Evaluation of energy efficiency measures for the ecuadorian antarctic station Pedro Vicente Maldonado through a calibrated building energy model

Evaluación de las medidas de eficiencia energética para la estación antártica ecuatoriana Pedro Vicente Maldonado a través del modelo de energía calibrada para edificaciones

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Abstract

In Antarctica, as a sensitive continent to human activities and a strategic site for research on the effects of climate change, it is important that the developed projects minimize environmental impacts. Within this context, the Ecuadorian Antarctic seasonal Station Pedro Vicente Maldonado, built in 1990, will become, in a few years a permanent station. For this reason, to optimize energy consumption, various energy efficiency measures were analyzed on a calibrated energy model based on the current base diesel consumption for heating. The results of this study show that the envelope elements, for which more energy is lost, are both floor and roof. Furthermore, due to the low window to wall ratio of the station, the reduction in diesel consumption generated by the use of triple and quadruple glazing is not significant. By combining different energy efficiency measures, up to 50% of savings on annual diesel consumption for heating can be achieved compared to the diesel consumption that the current station would present operating permanently. This study will serve as a reference for the changes to be implemented at the station.

Keywords: *Antarctica, building energy modelling, calibration, energy efficiency measures, ecuadorian station*

Resumen

En la Antártica, un continente sensible a las actividades humanas y un lugar estratégico para la investigación de los efectos producidos por el cambio climático, es importante que los proyectos desarrollados ahí minimicen su impacto medioambiental. Bajo este concepto, la estación antártica Pedro Vicente Maldonado, construida en 1990 y operada por Ecuador durante el verano austral, se convertirá dentro de pocos años en una estación permanente. Por ello y con el fin de optimizar el consumo energético, se han analizado diversas medidas de eficiencia energética de acuerdo a un modelo energético basado en el actual consumo de diésel para calefacción. Los resultados de este estudio demuestran que los elementos de la envolvente del edificio, por donde se pierde gran parte de la energía, son el piso y el techo. Por otro lado, debido a la baja relación ventana-paredes de la estación, la reducción en el consumo de diésel generado por el uso de vidrios triple y cuádruple no es significativa. Al combinar diferentes medidas de eficiencia energética, se puede ahorrar hasta un 50% del consumo anual de diésel para calefacción si se compara con el consumo que tendría la estación actual operando en forma permanente. Este estudio servirá de referencia para implementar los cambios necesarios en dicha estación.

Palabras Clave: Antártica, simulación energética en edificación, calibración, medidas de eficiencia energética, estación ecuatoriana

1. Introduction

Antarctica is a strategic point in research development mainly related to climate change issues, astrophysics, marine biology, earth sciences and geophysics. For this reason, since the 40's, more than 80 research stations have been built within the territory. These stations have mechanical services, plumbing and energy systems (COMNAP, 2014). Half of the stations operate only during the austral summer (seasonal stations), while the rest are stations operating throughout the year (permanent stations). In order to provide adequate living conditions for the occupants, stations need to have energy supplies (electricity and heat), excellent isolation design and the ability to meet energy demand even in periods of extreme low temperatures. This type of energy supply systems must be implemented with low environmental impact criteria since Antarctica is very sensitive to human activities. In fact, the Council of Managers of National Antarctic Programs (COMNAP), the Antarctic Treaty and several national Antarctic programs have developed numerous guidelines to assess and reduce the environmental impact of projects to be developed in Antarctica (Mason, 2007).(Mason, 2007). Similarly, such programs encourage to reduce fossil fuels consumption for energy generation (COMNAP, 2007)(COMNAP, 2007).

Depending on the season, the demand of fossil fuel for heating is very high. As reported by Steel and Guichard (1993), energy demands in Antarctic stations are dominated by heating requirements driving the need to implement energy efficiency measures (EEM) to reduce fossil fuels consumption. Unfortunately, the first Antarctic stations were not designed considering energy efficiency criteria. For this reason, much effort is made to remodel the facilities or renovate old high-energy consumption equipment nowadays. However, in recent years, EEM have been considered from the design stage. For example, the Swedish station Wasa, built in 1989, has a low energy consumption for heating by the use of 30 to 50 cm of rock wool insulation in walls and roofs and by the use of heat recovery from electric generators (Tin et al., 2010). In fact,

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heat recovery is the most common measure of energy efficiency used in the Antarctic stations (Tin et al., 2010)(Tin et al., 2010). Another example is the French-Italian Concordia station built in 1997. According to the study of Godon and Pierre (2000), through the use of heat recovery from generators, the station does not require the use of additional heating.(2000), through the use of heat recovery from generators, the station does not require the use of additional heating. Thus, annual diesel consumption ranges in 200 m^3 to cover energy demand of the 1800 m^2 of the facility. In this context, several stations have considered energy efficiency criteria from the design stage to the operation and use of energy equipment.

The Ecuadorian Antarctic Institute (INAE) operates the Antarctic research station Pedro Vicente Maldonado (PVM). Since its inauguration in 1990, a residential Module (M1) and a mixed Module (M2) came into operation. In 2011, a new scientific-use Module (M4) came into operation. A non-conditioned Module (M3) is part of PVM station, which contains electrical and thermal generators. The main power source of PVM station is diesel, which serves to run the electric generators and the heating system (boiler water). PVM station currently operates only during the austral summer but INAE plans to convert this station in a permanent facility. However, from the energy point of view, a permanent station requires more power capacity systems installed to meet the high heating demands in winter. Considering the high energy consumption required by a permanent station, it is imperative to analyze improvements in building fabrics and equipment operation through EEM.

Within this context, the main objective of this study was to model and simulate the energy consumption of the current PVM station and to propose EEM that help in the reduction of diesel consumption. The main analyzed EEM were thermal insulation, glazing configuration and heating system operation. Diesel consumption of PVM station was analyzed at yearly level in order to predict the energy consumption of a permanent station.

2. Methodology

This study was conducted in three stages. The first stage consisted of the data collection of the building fabrics, thermal zoning, internal gains and the heating system. The second stage was the calibration of the energy simulation model based on the actual diesel consumption for heating. Those data was collected during the last Ecuadorian Antarctic expedition in 2013. The calibration was carried out considering the energy consumption of the residential module (M1), mixed module (M2) and laboratory module (M4). In the final stage, the assessment of different EEM was performed in order to determine an optimal proposal for measures to be taken in the PVM station. The main purpose of these measures is to reduce the diesel consumption for heating. The measures were assessed only for modules M1 and M2 as the module M4 is a recent module having an improved constructive system that does not warrant any change. It is important to mention that the evaluation of EEM was performed on an annual basis in order to estimate the energy consumption when the station would be permanent.

2.1 Current base description

As mentioned before, Module 1 (M1) is entirely residential. This module has the cabins and bathrooms for most of the expedition staff. Module 2 (M2) is a mixed module which has 4 cabins, an office, a living room, a dining room, a kitchen and a storage room. These two modules are connected by a non-conditioned enclosed vestibule used to equip the occupants. Module 3 (M3) is a non conditioned module where the heating and electric generation equipment and machinery are located. Being a non-conditioned space, M3 is not part of this energy study. Module 4 (M4) is the laboratory module; it has laboratories, offices, a kitchen, an infirmary and a laundry room.

Since PVM station has not a permanent weather station, the weather file used for the simulations was the one of the Chilean Antarctic station Arturo Pratt (WMO 89057). In this climatic zone, the minimum dry bulb temperature varies between -2.4°C (January) and -18.0°C (July) and the maximum between 3.4°C (July) and 5.8°C (January). In addition, the daily average relative humidity varies from 85% to 87%. The Chilean station is on the same island as the Ecuadorian station (Greenwich Island) and the distance between the two stations is less than 5 km.

2.1.1 Building fabrics

Table 1 shows station building fabrics. Module M4, being the most recent, has better design characteristics. Glazing in modules M1 and M2 consist of single glass (6 mm thick) with aluminum frames, while module M4 consist of double glass (6 mm thick and 10 mm air) with PVC frames.

***Table 1.** Current station building fabrics*

	External Walls [CM]		**Roof [CM]**		**Internal ceiling [CM]**		**Floor [CM]**	
Module 1	Stell sheet	0.2	Steel sheet	0.2	Pine wood	0.1	Steel sheet	0.50
	Polyurethane	10.0	Pine wood	10.0			Pine wood	1.00
	Pine wood	1.0					Carpet	0.30
	Steel Sheet	0.2	Steel sheet	0.2	Cement plaster	0.1	Steel sheet	0.50
Module 2	Polyurethane	10.0	Pine wood	10.0			Pine wood	1.00
	Cement plaster	1.0					Carpet	0.30
	Steel Sheet	0.2	Steel sheet	0.2	Cement plaster	0.1	Steel Sheet	0.50
Module 3	Polyurethane	10.0	Polyurethane	10.0			Pine wood	1.00
	Steel sheet	0.2	Steel sheet	0.2			Carpet	0.30

Modules M1, M2 and M4 rest on a 1-m-high base to avoid contact with the ground. This base is protected by steel plates (0.2 cm thick) throughout its envelope. Thus, the accumulation of snow and freezing of pipes is avoided. According to the information collected during the 2013 expedition, the station has a high infiltration rate (1.5 ac/h). This infiltration rate was determined directly by EnergyPlus through the Effective Leakage Area model which is detailed on the ASHRAE Handbook of Fundamentals (ASHRAE, 2009). This effective air leakage area (900 cm^2) was estimated by visual inspection during the 2013 expedition.

2.1.2 Heating system

The station has a heating system through hot water radiators. The hot water comes from a diesel-operated boiler. The heating system operates 24 hours a day at a set point temperature of 20°C for the high occupancy areas (residential, offices and laboratories) and 18°C for low occupancy areas (bathrooms, corridors, store rooms, laundry room and kitchen).

2.1.3 Schedules and electric equipment

Occupancy, lighting and electric equipment schedules of the different areas are based on real monitored data in site. The electricity consumption of the station is difficult to define since there is not enough information of all the installed electrical equipment. Additionally, the electricity generation is not only for direct use in the modules but also for the operation of the water treatment plant, the heating hot water distribution system and for the use in maintenance equipment and machinery. For these reasons, the calibration was performed only in function to the diesel consumption for heating.

2.2 Building energy model calibration

As mentioned above, the calibration of the model was based on the diesel consumption for heating during the 2013. Since the station is only occupied in the austral summer (December to March) and the months of December and March were irregular in energy consumption (they were not completely occupied), the calibration was performed based on the diesel consumption for the months of January and February 2013 (Table 2).

The diesel consumption of the boiler was estimated considering an efficiency of 0.8 according to the technical specifications of the boiler; i.e., for each kWh of heating load, 1.24 kWh of diesel is consumed. According to the calorific value of the Antarctic diesel, 1 liter of diesel is able to generate 11 kWh (thermal).

For the simulation and calibration of the current station, a detailed building model of the modules M1, M2 and M4 was performed in DesignBuilder software (Figure 1) (Tindale, 2005).(Tindale, 2005). The input data required for the model are building materials thermal properties, occupation profiles of the different areas of the station, schedules and loads of the electrical equipment, lighting and the heating system characteristics. Figure 2 shows the thermal zoning used for the simulation. In order to minimize calibration errors, for each thermal zone, the installed capacity and operation schedules of each electric-equipment were defined.

Table 2. *Diesel consumption for heating at PVM*

Month	Diesel for heating [gallons]
January	776
February	670

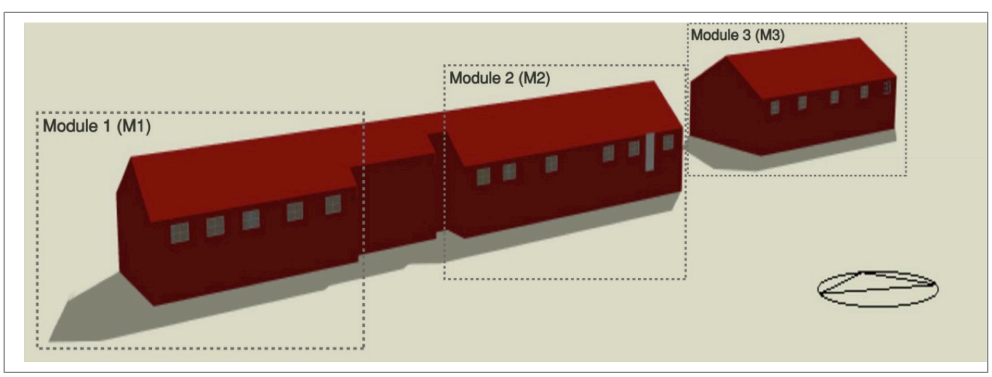

Figure 1. *PVM energy model in DesignBuilder software*

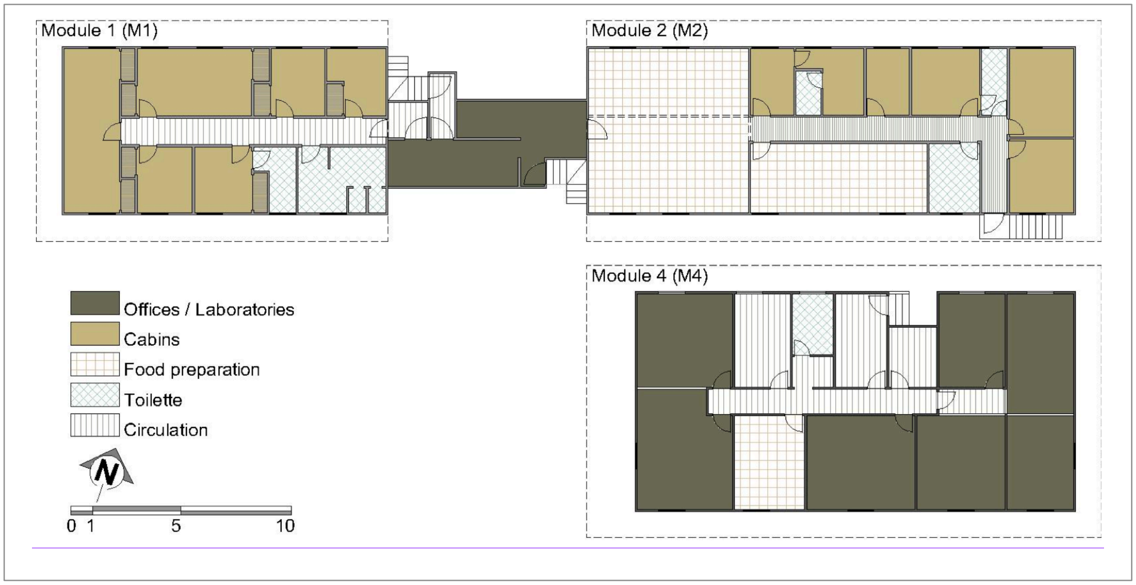

Figure 2. *PVM thermal zoning in DesignBuilder software*

2.3 Energy efficiency measures

From the calibrated energy model (CB), the impact of various EEM on the annual diesel consumption for heating was evaluated. Thermal insulation, glazing configuration and heating system operation were the EEM evaluated as part of this study. In order to perform the optimization process, the model should respect two constraints: a) reduce the heating load, and b) maintain the current station form (shape, structure and window to wall ratio). Therefore, thermal insulation in walls should not exceed 10 cm to avoid modifying the structure, but the thermal insulation level on the roof, ceiling and floor can be modified without any change in the structure.

First, the performance of different insulation materials (Table 3) was evaluated according to the thermal conductivity properties and the diesel consumption for heating. The material through which the diesel consumption for heating is less was selected for the next steps in this study.

On the other side, to identify the optimal thickness ratio between the envelope elements (floor, roof and facades), a parametric analysis was conducted. For this purpose, the thickness variesof each envelope elements was varied individually at intervalssteps of 2.5 cm from 5cm to 30cm, and several30 cm while the others stand fixed at 30 cm. Each of these scenarios were simulated. On each scenario, the overall insulation thickness was kept fixed (30 cm) (was defined as Case 1 – (C1) except forfollowed by the suffix corresponding to the envelope element studied (that was analyzed, as shown on Table 4) whose insulation thickness was varied in the mentioned range. Through this analysis, the ideal thermal insulation thickness for each envelope element was identified. Consequently, case $C2_{in}$ was defined considering the thermal insulation material with best performance and the ideal thickness.

Furthermore, the performance of different low emissivity glazing configuration (Table 5) was evaluated from the improved model $C2_{in}$ These configurations were selected according to their thermal properties (U-value). Due to low incidence of solar radiation on Antarctica, the solar heat gain coefficient (SHGC) was not considered in the glazing analysis. Similarly to insulation materials, glazing configurations were compared according to the diesel consumption for heating. Through the combination of $C2_{in}$ and the glazing configuration with best performance, an improved model of the current base was obtained ($C3_{in\_glz}$).

Then, based on the $C3_{in\_glz}$ model, the heating system was calibrated to ensure that air temperature reaches 20°C (high occupancy areas) and 18°C (low occupancy areas) just during the occupied periods. In addition, the system was configured to prevent the indoor air temperature drops below 12°C when the zones are unoccupied, resulting $C4_{in\_glz\_sch}$. Finally, in the future modifications of the current station, the change of thermal insulation can help in improving the tightness of the base. Thus, the infiltration rate of the new model was reduced to 0.7 ac/h. maintaining the recommendations of the International Energy Conservation Code (BECP, 2011). As a result, an improved model with the optimal insulation material, glazing configuration, heating system operation and lower infiltration rate was obtained (C5).

Table 3. *Insulation materials properties*

	Density [Kg/m^3]	Thermal Conductivity [W/mK]
Mineral Wool	16	0.038
Polystyrene	16	0.037
Polyurethane	24	0.028

Table 4. *Insulation combination*

Study Case	Floor [cm]	Roof [cm]	Insulation Thickness North Façade [cm]	South Façade [cm]	East/West Façade [cm]
$C1_{floor}$	5-30	30	30	30	30
$C1_{roof}$	30	5-30	30	30	30
$C1_{north\_facade}$	30	30	5-30	30	30
$C1^{south\_facade}$	30	30	30	5-30	30
$C1_{east/west\ facade}$	30	30	30	30	5-30

Table 5. *Glazing materials properties*

Glazing	Characteristics	Thermal Conductivity [W/mK]
$C2_{in\_glzA}$	Double Clear 3 mm/13 mm Air	1.798
$C2_{in\_glzB}$	Double Clear 3 mm/13 mm Argon	1.514
$C2_{in\_glzC}$	Triple Clear 3 mm/13 mm Air	0.993
$C2_{in\_glzD}$	Triple Clear 3 mm/13 mm Argon	0.786
$C2_{in\_glzE}$	Quadruple Clear 3 mm/8 mm Krypton	0.780

3. Results and discussions

The monthly simulation results showed a good correlation with the actual data of diesel consumption for heating (Table 6). The error between the actual and simulated data of diesel consumption for heating does not exceed 5% for the two months compared. Moreover, the actual and simulated data follow the same trend, i.e., a decrease in the diesel consumption in February compared to January. Therefore, the results of the EEM's evaluated are reliable.

Regarding the insulation materials, by using polyurethane 7 % of diesel savings was achieved compared to mineral wool. Likewise, 25 % of diesel savings was obtained in contrast to mineral polystyrene.wool. Therefore the parametric analysis of the insulation thickness was done considering polyurethane as the optimal insulation material. As shown in Figure 3, the envelope elements with the highest rates of heat losses were the floor and roof.

For this reason, in order to minimize these heat losses, the strategy of insulate the ceiling 20 and 30 cm by keeping the insulation on walls at 10 cm and insulate the ceiling 20 and 30 cm was analyzed, corresponding to study cases $C1_{in10/20}$ and $C1_{in10/30}$ respectively. The results of this analysis demonstrated that insulating the envelope 30 cm is equivalent to case $C1_{in10/20}$ (Figure 4). Consequently, $C1_{in10/20}$ was considered as the optimal case for the following analysis ($C2_{in}$).

Table 6. *Current simulated data of diesel consumption for heating*

	January Diesel for heating [gallons]	Thermal Conductivity [W/mK]
Simulated	740.96	695.79
Actual	776	670
Error	4.52%	3.85%

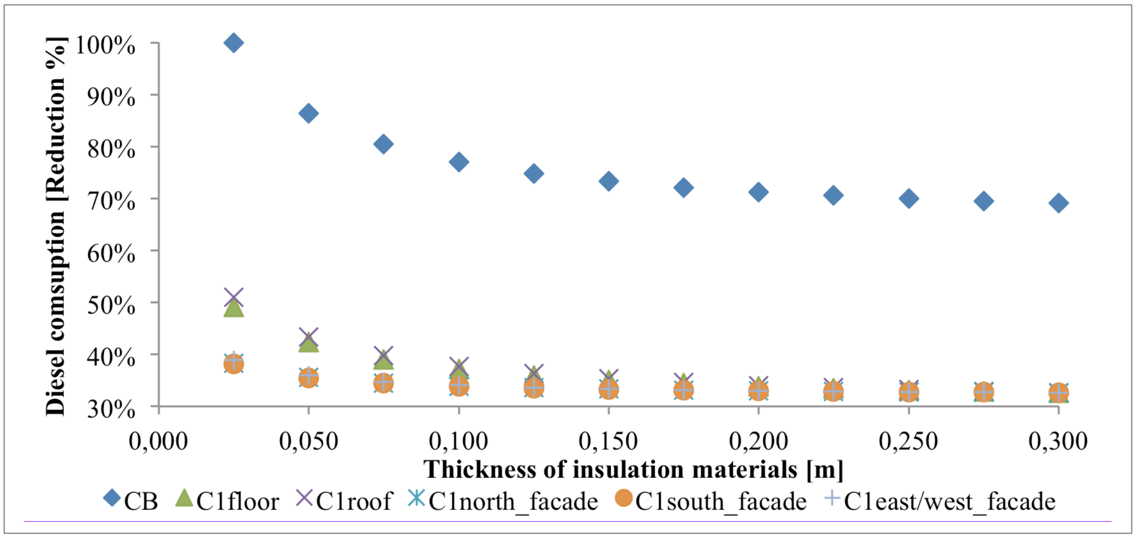

Figure 3. *Insulation thickness parametric analysis*

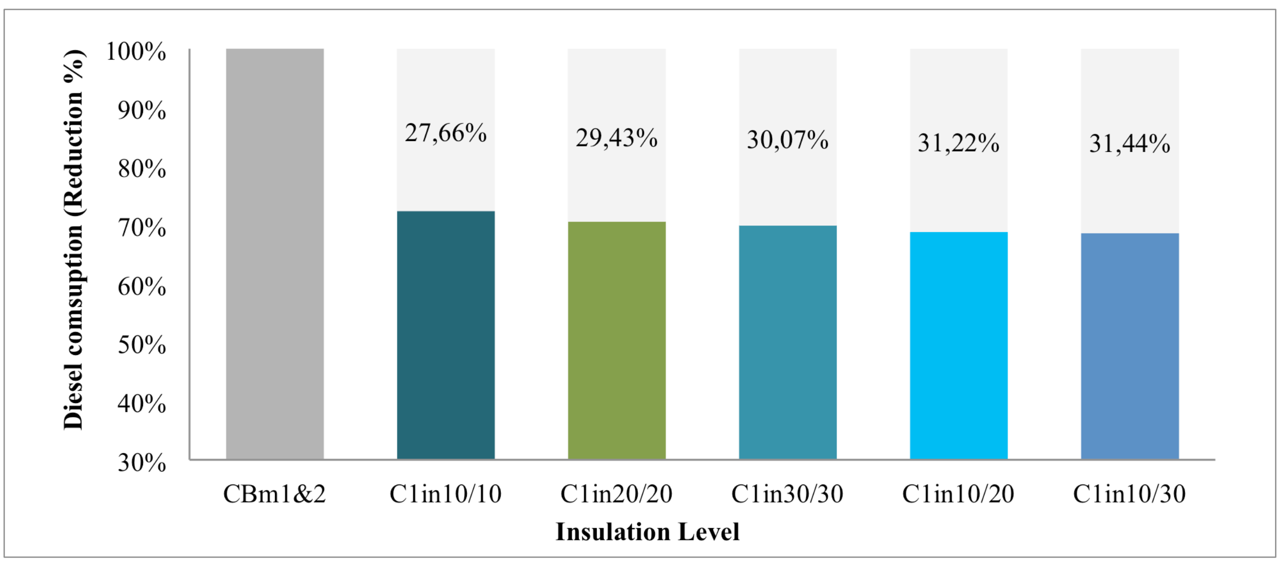

Figure 4. *Insulation level (C1 $_{\text{façade insulation thickness[cm] / roof \& floor insulation thickness [cm]}}$)*

Since the current base has only 9% of window to wall ratio, the reduction on diesel consumption reached by using triple and quadruple pane glazing was not representative. However, compared to single pane glazing (CB), 3.55% of diesel savings was achieved throughout the use of double pane glazing (Figure 5). Therefore, $C2_{in\_glzA}$ was defined as the optimal configuration ($C3_{in\_glz}$).

In the next step, the operation schedule of the heating system was evaluated. The results showed that using the heating system just on the occupied periods ($C4_{in\_glz\_sch}$), a reduction of 22% can be reached compared to $C3_{in\_glz}$(or 55% compared to CB) as shown in Figure 6. Finally, by reducing the infiltration rate to 0.7 ac/h (C5) the diesel consumption can be reduced by 59% in comparison to the CB.

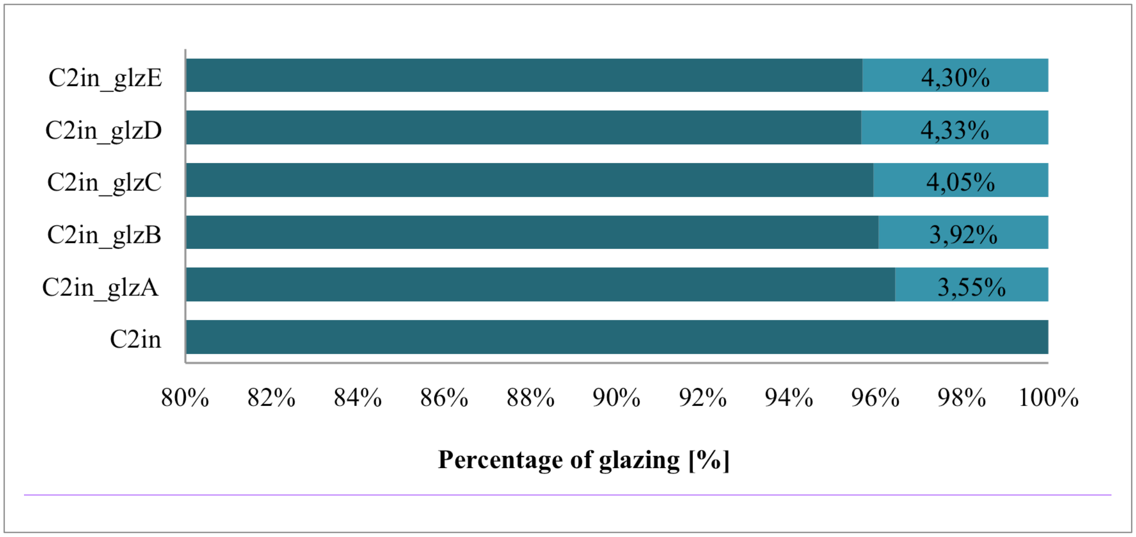

Figure 5. *Parametric analysis glazing types*

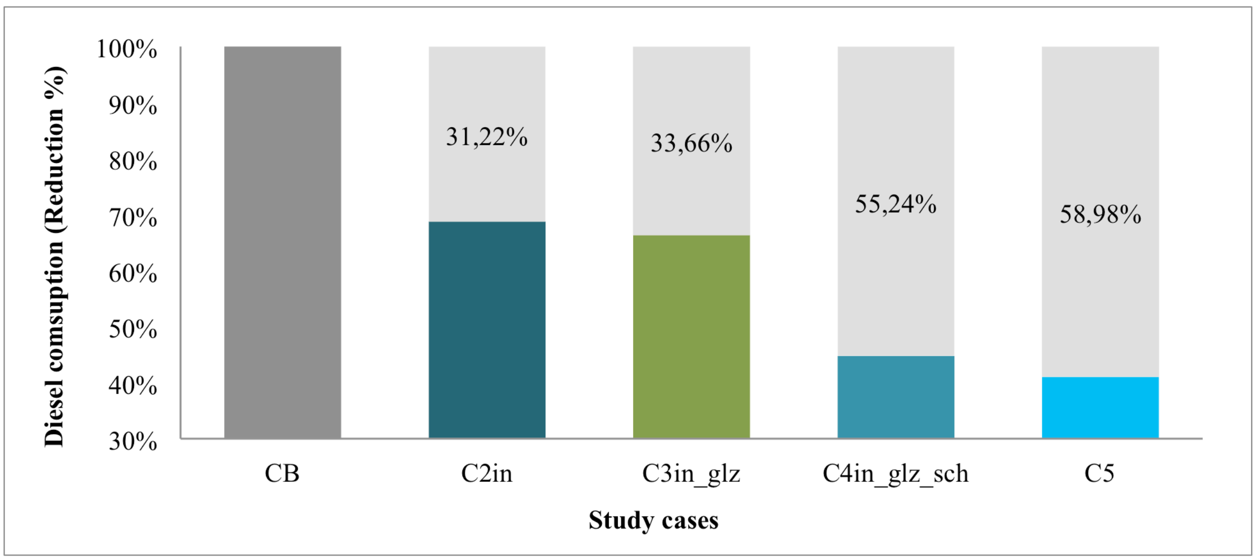

Figure 6. *Percentage of Diesel consumption reduction*

4. Conclusions and future work

This study was performed in order to evaluate the impact of different EEMs for the Ecuadorian Antarctic station Pedro Vicente Maldonado. For this purpose, a calibrated energy model was generated based on actual data collected during the 2013 Ecuadorian Antarctic expedition. All the EEMs were applied to the calibrated model.

The calibration results showed a good correlation between the actual and simulated data of diesel consumption for heating for the months analyzed (January and February 2013). The error between the simulated and actual data does not exceed 5% in any of the two months. However, the simulations were performed using a typical meteorological year (TMY) file since the station does not have a weather station installed on site. Therefore, the evaluation of efficiency measures will be a real approach in estimating the energy savings of the station.

By an energy balance of the thermal envelope of the station, it was determined that the critical elements through which more energy is lost are the floor and roof. It must be highlighted that the floor has no insulation in the current station. In consequence, the first EEM recommended is to use insulation on this element. The analyzed strategies in this study were: thermal insulation, glazing configuration, infiltration rate and heating system operation. Thermal insulation strategy was focused on using the insulating material continuously and adjacent to the occupied volume, therefore a higher level of insulation is considered in the ceiling instead of the roof. Regarding the glazing, although the thermal conductivity of triple and quadruple glazing is smaller than double, the reduction in the diesel consumption is not significant so, the use of glazing other than double is not recommended.

It is important to note that the easier measure to implement in PVM station is the modification of the operation schedule of the heating system, based on occupancy schedules. This measure contributes in achieving considerable savings in diesel consumption. Finally, considering all the feasible EEMs the annual diesel savings for heating could achieve up to 50%.

To complement this study, for further research, the potential use of renewable energy on the site of the station must be studied. Additionally, an optimization study must be carried out in order to minimize the diesel consumption at the lowest investment.

5. Acknowledgement

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In memory of Dr. Jerko M. Labus.

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