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

Tiago Malavazi de Christo*, Jussara Farias Fardin, Domingos Sávio Lyrio Simonetti, Lucas Frizera Encarnação, Cristina Engel de Alvarez

Federal University of Espírito Santo, Av. Fernando Ferrari, 514, Goiabeiras, Vitória, ES, 29075-910, Brazil

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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

* Corresponding author.
E-mail address: tmalavazi@ifes.edu.br (T.M. de Christo).

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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