder is composed of paper, plastic, metal and glass. The data surveyed from November 2006 to March 2007 (the summer period) exclusively related to the food production and consumption showed that, in the period, 573.6 kg of waste was generated, which was equivalent to 0.31 kg/inhabitant/day on average [14]. From March 2009 to February 2010, the average organic solid waste production was 640 kg/month. According to the parameters of performance achieved in the literature [16], is estimated that the total of waste is able to produce only a volume of about 20 m^3 of biogas (20 MJ/m^3) per month on average. In energy, this amount equates to 9 L of diesel oil per month.

Thereby, this process is disregarded for the energy production in the EACF because of the low gross amount. Though, the potential environmental contribution aggregated for such an initiative should be considered. The use of a biodigester in the Station could reduce the incinerator use and the methane produced could be used to generate thermal energy. However, the technology to be adopted should address three critical aspects: safety, temperature and water scarcity.

Table 1
Fuel consumption of the EACF in 2011 detailed per process, considering that the amount of recoverable and usable thermal energy in generator is equivalent to 40% of the total diesel consumed by the engine.

Diesel consuming process		Annual consumed volume [liters and %]	
Generator	Electricity	280,818 (78.23%)	103,552 (28.16%)
	Useful thermal energy		115,058 (31.29%)
	Not usable thermal energy and losses		69,035 (18.77%)
Boilers		65,690 (18.30%)	
Incinerator		5,650 (1.57%)	
Vehicles and vessels		6,827 (1.90%)	
Total consumption		**358,985 (100%)**	

3.2.2. Cogeneration capacity analysis

In a generator group powered by diesel engines, the quota of fuel effectively transformed into electric energy is approximately 36%, which results in 64% total loss. However, recovering part of the heat lost in the gases of the exhaust and the water and oil from the engine cooling, the global efficiency of the system reaches 76% [17]. In this case, up to 40% of the input fuel energy can be recovered as useful heat depending of the system technology. This type of generation is known as Combined Heat and Power generation (CHP). The use of the heat recovered from the generators' prime mover can be used to heat the Station's interior, to the water heating, and also on the freeze protection of piping (water and sewage pipes).

Table 1 presents the diesel consumption, detailed per process, of the EACF in 2011. In that year, the estimated useful thermal energy that could be recovered represented 31.29% of the total oil burned in the Station, 1.7 times greater than the boiler consumption. The mean daily consumption of the boilers in 2011 was around 150 L/day in the summer and 200 L/day in the winter, whereas the thermal supply in the generators was equivalent to 350 L/day in the summer and 300 L/day in the winter. It shows that a reduction of almost one fifth (18.30%) of the Station consumption is possible, only with the integration of a cogeneration system.

Although the thermal supply is higher than the demand on average, the occurrence of instantaneous peaks of demand higher than the supply was detected. In this case, a thermal energy storage system can be designed to add more features: supply the peaks of demand; increase the autonomy of clean water; and help to absorb the power flows and surplus energy of the renewable sources. The Mawson Australian Antarctic Station adopted this concept by using a system known as Boiler Grid Interface (BGI) [23].

3.2.3. Solar resource assessment

Considering Station's geographic position (62°05′ south, 58°23′ West), and methodology presented in the Materials and Methods section, was conducted a resource analysis and the performance assessment of a photovoltaic system for fixed-tilt positioning and for optimal sun tracking technique.

In the optimal sun tracking technique simulations, the annual capacity factor reached was 14.9%, the expected energy generation is 1309 kWh/year for each 1 kWp installed, and the maximum decrease of consumption expected is 354.5 L/year for each 1 kWp installed.

The expected energy production for fixed-tilt installation (180° of azimuth and 60° of slope) is approximately 950 kWh/year for each 1 kWp installed and the capacity factor reached was 10.8%. The maximum decrease in diesel consumption expected for the fixed-tilt installation is 257 L/year for each 1 kWp placed.

Fig. 2a and b, shown the expected power generation for the fixed and tracking positioning techniques along one year, for 1 kWp of photovoltaic panels (800 Wp effective, considering losses). The positive influence of the low temperatures on the panels along situations of high exposure to solar radiation suggests that the power cold be 41% greater than nominal effective power of the solar system, or 12% greater than the installed power. This fact must be observed for an efficient and secure specification of electronic power systems. However, in winter months the generation is insignificant and the risks of snow cover and damages by strong winds increase.

The analysis of the influence of the albedo identified that, for the fixed-tilt installation technique, the panels can be placed with slope angles higher than 60° (for example, on the walls of the buildings) with low losses when the albedo is higher than 70%. In this case, the expected reductions in annual energy produced due to the repositioning of the slope to 80° are less than 3.3% compared to the optimal slope. As for albedo less than 20%, the reduction can exceed 13%. This can be an alternative to avoid snow cover and damages by strong winds. Fig. 3 illustrates the situation described and can also be used as a quick reference to estimate the annual energy production of a photovoltaic system for EACF's and surroundings, in function of PV slope and annual average ground reflectance. The circles in Fig. 3 highlights the energy production related to albedo of 20% and 70%, in the cases of optimal slope positioning and repositioned to 80° of slope. The others possible cases between 20% and 70% of albedo, are highlighted by the dotted arrows.

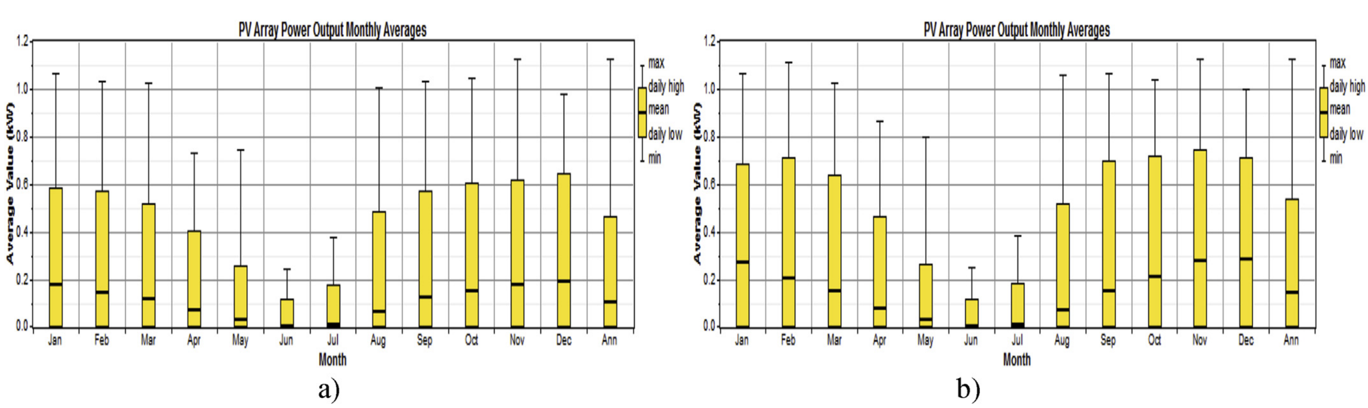


Fig. 2. Monthly PV array power output averages, maximum and minimum values, for 1 kWp of panels. a) Fixed-tilt installation, albedo of 70%, at 60° slope and azimuth 180°; b) Tracking the optimal position and for an albedo of 70%.

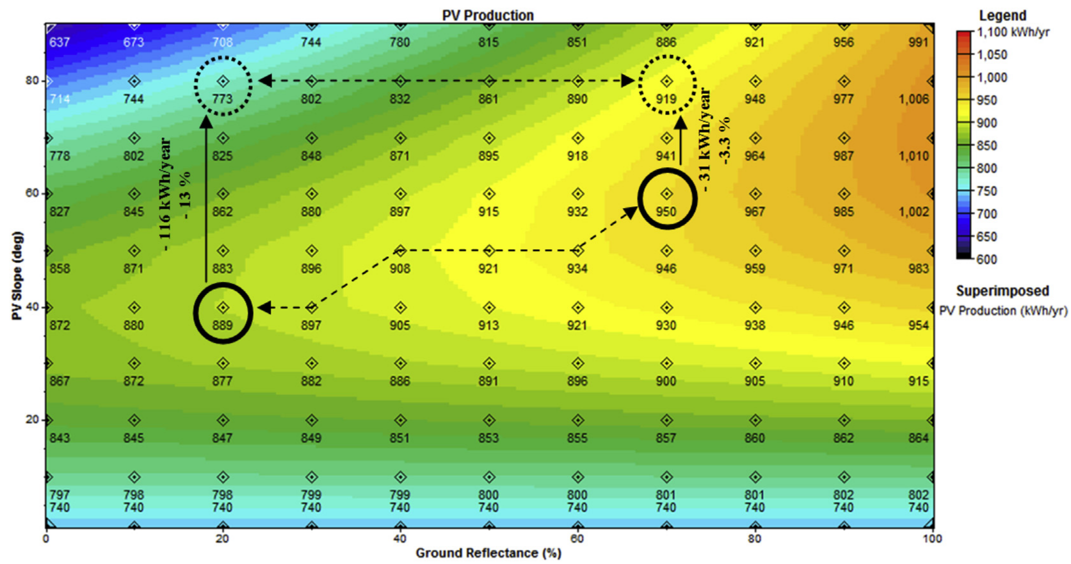


Fig. 3. Influence of ground reflectance in the optimal slope angle of the photovoltaic panel. Simulated for 1 kWp of panels, at 180° of azimuth.

3.2.4. Wind resource assessment

The variability of the wind resource from 1986 to 2010 shows that larger annual variations occurred from 1988 to 1989 ($\Delta = +1.2$ m/s) and from 2004 to 2005 ($\Delta = -1.4$ m/s). The minimum and maximum annual averages occurred, respectively, in 1986 (4.6 m/s) and in 2010 (7.1 m/s). The standard deviation of the data series is 0.6 m/s. The greater winds occur from June to October and the mean annual speed is 6.1 m/s. Fig. 4 shows the average wind behaviour in EACF along 25 years. The green and red circles highlight respectively the maximum and minimum values of wind speeds. The arrows indicate the variability characteristics observed in the wind average speeds.

The characterization of the wind data with the Weibull distribution curve from 1994 to 2006 (period with averages recorded every 3 h), obtained an annual "k" shape parameter of 1.45, and the "c" scale parameter of 6.72 m/s. The mean air density was 1.271 kg/m^3, ranging on average from 1.25 kg/m^3 in the summer to 1.30 kg/m^3 in the winter. The annual average Wind Power Density (WPD) is 398.4 W/m^2, the best power density occur in August, 760.3 W/m^2, and the minimum in January, 194.4 W/m^2. Table 2 presents the wind resource characterization, expressing the annual profiles of the Weibull parameters and air density in the EACF. A higher value of "k" represents a higher concentration of the wind speeds around the "c" speed value [24,25].

Fig. 5 presents an overlay of the monthly averages WPD and average wind speeds in EACF, considering data from 1994 to 2006. Was observed that the values of WPD in October did not follow the trend of the wind speeds. It occurs due to the decrease of air density and the significant increase in "k" parameter for almost the same average wind speed. It reflects reduction of the percentage of strong winds in relation to September. This fact highlights the importance of considering seasonality of air density and distribution of frequency of wind speeds for the proper estimation of the wind resource.

To assess the distribution of wind energy and speeds frequency in the EACF, Fig. 6a shows on the same graph, the wind speed frequency distribution and the wind energy content distribution per wind speed for the years 1994–2006. Although the wind speeds most often occur below 10 m/s, the largest wind energy is located after this speed. This occurs because wind power is related to the wind speed cubed.

In order to quantify the amount of wind energy that can be effective generated and the volume of fuel that can be saved by wind turbine placement, various wind turbines from different technologies and potencies were evaluated as to their power curves, performance and robustness. To obtain the performance data of the turbines were presumed losses related to downtime for maintenance (6%), interference between turbine (5%), freezing the propellers (4%) and losses in conversion and transmission systems (4%). Thus, the overall losses considered were 17.7%. The selected wind turbine was a model with 15 kW of nominal power, direct driven (no gear box), stall control, no cut out and survival speed of 70 m/s, specially designed to cold climates. The selection was made considering the adequacy to the local wind gusts, lowest temperatures, complexity of maintenance and the logistics restrictions.

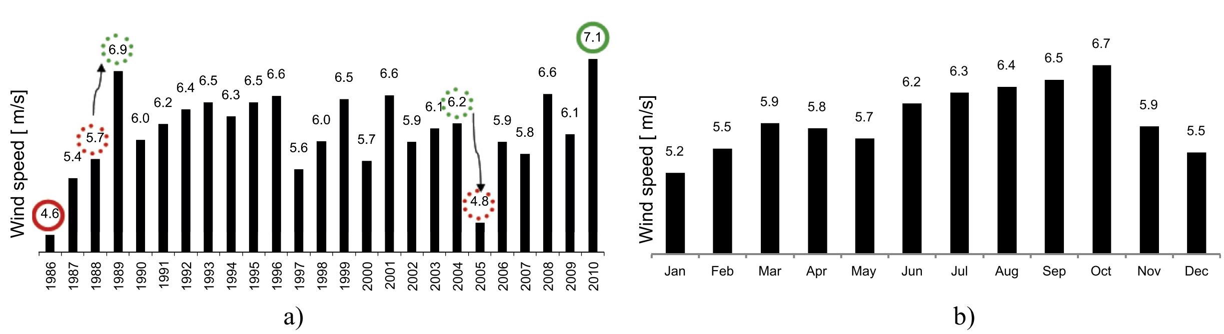


Fig. 4. a) Graph of annual average speeds from 1986 to 2010. Highlighted extreme values and the larger variations observed. b) Graph of monthly average wind speed in EACF 25 years (1986–2010). Elaborated based on data collected by CEPTEC-INPE [20].

Table 2
Characterization of the wind resource of the Brazilian Antarctic Station. Monthly Weibull distribution parameters and air density averages. Elaborated based on data collected by CEPTEC-INPE [20].

MONTHS (1994-2006)	WEIBULL k [dimensionless]	WEIBULL c [m/s]	AIR DENSITY [kg/m³]
Jan	1.47	5.34	1.25
Feb	1.55	6.15	1.25
Mar	1.53	6.52	1.26
Apr	1.49	6.71	1.27
May	1.46	6.44	1.28
Jun	1.41	7.11	1.29
Jul	1.38	7.30	1.30
Aug	1.41	8.19	1.28
Sep	1.37	7.42	1.29
Oct	1.59	7.64	1.27
Nov	1.52	6.44	1.26
Dec	1.51	6.01	1.26
ALL DATA	1.45	6.72	1.27

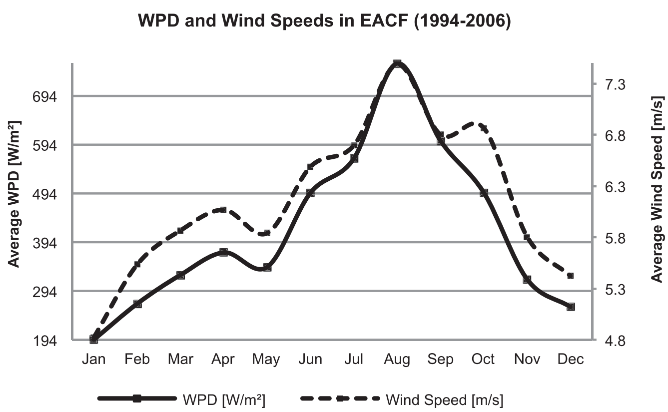


Fig. 5. Monthly averages of Wind Power Density (WPD) and wind speeds, 1994–2006. Elaborated based on data collected by CEPTEC-INPE [20].

The best annual capacity factor achieved was 40.9% and the maximum annual decrease of fuel consumption expected was about 970 L/year/kWp, almost 3 times greater than photovoltaic alternative. Fig. 6b, shows the power curve of the turbine for the wind profile and the influence of the air density in the turbine output power. For the same wind speed, the higher the air density is, the greater the power generated will be. The differences in the power generation can reach 20%, considering the maximum and minimum air density observed at a same wind speed (1.40 kg/m^3 and 1.17 kg/m^3).

3.3. Hybrid energy system design

Initially, for the validation of the consumptions profiles and Station' assets parameters defined in HOMER software, a reference system with the same characteristics of the real Station (2011 EACF data) was simulated. The annual fuel deviation reached was +2.3% compared to the real consumption of the generators and - 0.3% for the boilers. In total, the deviation was +1.8%.

In order to analyse the annual consumption of the Station in function of the renewable integration, some hybrid power plants were defined considering four topologies. In this first investigation, the integration of wind and solar energy were assessed individually, each one with and without the adoption of batteries. For the simulations, the capacities of the batteries were specified to not impose limitation on the system, but the losses in converters are considered equivalent to 95% in the inverter circuit and 85% in the rectifier. The CHP generation was defined by a security factor for all the plants and consists in three generators of 240 kVA each (one for generation, one for redundancy and one for emergency).

With the purpose of conduct a adequate comparison between the various possibilities of energy matrices, the hybrids energy systems were organized in three groups by considering the relationship between the Installed Renewable Potency (IRP) and the annual Mean Demand (MD) of the Station (about 117 kW). The following possibilities were assumed: IRP $<$ MD; IRP $\approx$ MD; and IRP $>$ MD. The higher the relationship is, the greater the expected renewable penetration will be, but also more complex and expensive will be the system.

Fig. 7a shows the expected annual diesel consumption at EACF in function of the installed renewable power considering the four topologies described. The use of batteries only showed a notable reduction in annual oil consumption on energy systems with more than 135 kWp of installed wind power or more than 210 kWp of installed solar power. For these values, the renewable systems began to produce surplus energy equivalent to 5% of the annual average consumption. This difference between the wind and solar technologies occurs because the wind turbine produces more energy per installed kWp than the solar technology in the EACF, as presented in the Local Energy Resources Assessment section.

To evaluate the annual performance of the energy matrices, the ratio between expected fuel savings and installed renewable power, were calculated for each matrix. The fuel savings in relation to the annual consumption of the CHP only matrix (287,382 litters) were

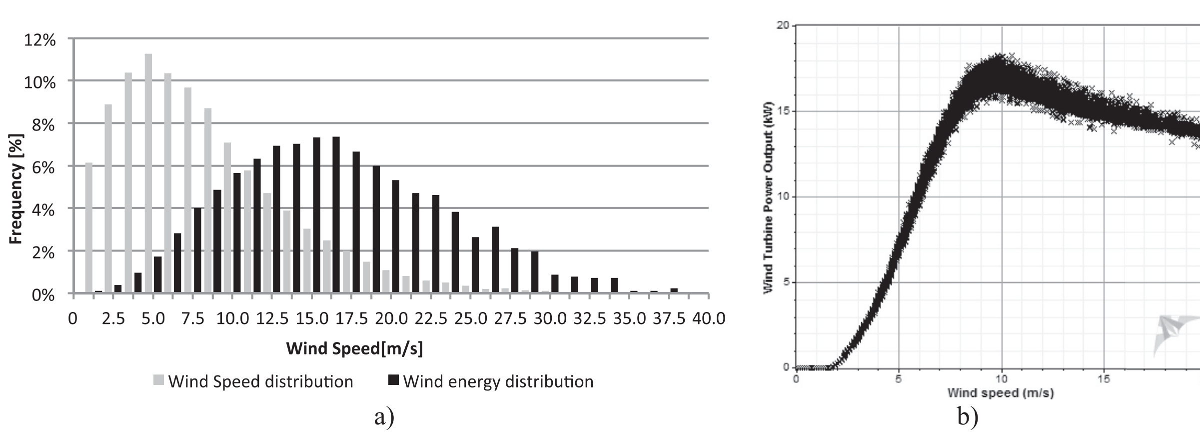


Fig. 6. a) Distribution of speeds and energy density of the winds in EACF, 1994–2006.; b) Power curve of the wind turbine for the 1994–2006 winds with the influence of the air density in the output power. Elaborated based on data collected by CEPTEC-INPE [20].

divided by the IRP of the hybrid matrices. This indicator of performance is shown in Fig. 7b. The higher the fuel saved per installed kilowatt of renewable is, the better the performance and payback time of the matrix can be considered. Fig. 7b shows that, for the EACF thermal and electrical demands, the best performances were obtained for power plants with up to four wind turbines (4×15 kWp). This suggests a shorter payback time of this solution compared to configurations of higher power. For plants that have more than four wind turbines the relationship of fuel saved per each installed kilowatt decreases. With the increase of the IRP, the generator becomes less requested, reducing the cogeneration. The performance of the plant decreases in the proportion that the cogeneration power and even renewable surplus power becomes insufficient to supply the Station thermal demand. In this situation the boilers start to operate and burn oil to meet the thermal demand.

In order to assess wind, solar and CHP technologies working together, 100 combinations of power plants were simulated up to the equivalent to 9 wind turbines ($9 \times 15 = 135$ kWp) and 413 solar panels ($413 \times 0.327 = 135$ kWp). Table 3 presents the annual results for the surplus renewable energy and the percentage of diesel saved in function of IRP, considering the EACF 2011 demand profile as reference. For a better visualization, the cells borders where the surplus energy reaches 2.8 MWh (average daily electricity consumption of the EACF in 2011) were highlighted.

Hybrid energy systems with less than 2.8 MWh of annual surplus energy are feasible to operate without batteries if an adequate BGI system is specified in function of the system IRP and surplus energy values. This possibility is attractive once the use of batteries in cold and extreme ambient is complex and expensive, due to the temperature interference and logistics effort. The adoption of a Boiler Grid Interface coupled to multiple reservoirs of water can also permit to extend the water autonomy of the Station. The results presented in Table 3 show it is feasible to reach up to 46% of reduction on oil consumption with no batteries, considering the 2011 EACF demands.

In order to choose one of the options to propose for deployment in the EACF, several aspects of feasibility were considered such as: environmental security, logistics constraints, area needed for installation, maintenance complexity, annual oil saves and performances factors.

Hybrid power plants composed by CHP, solar and wind technologies, with IRP > DM were shown to be particularly attractive due the high performance and the possibility of operation without batteries, reducing the complexity for placement and maintenance in Antarctic regions. However, the diesel generators have to stay always on to provide complementary energy and spinning reserve to synch the inverters of the renewable systems. In case of renewable supply being greater than instantaneous demand, the energy can be absorbed by a BGI system and deferrable loads.

Energy systems with IRP ≈ MD and IRP > MD can reaches greater renewable penetration and allows more diesel oil savings, but these configurations require damping systems for stability under variations of power, systems for storing energy surpluses and larger areas for installation. The typical stabilization systems adopted in Antarctica in these cases are the use of batteries, BGI and flywheels [5,23]. In this configuration the management of the CHP generator can be optimized to operate only on specific situations, when the batteries need charge, in periods of maintenance and in emergency.

The simulations showed that configurations with IRP > DM can reach more than 50% of saves. However, this solution may become infeasible due to the required area for installation of wind turbines and systems. Based on the studies presented by Manwell et al. [25, pp. 384-389], the spacing of the wind turbines is between 5 and 9 times the rotor diameter in the direction of dominant winds, and 3 to 5 times in the direction perpendicular thereto. Thus, given the area available for installation in EACF surroundings, the adoption of 9 or more wind turbines of 15 kW can increase the interference losses. In this case the use of larger turbines becomes an alternative, but the difficulties of logistics and preparation of the foundations for the turbines are also increased.

Thus, based on the analysis of performance, annual saves and complexity, was selected as most adequate a hybrid energy system with IRP > DM, with three diesel generators (one for main operation, one for redundancy and one for emergency) with cogeneration, four direct drive wind turbines (4×15 kWp) and 45 photovoltaic panels (45x327 Wp), totalling 74.7 kWp of installed renewable power. This matrix can reach 37% of saves, which is higher than the goal established by the climate and energy package known as 20-20-20 [26], and also allows an investigation of the real costs and performance for a future optimization and enlargement of the systems. The annual reduction in consumption reached 23.5% in the generators and 97.4% in the boilers. Table 4 presents the topology of the proposed energy system, the annual oil consumption and annual energy production by each technology.

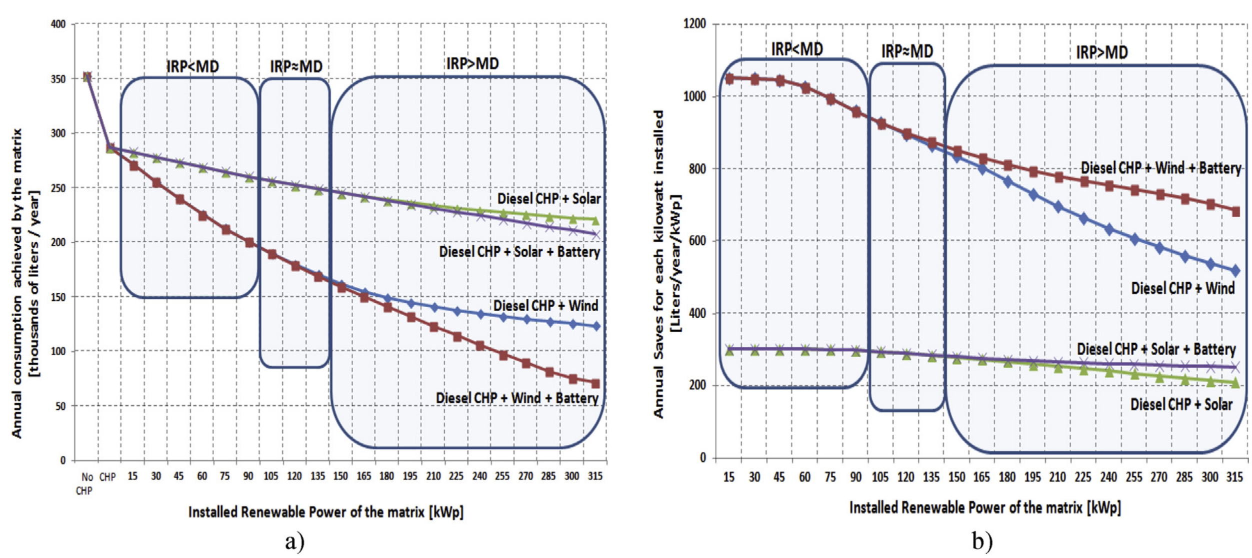


Fig. 7. a) Annual diesel consumption in the Station as a function of the installed renewable power; b) Annual diesel saved per installed kilowatt of renewable, for each matrix configuration.

Table 3
Annual surplus renewable energy and the percentage of fuel savings in function of CHP and renewable integration. Performed based on the 2011 consumption profile of the EACF.

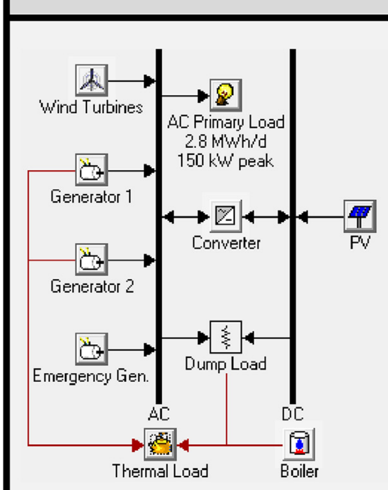
ANNUAL EXCESS OF ELECTRICITY PER ENERGY SYSTEMS CONFIGURATION CHP-WIND-SOLAR WITH NO BATTERIES [MWh/year]

INSTALLED PHOTOVOLTAIC POWER	INSTALLED WIND POWER									
	0 kWp	15 kWp	30 kWp	45 kWp	60 kWp	75 kWp	90 kWp	105 kWp	120 kWp	135 kWp
0 kWp	0.0	0.0	0.0	0.0	0.0	0.0	0.2	2.4	17.3	47.6
15 kWp	0.0	0.0	0.0	0.0	**0.0**	0.0	0.3	4.2	22.1	54.2
30 kWp	0.0	0.0	0.0	0.0	0.0	0.1	1.1	7.7	28.0	61.5
45 kWp	0.0	0.0	0.0	0.0	0.0	0.4	3.3	12.4	34.8	69.3
60 kWp	0.0	0.0	0.0	0.0	0.2	1.9	7.0	18.4	42.3	77.7
75 kWp	0.0	0.0	0.0	0.1	1.3	4.8	12.0	25.3	50.4	86.6
90 kWp	0.0	0.0	0.1	0.9	3.6	9.2	18.1	32.9	59.1	95.9
105 kWp	0.0	0.1	0.7	2.8	7.4	14.7	25.2	41.2	68.4	106.0
120 kWp	0.2	0.6	2.4	6.3	12.7	21.4	33.1	50.3	78.4	116.7
135 kWp	1.0	2.6	6.0	11.6	19.3	29.2	42.1	60.4	89.4	128.2

ANNUAL FUEL SAVINGS PER ENERGY SYSTEM CONFIGURATION CHP-WIND-SOLAR WITH NO BATTERIES [PERCENTAGE/YEAR]

INSTALLED PHOTOVOLTAIC POWER	INSTALLED WIND POWER									
	0 kWp	15 kWp	30 kWp	45 kWp	60 kWp	75 kWp	90 kWp	105 kWp	120 kWp	135 kWp
0 kWp	19%	23%	27%	32%	36%	40%	43%	46%	49%	52%
15 kWp	20%	24%	29%	33%	**37%**	41%	44%	47%	50%	53%
30 kWp	21%	26%	30%	34%	38%	42%	45%	48%	51%	54%
45 kWp	22%	27%	31%	36%	40%	43%	46%	49%	52%	55%
60 kWp	24%	28%	33%	37%	41%	44%	47%	50%	53%	56%
75 kWp	25%	29%	34%	38%	42%	45%	48%	51%	54%	56%
90 kWp	26%	31%	35%	39%	43%	46%	49%	52%	55%	57%
105 kWp	27%	32%	36%	40%	44%	47%	50%	53%	55%	58%
120 kWp	28%	33%	37%	41%	45%	48%	51%	54%	56%	58%
135 kWp	29%	34%	38%	42%	45%	49%	51%	54%	57%	59%

Table 4
Topology of the proposed energy system, annual consumption and annual generation expected for each technology. Highlighted in blue the electric energy and in salmon the thermal energy.



PROPOSED ENERGY SYSTEM	CHP DIESEL GENERATOR	BOILERS	RENEWABLE SOUCES
	ANNUAL OIL CONSUMPITION		
	219,713 liters/year	1,706 liters/year	-
	ELECTRIC (kWh_e) AND THERMAL (kWh_t) ANNUAL ENERGY PRODUCTION		
	Electricity: 772,111 kWh_e/year	15,106 kWh_t/ year	Wind: 246,456 kWh_e/ year
	Cogeneration: 868,670 KWh_t/ year		PV: 17,669 kWh_e/ year
	ANNUAL ENERGY SURPLUS		
	304,166 KWh_t/ year	-	-

Fig. 8 shows the monthly average power produced for each technology of generation. The annual percentages of participation in production of electricity were 2% for photovoltaic panels, 24% for wind turbines and 74% for motor generators.

Fig. 9 presents, in the same graph, the renewable sources generation and electric demand, along one year. The reduction on the renewable power generation in the months of May to July is related to the low production of the solar panels during the winter. During the summer months, the total renewable power reaches 80 kW.

Fig. 10 shows the maximum, minimum and averages renewable penetration expected along the year. For all months the average penetration remained above 20%. The maximum instantaneous penetration was 90%.

Fig. 11 presents, in the same graph, the thermal supply and demand along one year, for the proposed system. The cogeneration supplied almost all of the heat demand (97.4%), and the operation of the boilers occurred only on situations of low electrical demands or high penetration of renewable sources. To avail all the cogeneration capacity, a thermal energy storage system is needed. However, it is observed that occurred a considerable amount of surplus heat, that can be used to extent the hot water autonomy of the Station.

In order to evaluate the sensitivity of the energy system with the variation in the availability of renewable resources or ineffectiveness of the renewable systems, a complementary simulation of the hybrid energy system was made for different scenarios of abundance and lack of the resources. Fig. 12 shows the expected annual diesel consumption in function of the renewable resources availability for a range from zero to 1.5 times the annual average of the resource (Best Estimate values). The blue curve shows the expected annual fuel consumption depending on the wind resource and considers the solar resource at its annual average value. The red curve shows the expected annual fuel consumption depending on the solar resource and considers the wind resource at its annual average value. Considering the maximum and minimum values for the annual average wind speed already recorded in the EACF region from 1986 to 2010 (4.6 m/s and 7.1 m/s), the expected fuel consumption for the proposed system will be between 236,659 L/year (+6.8%) and 213,329 L/year (−3.6%).

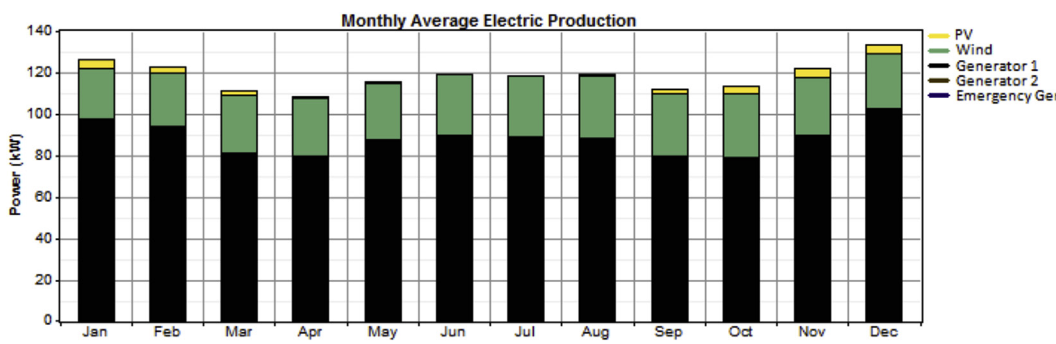


Fig. 8. Monthly average electric production for each technology of generation, for the proposed hybrid energy system.

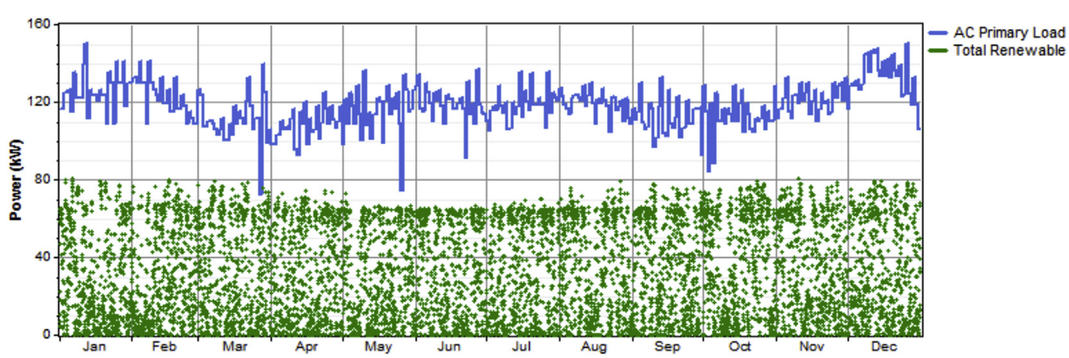


Fig. 9. Hourly AC primary load and renewable generation for the proposed hybrid energy system.

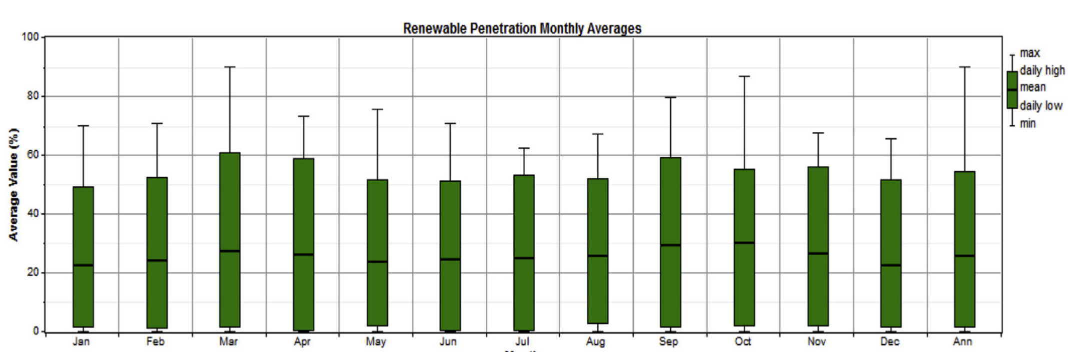


Fig. 10. Averages of the renewable penetration expected for the proposed hybrid energy system.

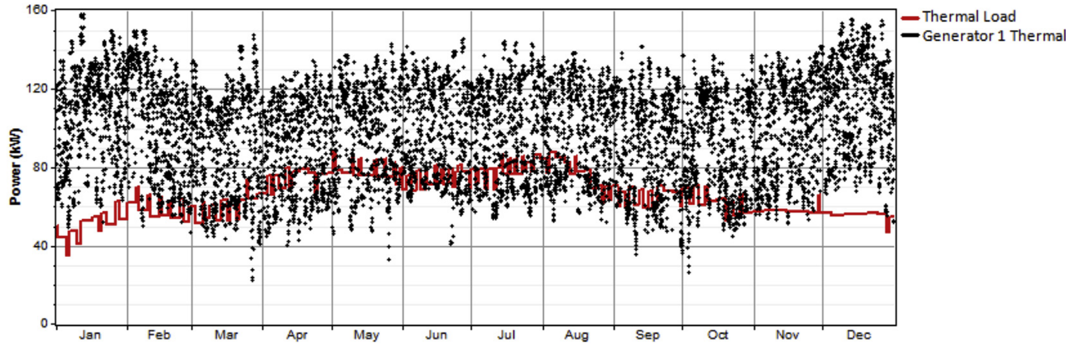


Fig. 11. Production of thermal energy of the power generator, superimposed on the thermal load.

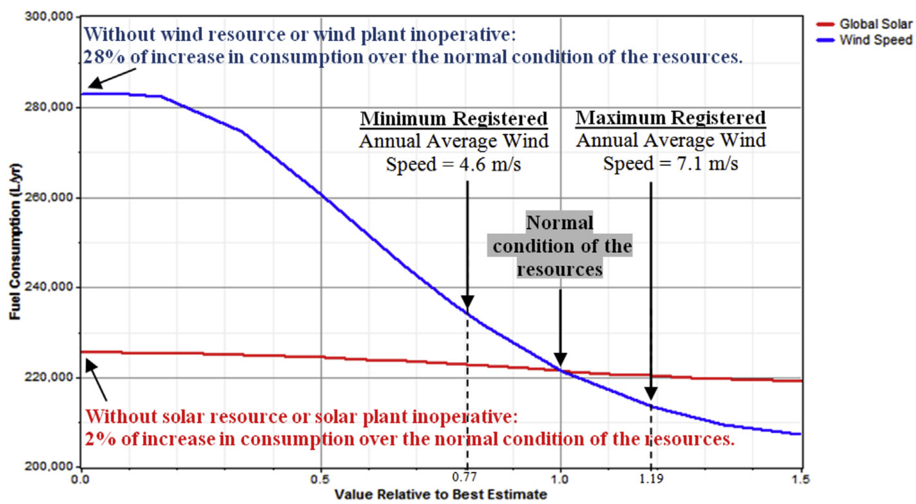


Fig. 12. Variation in annual fuel consumption of the proposed energy system in function of renewable resources availability.

4. Discussion

The anaerobic digestion may produce methane for in process usage, however, the safety, the operation temperature of the anaerobic digester and possibility of the use of sewers, should be investigated by a specific research. The use of bioreactors for water treatment is also an alternative to reduce the local environmental impact that can be useful to reduce the consumption of energy related to water and sewers systems [5].

The fact that 54% of electricity consumption, equivalent to 42% of total diesel, was consumed by circuits of heating cables indicates that the application of this equipment has to be rethought. The excess heat from cogeneration could be used for recirculation and thermal maintenance of the lake water pipes, in addition to automation of the heating cables and isolation reinforcements.

The use of diesel-electric boilers integrated to the grid and coupled with multiple thermal reservoirs could allow percentages of penetration above 100% (storing the energy as heat), with no use of electric batteries, however an adequate management system must be extensively studied for optimum operation. In spite of that, the use of batteries can permit dual flux of electricity for grid stabilization, and the stored electricity could be injected in the grid or be converted to heat at any time required. The choice of one, or even the integration of both, will depend upon the characteristics desired for the energy system, as well the possible technical and financial constraints.

In Antarctica, due the extreme low temperatures, metals are more fragile and less fatigue resistant, the lubricants and fuels become more viscous, damaging gearboxes and mechanical systems prematurely. The soil characteristic increases the complexity of installation of wind turbines, solar panels and fuel storage structures, the icing in the blades can unbalance the turbine rotor, the fine snow can penetrate in nacelle and the wind gusts can lead to frequently turbine overloads causing fatigue, automatic shut-downs or even damages. To withstand the extreme climate, the equipments must be designed or suited with special materials, lubricants, minimum or no use of gearboxes, extra insulation, heating for the components and modified controls systems rated for cold climates.

5. Conclusion

The proposed methodology made possible the comprehension of the Station's energy system dynamics with the integration of renewable and cogeneration systems, and the identification of the most adequate configuration for EACF.

The energy resources assessment shown suitability for renewable energy deployment in the Brazilian Antarctic Station and can also be used as a reference for new projects in the region. Cogeneration and wind turbines demonstrated the greatest potential for reducing the consumption of diesel in the Station, followed by the use of photovoltaic panels. The use of solid waste is not energetically attractive for the Station due the low rate of waste production.

The cogeneration would be able to supply the entire thermal demand of the Station, resulting in an annual reduction of 18%, 65,000 L of diesel (annual boilers consumption), and also leaving a surplus of approximately 300 MWh/year. This surplus could be stored by multiple thermal reservoirs, which would allow greater autonomy and safety in the operation of the Station.

The wind resource assessment shows that the annual mean WPD is around 400 W/m^2 (at 10 m of high), the best power density occur in August, 760.3 W/m^2, and the minimum in January, 194.4 W/m^2. The analysis of the wind turbines results in an annual capacity factor of 40.9% and an annual reduction of up to 970 L of diesel for each installed kilowatt.

The use of photovoltaic panels can reach an annual capacity factor of 14.9%, but had a potential for reducing diesel consumption almost three times smaller than the wind generation. The low intensity of solar radiation in winter and the snow cover can lead the photovoltaic system to the non operational condition in this season. However, during the summer, when most of the research is developed, the system presents an excellent production rate. Due the risk of damage by wind gusts, the installation in the walls of the buildings prove to be alternative, reducing only 3.3% the annual production, for an albedo of 70%.

Was identified that is feasible to reach up to 46% of reduction on oil consumption with no batteries, considering the 2011 EACF demands. However, the best performances were obtained for configurations with up to three or four wind turbines. For matrices with more than four wind turbines the relationship of fuel saves per installed kilowatt decreased in greater proportion. This decrease was related to the cogeneration reduction and boiler operation.

The energy systems design methodology presented in this research, led to an energy solution of IRP < DM, with three CHP generators (one for main operation, one for redundancy and one for emergency), four direct drive wind turbines and 45 photovoltaic panels, totalling 74,7 kWp of installed renewable power. This specific system configuration can reach 37% of saves, suggests the best payback, and also allows an investigation of the real costs of deployment, maintenance and operation of the systems, as well as the life span, for future optimization and enlargement of the Station.

In this paper, the systems assessments were performed using the litre of diesel as a currency. Thus, in any future time these results can be converted to financial indicators.

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