PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

DESIGN BY OPTIMIZATION OF A NET ZERO ENERGY MINING CAMP AT HIGH ALTITUDE AND COLD CLIMATE IN THE CHILEAN ANDES MOUNTAIN

ANNELORE ILSE DIETZ MUÑOZ

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:
SERGIO VERA ARAYA

Santiago de Chile, January 2018

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To my family, boyfriend, and friends…

For being there when I needed you the most.

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ABSTRACT

The mining industry is one of the largest energy consumers in Chile with 32% of the total electricity consumption. It is projected that the electricity consumption of the mining sector will grow 53.3% between 2015 and 2026. Mining camps in Chile are mostly located in Andes Mountain above 3,000 m.a.s.l. and exposed to cold weather conditions. Sustainability reports of mining companies show electricity energy consumption of mining camps is between 350 and 500 kWh/m^2. The present work aims to develop a net zero energy camp through the GenOpt optimization tool coupled with EnergyPlus and Python, taking into consideration conditions of mining camps that influence the building's energy performance, innovative HVAC and DHW systems, existing renewable energy solutions in Chile and the reduction of the risk of overheating. This study is based on a real mining camp, Quebrada Blanca 2, which is located at 4400 m.a.s.l with 30,000 m2 that host 1700 workers, built of timber prefabricated lightweight modules, while the outdoor temperature varies from -5.6°C to 10.7°C. The main results show that the optimized energy efficiency strategies and the proposed HVAC system can reduce in 65.8% the original energy consumption of Quebrada Blanca 2 and avoid overheating. Furthermore, the mining camp can reach NZEB targets only by using 57% of the available roof area and 12% TFSM efficiency.

RESUMEN

La Industria de la minería es uno de los mayores consumidores de energía eléctrica en Chile, consumiendo un 32% del total de producción de esta energía. Se proyecta que el consumo de electricidad del sector de la minería crecerá en 53.3% entre el 2015 y 2026. Los campamentos mineros en Chile se encuentran en su mayoría en la cordillera de los Andes, por sobre los 3,000 msnm y expuestos a condiciones climáticas frías. Reportes de sustentabilidad de las compañías mineras muestran que el consumo promedio de los campamentos mineros es entre 350 y 500 kWh/m^2. El presente trabajo tiene como objetivo desarrollar un campamento de energía neta cero mediante la herramienta de optimización GenOpt acoplado con Energy y Python, tomando en consideración las condiciones de los campamentos mineros que influyen en el desempeño energético, innovadores sistemas de calefacción y aire acondicionado en conjunto con agua caliente sanitaria, las energías renovables existentes en Chile y reducir el riesgo de sobrecalentamiento. Este estudio se basa en un campamento minero real, Quebrada Blanca 2, el cual se encuentra a 4,400 msnm. Tiene 30,000 m^2, capacidad para 1,700 trabajadores y está construido de módulos prefabricados de madera. La temperatura exterior varía entre los -5,6 °C y 10.7°C. Los principales resultados muestran que las estrategias optimizadas de eficiencia energética y el sistema de clima propuesto pueden reducir en un 65.8% el consumo original de energía de Quebrada Blanca 2 y evitar el sobrecalentamiento. Además, el campamento puede alcanzar los objetivos de NZEB solo utilizando el 57% del área de techo disponible y con 12% de eficiencia de los TFSMs. Por lo tanto, se puede concluir que se puede diseñar por optimización campamentos mineros de energía neta cero.

1 INTRODUCTION

1.1 Background

1.1.1 Energy consumption of the mining sector in Chile

Chile is the world's largest copper producer and exporter, owning more than 30% of the cooper world's reserves. The mining industry is one of the largest responsible of the energy and electricity consumption in Chile (Marin et al., 2016). This sector counts for 17% of the Chile's total energy comsumption, 32% of total electricity consumption and 6% of national fuel consumption (Woodhouse, 2011; Ministerio de Energía, 2015). In Chile, the price of electricity is up to twice the price than in other mining countries (Vásquez R. , 2015) and electricity is responsible for 20% to 40% of the operational cost of Chilean mining companies (Consejo Minero, 2015). Comisión Chilena del Cobre (2015) indicated that the electricity consumption in copper mining will grow 53.3% between 2015 and 2026 (see Figure 1). In addition, the unit consumption per copper extracted ton grows by 7% per year (Minería Chilena, 2015).

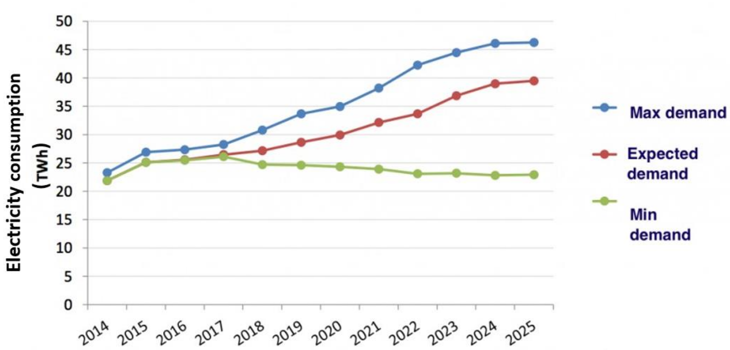

Figure 1. Projected electricity consumption by Chilean copper industry (Cochilco, 2014)

Regarding the Greenhouse Gases (GHGs) emission, the direct emission produced by the mining industry in 2015 was reported as 5.7 million tons of CO_2 equivalent, which represents an increase of 95.89% compared to the year 2001 (Comisión Chilena del Cobre, 2016). These GHGs are mainly caused by the use of electricity generated by coal power plants and the use of fossil fuels

(Zuñiga, 2009). These numbers reveal the importance of looking for sustainable alternatives in the mining sector and implementing energy efficiency measures (Minería Chilena, 2015).

The Chilean Energy Agenda sets a 2025 target of 20% energy savings for the whole country, which is equivalent to 20.000 GWh/year, to promote the efficient use of energy. Also, between 2014 and 2025, it sets that 45% of the installed electric generation capacity in the country should come from renewable energies. In addition, the Chilean Energy Agenda has the goal to promote the use of on-site energy resources in extreme and remote areas, using renewable energies to reduce dependence on fossil fuels (Ministerio de Energía, 2014).

In Chile, about 80% of the internationally recognized mining sites are in remote locations over 3,000 meters above sea level (m.a.s.l). Most of them are in the northern region, specifically between the regions of Tarapacá and Coquimbo (Carrasco & Vega, 2011). In response to the Energy Agenda, mining industry has shown a trend toward using renewable energy to reduce the vast use of fossil fuels as the main energy source (Paraszczak & Fytas, 2012; Minería Chilena, 2015). For example, the El Arrayan wind farm project has 44 wind turbines with an installed capacity of 115 MW, which supplies 20% of the annual consumption of Los Pelambres mine (31.8°S, 70.9°W), equivalent to 280 GWh/year (Saavedra, 2017). The mining company El Tesoro (22.9°S, 69°W) installed a solar thermal plant of parabolic collectors with solar tracking in one direction in 2012, reaching an annual production of 25 GWh/year, which replaces 55% of the diesel use (Minería Chilena, 2015). Other mining companies buy renewable energy from photovoltaic (PV) plants in northern Chile. For example, the Collahuasi mine (20.9°S, 68.7°W) purchases 60 GWh/ year of energy generated from PV power plants Pozo Almonte 2 and Pozo Almonte 3 (20.3°S, 69.8°W), which is equivalent to 13% of its energy consumption (Minería Chilena, 2015). Although there is progress in the incorporation of renewable energies in the mining industry, Los Andes mine (32.8°S, 70.6°W) is the only mine that incorporates in-situ renewable energy generation in their mining camp, which has an installed capacity of 3.2 kW of PV panels and generates 7,464 (kWh/year), reducing the use of electricity generators that operates with diesel (Tritec, 2016).

1.1.2 Chilean mining camps

Since the middle of the nineteenth century, Chile had numerous mining towns characterized by a concentrated and stable population, where the workers lived together with their families and friends. Nowadays, Chilean mining has resorted to high technology, large capital investments and the widespread use of specialized labor, which has made imperative to build camps in almost all sites located far from urban centers (Orellana, 2015). The size of existing mining camps varies approximal from 6,500 m^2 to 95,000 m^2, which host between 600 to 7,000 workers, respectively (Correa 3 Arquitectos Ltda, 2011). Sustainability reports of mining companies show electricity energy consumptions of mining camps between 350 and 500 kWh/m^2 year (Antofagasta Minerals, 2015; Minera Escondida Ltda, 2015). Mining camps are built for high-occupancy workforce, due to workers day/night shift system. A typical miners work shift is the 7x7 system, which means working for 7 days and 12 hours per day, and then, 7 days of rest outside the mining camp (Hernández, 2015). When the miners are in their rest week, another group work occupying the same facilities, thus the mining camp is always at its maximum capacity (Cossio, 2013). Most of the mining camps are located next to the work sites and are built of prefabricated wooden modules, which are constructed off-site. This is the main mining camp construction method in Chile (Féliz et al., 2014). One of today's challenge is to provide a good quality of life of the workers, while minimizing the energy consumption and GHG emissions (Carrasco & Vega, 2011). The concept of design energy-efficient buildings is related with these two concepts: to minimize the energy consumption and to achieve comfortable indoor environmental quality (IEQ) to improve miner's life quality (Omer, 2008).

1.1.3 Energy-efficient building design: Relevant parameters in the energy performance of mining camps and miner's life quality

Due the large-scale volume of mining camps, its increased energy consumption levels and high occupancy, require a depth study of its operations and requirements, focus on quantifying its energy needs and using a climatically responsive perspective to consider a strategy according to the building's main characteristics (Givoni, 1969).

1.1.3.1 Envelope thermal performance

A relevant parameter that influences the energy performance of mining camps are the low thermal envelope requirements which contribute to the increase of heating and cooling loads (Berardi et al., 2014). The energy design of the mining camps modules in Chile are generally comply with the Chilean General Urban Planning Ordinance standard that established the maximum U-value for roofs, walls, windows and ventilated floors based on the climatic and geometric height conditions as 0.25 (W/m^2K), 0.6 (W/m^2K), 1.22 (W/m^2K), and 0.32 (W/m^2K), respectively (Minería Chilena, 2014). These requirements are low compared to efficient building standards, for example, in the international organization focused on optimize building energy policies and accelerate net zero energy or positive energy for the building sector, the Global Building Performance Network (2017), required an overall U-value of 0.36 (W/m^2K) and a maximal energy consumption of 45-60 kWh/m^2 year for new buildings. Normally, to achieve the high efficiency-energy buildings, different energy efficiency strategies are carried out, such as improving the building envelope (Fan & Xia, 2017), implementing passive design strategies (Stevanovic, 2013), installing high performance HVAC systems to reduce heating and cooling energy consumption (Arkar et al., 2016), reducing the use of artificial light (Kruzner et al., 2013) and other power loads to meet the remaining demand with renewable energy (Aksamija, 2015 ; Haidar et al., 2017). In lightweight buildings, the majority of the studies are focused on the influence of thermal mass in energy consumption and overheating (Hoes & Hensen, 2016; Marin et al., 2016; Ochoa & Capeluto, 2008; Evola & Marletta, 2014; Karaoulis, 2017; Heim, 2012; Koschenz & Lehman, 2004; Peippo et al., 1991). Only few papers are focused on the evaluation of energy design strategies to improve the energy-efficiency of lightweigt buildings and thermal comfort. For example, Pataky et al. (2014) implement passive and active energy-efficient strategies to reduce the risk of overheating and energy consumption in a mobile Plus-energy house of 45 m^2 for the Odooproject. They conclude that the project is a good example for the current and future complex ecologically conscious thinking architecture which requires to build energy/efficient, plus-energy and healthy buildings. Soares et al (2017) review passive design strategies to improve thermal response, thus thermal comfort and reduce the energy for air-conditioning in lightweight steel-framed construction. They conclude that one of the main driving research topic to improve thermal performance is to develop combined strategies to increase thermal resistance, take advantage of solar thermal energy and the use of holistic simulation methods. Pajek et al (2017) are focused on enhancing lightweight timber construction in terms of thermal response using a finite element software in a 2 m^2 representative model in three different European cities. They conclude that the design of lightweight constructions should be thoughful to achieve suitable thermal response of buildings. Despite there are studies focusing on thermal response and energy-efficient design parameters in lightweight buildings, there is a lack of studies focusing on responsive design of energy-efficient wooden high size buildings with better holistic performance in energy efficiency and improved IEQ.

1.1.3.2 Indoor Environmental Quality (IEQ)

The indoor environmental quality (IEQ) of mining camps it’s a very imperative factor for miner’s physical and mental health and life quality (Marcus, 1997). In a survey realized by Carrasco & Vega (2011) almost 40% of the miners that worked over 3,000 m.a.s.l found mining camp bedrooms uncomfortable. Another study shows that 80% of the miners agree that the quality of mining camps has a direct consequence on the industry productivity (Aramark, 2013). In terms of outdoor environmental conditions, as can be seen in Figure 2, high altitude mining is inserted in an adverse geographic and climatic environment. The main atmospheric characteristics are extremes low air humidity, low temperatures that decrease from 5 to 10°C each 1,000 meters height, and the ultraviolet radiation increases by 30%, the available oxygen reduce by 14% and the air pressure decrease in about 35% in relation to sea level at 3,000 m.a.s.l. (SERNAGEOMIN, 2013). This characteristic makes miners life harder, causing a decreased aerobic capacity, headaches, nausea and vomiting, while these effects increases between 3,800 - 5,800 m.a.s.l. This condition increases the need of a suitable IEQ (Carrasco & Vega, 2011). Based on this, a potential area of development is to incorporate energy efficiency strategies to improve the IEQ and to reduce the mining camps energy consumption, but most important, improve miner’s life quality.

1.1.3.3 Overheating

To achieve proper IEQ, the most important parameter is the thermal comfort (Al Horr et al., 2016). Under this context, a relevant factor is the thermal performance of prefabricated modular wooden buildings. Many researches have studied the thermal performance of lightweight buildings and conclude that this type of construction typically shows high indoor temperature fluctuations in the heating and cooling seasons due to the lack of sufficient thermal mass, large heat gains, high solar radiation and/or extreme hot weather (Navarro et al., 2012; Soares et al. 2014; Pajek et al., 2017; Zhu et al., 2009; Adekunle & Nikolopoulou, 2016). This increases the risk of overheating, which decreases the IEQ (Koen et al., 2015; Heier et al., 2012; Kalema et al., 2008). Overheating is also a problem when implementing passive energy efficiency strategies, because the improving of the thermal insulation and airtightness of the envelope might cause poor thermal performance in summer (CIBSE, 2013; Marin et al., 2016). For example, Figueiredo et al. (2016) studied the compatibility between Passive House (PH) standards and summer thermal overheating rates in Portuguese climate. They conclude that the technical and constructive solutions vary for different climates conditions to avoid the overheating risk. Azlizawati et al. (2017) studied two energy-efficient standards, CIBSE Guide A 2006 and PH, for two case studies in Sheffield. The aim of this study was to evaluate the effect on overheating of these standards. They conclude that in both cases, overheating mitigation measures were necessary in summer season. Therefore, the overheating risk is a key factor in the making decision process of the energy efficiency strategies to optimize building energy performance and achieve high IEQ of mining camps.

1.1.3.4 Weather conditions

Climate conditions influence the thermal and energy performance of buildings. In terms of the climatic conditions associated to the high-altitude site, several authors have studied the influence of these factors on the design parameters of efficient buildings. Some authors reported the effect on specific design strategies of efficient buildings of the main atmospheric characteristics of mining camps expressed in section 1.1.3.2. For example, air humidity influences the probability of surface condensation, which is higher when the relative humidity of ambient air is greater than 80%, as long as the convective and radiative heat transfer coefficients of the exterior walls are small (Sadineni et al., 2011). Cold climate has impact in many factors, for instance, decreases the performance of HAVC systems (Ahmed et al., 2015), increases the optimal U-value of windows (Huang et al., 2014), affects the heating and cooling requirements (Pacheco et al., 2012), the effectiveness of insulation (Pan et al., 2012), among others. In terms of high radiation, having a super-insulated building might cause higher energy demand for space cooling and indoor overheating in high radiation zones (Murano et al., 2017). Despite the advancement of the influence of climate factors on specific design parameters, there is a lack of studies on the effect of these climate factors related to high altitude on the overall building energy performance and overheating risk.

Because of the high radiation levels, the limited access to the electricity mains grid, the trend toward using renewable energy in mining sites, large roof surface and only one or two stories (Figure 2), mining camps have good characteristics for PV installed to reduce the amount of electricity used from the grid.

a) b)

Figure 2. Examples of remote mining camps in Chile. a) Quebrada Blanca 2 and b) Sierra Gorda camp.

Therefore, mining camps in Chile have the potential to accomplish Net Zero Energy targets or even though to be EnergyPlus building to provide energy to the mining processes.

1.1.4 Net Zero Energy Buildings (NZEBs)

1.1.4.1 The common definition for NZEBs

For a long time, there were varied definitions of the concept of "Net Zero Energy Buildings" (NZEBs), without having a clear execution procedure, limits, methodology of energy measurement, calculations of energy measurement, among others. In September 2015, the US Department of Energy proposed the document "A common definition for NZEBs" in which state the definition as: "*An energy-efficient building where, according to a base energy source, the actual annual energy is equal to the existing renewable energy at the site”* (U.S. Departament of Energy, 2015). This indicates that a NZEB is a high energy efficiency building due to design strategies that significantly reduce its energy demand. Then the reduced remaining energy demand is supplied with in-situ renewable energy sources, so that the balance of energy consumption is zero in a given time, which is usually one year (Salom et al., 2012). It is assumed that NZEBs are connected to energy supply networks, such as electricity or gas networks, district heating and/or cooling networks, among others. The premise is that NZEBs use the electric grid or other energy networks to transfer any surplus of on-site renewable energy to other uses (exported energy) and buy the required electricity in the hours of non-generation of renewable energies from the energy networks, which is called delivered energy (Salom et al., 2012). The correct use of the definition requires defining the site boundary, through which the exported and imported energy is accounted for. Figure 3 shows how energy exported, energy imported, renewable energy generated on the site and energy consumed are related to the site boundary.

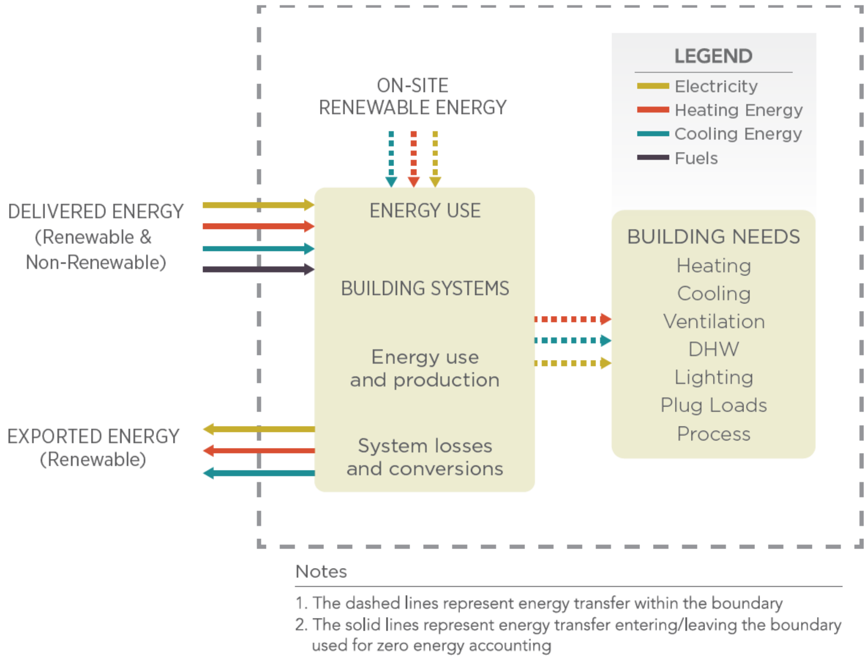

Figure 3. Site Boundary of Energy Transfer for Zero Energy Accounting (U.S. Departament of Energy, 2015)

For a construction to be NZEB, buildings must ensure that the sum of the energy delivered per year ($E_{del,i}$) is equal to the sum of the annual energy exported ($E_{exp,i}$). The source energy conversion factor ($r_{del,i}, r_{exp,i}$) to assess the relative efficiencies of varying fuel types. It is necessary to convert the different fuel types into equivalent units of raw material and include the energy consumed in the fuel production process. To do this, national average ratios are normally used. The following formula represents the NZEB balance (U.S. Departament of Energy, 2015):

$$\sum_i (E_{del,i} r_{del,i}) - \sum_i (E_{exp,i}\, r_{exp,i}) = 0$$

Where i means the fuel type$_i$ (U.S. Departament of Energy, 2015).

1.1.4.2 Global development of the NZEBs

Large part of the developed countries has adopted the objectives of including best practices in the field of energy efficiency and NZEBs in their future constructions (Sartori et al., 2012). In Europe, 28 members of the European Union plus Norway are part of The Concerted Action Energy Performance of Buildings Directive (CA EDPB), which aims to contribute to the reduction of energy consumption in European buildings through the exchange of knowledge and best practices in the field of energy efficiency and energy savings by requiring that all new buildings will be zero-energy by the end of 2020 (European Commission, 2010). In Japan, the 2014 strategic energy plan aims to ensure that all new public buildings would be NZEBs by 2020 and that all new buildings are also NZEB by 2030 by implementing and introducing energy-efficient technologies (Gobierno de Japón, 2014). On the other hand, India developed the NZEB Alliance, whose mission is to proportionately increase the design and construction of NZEBs in India (NZEB Alliance, 2015). The International Living Future Institute of the United States and Canada developed the first and unique existing certification for NZEB called "Net Zero Energy Buildings Certification" (Dephtereos, 2014). The U.S. has a target that 50% of the U.S. commercial buildings by 2040 must be NZEB and all commercial building by 2050 (NREL, 2009).

NZEBs are not only a development opportunity for the public and residential sector, but also for military camps, university campuses, and even, mining camps. For example, in October 2010 the Net Energy Army initiative was created in the United States and it is expected to replace approximately 8% of the total energy use of the Navy by renewable in-situ energy (Hammack, 2013). Grayling Camp, located in Michigan, was the first military base to be NZEB, where all the energy requirements are supplied by photovoltaic panels, wind funnels and biomass generation plant using wood, grass and other local materials. There are also net zero energy universities, for example the Loyola Retreat and Ecology Campus located in McHenry County, (Chicago, USA) and the East Campus of the Guru Gobind Singh Indraprasthe University (New Delhi, India) have as mission to run only with renewable energies (Loyola University Chicago, 2016; Modern Green Structures & Arquitecture (MGS), 2016).

In Chile, GIZ, a German joint-venture company (Deutsche Gesellschaft für Internationale Zusammenarbeit), identified the specific energy needs with potential for renewable energies in mining camps in Chile, such as mining infrastructure (buildings, workshops, offices, lighting, among others), preheating water and heating mining camps (Vásquez R. , 2015).

Despite detecting possible sources of use of renewable energy in mining camps, there is a lack of studies about the impact of implementing energy efficiency strategies and in-situ renewable energy in mining camps and the possibility of building Net Zero Energy mining camps (NZEMC).

1.1.4.3 NZEBs benefits

The great acceptability and development of net zero energy buildings is due to their multiple benefits. There are environmental, economic and social advantages associated to the construction of NZEBs. NZEBs reduce the environmental impact of the operation phase due to their balance energy consumption based on fossil fuels and renewable energies (Hamdy et al., 2016), which is also an economic benefit because maintenance cost of buildings is reduced. In the case of mining camps this benefit reduces the risk of energy cost fluctuations due to most of fuels are imported in Chile. This dependence was 78% in 2011 (Ministerio de Energía, 2013). As social benefits, NZEBs have greater resilience to energy disruptions and natural disasters, which have a higher probability of occurrence at high altitude and extreme climates (U.S. Departament of Energy, 2015); greater thermal comfort due to more uniform temperature distribution (ECOFYS, 2013); and greater visual comfort due to greater availability of natural lighting (ECOFYS, 2013; BPIE, 2013) that improves the IEQ. The improvement of IEQ is associated to health and mental benefits due to the greater comfort, better interior environment and productivity increasement.

Based on these benefits and the previous conditions and requirements of mining camps, constructing NZEMC could be a great solution to the current challenges of mining camps, which are reducing energy consumption due to high electricity prices, difficult access to reliable, safe, environmental friendly energy sources and to the electricity grid and improve the IEQ for miners.

1.1.5 Influence of existing constraints for remote sites and prefabricated modular construction in design strategies for NZEB

To design a NZEB, it is important to identify synergies between the building characteristics, construction restrictions and energy systems to ensure compatibility with renewable energy sources (Almeida et al., 2013). Accordantly to Paraszczak & Fytas (2012) the most critical problems of remote mines is: (1) Extreme weather conditions (2) Difficult access to land (3) Difficult access to the electricity grid (4) Presence of dust, lack of humidity or snow. However, the most critical problem is the access to electricity. In addition, lightweight prefabricated modules also lead to transportation and constructive restrictions. These characteristics must be considered for the choice of energy sources to be installed.

1.1.5.1 Transportation and constructive restraints

To reach the NZEB target, is needed to incorporate an in-situ renewable energy to satisfy the remaining energy consumption. Prefabricated construction increases the speed of construction, workers safety and reduction of construction waste as compared with traditional on-site construction (Boafo et al, 2016). Prefabricated modules must comply with transportation limitations of size, weight and dimensions of modules to be transported and easily assembled in the construction site (Deng et al, 2014; Minería Chilena, 2014). Regarding this, any energy saving strategy should be an integrated approach to prioritize the easy installation of the modules, the reduction of construction materials and equipment, no need for extra trucks, few maintenance work and no need for extra structures that might add weight or size to the modules (Kamali & Hewage, 2016). Chile has a potential of 1,640 GW for the generation of photovoltaic energy and 70% of this is concentrated in the northern Chile (Santana, 2014). This makes the use of PV and solar panels an increasingly popular option. However, traditional PV panels add additional weight and require additional structures to be installed in the roof. To overcome this aspect, the use of building integrated photovoltaics (BIPV) with thin-film solar modules (TFSM) a suitable renewable energy production strategy.

Several lightweight and TFSM are ideal for mining camp applications thus TFSM can be installed over low-load-capacity roof with almost no extra weight and size to the structure (Lee & Ebong, 2017; Petter et al., 2012). The geometrical and dimensional flexibility of TFSM allow them to be adjusted to any surface geometry (Shah, 2018; Du et al., 2017). Moreover, have a factory-applied butyl-based self-adhesive, thus the TFSMs become an integrated part of the roof system with the same wind uplift and seismic performance characteristics of the roof system (Biyik et al., 2017; Pandey et al., 2016; Cronemberger et al., 2014). These advantages also make them the simplest, fasters and lowest labor cost than traditional PV panels (Pandey et al., 2016; Han et al., 2017).

As evidenced by the literature, TFSMs are a suitable/feasible option for the BIPV on mining camps in Chile due volume, weight and transportation constraints of prefabricated modules and the ease of installation on the roof, which can reduce significantly the installation costs and complexity.

1.1.5.2 Limited access to the electricity grid

As more mining operations have to move to remote locations due to increased demand for metals and minerals in the world, is becoming more difficult to have access to reliable, safe and environmentally friendly sources of energy (Equipo MMSD América del Sur, 2011). Under this context, is a key factor to ensure stability and reliability of the electricity grid (Galen & Truman, 2016). One approach to achieve this is to reduce the peak loads to ensure stability (Battaglia et al., 2017). The literature shows that the two most common methods to reduce peak loads are: using thermal or electrical storage from renewable sources, like using hot water storage tanks or batteries to increase the matching between local generation and consumption; and demand response strategies, where consumers or programs reduce the electricity usage during peak periods (Electricity Delivery & Energy Reliability, 2017; Mostafa et al,, 1998; Viereiraet al., 2017). Both methods aim to achieve more self-consumption of the in-situ renewable energies, either saving the renewable energy in thermal or electrical storage to use it in peak hours or increasing the electric energy use in hours with renewable energy generation (Battaglia et al., 2017; Fattahi & Gehimi, 2017). To satisfy the constructive restrictions expressed in the previous section 1.1.5.1, the method of increasing the electric energy use in hours with renewable energy generation will be used.

Another approach to ensure stability and reliability of the grid is to include energy strategies to minimize the energy use due the limited access to the electricity grid. A new concept to reduce the energy consumption is to maximize the use of the installed energy sources to supply multi-functions in buildings (Buso & Stefano, 2017). In extreme climates such as northern Chile, desertic, cold and high-altitude regions, buildings require a powerful heating and domestic hot water (DHW) system, which includes additional energy requirements (Paraszczak & Fytas, 2012). For example, hotels biggest energy use is also associated to HVAC and DHW systems (Pérez et al., 2008), so a lot of integrated systems to satisfied both energy needs have been developed. For example, reversible heat pump for space heating, cooling and DHW, which have a variable COP depending on system components, source temperature and medium used (Kara et al., 2007), producing thermal energy and electricity by cogeneration (CHP) (Onovwiona & Ugursal, 2006; Raj et al. , 2011), among others. In this case, the feasible option must to have minimal pipes, pumps, ease to assemble in the modules and comply with the construction constraints exposed in section 1.1.5.1.. Polanco & Yousif (2015) studied measures to achieve a net zero energy hotel in the central Mediterranean and conclude that the more flexible, with better performance and simpler system for DHW and HVAC is using solar photovoltaic installation with high efficiency solar-ready heat pumps and water storage tanks.

Based on this, the most suitable method to ensure stability and reliability of the grid is to maximize the use of the energy sources using multi-functional systems and reduce grid peak loads with maximizing the use of in-situ renewable energy generation. Thus, responding to the Chilean Energy Agenda, the lower prices of PV electricity and the limited grid connection in mining camps increase the value of renewable energies self-consumption strategies and multifunctional systems to maximize the use of the existing energy sources.

1.1.6 Design by optimization

Building energy simulation is a key factor to represent the real-world operation (Rallapalli, 2010). Building energy-efficient design is a multi-variable design task, so the technique of using energy-efficient design optimization has emerged to find the best optimal combination in terms of predefined design objectives and simulation results (Si, et al., 2016). This reduces the computational time and allows the analysis of different energy efficiency strategies simultaneously (Ihm & Krarti, 2012). This technique is based on coupling optimization and simulation engines. The most used software for optimization are GenOpt and Matlab (Shi et al., 2016; Attia et al., 2013). To find the optimum solution based on two goals is called multi-objective optimization (Wu et al., 2015). To design a Net Zero Energy mining camp a design by optimization is a suitable tool to find the optimal combination of energy-efficient strategies to reduce the mining camp consumption, optimal PV efficiency/surface and then to reach the NZEB target (Ihm & Krarti, 2012).

Previous researches studied building energy-efficient design optimization in different cases and types of buildings. Shi et al. (2016) reviewed the state-of-art building energy-efficient design optimization based on 116 case studios, and concluded that only 32 of them used this tecnicque on real world case buildings. This reflects that 73% of the cases studied were applied to simplified and fictitious case buildings that cannot completely address the intrinsically challenges and complexities of real building design processes. On the other side, this study shows that the building types that are mostly studied are residential and commercial. Non-residential or non-commercial buildings require to be studied due the heterogeneous nature activities conducted inside (Buso & Corgnati, 2017). For example, hotels or mining camps offer many different activities like sport facility, bedrooms, restaurant, among others, which cause very different energy use patterns. Regarding to mining camps, the literature review shows very few investigation on the energy performance of mining camps while these studies consider mining camps in very simplified ways. For example, Marin et al (2016) study the feasibility of reducing HVAC energy consumption and temperature fluctuations by adding Phase Change Material (PCM) to the enclosure in a Chilean mining camp (Marin, et al., 2016). The study is based on a simplified single-zone dorm building prototype design with 5.76 m^2 with no internal partitions. Another study evaluate wireless home automation (WHA) in a single person quartes units for mining camp to evaluate the most suitable technology (Rathnayaka et al., 2012). Moreover, the literature review also evidence the lack of implementing the design by optimization to complex buildings such as mining camps. Due to the high complexity, magnitude, occupation and outdoor conditions of mining camps, design by optimization is suitable because it deals with multi-objective optimizationan that can significantly reduce computing time to design a Net Zero Energy Mining Camp.

1.2 Research opportunities

Based on the preview literature review, NZEBs have a fundamental role due to concerns of increasing energy cost, rising impact of GHG on world climate and energy used. Because of this, in the last two decades a growing number of project and studies of NZEBs have been made across various economic sectors and climate zones. Mining camps face extreme outdoor conditions, difficult access to reliable and safety energy sources and require high IEQ, which can be solve by building net zero energy mining camps. In addition, there is a lack of studies about the impact of energy efficiency strategies on the energy performance mining camp built with wooden prefabricated modules. Mining camps that are made with lightweight prefabricated modules must comply with constructive restraints that have different impacts on their design. Therefore, the size and mining camp complexity make necessary to optimize the design based on multi-objective targets, two of them are achieving IEQ and net zero energy goal. The results of this thesis are relevant scientifically not only for Chilean mining, but also for any building with similar operation conditions.

According to the literature reviewed, the following study is based on the following research opportunities:

1. Lack of research on the impact of energy- efficient strategies in the energy performance of complex building like mining camps due to particular operational and climate conditions.
2. There is no evidence about the suitability of the design by optimization of mining camps to achieve NZEB target

1.3 Hypothesis

This investigation is based on the following hypothesis:
Optimize the building envelope, architecture, lighting and the integrated multifunctional system between HVAC, DHW and PV system allow to achieve the net zero energy target and increase the IEQ.

1.4 Objectives

The general objective of this research is to design by optimization a net zero energy camp at high altitude and cold weather conditions in Chile, considering the complex operational conditions of mining camps that influence the building's energy performance and IEQ.

The specific objectives are:
1) Design by multi-objective optimization an energy-efficient mining camp, minimizing energy consumption and preventing overheating.
2) Design by optimization a net zero energy mining camp considering a multifunctional integrated system between HVAC system, DHW and PV system to reduce peak loads and energy consumption.

1.5 Methodology

To accomplish the main objective and test the hypothesis presented in the previous section, the following methodology is proposed:

i. Literature review: Since the main goal includes to evaluate and optimize an existing Chilean mining camp to reduce energy consumption toward NZEB target, a detailed literature review is needed to define the design parameters of mining camps, their characteristics, constructive methods, constraints, and the existing renewable energy solutions that can be implemented to reach the NZEB target. This stage will contribute to define and configure the work to be done in stage iii) and iv).

ii. Quantitative assessment of the current energy consumption of the studied mining camp: Based on the literature review, this stage aims to estimate by simulation, the energy consumption for the actual mining camp. The activities at this stage are as follows:
    a. Select the case study mining camp, which should be a real mining camp project.
    b. Obtain plans, operational conditions, weather data, technical specifications and documents associated with the camp in order to perform the simulation as similar to the real situation and obtain the inputs that are requested by the software.
    c. Generation of the required weather file based on two validated sources: Explorador Solar and Era40.
    d. Carry out the simulation of the base case mining camp.

iii. Optimization of energy-efficient strategies avoiding overheating: At this stage the main parameters will be set to optimize the original design of the mining camp (base case), based on the opportunities of improvement of the mining camp studied in stage ii). A quantitative comparison is made between the energy consumption obtained in stage ii) in order to quantify the reduction in annual energy consumption and select the best combination of energy-efficient strategies that increases the IEQ. Four cases are evaluated: (1) Optimization of the design parameters with electric terms as the heating source with overheating constraint, (2) the same as (1) without the overheating constraint, (3) Optimization of the design parameters with an efficient HVAC system with overheating constraint and (4) the same as (3) without the overheating constraint.

iv. Integrate the heat pump for HVAC with the DHW system to maximize the use of the available energy sources and thus reducing mining camp energy use in DHW. A quantitative comparison is made between the original DHW system based in electric terms to quantify the reduction in annual energy consumption.

v. Implement an integrated multi-functional system of HVAC, DHW and PV system and optimize the PV system: Assess the effectiveness of implementing an integrated multi-functional system to maximize the available energy sources, reduce the grid peak loads and evaluate different types and configurations of TFSM to reach NZEB. The reduction of peak loads is quantifying in comparison with the energy-efficient design found in stage iii).

The methodology of point i), ii) and iii) are accomplish in Chapter 2 and point iv), v) and vi) are accomplish in Chapter 3 and can be seen in Figure 4.

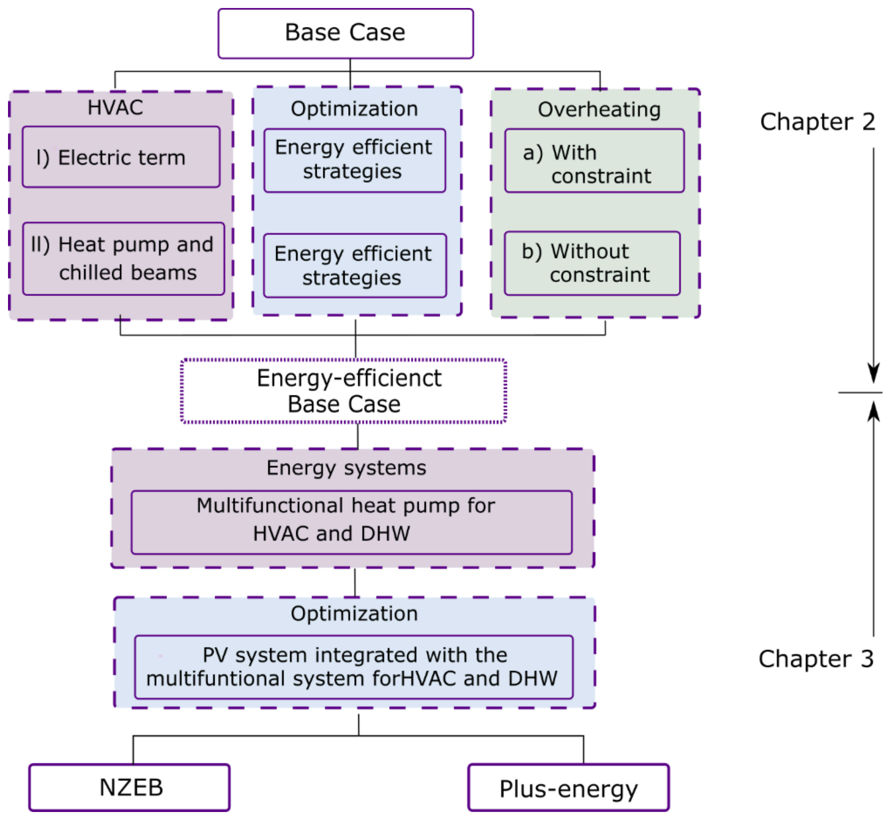

Figure 4. Methodology

1.6 Thesis structure

Beside the introduction, other two chapters compose the thesis, each one of them being an auto-contained potential journal article. Those chapters correspond to (1) Multi-objective optimization of energy efficiency strategies in an existing mining camp under cold climate and high altitude, Chile, and (2) Optimization of an integrated multifunctional HVAC, DHW and PV system based on flexible TFSMs in a Chilean Mining camp to reach Net Zero Energy target Chapter 2 search to accomplish specific objectives 1, 2 and 3 and chapter 3 to accomplish specific objectives 4 and 5.

1.7 Conclusions

The main findings to design a net zero energy mining camp in Chile are:

- Mining camps present overheating in their thermal zones, especially in the office building, due the high internal gains, the lack of thermal mass in the envelope and the use of an HVAC system only with heating option.
- To include an efficient HVAC system that can provide heating and cooling loads ensures adequate thermal comfort and reduce the energy consumption compared to the current HVAC system, electric heaters.
- The HVAC system with free cooling option enable to minimize the mining camp energy consumption through different energy efficiency strategies, while maintaining the thermal comfort. In this context, the optimization results showed a large set of applicable solutions with direct effect on reducing mining camp's energy consumption and maintaining internal thermal conditions, which allows more flexibility of designing strategies to reach an energy-efficient mining camp.
- To include a multifunctional heat pump for HVAC and DHW generation in the design stage of mining camps is an effective solution to reduce the energy consumption in comparison with a non-integrated HVAC and DHW system.
- To design an integrated system among HVAC, DHW and TFSM can reduce peak loads and ensure stability of the electrical grid and reliability of the energy supply.
- Quebrada Blanca 2 mining camp can reach the net zero energy performance with a long pair of parameters among area and efficiency, represented by the NZEB curve, which varies among 40% roof area with TFSM of 17% efficiency up to 90% roof area with TFSM of 7.5% efficiency.

- Quebrada Blanca 2 can also be designed to achieve plus-energy performance using the pair of area-efficiency parameters represented by the area over the NZEB curve.

This methodology and results can be applied to design other mining camps and buildings in similar operational and weather conditions.

1.8 Recommendations

The main recommendations to design a net zero energy mining camp in Chile are:

- Conducting an energy analysis in the design stage of Chilean mining camps, considering different energy efficiency strategies, can allow a reduction of 70% of the operating costs associated with the energy consumption of the mining camp, which is equivalent to 232 kWh/m^2 year of the base case studied.
- The infiltration rate is the most influential parameter of energy efficiency measures in reducing mining camp energy consumption, therefore is a key factor to measure and mitigate the infiltration rate in these buildings.
- To include the overheating risk in the design stage of mining camps can significantly influence the energy efficiency strategies performance.
- A key factor to eliminate the overheating risk is to consider an HVAC system that can provide cooling and heating efficiently to ensure the thermal comfort during the whole year. For example, using efficient heat pump with chilled beams with free cooling option.
- Use TFSM as the in situ renewable energy is the best choice for modular mining camps, because it can be an integrated part of the modules which is beneficial to prevent construction issues, like extra weight and size, comply with transport restrictions and modular construction and require minimal maintenance.
- A suitable option to decrease the in-situ mining camp energy requirement is to integrate energy systems, such as DHW and HVAC.

It is worth mentioning that to achieve net zero energy performance is needed to consider several construction practices and materials, which should be studied and detailed at the design stage of each project.

1.9 Future work

This work can be divided in two main parts: (1) reducing the mining camps energy consumption and (2) supplied the remain energy with renewable energy sources.

Base on the results of (1), future work should perform a similar research from the economic point of view with restriction of overheating, to find the best economically feasible and energy-efficient solution that assess IEQ. Also, future work should validate the strategies experimentally and, evaluate the implemented solutions under other climates to explore the possibility of implementing this solution in other mining camps or buildings with similar operational conditions, like mining hotels.

In terms of (2), future work should focus on encouraging the construction of NZEB mining camps in Chile. A possible first step should focus on create the national average source energy conversion factors, to be able to convert the fuel types into equivalent units of raw fuel consumed in generating one unit of energy consumed on-site and national plans that focus on NZEBs targets. Also, future work should build a pilot NZEB mining camp to validate the studied strategies.

To increase NZEBs studies in remote sites and based on the difficulties faced in developing this work, future effort should be made to make a much more complete database of climate files.

2 MULTI-OBJECTIVE OPTIMIZATION OF ENERGY EFFICIENCY STRATEGIES IN AN EXISTING MINING CAMP UNDER COLD CLIMATE AND HIGH ALTITUDE, CHILE

2.1 Abstract

The mining industry is one of the largest energy consumer in Chile with 32% of the total electricity consumption of the whole country. The electricity consumption of the mining sector is projected to grow 53.3% between 2015 and 2026. Mining camps in Chile are mostly located in Andes Mountain above 3,000 m.a.s.l. and exposed to cold weather conditions. Sustainability reports of mining companies show electricity energy consumption of mining camps is between 350 and 500 kWh/m^2 year. Therefore, they are fertile ground to incorporate energy efficiency strategies and advance to reduce the mining camps energy consumption. This paper aims to optimize the building envelope design to minimize the total energy consumption (heating, ventilation, lighting, and equipment) and eliminate the risk of overheating of a real mining camp, Quebrada Blanca 2 (21.0°S, 68.8°W). Quebrada Blanca 2 is located at 4,400 m.a.s.l with built surface of 30,000 m^2 that host 1,700 workers, while the outdoor temperature varies between -5.6°C and 10.7°C. This camp is built of timber prefabricated lightweight modules. Most of buildings are dorms but the camp also includes an office building, a gym and a dining room. The energy consumption of the base case is 329 kWh/m^2 year and heating, power, lighting and DHW count for 67%, 20%, 6% and 7% of the total electricity use, respectively. A multi-objective optimization has been carried out using a hybrid multidimensional optimization algorithm GPSPSOCCHJ coupled with EnergyPlus that minimizes the total energy consumption and avoid overheating. The main parameters that are evaluated correspond to roofs, walls and floors insulation, U-value and SHGC of windows, window area, orientation, and lighting power density. Two different cases are optimized depending of the heating systems: (I) heating provided by electric heaters, which is the current situation, and (II) heating provided by heat pumps with chilled beams. The results indicate that in the case I the mining camp energy consumption is reduced up to 7% (22.75 kWh/m^2 year) without overheating. In addition, in case

II energy efficiency measures reduce 65.8% (194.33 kWh/m^2 year) the camp's energy consumption avoiding overheating, whereas there are a lot of other available solutions close to the optimum.

2.2 Introduction

Today, mining operations move to more remote locations due to the progressively increase in the world's demand for metals and minerals (Paraszczak & Fytas, Renewable energy Sources - A promising opportunity for remote mine sites, 2012). In Chile, about 80% of the mining sites are located at 3,000 meters above sea level (m.a.s.l), most of which are in the north, specifically in the regions Tarapacá and Coquimbo (Carrasco & Vega, 2011). These remote mines have the need to provide camps, which means having kitchen, leisure spaces, bathrooms, showers, drinkable water, medical facility, sport areas, among others, to accommodate workers (Minería Chilena, 2014). The dimension of the mining camps in Chile varies approximal from 6,500 m^2 to 95,000 m^2 and host from 600 to 7,000 workers (Correa 3 Arquitectos Ltda, 2011). Most of the mining camps are located next to the working sites, away from urban centers and with difficult access. Because of this, prefabricated buildings, which are constructed off-site, are being used as the alternative to the on-site method to fabricate and pre-assemble building elements, components or modules before being installed at the construction site (Kamali & Hewage, 2016). This type of buildings is used extensively as the main mining camp in Chile (Félix et al., 2014). Sustainability reports of mining companies show electricity energy consumptions of mining camps between 350 and 500 kWh/m^2 year (Antofagasta Minerals, 2015; Minera Escondida Ltda, 2015). Remoteness of mine sites usually implies limited or no connection to available energy sources (Paraszczak & Fytas, Renewable energy Sources - A promising opportunity for remote mine sites, 2012). At the present, a great majority of remote mines relies heavily on fossil fuels that must be transported over long distances, which entails significant economic cost and environmental risks (Davourie, 2016).

Figure 5. Examples of remote mining camps in Chile, Quebrada Blanca camp and Sierra Gorda camp respectively.

Building energy-efficient design is associated to the energy supply needed to achieve comfortable indoor environmental quality (IEQ) while minimizing the energy consumption (Omer, 2008). Mining camps IEQs is a very imperative factor for miner's physical and mental health and life quality (Marcus, 1997), due to mining camps environment that is characterized by being arid and dominated by rocks and dust (Carrasco & Vega, 2011). A survey realized by Carrasco & Vega (2011) shows that almost 40% of the miners that works over 3,000 m.a.s.l find mining camp bedrooms uncomfortable. Another study shows that 80% of the miners agree that the quality of mining camps has a direct consequence on the industry productivity (Aramark, 2013). In terms of outdoor environmental conditions, as can be seen in Figure 5, high altitude mining is inserted in an adverse geographic and climatic environment. The main atmospheric characteristics are extremely low air humidity, low temperatures that decrease from 5|C to 10°C each 1,000 meters height, and in relation to sea level at 3,000 m.a.s.l., the ultraviolet radiation increases by 30%, the available oxygen reduces by 14% and the air pressure decreases in about 35% (SERNAGEOMIN, 2013). These characteristics make miners life harder, causing a decreased aerobic capacity, headaches, nausea and vomiting effects that increase between 3,800 and 5,800 m.a.s.l.. Therefore, is clear the need of a suitable IEQ (Carrasco & Vega, 2011). Based on this, a potential area of development is to incorporate energy efficiency strategies to improve the IEQ and reduce the mining camps energy consumption, and thus, improve miner's life quality.

To achieve high IEQ, the most important parameter is the thermal comfort (Al Horr, et al., 2016). Lightweight buildings typically show high indoor temperature fluctuations during heating and cooling seasons due to the lack of sufficient thermal mass in their envelopes (Navarro et al., 2012; Soares et al., 2014; Pajek et al., 2017; Zhu et al., 2009; Adekunle & Nikolopoulou, 2016). For example, Kalema et al. (2008) concluded that increasing the thermal mass in 20% of a well-insulated building decreases the cooling load in 30-50%. In terms of overheating hours, Heider et al. (2012) report that replacing a lightweight structure with a concrete external wall reduce the overheating hours in 20%. Therefore, it is expected that modern Chilean mining camps are more likely to present overheating due to fact that mostly are built with timber prefabricated lightweight modules. Overheating has also become a problem when implementing energy efficiency strategies because improving the thermal insulation and air-tightness of the envelope lead to poor thermal performance in summer (CIBSE, 2013; Marin, et al., 2016). For example, Figueiredo et al. (2016) studied the compatibility between Passive House (PH) standards and summer thermal overheating rates in Portuguese climate. They conclude that to avoid the overheating risk the technical and constructive solutions vary for different climates conditions. Azlizawati et al. (2017) studied two energy-efficient standards, CIBSE Guide A 2006 and PH, for two case studies in Sheffield to evaluate their effect on overheating. They concluded that in both cases, overheating mitigation measures were necessary for summer season. Thus, based on literature review, evaluating the risk of overheating is a key factor to design energy-efficient mining camps and improve the IEQ.

Building energy efficiency can be improved by implementing either active or passive energy-efficient strategies. Most common active strategies are, improvements in heating (Yan et al., 2018), ventilation (Mikola et al., 2017), air conditioning (Meggers et al., 2017) and lighting systems (Kwon & Lim, 2017). Passive strategies refer to any improvement of the building envelope elements, such as building form (Sharizatul & Mohamed, 2016), opaque envelopes

(Long et al., 2016), fenestrations (Bueno et al., 2017), thermal mass materials (Marin et al., 2016), shadings (Khalilian, 2017), among others (Tian et al., 2018; De Boeck et al., 2015; Seok-Gil et al., 2017). Regarding the energy-efficient design of lightweight buildings the majority of the studies has been focused on evaluating the influence of thermal mass in energy consumption, such as using Phase Change Materials (PCM), in either steel or wood frame buildings (Hoes & Hensen, 2016; Marin et al., 2016; Ochoa & Capeluto, 2008; Evola & Marletta, 2014; Karaoulis, 2017; Heim, 2012; Koschenz & Lehman, 2004; Peippo et al, 1991). Some studies focused on implementing other passive and active energy-efficient strategies, however they did not evaluate their effect on thermal comfort (Islam et al., 2016; Mohammad & Hewage, 2016). While other studies had evaluated the thermal performance and energy efficiency of lightweight steel frame construction (Soares et al., 2017; Sorsak et al., 2014; Figueiredo et al., 2016). Few studies evaluated passive and active strategies in lightweight buildings. For example, Pataky et al. (2014), implement passive and active energy-efficient strategies in lightweight modules to reduce energy consumption in conjunction with strategies to reduce the risk of overheating. Nevertheless, they did not evaluate the thermal comfort.

On the other side, several studies evaluated the effectiveness of energy efficiency strategies in different types of buildings and climates. Sadineni et al. (2011) studied passive energy savings for residential building envelope components and concluded that passive energy efficiency strategies are highly sensitive to meteorological factors. Ekici & Aksoy (2011) determines that the physical-environmental parameters that affects more residential building energy requirements are wind direction and speed, daily outside temperature and solar irradiation. Ochoa & Capeluto (2008) reviewed the influence of local climate in office energy design strategies, and concluded, that the main cold climate measures are reduce ventilation, promote daylight admission and heat collection and storage. On the contrary, in hot climate, the main measures are ventilation for comfort and cooling thermal mass, sunlight control and heat rejection (Ochoa & Capeluto, 2008). Under this context and considering the high variability of energy-efficient strategies under different conditions like building type, weather conditions and construction materials, there is a lack of studies focusing on designing wooden lightweight buildings with better overall performance in energy efficiency and thermal comfort.

Due to the complexity of the mining camps environment, their long surface and the prevalence of a large number of independent interacting variables, building energy simulation plays a fundamental role in the design to represent the real-world building operation (Rallapalli, 2010). Building energy-efficient design is a multi-variable design task, thus the technique of using energy-efficient design optimization has emerged to find the best optimal combination in terms of predefined design objectives and simulation results (Si et al., 2016). This allows the analysis of different energy-efficiency strategies and reduce the computational time (Ihm & Krarti, 2012). This technique is based on coupling optimization and simulation engine. The most used software for optimization are GenOpt and Matlab (Shi et al., 2016; Attia et al., 2013). Many studies use single objective optimization to evaluate the contribution of a set of aspects on the energy performance of buildings (Guillén-Lambea et al., 2017;Aste et al., 2017; Lu et al., 2017), while few studies use multi-objective optimization to evaluate the contribution of various parameters having several objectives. The most studied multi-objectives are energy consumption and initial investment cost (Ascione et al., 2016; Karmellos et al., 2015; Ascione et al., 2017), net present value with cost (Chantrelle et al., 2009; Asadi et al., 2012; Wright et al., 2002), and thermal comfort with energy consumption (Guillén-Lambeae et al., 2017; Griego et al., 2012).
To evaluate energy-efficient strategies while considering the overheating risk in timber prefabricated lightweight construction, this research will apply a multi-objective optimization problem to reduce the mining camps energy demand and avoid overheating.

Previous researches studied building energy-efficient design optimization in different cases and types of buildings. Shi et al. (2016) reviewed the state of art building energy-efficient design optimization based on 116 case studies . They concluded that only 32 cases used this technique on real world case buildings. This mean that 73% of the cases studied were applied to simplified and fictitious case buildings that can not completely address the intrinsically challenges and complexities of real building have. The low number of real case studies also may reflect that only few cases were studied and then adopted into building design practice. On the other side, of the 116 case studies, the building types that are mostly studied are residential and commercial. The non-residential or non-commercial buildings require to be studied due the heterogeneous nature activities conducted inside, depending on the main activity of the facility (Buso & Corgnati, 2017). For example, hotels or mining camps offer many different activities like sport facility, bedrooms, restaurant, among others, which cause very different energy uses. Regarding mining camps, there is only one study that assesses the feasibility of reducing HVAC energy consumption and temperature fluctuations adding PCM to the enclosure in a Chilean mining camp (Marin, et al., 2016). The study is based on a simplified single-zone dorm building prototype design with 5.76 m^2 with no internal partitions. Due to the high complexity, magnitude, occupation and outdoor conditions of mining camps, it is imperative to study the overall mining camp energy consumption to evaluate and determine the set of building energy design factors to minimize the mining camp energy consumption and increase thermal comfort.

This paper aims to design by multicriteria optimization an energy-efficient mining camp based on a typical Chilean mining camp to determine the optimal energy-efficient strategy considering not only the energy consumption but also the overheating risk. To include all complex factors of mining camps, this study takes as base case a real mining camp, Quebrada Blanca 2. This paper contributes to indicate which are the most influential design parameters to reduce energy consumption of mining camps. This result can be useful to new and refurbishment projects in similar operational conditions as sky centers, hotels, and mining camps. Also, this paper contributes to implement multi-objective optimization of a large project with many parameters to be optimized.

2.3 Methodology

The energy performance of the mining camp is evaluated through energy simulations in terms of heating, equipment, lighting and DHW consumption in its current operating condition. A set of 10 energy efficiency measures, correspond to roofs, walls and floors insulation, U-value and

SHGC of windows, window area, orientation, and lighting power density, are optimized to reduce mining camps energy consumption. The energy efficiency strategies analyzed are conventional technologies applied to lighting and envelope components and are based on existing technologies available in the Chilean market. As active energy-efficient strategies, two heating system are evaluated; the current electric heaters and heat pump with chilled beams. Overheating measurement was included with a restriction applied with Python that runs in conjunction with GenOpt and EnergyPlus based on TM52-2013 (CIBSE, 2013). End-use energy consumption and thermal comfort are the criteria used for the prioritization of the energy efficiency measures.

The research presented in this paper is divided into five main parts: (1) the analysis of the main parameters and energy consumption of the existing mining camp Quebrada Blanca 2; (2) the optimization of the energy efficiency strategies with the current heating system and the overheating constraint (Case I-a) ; (3) the same as the second part but without the overheating constraint (Case I-b); (4) The optimization of the energy efficiency strategies with an efficient HVAC system based on chilled beams and heat pumps with the overheating constraint (Case II-a) and, (5) the same as the fourth part but without the overheating constraint (Case II-b). Along this paper, the cases nomenclature used are resumed in Table 1.

Table 1. Nomenclature

Case I	Electric heaters (current case)
Case II	Chilled beams - Heat Pump (new system proposed)
a	With overheating constraint
b	Without overheating constraint

2.3.1 Definition of the reference mining camp Quebrada Blanca 2

This research focuses on the Quebrada Blanca 2 mining camp, which is located in the Andes Mountains, Chile (21.0°S, 68.8°W), 240 km southeast of Iquique in the Tarapacá region at 4,400 m.a.s.l. with cold weather. This mining camp was selected because it represents the general typology of mining camps in Chile that are located over 3,000 m.a.s.l. and are mainly built with timber prefabricated lightweight modules (Minería Chilena, 2014; Féliz et al., 2014). The external temperature ranges from -5.6°C in winter to 10.7°C in summer and high radiation due to only 5% cloud presence during the whole year (Arcadis, 2010). Quebrada Blanca 2 has an accommodation capacity for 1,700 workers and a total built up area of 30,317 m^2, which is occupied mainly by dorms and other areas such as offices, gymnasium, polyclinic, recreation areas and dining room (Table 2). The original design of Quebrada Blanca 2 does not have an HVAC system installed, for heating, 1,500 W electric heaters are incorporated only in rooms and offices. The detailed information of the mining camp envelope and lighting, hot water distribution and temperature setpoint can be found in Table 3.

Activity loads and ventilation rates were calculated based on ASHRAE Fundamentals (ASHRAE, 2001). The mining camp is always at its maximum capacity (Cossio, 2013), because the miners working shifts is the 7x7 system, which means working shifts for 7 days and 12 hours per day and then, 7 days of rest outside the mining camp. When the miners are in their rest week, another group replace them. The actual occupation condition is based on rooms with day shift or night shift from eight to eight. The work in offices resembles the miner's day shifts in terms of schedule. The kitchen and dining room schedules were established for breakfast, lunch and dinner times as 06:00-09:00, 12:00-15:30 and 18:00-21:00, respectively. The camps lighting consists mainly of fluorescent and incandescent lights to reach the minimum of 200 lux required per zone and 150 lux in the hallways (Tecnofast, 2012).

Table 2. Camp Surface (Tecnofast, 2012)

		Ground floor (m^2)	First floor (m^2)
Bedrooms	Bedrooms type A and type A-1	3,577	3,577
	Bedrooms type B and type B-1	8,332	8,332
Central Building	Access hall	82	
	Check out	103	
	Boots room	140	
	Dining room bathrooms	70	
	Dining room	983	
	Kitchen	849	
	Administration	183	
	Multiple room	85	
	Sanatorium	284	
	Recreation	578	
	Laundry	131	
	Music room	44	
	Judo and Karate room	87	
	Gym bathrooms	44	
	Gym machines	77	
	Gym	669	
	Massage room	18	
Adminitration office	Office	1,063	
Hallway	Hallway	1,009	
	Total surface per floor	18,408	11,909
	Total surface		**30,317**

The bedrooms buildings are type A, type A-1, type B and B-1 with two floors. Type A are single rooms with 40 bedrooms per floor, while type A-1 have 30 bedrooms per floor. Type B are double rooms with also 40 bedrooms per floor and B-1 only 30 bedrooms (see Figure 6). There is only one A-1 and B-1 type bedroom building, unlike types A and B, which have 3 and 8 buildings respectively. Each type A dorm building has 80 bedrooms (40 per floor) with a capacity of 80 people per building, while the building with bedrooms type B has a capacity of 160 people each. The bedroom buildings have their largest façade in north-west and northeast orientation.

The domestic hot water (DHW) system is based on 600 liters electric storage tank that must be maintain at a water temperature of 60°C to avoid the origin of legionella (World Health Organization, 2011). The number of tanks per building is variable, determined by calculating the use of 45 liters per person per day (see Table 2 and Table 3).

Table 3. Energy related characteristics of the mining camp.

Thermal resistances values			
	Dinning room and Gimnasium	External Wall	Superwall (100 mm polyurthane) U-value= 0.19 W/m^2 K
		Roof	Glamet techmet (100 mm Polyurethane) U-value= 0.19 W/m^2 K
		Ground Floor	100 mm concrete floor. U-value= 0.06 W/m^2 K
	All others	External Wall	(11 mm Wood composite, 140 mm Mineral wool; 15 mm gypsum board) U-value= 0.29 W/m^2 K
		Roof	(1.2 mm PVC layer; 15 mm OSB layer; 140 mm Mineral wool) U-value = 0.3 W/m2 K
		Ground Floor	(9.5 OSB layer; 140 mm Mineral wool; 16 mm plywood) U-value = 0.28 W/m^2 K
Thermal mass		None	
Window type		Aluminium (SGHC = 0.7) Window	Double glazing windowthickness of 6 mm and an air gap of 6 mm U-value = 0.32 W/m
Occupants		1700 workers:	Bedrooms day shift occupied from 19:30-7:30 Bedrooms night shift occupied from 7:30-19:30 Offices occupied from 7:30-19:30 Dinning room occupied from 6:00-9:00; 12:00-15:30; 18:00-21:00 Kitchen occupied from 5:30-21:30
Setpoint temperatures		Bedrooms	Heating setpoint: 20°C
		Offices	Heating setpoint: 20°C, Cooling Setpoint: 24°C*
DHW		Bedrooms type A	3600 l; Bedrooms A-1 3000 l
		Bedrooms type B	7200 l; Bedrooms B-1 5400 l
		Kitchen	120 l
		Gym bathrooms	800 l
Infiltration rate		2 ACH	

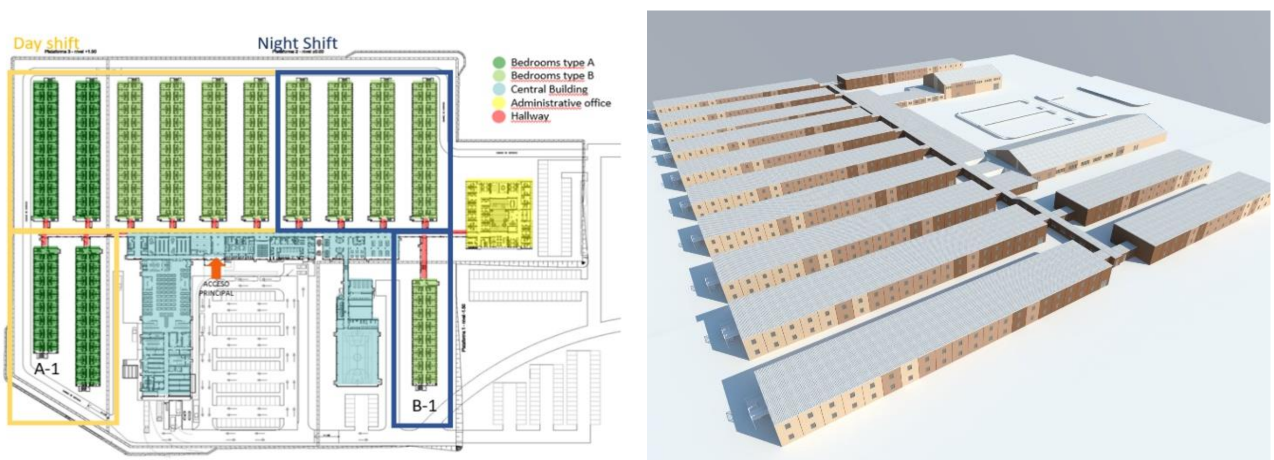

Figure 6. Mining camp floor plan and geometry of the base case in Sketchup + Openstudio (Tecnofast, 2012).

2.3.2 Weather File

To include the external factors in the energy simulation models of an entire building, the typical meteorological years (TMY) are used (Bre & Fachinotti, 2016). Nowadays, there is a vast number of databases with typical meteorological years of several cities of the world, but there is no public information of remote places where mainly mining camps are located. Mining camps used to have their own meteorological station, but the only available information from the meteorological station of Quebrada Blanca 2 is the monthly climatic average between 2001-2008. Thus, the wheatear file was generated based on two validated tools. First, Explorador Solar, a tool that delivers public information of the Chilean solar resource, being the most detailed one today in Chile (Explorador Solar, 2017). Secondly, Era40, a project of re-analysis of global atmosphere and surface conditions for 45 years by the independent intergovernmental institution ECMWF. The traditional approach (TMYP50) representing the average year (or also called the normal year) will be used, ignoring extreme months. For this research, information of 10-20 years from Era40 and Explorador Solar will be used. The fields required, and the associated source are shown in Table 4. The relative humidity and atmospheric station pressure were calculated based on the dew point temperature and dry bulb temperature obtain in Era40 (Meruane & Garreaud, 2017; Ingeniería Efraín , 2011; Martinez, 1992).

Table 4. Fields required to formulate the TMY50 file and source.

Source	Parameter
Era40	Total Sky Cover; Dry Bulb Temperature (°C); Dew Point Temperature(°C); Total Sky Cover 10 meters above ground; Opaque Sky Cover 10 meters above ground; Snow Depth (cm); Relative Humidity (%); Atmospheric Station Pressure (Pa)
Explorador Solar	Global Horizontal Radiation(Wh/m^2); Direct Normal Radiation (Wh/m^2); Diffuse Horizontal Radiation(Wh/m^2); Wind Speed(m/s)

To adjust and validate the data obtained from Era40 and Explorador Solar (shown in Table 4), the only available information is the monthly climatic average between 2001-2008 from the meteorological station of Quebrada Blanca 2. The values obtained were statistically adjusted with the monthly average information of the meteorological station, to respond more adequately to the oscillations in the camp and, thus, to reduce the existing coefficient of variation. Figure 7 shows that the adjusted temperature presents few daily and annual temperature oscillation for both variables, with the maximum temperatures being reached at 10.7°C and the minimum at -5.6°C.

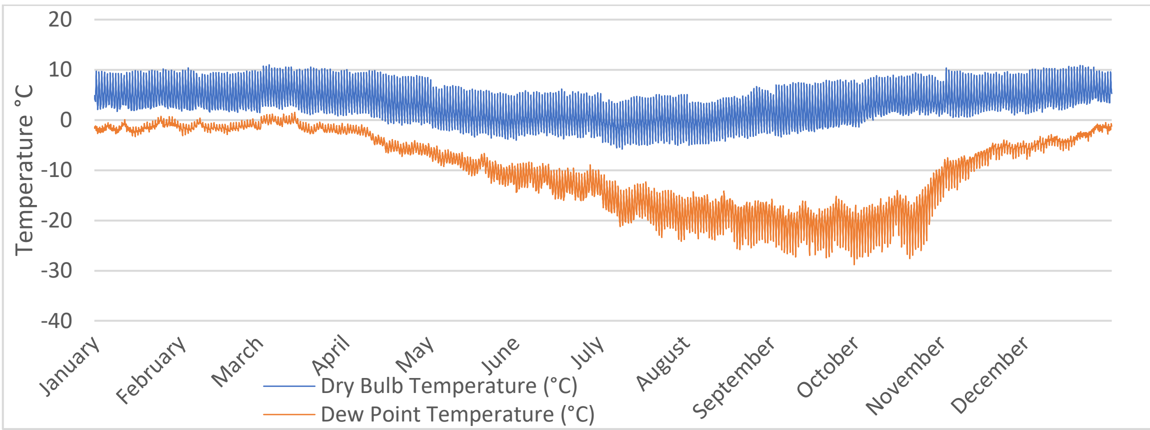

Figure 7. Annual adjusted dry bulb temperature and dew point temperature.

Figure 8 shows the daily radiation during the year. It should be noted that the amount of hourly radiation is practically constant throughout the year and the diffuse radiation is minimal given the low presence of clouds.

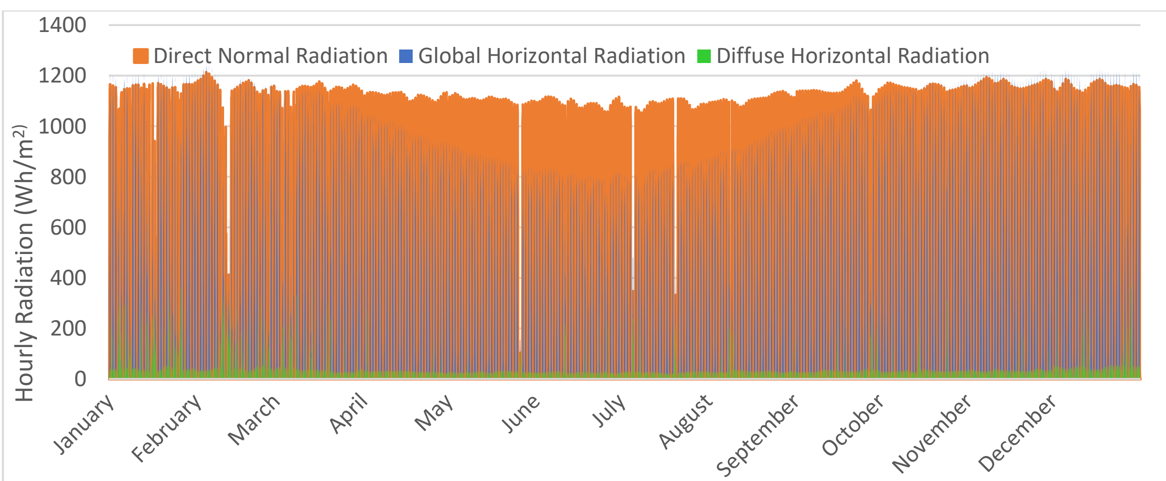

Figure 8. Annual solar radiation

2.3.3 HVAC systems

To choose an energy-efficient solution for the HVAC system is required to search for a system that ensure the compatibility with the entire construction constraints, such as transportation weight and size restrictions of the prefabricated modules, ease placement, minimal interventions of the main infrastructure, easily assembled in the construction site and requirement of minimal maintenance work. The installation of high efficient heat pumps (HP) with chilled beams is a simpler system that require minimal amount of piping works and pumps. Chilled beams are a low temperature (30-45°C) heating system, which is particularly suitable for heat pumps due to its high efficiency at low outdoor temperature, which maximizes the free-cooling option in cold climates. Chilled beams can also be integrated in suspended ceilings directly, which is the condition in bedroom buildings and the main pipes can be above the suspended ceiling. Also, this system requires minimal maintenance due to the absence of moving parts. The system does not include condensation collection drains or filters, which would require cleaning. The cleaning of the coils and surfaces is needed once in every 5 years (REHVA, 2012). Other typical energy-efficient HVAC system, such as geothermal energy, combined heat and power generators, imply greater interventions, control, costs and maintenance which make them not as good as chilled beams with energy-efficient HP.

In the optimization cases, two different HVAC cases were implemented. The first is based on the current heating system consisting of 1500 W electric heaters in each room and office space with a Coefficient of Performance (COP) equal to 1 (Case I). Case II is based on chilled beams in each bedroom and office with high efficient Heat Pumps (HP) as heat sources. The offices have also the option of free-cooling, to avoid the risk of overheating. The free-cooling mode is based on the use of the low external air temperatures to assist in chilling water, for this, shutters and air handling units (UMAs) are installed to inject external air to the cold beams. This system has a COP of 2.2, due to the climatic conditions of the camp and the operation at 4,400 m.a.s.l. The extreme temperatures of the camp are within its operational limits (-15°C to 40°C), which prevent freezing failures. The temperature setpoints were set at 20°C for heating and 24°C for cooling based on TM52:2013 (CIBSE, 2013). The peak load power per bedroom building is 120 kW. Instead of installing one HP of 120 kW, two HPs of 65.1 kW (model NRL550) were implemented in each bedroom building to have a backup in case of failure or maintenance. The peak load power of the offices is 45 kW, where a HP of 50.9 kW (model NRL 350) and a COP of 2.26 at 4,400 m.a.s.l. was selected. The office climate system was also dimensioned to supply cooling loads with a free-cooling system. The cooling peak load power is 12 kW to keep the interior temperature within the ranges of thermal comfort. Figure 9 shows the schematic drawing of the implemented HPs and chilled beams for case II. In the heating mode, the HP generates hot water at 40°C to feed the heating inductors. The hot water circulates through a water coil within the chilled beams and utilize induction of room air across the water coil to provide sensible heating.

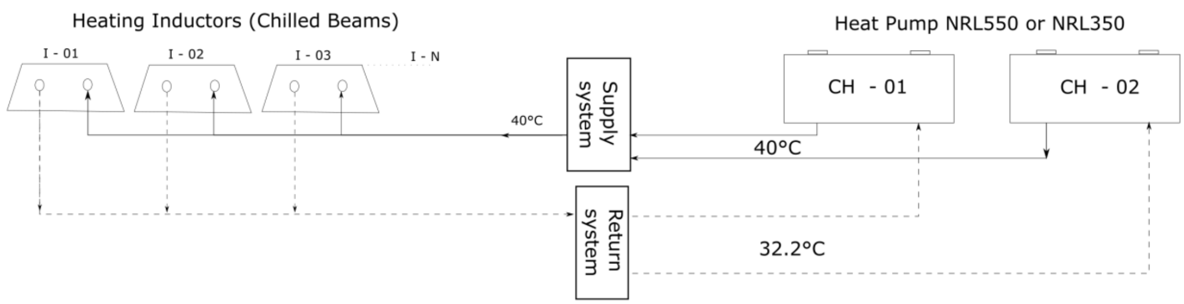

Figure 9. Schemes of the proposed HVAC system.

2.3.4 Multi-Objective Optimization

To determine if the design of the building reaches the target energy efficiency level, it is necessary to estimate the energy performance of the mining camp using simulation engines and local weather files (Kneifel & Webb, 2016). Many simulation tools have been developed to help engineers and policy makers to try out energy efficiency scenarios of buildings that allow assessing the existing alternatives and their energy-related consequences (Marin et al., 2016). In this research, EnergyPlus is used as the building energy simulation tool. This software was developed by the Department of Energy (DOE) of United States in the Office of Construction Technologies (OCT) and it is managed by the National Renewable Energy Laboratory (NREL)

(EnergyPlus, n.d). EnergyPlus is a powerful and state-of-art building energy simulation tool that estimate thermal loads, energy consumption and indoor temperatures of building spaces.

To evaluate different parameters of energy efficiency strategies that improve the energy performance of the mining camp, a multi-objective optimization is carried out. In this context, the most commonly optimization engines used for multivariable optimization are GenOpt and Matlab optimization tools (Machairas et al., 2014; Shi et al., 2016). These two optimization engines allow the use of various optimization algorithms, such as: genetic algorithms (GA), particle swarm optimization (PSO), hybrid algorithms, Hooke-Jevees algorithms (HJ), simplex algorithms, among others. Population-based stochastic algorithms (GAs, PSOs, hybrid algorithms and evolutionary algorithms) are the most used in building performance optimization (Nguyen, Reitter, & Rigo, 2013). The PSO algorithm typically requires less computational time because it evaluates a set of parallel solutions, whereas the hybrid algorithm of PSO and HJ is recognized to have a better solution over the others when it comes to optimizations of more than 10 dimensions (Hamdy et al., 2016), like it is in the current case. Based on the literature review, the hybrid multidimensional optimization algorithm PSO using a constriction coefficient and HJ, referred as GPSPSOCCHJ, which is coupled with EnergyPlus, is used to minimize the total energy consumption of the mining camp and avoid the overheating risk (see section 2.3.4.2).

2.3.4.1 Selected optimization algorithms

We selected GPSPSOCCHJ as the optimization algorithm, that is the PSOHJ hybrid algorithm with a constriction coefficient that limit the velocity to converge more efficiently in an optimum point. The algorithm based on GPS algorithms refers to the Hooke Jeeves (HJ). Such algorithm starts by performing PSO in a mesh for a specified number of generations. Then the HJ GPS algorithm is started to find the particle with the minimum value. Thus, the hybrid algorithm combines the global characteristics of the PSO algorithm with the probable convergence properties of the GPS algorithm (Uribe et al., 2017).

PSO algorithm generates a set of potential solutions to the optimization problem, called particles, and a set of potential solutions of each particle, which are called population. There is an input parameter that controls the number of particles generated. From each evaluated particle, the best solution found in its neighbors (neighborhood best) is chosen, and the best solution of all neighbors visited is kept (Uribe et al., 2017). The neighborhood topology parameter and the neighborhood size parameter control the amount of neighborhood particles. At each iteration, the magnitude of acceleration of the particle is changed in the direction of the best neighbor's solution, with the cognitive acceleration parameter. The acceleration is controlled by the social acceleration parameters and a random number between 0 and 1 that is dynamically generated (Futrell et al., 2015). A constriction coefficient is very important because it has been shown that when particle velocity is not limited, these tend to accelerate around the optimum solution and fails to converge (Kennedy & Eberhart, 1995).

The base point is the optimum point found with the previous PSO algorithm. The HJ algorithms base on the GPS algorithm looks at the neighborhood with a certain step size, which consists of a sequence of exploratory movements around the base point (Futrell et al., 2015). When it is successful, i.e. when it finds the minimum consumption of the camp, it is followed by pattern moves that identify the best search direction. The initial base point is moved along the line between it and the successful solution found with pattern moves. The solution evaluation process is repeated in the new location of the base point (Uribe et al., 2017). When a better solution is no longer found than the previous base point, the size of the skip controlled by the mesh size divider, initial mesh size exponent, mesh size exponent increment, and number of step reductions parameters is reduced, allowing the search to continue within the region of design space (Wetter, 2016).

Table 5. Parameters of Particle Swarm Optimization and Hook-Jeeves algorithm used

PSO		GPSHJ	
Parametrer	Value	Parameter	Value
Neighborhood topology	Von Neumann	Mesh size divider	2
Number of particles	10	Initial mesh size exponent	0
Number of generations	10	Mesh size exponent increment	1
Cognitive acceleration	2.8	Number of step reductions	4
Social acceleration	1.3		
Maximum velocity gain	0.5		
Constriction gain	0.5		

2.3.4.2 Overheating constraint

To ensure the thermal comfort of the miners with the new energy efficiency measures, the overheating restriction was included in the GenOpt optimization process as a constraint. CIBSE formed the "Overheating Task Force" in 2013 due to the lack of definition of overheating in buildings without mechanical cooling, which is the current situation of the mining camp, and the conclusions are reported in the Technical Memorandum TM52:2013 (CIBSE, 2013). TM52:2013 is based on the BN EN 15251 standard which uses EN ISO 7730 for design (BSI, 2006; AENOR, 2006). The methodology to identify overheating is based on 3 criteria: (1) hours of exceedance (H_e), (2) Daily weighted exceedance (W_e), (3) Upper limit temperature (T_{upp}). The 3 criteria are explained in Table 6. When a thermal zone of the building fails in 2 of the 3 criteria, the mining camp is classified with overheating. Both cases analyzed (I and II) were carried out with and without the overheating constraint to quantify the effect of this restriction on the results and the relevance of including it. All analysis and comparisons were performed with the baseline case.

The three criteria are based on $\Delta T = T_{op} - T_{max}$, which is the difference between the current operative temperature (T_{op}) and the maximum acceptable temperature (T_{max}). The thermal comfort adaptive model proposed by TM52:2013 indicates that the thermal comfort temperature in buildings without mechanical cooling is related to the average daily air temperature (T_{rm}), which is obtained by the formula (CIBSE, 2013):

$$T_{rm} = (1 - \alpha)(T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} \ldots \ldots)$$

Where α is a constant equal to 0.8 and T_{od-i} is the average outside temperature of the previous days i. Then T_{max} is obtained with the following formula:

$$T_{max} = 0.33T_{rm} + 21.8$$

The three main criteria are explained in Table 6.

Table 6. Definition of the three overheating criteria (CIBSE, 2013)

TM52:2013	Formula	Description
Criterion I: Hours of exceedance (H_e)	$\Delta T \geq 1°C$	The number of hours H_e during which ΔT is greater than or equal to 1°C during the summer period should not exceed 3% of the hours occupied. This criterion was applied in summer months in Chile, from December to March.
Criterion II: Daily weighted exceedance (W_e)	$W_e = \left(\sum h_e\right) WF = (h_{e0} * 0) + (h_{e1} * 1) + (h_{e2} * 2) + (h_{e3} * 3)$	This criterion is used to consider the severity of the overheating. The weighted exceedance (W_e) is obtained by multiplying the hours that exceeded T_{max} by the amount of degrees that is exceed. W_e shall be less than or equal to 6 in any day. If the weighting factor (WF)=0 if $\Delta T \leq 0$, otherwise WF = ΔT and h_{ei}= in the time (h) when WF=i
Criterion III: Upper limit temperature (T_{upp})	$\Delta T < 4°C$	This criterion is used to define an absolute maximum value for the indoor operating temperature, the value of ΔT shall not exceed 4°C.

2.3.4.3 Optimization Problem

The optimization problem is continuous and has the following objective function, which includes the uses of electricity of the mining camp and overheating constraint as follows:

$$\min_{y \in Y} f(x)$$

$$f(x) = \sum ElectricEquipment + DHW + HVAC + Lighting + Overheating$$

where $y \in Y$ is the design parameters vector, $f: \mathbb{R}^n \rightarrow \mathbb{R}$ is a differentiable continuous cost function and Y is the constraints set.

The overall energy consumption of the camp is the function to minimize, which include the electricity use by Electric Equipment, DHW, HVAC and Lighting. To maintain the thermal comfort of the camp within acceptable ranges, it is necessary to add a restriction that allows to obtain an optimized solution and at the same time meets the overheating criteria. GenOpt can include constraints directly as a penalty function, which attaches a positive term to the energy consumption function $f(x)$ if the constraint is violated (Wetter, 2016). The methodology applied follow the same concept, but the overheating criterion used is not met by failing in 2 of the 3 criteria outlined in section 2.3.4.2, is. Due to this, a Python script was created that penalizes the objective function by adding a positive term if 2 of the 3 criteria for overheating do not met. The overheating criteria were applied to all the heated thermal zones in the camp through a post-analysis based on the results of the EnergyPlus simulations (section 2.3.4.5). If some space of the mining camp shows overheating, the “Overheating” term acquires a value of 100,000,000 kWh/year as penalty. If all zones are within the acceptable temperature range, it is 0.

2.3.4.4 Optimization parameters

The design parameters to optimize the energy consumption of the base case were defined based on the current energy consumption of Quebrada Blanca 2 and the most recognized energy-efficient strategies (Sadineni et al., 2011). The total energy consumption of the existing camp is equal to 330 kWh/m^2 year, heating, electric equipment, DHW and lighting count for 67% (220.6 kWh/m^2 year), 20% (65.95 kWh/m^2 year), 7% (22.15 kWh/m^2 year) and 6% (21.31 kWh/m^2 year), respectively. The definition of the ranges and values of the optimization parameters are based on the existing options in the Chilean market, ranges of values commonly used in buildings to be net zero energy (Bucking et al., 2013) and design variables that reduce internal gains, and thus, the energy consumption in lighting and heating (De Boeck et al., 2015; Pacheco et al., 2012). Table 7 shows the initial values and range of the parameters to be optimized. Also, Table 8 shows the lighting values for each building zone.

Due to the large size of the camp and to reduce the computing time, the lighting parameter and size of the windows were incorporate in the optimization as discrete variables. Firstly, the lighting parameter has an associated consumption value depending on the macro zone to be illuminated, as the discrete parameters "Base case", "LED", or "LEDSM", which are then replaced by the value associated with the zone by using a code programmed in Python (APPENDIX B). Secondly, the variations of increase in the size of the windows were evaluated by the southwestern and northeast façades, varying the decrease or increase in the windows high with the discrete parameters “DeltaNE”, “DeltaSW” and “DeltaOffice”. These values are calculated with functions inside the GenOpt engine (APPENDIX C).

Table 7. Optimization design parameters

Variable	Units	Initial	Min.	Max.	Steps	Description
azimuth	Grados	-139	-180	180	45	Building orientation
WindowU	W/m^2K	3	1.5	3	0.5	U-value
WindowSHGC		0.7	0.4	0.7	0.1	Solar heat gain coefficient
InsulationConductivity	W/mK	0.045	0.02	0.045	0.005	Walls conductivity
InsultionThickness	m	0.14	0.1	0.16	0.01	Insulation thickness
Lighting		Base case			3	Base case, LED, LED with motion sensor
ACH	ACH	2	0.25	2		Infiltrations. ACH= 2; 1; 0.5, 0.25
DeltaNE	m	0	-0.5	0.5	0.25	High variation window NE bedrooms
DeltaSW	m	0	-0.5	0.5	0.25	High variation windowe SO bedrooms
DeltayOffice	m	0	0	1	0.5	High variation window office

Table 8. Light district parameters values

W/m^2	Base case	LED	LED with motion sensor
Bedrooms	11.89	5.71	4.57
Hallway	7.85	3.78	3.02
Kitchen and Dinning room	3.85	2.86	2.29
Gymnasium	3.35	2.38	1.90
Offices and Central Building	3.92	2.20	1.76

2.3.4.5 Optimization process

To perform the optimization, GenOpt, EnergyPlus and Python routines were integrated. GenOpt is the optimization tool, while EnergyPlus perform the energy simulation of the set of parameters indicated by GenOpt. Python scripts were developed to:

- Calculate "Overheating" from EnergyPlus simulation, and use this parameter as a constraint of GenOpt, as shown in section 402.3.4.2. (APPENDIX A)
- Incorporate the lighting consumption value associated to each discrete parameter set by GenOpt in the inputs require to EnergyPlus simulation, as shown in section 402.3.4.2. and Table 8. (APPENDIX B)

The search workflow for the optimal solution can be seen in the Figure 10. The steps are the following:

1) GenOpt receives the input parameters to be optimized within the ranges and initial values.
2) GenOpt generates the EnergyPlus files with the assigned values.

3) The Python code "Lights" replaces the values "Base case", "LED" and "LEDSM" by the respective values for each zone depending on which parameter was assigned.
4) The annual EnergyPlus simulation is executed and generates heating, lighting, hot water and electrical equipment annual consumption output, which is converted into kWh/year design values.
5) Once all the EnergyPlus simulations are finished, the Python code "Overheating" is executed, and it analyzes if any zones were overheated, adding a line to the output file. This step is not executed in cases without overheating (b).
6) GenOpt reads the output file from EnergyPlus and replaces the values in the target function.
7) This process is continued until GenOpt reaches its convergence point or stops.

This process was carried out in 4 cases: Case I-a, Case I-b, Case II-a and Case II-b.

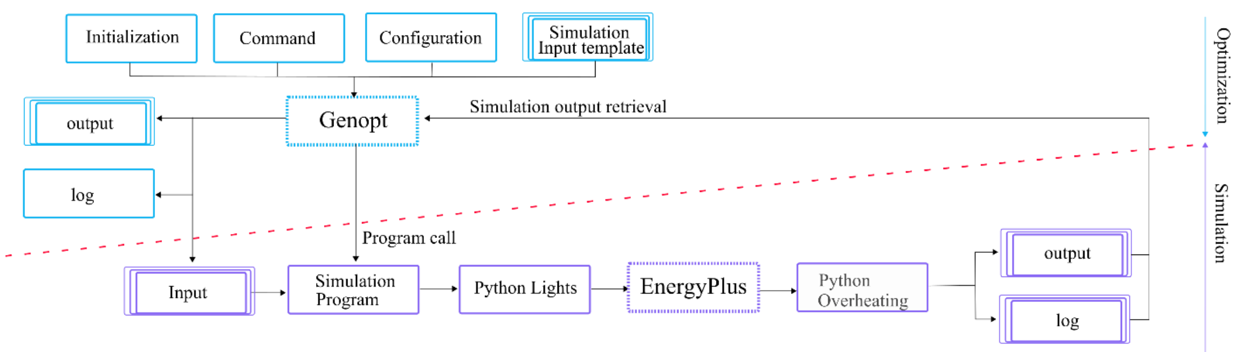

Figure 10. Optimization process. Adapted from (Wetter, 2016)

2.4 Results and analysis

The results are presented in terms of total electrical consumption of Quebrada Blanca 2 mining camp which is the sum of heating, equipment, lighting, and DHW. All analysis and comparisons were performed with the baseline case. In Case II-a, the overheating constraint only applies to bedrooms because the office HVAC system self-regulates interior conditions by free-cooling or heating within the thermal comfort ranges. The new heating system also heats bedrooms.

2.4.1 Energy performance optimization Case I: Original heating system (electric heaters)

Using the optimization approach described in section 2.3.4.5 for Case I-a, the minimized electrical consumption reaches only 307.25 kWh/m^2 year. The optimized electrical consumption represents a decrease of 6.9% in comparison to the energy consumption of the baseline case. This reduction is due to 13 kWh/m^2 year decrease in lighting electricity consumption and a reduction of 10 kWh/m^2 year in heating energy consumption. The optimal value was achieved in a total of 180 simulation cases, where 157 of the cases presented overheating according to the criteria of TM52:2013 (Figure 11). This situation occurs mainly in the administrative office building that is the one that has higher internal heat gains. On the other hand, the Case I-b reached an optimal energy consumption of 115.93 kWh/m^2 year, but the solution is overheated. Figure 11 shows all the simulation results for Case I-a and Case I-b. The green solutions represent the evaluated cases that present overheating in the Case I-a. In spite of the fact that for the Case I-a cases with lower energy consumption are evaluated (green solutions), since the overheating restriction is not fulfilled, this presents a very restrictive objective function, so when arriving at the GPS HJ algorithm, it continues searching for the optimum within the cases that did comply with the restriction (yellow cases). This is shown in the slight decreasing behavior of Case I-a solutions in Figure 11. On the other hand, the Case I-b evaluates very similar cases in terms of energy consumption, but due the objective function only minimizes energy, the GPS HJ starts in the options with lower annual use of energy. The biggest yellow triangle with red edges shows the optimal solution in terms of IEQ and minimal energy consumption for Case I-a without overheating. Although the minimal energy consumption is reach by the Case I-b, this option is not optimal, because the camp doesn’t accomplish the overheating criteria.

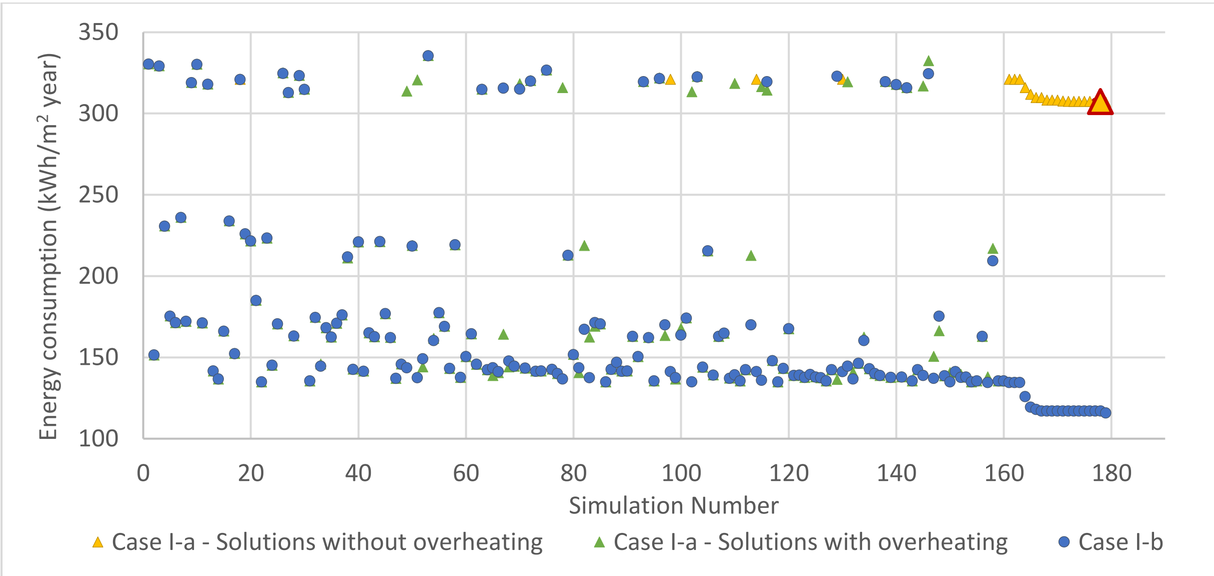

Figure 11. The results of Case I-a and Case I-b

The parameters that allow the minimum optimum consumption of 307.25 kWh/m^2 year and avoid overheating can be observed in the Table 9. This table contains also the other 7 combinations that satisfied both objectives and are feasible options to improve the energy efficiency of mining camps. It can be observed that all the solutions are obtained by maintaining the level of infiltration in the thermal zones, while the other parameters varied. These results show that maintaining the current level of infiltration reduce the probability of overheating due to the greater air changes of the thermal zones. However, this parameter is the one that has a major effect on the reduction of the energy consumption of the camp since it generates the greater heat losses. Thus, maintaining the current heating system significantly restricts the decrease in energy consumption and the set of feasible solutions to achieve high energy efficiency without getting overheated. Therefore, these results evidence that the HVAC system needs to be replaced by a more efficient system that reduces/eliminate the risk of overheating and significantly reduces the electricity use.

Table 9. Set of solutions that comply with the restriction of overheating and minimization of energy consumption.

kWh/m2	Azimuth	WindowU	WindowSHGC	InsulationConductivity	InsulationThickness	DeltayNE	DeltayVSO	DeltayOFICINA	ACH	Lighting
321.25	86	2	0.5	0.03	0.16	-0.25	0.25	1	2	LEDSM
321.25	86	2	0.5	0.03	0.16	-0.25	0.25	1	2	LEDSM
321.25	86	2	0.5	0.03	0.16	-0.25	0.25	1	2	LEDSM
316.05	86	1.5	0.5	0.025	0.16	0	0.5	1	2	LEDSM
312.01	86	1.5	0.5	0.02	0.16	0.25	0.5	1	2	LEDSM
309.99	86	1.5	0.5	0.02	0.16	0.5	0.5	1	2	LEDSM
308.40	108.5	1.5	0.5	0.02	0.16	0.5	0.5	1	2	LEDSM
307.79	108.5	1.5	0.5125	0.02	0.16	0.5	0.5	1	2	LEDSM
307.56	108.5	1.5	0.5125	0.02	0.16	0.5	0.5	1	2	LEDSM
307.25	108.5	1.5	0.51875	0.02	0.16	0.5	0.5	1	2	LEDSM

2.4.2 Energy performance optimization case II: efficient HVAC system

Case II-a was carried out in a total of 260 simulations. In this case, the number of permissible combinations of energy efficiency measures that allows the reduction of energy consumption and the maintenance of indoor thermal conditions was 68% versus 32% of cases that had overheating. This shows that the new HVAC system prevents the offices from overheating and the bedrooms shows overheating in 32% of the evaluated solutions. The 177 combinations of energy efficiency strategies that meet the goal of reducing energy consumption and maintain thermal comfort condition can be observed in Figure 12. The minimum value achieved in Case II-a is 112.9 kWh/m^2 year, which is equivalent to a reduction in the annual energy consumption of the mining camp of 65.8% compared to the base case (see Figure 12 and Table 10). This electricity consumption corresponds to equipment's (58%), DHW (20%), heating (15%) and lighting (7%). The largest reduction of electricity is heating (92%) and lighting (61%). Case II-b reached a minimum consumption of 104.87 kWh/m^2 year, which is only 7.1% lower than the optimum reached in Case II-a. Therefore, the new HVAC system allows to avoid overheating and reach very low electricity consumption. The optimized camp has an optimized enclosure with a U-value = 0.125 W/m^{2}K (Outdoor walls, roof and floor), windows with a U-value of 1.5 W/m^{2}K and SHGC = 0.52, infiltrations of 0.25 ACH, LED lights with movement sensor in all zones, a reduction of the northeast windows width of 0.125 m, an increase of the height of the southwest windows in 0.5 m of height, and an increase of 1 m in the offices windows.

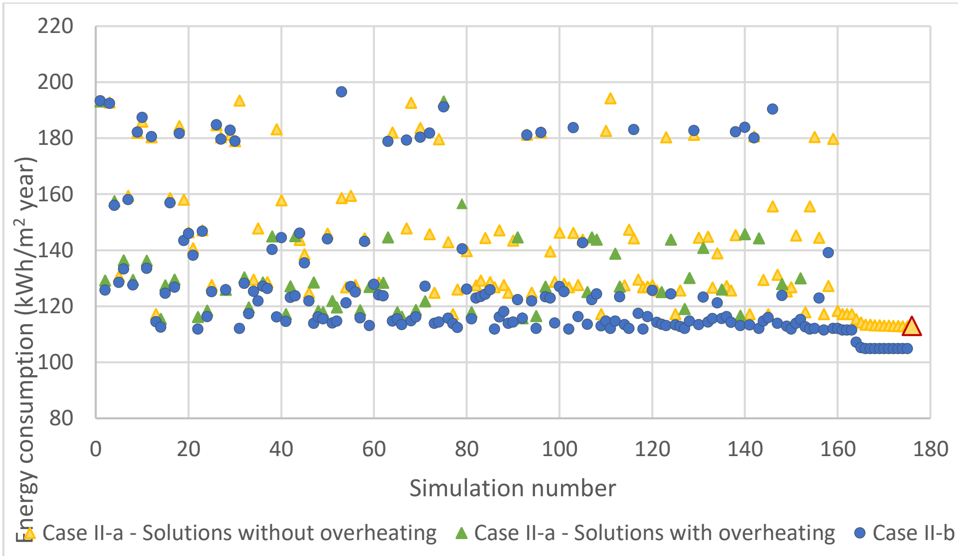

Figure 12. The results of Case II-a and Case II-b

The possible solutions of annual energy consumption ranges from 194.32 kWh/m^2 year to 112.92 kWh/m^2 year. The set of energy efficiency strategies that generate results close to the optimum is varied, presenting several combinatorial options among the optimized parameters that can be adapted according to economic, geographical or market constraints. The sets of solutions close to the optimum are presented in Table 10. This table serves to raise awareness of the vast amount of possibilities that exist for designing a low-energy mining camp. Among the most striking options is the possibility to maintain the current orientation, as well as showing low electricity consumption between 113.18-138.56 kWh/m^2 year. Building orientation usually has a greater difficulty to be varied once the project is accepted, due to a set of constraints and conditions that make it difficult, such as the geographical conditions, access roads, and the volume of earth movement required to locate the project camp, which should be minimized. Normally mining camps orientation is determined based on the position that means less earth movement during construction, the existing access roads and geographical conditions to reduce costs. These factors cause that building orientation is the parameter that has greater difficulty to be varied. On the other hand, there are different road size limitations in every country, so the increased insulation of walls can become a problem. In this case, there are combinations of parameters that causes electricity consumptions between 118.37- 139.57 kWh/m^2 year by maintaining the current insulation thickness of 140mm or lower insulation thickness (Table 10).

Table 10. Set of close-to-optimal solutions that accomplish the camp's overheating and energy consumption minimization constraints (Case II-a)

Annual energy consumption (kWh/m^2)	Azimuth	Window U	Window SHGC	Insulation Conductivity	Insulation Thickness	DeltayNE	Deltay VSO	Deltay OFICINA	ACH	Lighting
140.78	-4	2.5	0.5	0.035	0.11	-0.5	-0.25	0	0.5	Base case
139.68	41	2	0.5	0.04	0.13	0	-0.25	0	0.5	Base case
139.57	86	2	0.5	0.03	0.14	-0.5	0.25	1	0.5	Base case
138.92	41	2	0.5	0.03	0.12	-0.25	-0.25	0	0.5	Base case
138.56	-139	2.5	0.5	0.035	0.15	-0.25	0	0.5	0.5	Base case
131.25	86	2	0.5	0.035	0.12	-0.5	0.25	0.5	0.5	LED
130.67	-4	2.5	0.5	0.035	0.11	-0.5	-0.25	0	0.5	LED
129.61	-4	2.5	0.5	0.035	0.13	-0.5	-0.25	0	0.5	LED
129.55	86	2	0.5	0.03	0.14	-0.5	0.5	1	0.5	LED
129.48	-49	2	0.5	0.04	0.14	0	-0.25	0	0.5	LED
129.26	86	2	0.5	0.035	0.12	-0.5	0.25	0.5	0.5	LEDSM
128.77	86	2	0.5	0.035	0.13	-0.5	0.25	0.5	0.5	LEDSM
128.69	-4	2.5	0.5	0.035	0.11	-0.5	-0.25	0	0.5	LEDSM
128.45	-139	2.5	0.5	0.035	0.15	-0.25	0	0.5	0.5	LED
128.12	-4	2.5	0.5	0.035	0.12	-0.5	-0.25	0	0.5	LEDSM
127.65	-4	3	0.6	0.04	0.12	-0.25	0	0.5	0.5	LEDSM
127.59	86	2	0.5	0.035	0.13	0	0.25	0.5	0.5	LEDSM
127.56	86	2	0.5	0.03	0.14	-0.5	0.5	1	0.5	LEDSM
127.50	86	2	0.5	0.03	0.14	-0.5	0	1	0.5	LEDSM
127.31	-94	2.5	0.5	0.035	0.15	0	0	0.5	0.5	LEDSM
127.29	-4	2.5	0.6	0.04	0.12	-0.25	0	0.5	0.5	LEDSM
127.03	41	1.5	0.6	0.035	0.11	-0.25	0	0.5	0.5	LEDSM
126.84	41	2	0.5	0.03	0.12	-0.25	-0.25	0	0.5	LEDSM
126.70	-4	2.5	0.5	0.035	0.13	-0.25	0	0	0.5	LEDSM
126.02	-49	2	0.5	0.03	0.14	-0.25	-0.25	0.5	0.5	LEDSM
125.67	-49	2	0.5	0.025	0.14	0	-0.5	0.5	0.5	LEDSM
125.66	-49	2	0.5	0.035	0.14	0	0.25	0.5	0.5	LEDSM
125.37	-4	2	0.5	0.035	0.13	0	0.25	0.5	0.5	LEDSM
124.93	-4	2	0.5	0.035	0.14	0	0.25	0.5	0.5	LEDSM
124.84	-4	2	0.5	0.025	0.14	0	-0.5	0.5	0.5	LEDSM
118.37	-94	2.5	0.5	0.035	0.14	-0.25	0	0.5	0.25	LEDSM
117.98	-94	2.5	0.5	0.035	0.15	-0.25	0	0.5	0.25	LEDSM
117.25	-139	2.5	0.5	0.035	0.15	-0.25	0	0.5	0.25	LEDSM
115.41	-139	2	0.5	0.03	0.16	-0.25	0.25	1	0.25	LEDSM
114.28	-139	1.5	0.5	0.025	0.16	-0.25	0.25	1	0.25	LEDSM
113.46	-139	1.5	0.5	0.02	0.16	-0.25	0.25	1	0.25	LEDSM
113.27	-139	1.5	0.5	0.02	0.16	-0.125	0.25	1	0.25	LEDSM
113.18	-139	1.5	0.5	0.02	0.16	-0.0625	0.25	1	0.25	LEDSM
113.01	-144.625	1.5	0.5	0.02	0.16	-0.0625	0.25	1	0.25	LEDSM
112.94	-147.4375	1.5	0.5	0.02	0.16	-0.0625	0.25	1	0.25	LEDSM

Table 11 shows the summary of the optimal energy efficiency measures of each case evaluated. As can be seen, the two cases with no restriction of overheating obtain almost the same combination of parameters, while the only difference is the size of the office windows. It can be observed that with the new HVAC system, the overheating constraint is no longer restrictive in offices, which allows to increase the glazed area and to increase the solar gain to reduce heating electricity use without overheating. On the other hand, for the cases with overheating restriction (bedrooms) the greatest difference is presented in the windows size and orientation variables. This is because taking these two parameters into account at the design stage, solar radiation can be better utilized and optimized to acquire the required amount to reduce heating without overheating. Table 12 and Figure 13 show a summary of the results of each optimization case.

Table 11. Optimization results: Optimal design for the two case studies with and without overheating constraints.

			Baseline	**Case I**		**Case II**	
Variable	Description	Units		a	b	a	b
Azimuth	Building orientation	Degrees	-139	108.5	10.06	-147.4	10.06
WindowU	Thermal transmittance	W/m2K	3	1.5	1.5	1.5	1.5
WindowSHGC	Solar Heat Gain Coefficient		0.7	0.51875	0.7	0.5	0.7
InsulationConductivity	Walls conductivity	W/mK	0.045	0.02	0.02	0.02	0.02
InsulationThickness	Insulation thickness	m	0.14	0.16	0.16	0.16	0.16
Lighting	Actual, LED, LED with motion sensor		Actual	LEDSM	LEDSM	LEDSM	LEDSM
ACH	Infiltrations. ACH= 2; 1; 0.5, 0.25	ACH	2	2	0.25	0.25	0.25
DeltaNE	High variation window NE bedrooms	m	0	0.5	0.5	-0.0625	0.5
DeltaSW	High variation window SO bedrooms	m	0	0.5	0.5	0.25	0.5
DeltaOffice	High variation window office	m	0	0.5	0.03	1	1

Table 12. Electric equipment, lighting, DHW and heating energy demand optimized in all 3 evaluated cases: Baseline, with the current electric heaters and with the proposed HVAC system

kWh/m2 year	Electric equipment	Lighting	DHW	Heating	Total
Baseline	65.95	21.31	22.15	220.64	330.05
Case I	65.95	8.32	22.15	210.99	307.40
Case II	65.95	8.32	22.15	16.52	112.93

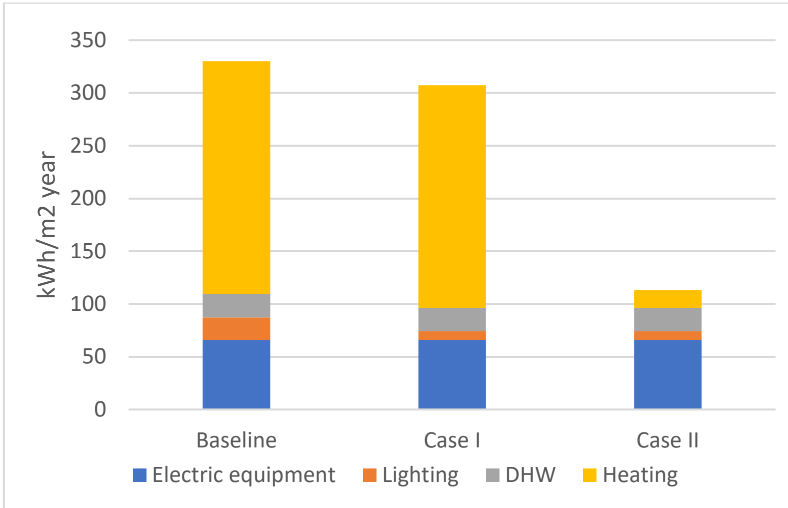

Figure 13. Measured energy consumption for electric equipment, lighting, DHW and heating for each optimized scenario with overheating constraint (a).

2.5 Conclusions

The following research aims to design by multicriteria optimization an energy-efficient mining camp based on a real Chilean mining camp as base case to determine the optimal energy-efficient strategy considering not only the energy consumption but also the interior thermal comfort. A set of 10 energy efficiency measures, corresponding to roofs, walls and floors insulation, U-value and SHGC of windows, window area, orientation, and lighting power density, were optimized to reduce mining camps energy consumption in four different cases: Case I-a has electric heater as HVAC system and overheating constraint to ensure thermal comfort; Case I-b use the same electric heaters but without the overheating constraint; Case II-a use a high efficient heat pumps with chilled beams as HVAC with the overheating constraint and Case II-b uses the same HVAC system than Case II-a but without the overheating constraint.

The main conclusions out of this research are:

- The presented optimization cases show that mining camps have a high risk of overheating. Thus, to include the overheating risk in the design stage of mining camps can significantly influence the energy efficiency strategies to be chosen. To reduce the overheating risk, is a key factor to consider an HVAC system that can provide cooling and heating efficiently.

- The infiltrations rate is the most influential factor in the decrease of the camp energy consumption, because it is the one that generates the greatest energy losses. Thus, if electric heaters are chosen, the possibility of implementing additional energy efficiency measures should be studied in order to reduce the infiltration level without increasing the temperature levels above the allowed ones, such as natural ventilation measures.
- Changing the electric heaters for the heat-pump with chilled beams system can reduce the overheating risk in approximal 60% of the optimized cases.
- The optimized energy efficiency strategies with overheating constraints minimized the energy efficiency of the mining camp, while maintaining the thermal comfort. The optimized design of case II-a saves about 65.8% of the original mining camps energy consumption.
- The presented optimizations are not only useful to determine the most energy-efficient configuration, but also to discover a large set of applicable solutions with direct effect on reducing the camp's energy consumption and maintaining internal thermal conditions. The set of parameters near the optimum solution of energy consumption present several options that allows flexibility in designing energy efficiency mining camps depending on the objective and desired results. The set of feasible solutions varies within an annual consumption range from 112.92 kWh/m^2 year to 194.32 kWh/m^2, providing a great variability of energy efficiency measures packages that can be applied both in rehabilitation of camps and in the construction of new ones.

Future work can expand the set of energy-efficient strategies to reduce the DHW or Electric equipment energy consumption, combining energy sources or changing the original system to a more efficient one. Future studies can also assess the feasibility of building net zero energy mining camps by applying renewable energies to supply the reduced energy demand. It would be also interesting to perform a similar research from an economic point of view.

3 OPTIMIZATION OF AN INTEGRATED MULTIFUNCTIONAL HVAC, DHW AND PV SYSTEM BASED ON FLEXIBLE TFSMS IN A CHILEAN MINING CAMP TO REACH NET ZERO ENERGY TARGET

3.1 Abstract

Multifunctional integrated systems to cover with maximum efficiency the building energy demand and the implementation of renewable energies to supply exported energy are key components to achieve NZEB target in new and retrofitted buildings (Lydon et al, 2017). The present work aims to optimize a thin-film solar membrane (TFSM) configuration to reach NZEB target in addition to incorporate a multi-functional integrated system of HVAC, DHW and TFSM to improve the energy performance of a mining camp, taking into consideration the particular climatic conditions, construction constraints, and PV market. Within the designed system, the heating, cooling and DHW demand is satisfied by chilled beams with high efficiency heat pumps. The dorms only count with heating while offices have also a free-cooling mode. A building integrated photovoltaic (BIPV) system, consisting Thin-film Solar Modules (TFSMs) are considered because of viability to be incorporated to the prefabricated modules in the factory without adding extra volume and weight to the structure due to transportation and cost constrains. TFSM provide electricity for heating, lighting, electric equipment and DHW. This is a grid connected photovoltaic power system that use power from the electrical mains grid during the night or cloudy days and all the surplus energy is used directly in mining processes. To reach the NZEB target, an optimization has been carried out using a hybrid multidimensional algorithm Particle Swarm Optimization and pattern search algorithm Hooke Jeeves (GPSPSOCCHJ), which is coupled with EnergyPlus to investigate the set of possible solar membranes configurations. The results demonstrate that the multifunctional HP for HVAC and DHW can reduce the annual electricity consumption in 15 kWh/m^2 year. On the other hand, according to the match between PV electricity generation and power use from the electrical mains grid, this paper demonstrates that a mining camp in Chile can be NZEB with 57% of the roof with 12% efficiency of TFSMs. This camp has also the option of being a plus energy building generating a surplus of 127.3 kWh/m^2 year using 90% of the available roof.

3.2 Introduction

Worldwide the building sector, commercial and residential, consumes over one-third of the final energy consumption and causes one-third of carbon dioxide emissions (CO_2) (International Energy Agency, 2013). In this global context, the reduction of energy consumption and the use of energy from renewable sources in the building sector constitute important measures to reduce greenhouse gas emissions (GHGs) and energy dependency (BPIE, 2011). In the building sector, one of the main global actions considered in terms of energy efficiency and CO_2 emissions reductions it is to build Net Zero Energy Buildings (NZEBs) (Paoletti et al., 2017). A NZEB is an energy-efficient building/campus/portfolio or community where, on a source energy basis, the actual annual delivered energy is equal to the on-site renewable exported energy (U.S. Department of Energy, 2015). NZEBs are claimed to increase the installed capacity of electricity generation from renewable energies, reduce building energy consumption and improve the indoor environmental conditions of buildings (Yu et al., 2016; Zero Energy Project, 2015). Several authors have reported other advantages of moving toward NZEBs, such as: lower the environmental impact of occupation stages (Deng et al., 2014; Lu et al., 2015); lower operating and maintenance costs (Gaiser & Stroeve, 2014; Garde et al., 2014; Bajenaru et al., 2016; Lu et al., 2015); improved energy security (Zero Energy Project, 2015); better resiliency to power outages and natural disasters, (Ministerio de Energía, 2013; U.S. Department of Energy, 2015; Shen & Lior, 2016) and improving the indoor environmental quality (IEQ), due to more uniform temperature distribution and more availability of natural lighting (ECOFYS, 2013; Bajenaru et al., 2016; Shen & Lior, 2016). As a result of the amount of benefits of building NZEBs, several countries have adopted NZEBs targets in their future constructions (Sartori et al., 2012). In the last decade, the NZEB concept has been applied to a large kind of projects, from small to big buildings, with different complexities, independent interacting variables and occupation schedules, among others. Some examples as Net Zero Army's (Hammack, 2013), University Campus (Loyola University Chicago, 2016; Modern Green Structures & Architecture (MGS), 2016) and hotels (Bodach et al., 2016), showing the large applicability of net zero energy projects.

Despite of worldwide acceptance on the NZEB concept, Latin America has not developed NZEB projects. However, it has begun an interest on implementing renewable energy on buildings to supply part of the buildings energy consumption to reduce the GHG emissions. The Chilean Energy Agenda has as goal to promote the use of on-site energy renewable energy in extreme and remote areas to reduce dependence on fossil fuels (Ministerio de Energía, 2014). Mining sites are increasingly in more remote places, which increases the difficulty to access, secure and reliable energy sources (Comisión Chilena del Cobre, 2016). Chile is the world's largest copper producer and exporter. Above 80% of the mining sites are located in northern remote locations above 3,000 meters above sea level (m.a.s.l) (Equipo MMSD América del Sur, 2011). These locations are characterized mainly by cold weather, dust, snow, low humidity, high radiation, limited access to water and electricity main grids (Paraszczak & Fytas, Renewable energy Sources - A promising opportunity for remote mine sites, 2012). In consideration of this, a great majority of remote mines relies heavily on fossil fuels that must be transported over long distances, which entails significant economic cost and environmental risks (Davourie, 2016). To have a renewable energy sources to supply electricity to mining camps allows decreasing the GHG emissions and the energy bought costs. However, the first step is to build high-efficient mining camps to reduce the energy demand (Zero Energy Project, 2015).

One new approach to reach the NZEB target is to consider building components as multifunctional elements, as opposed to traditional sequential design in which each building elements performs its own function (Lydon et al., 2017). These components perform several purposes simultaneously such as retrofitting panels with Phase Change Material (PCM), which perform as a building physic and as a climate control component (Paiho et al., 2015; Opt Veld, 2015); ventilated facades that are exploited as heat recovery system to preheat the ventilation air (Brandl et al., 2014; Favoino et al., 2016); and energy sources with building components, like multifunctional building integrated photovoltaic (BIPV), which are photovoltaic modules integrated into the building envelope and hence, also replacing traditional parts of the building envelope, e.g. the roofing (Cronemberger et al, 2014; Biyik et al., 2017)

To design a multifunctional system, it is important to identify synergies between the building characteristics, construction restrictions, energy systems and to ensure compatibility with renewable energy sources (Almeida et al., 2013). Because of the high labor cost of construction works at high altitudes, typical mining camps in Chile are built of timber prefabricated lightweight modules due to the reduction of construction times and less labor required on-site. Prefabricated modules must comply with size and weight limits to be transported and easily assembled in the construction site (Deng et al., 2014; Minería Chilena, 2014). Regarding this, any energy saving strategy should be an integrated approach to prioritize the easy installation of the modules, the reduction of construction materials and equipment, few maintenance work and no need for extra structures that might add weight or size. Among various renewable energy sources, Chile has an available potential of 1,640,128 MW for the generation of photovoltaic energy and technologies, where 70% of this is concentrated in the northern Chile (Santana, 2014). This makes the use of Photovoltaic (PV) panels an increasingly popular option. Since PV technology rapidly-grow compared to other renewables sources, many researchers around the world explore the options of creating solar cells that generate electricity more efficiently (Biyik et al., 2017). Nowadays, the efficiency of existing PV technologies ranges from 4 to 23% (Pandey et al., 2016). Nevertheless, the traditional PV panels add additional weight and require additional structures to be installed in the roof. Regarding this, to use building integrated photovoltaics (BIPV) of thin-film solar modules (TFSMs) is a suitable innovative renewable energy strategy for mining camps. Many studies have reported the following advantages of flexible TFSM that make them ideal for mining camp applications: they are lightweight and thin, thus they can be installed over low-load-capacity roof adding only few extra weight and size to the structure (Lee & Ebong, 2017; Petter et al., 2012); they are flexible, so that, can be adjusted to any surface geometry (Shah, 2018; Du, Yang et al., 2017); and they have a factory-applied butyl-based self-adhesive, with which the TFSM become an integrated part of the roof system with the same wind uplift and seismic performance characteristics of the roof system itself (Biyik et al., 2017; Pandey et al., 2016; Cronemberger et al., 2014). These advantages also make them the simplest, fastest and lowest labor cost than traditional PV panels (Pandey et al., 2016; Han et al., 2017)

The integration between a renewable source with multi-energy systems has been used to supply as much as possible the building energy used with renewable energy (Fabrizio et al., 2010). For example, HVAC and DHW represent the longest energy consumption in hotels, which have similar use and complexities than mining camps (Pérez et al., 2008). Therefore, several integrated systems have been studied to reduce the energy demand of HVAC and DHW, like using multi-functional heat-pump systems (Ji et al., 2005), solar thermal assisted heat pumps (Omojaro & Breitkopt, 2013; Amin & Hawlader, 2013), producing thermal energy and electricity by cogeneration (CHP) (Onovwiona & Ugursal, 2006; Raj et al., 2011), among others. For remote mining camps, the feasible options must satisfy and be compatible with the construction constraints and characteristic of prefabricated lightweight building modules. In chapter 2 was identify that the best HVAC system for mining camps are chilled beams with energy-efficient Heat Pump (HP). Polanco & Yousif (2015) studied strategies to achieve a net zero energy hotel in the central Mediterranean and concluded that the more flexible, with better performance and simpler system for DHW and HVAC is using solar photovoltaic installation with high efficiency solar-ready heat pumps and water storage tanks. Due the BIPV system is the best option for the lightweight prefabricated modules, the need for simpler systems (e.g. minimal pipes, pumps), to use the installed energy-efficient water-to-water HP to supply space heating and DHW assisted by the BIPV is proposed to reduce the DHW energy consumption and evaluate its performance on high altitude and cold weather conditions.

To design a Net Zero Energy mining camp supplied with TFSM and electricity from the grid, a design by optimization is a proper design tool to find the optimal combination to reach the NZEB target (Ihm & Krarti, 2012). To comply with the principal constraint of limited access to the electricity grid is necessary to make a correct use of the renewable energies to be installed, focusing on achieving more self-consumption of renewable energies to reduce the grid peak loads, improve the self-sufficiency and, ensure stability of the electrical grid and reliability of the energy supply (Battaglia et al., 2017). Responding to the Chilean Energy Agenda, the lower prices of PV electricity and the limited grid connection in mining camps increase the value of renewable energies self-consumption (Battaglia et al., 2017; Fattahi & Gehimi, 2017). To reduce peak loads from the grid energy consumption, the two most common methods are using thermal or electrical storage from renewable energy sources and demand response strategies (Wu & Xia, 2017). For example, Aste et al. (2017) assess the energy performance of a multi-functional integrated system designed to cover the DHW and HVAC needs by using reversible heat-pumps feed directly by DC from a BIPV system. The surplus is stored in thermal energy tanks, thus this strategies achieves 90% of energy saving compared to the use of condensing boilers to produce DHW. Vieria et al. (2017) studied the energy storage with a lithium-ion batteries system designed for residential buildings with PV generation. The results show a reducing of 78.3% of the energy consumed from the grid. Other researches focus on using demand-side management (DSM), where the most useful strategies are: energy efficiency, demand response and distributed generation (Wu & Xia, 2017). DSM has been studied in residential buildings (Mostafa et al., 1998; Haider et al., 2016; He et al. 2012; Hedin, 2012; Masa-Bote et al., 2014; Widén, 2014; Viereira et al., 2017; Luthander et al., 2015; Munkhammar et al., 2013; Hoon et al., 2014) and offices-commercial buildings (Zhu et al., 2014; Jang et al., 2016; Kiliccote et al., 2011; Martín & Montero, 2017). In comparison with electrical and thermal storage, DSM only require small amount of investment and equipment to achieve the satisfaction of demand (Fattahi & Gehimi, 2017). Based on the previous literature review, in this paper we proposed a demand response strategy to use as much PV generation as possible to heat water for domestic use to reduces the grid peak loads in the mining camp. This could be a great opportunity for buildings in remote locations, because they used to have limited HP conditions and difficult access to the power grid. The aforementioned literature review shows a potential focus on implementing renewable energy sources in energy-efficient mining camps to reach net zero energy targets. In addition to the renewable energy sources, there is a potential opportunity to take advantage of the installed energy sources for space heating to produce DHW and integrate it with the PV generation to maximize energy use and reduce the peak loads**.**

The main objective of this work is to optimize a flexible TFSM configuration coupled with an integrated multifunctional system of DHW and HVAC to reduce the energy use and grid energy peak loads in a Chilean mining camp to reach the net zero energy target.

3.3 Review of existing flexible thin-film modules and the Chilean PV market

Over the last two decades, several efforts are being directed to thin-film technologies. The existing PV technologies are divided into two sub-categories: (1) silicon based and (2) non-silicon based (Biyik, et al., 2017). Thin-film solar cells (TFSC) are made by deposition of thin layers of semiconductor material allowing to obtain thin, flat-plate grass (rigid) or flexible PV elements (Jia et al., 2017). The thin-film technology provides alternative absorber material from both subcategories, such as amorphous silicon (a-Si) of sub-category 1 or combination of amorphous and microcrystalline silicon (a-Si/µc-Si), the compound semiconductor cadmium telluride (CdTe), compound semiconductor made of copper, indium, gallium and selenium (CIGS) and III-C materials (GaAs, InP and AlGaAs) all of sub-category 2 (Placzek-Popko, 2017). The three-major thin-film solar cell technologies include amorphous silicon (a-Si), CIGS, and CdTe (Lee & Ebong, 2017). Amorphous silicon cells consist on a very thin layer of un-crystallized silicon deposited onto the substrate. Typical efficiencies for this technology vary from 4% to 10% (Andressen, 2004). Due to its low efficiency compared to CdTe and CIGS, they are used in electronics such as calculators, watches, etc. (Lee & Ebong, 2017). CIGS typical cell efficiencies are between 11 and 18.7% (Petter et al., 2012). CdTes usage of cadmium proves to be harmful to both the producer and the consumer, but the standard processing step using cadmium chloride has been replaced by inserting a small number of phosphorus on tellurium lattice sites with a record efficiency of 21% and the lowest production price (Placzek-Popko, 2017).

Despite these global development and improvement of thin-film solar cells, the PV Chilean market is composed of 80-90% crystalline silicon photovoltaic panels subcategory (1) and the remaining 10-20% is equivalent to thin fill cells and solar concentrators (Bello, 2016). The commercialization of thin-film membranes in Chile is still limited for residential applications.

Due to the law 20,571, which allows the self-generation of electricity based on renewable energies, efficient cogeneration, and users to sell their surplus directly to the mains grid, commercialization of photovoltaic panels has increased (Bello, 2016). In the case of solar membranes, CIGS technology and amorphous silicon are the technologies sold in Chile and worldwide. The imported CIGS technology has an operative efficiency of 17% (MiaSolé, 2017), while amorphous silicon has an overall efficiency of 4-5% (Godoy, 2013). This research will focus on these two solar membrane technologies which shows the existing minimum and maximum energy efficiencies available for TSFMs. The CdTes are not evaluated due to the fact that the new safe production process is not widely distributed.

The main advantages of TFSMs are lower thickness and weight, wide range of integration possibilities, geometrical and dimensional flexibility and good performance on flat roofs (Cerón et al., 2013; Petter et al., 2012). These characteristics made TFSMs a suitable/feasible option for the BIPV on mining camps in Chile due volume and weight constraints in modules transportation and ease emplacement on roof, which can reduce the installation costs and complexity significantly.

3.4 Methodology

The study presented in this paper extends the optimized energy-efficient mining camp design obtained in section 2, Quebrada Blanca 2, which consumes 112.92 kWh/m^2 year and explores the feasibility of developing it into a solar powered Net Zero Energy Camp (NZEC). The energy-efficient mining camp has an efficient HVAC system based on chilled beams and HP, efficient lighting system and optimal envelope insulation, air tightness and use of passive solar gains. To maximize the optimized energy performance of this camp towards NZEB, a multifunctional integrated system of HVAC, DHW and flexible TFSM has been implemented. It is based on firstly integrate the DHW system with the HVAC system in order to use the hot water generated for heating to preheat domestic water. Thus, there is reduced use of the energy for DHW. Then, an integrated multifunctional system is proposed to maximize the self-consumption of PV generation, reducing the delivered energy and grid energy peaks, where the DHW is heated in periods where there is high solar radiation.

Prefabricated modules have a systemized construction process with minimal waste, thus it is desired to adjust the new equipment as best as possible to the existing design. The proposed renewable energy system is based on a grid connected TFSM array. To evaluate the best configuration of TFSMs integrated with the multifunctional HVAC and DHW system an optimization is performed out using a hybrid multidimensional algorithm GPSPSOCCHJ coupled with EnergyPlus. To formulate the net zero energy balance, the definition of NZEB delivered by the Department of Energy United States is used (International Living Future Institute, 2016).

This research is divided in 4 main parts: (1) the implementation of the multifunctional HP for HVAC and DHW to evaluate the effect of the system in the DHW energy consumption, (2) The optimization of the PV configuration integrated with the multifunctional system of HVAC and DHW to reach the NZEB target and the reduction of daily peak loads. (3) The results of the optimization and the optimal option that reach the NZEB target. Finally, (4) assess the feasibility of being a plus-energy mining camp. The schematic workflow of this paper is in Figure 14.

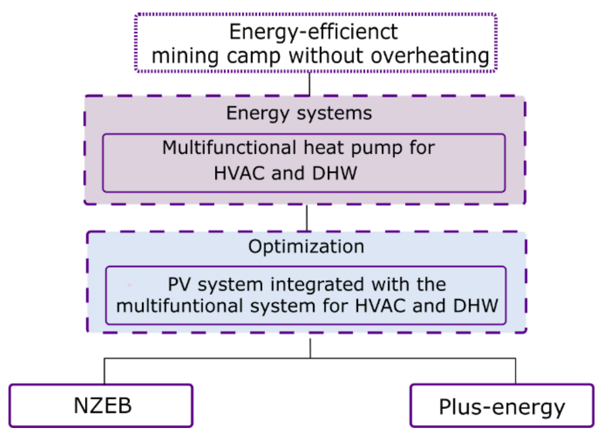

Figure 14. Schematic workflow

3.4.1 Description of the mining camp

3.4.1.1 Location

Quebrada Blanca 2 mining camp is located in the commune of Pica, region of Tarapacá, at 240 km southeast of Iquique in the Andes Mountains, Chile (21.0°S, 68.8°W) which is used as base case for this investigation. This camp is at 4,400 m.a.s.l. with a surface of 30,000 m^2 and hosts 1,700 workers. The weather file generated in section 2.3.2 is used due to the lack of typical meteorological years from remote locations. This weather file was adjusted based on the average monthly data obtained from the Quebrada Blanca 2 Station between 2001 and 2008 (Arcadis, 2010). The outdoor temperature varies from -5.6°C and 10.7°C and has high radiation during the whole year. The location of Quebrada Blanca 2 possesses about 95% of sunny days during the year, with hourly average radiation between 180.7 W/m^2 and 318.9 W/m^2 (Teck QB, 2010).

The mining camp operates 100% based on electricity from the mine power grid. No other fuel sources, like natural gas, oil, solar thermal or ground-source heat pumps are used. The mining camp has a permanent electrical connection point to the installations located 100 meters from the area of the buildings.

3.4.1.2 Base Case

Mining camps energy design in Chile are generally based on the Chilean General Urban Planning Ordinance standard that established the maximum U-value for roofs, walls, windows and ventilated floors based on the climate, which are 0.25 (W/m^2K), 0.6 (W/m^2K), 1.22 (W/m^2K), and 0.32 (W/m^2K), respectively (Minería Chilena, 2014). To reach the NZEB target, an energy-efficient mining camp is needed before implementing any renewable energy source. Base on that, the optimized model of Quebrada Blanca 2 carried out in chapter 2 is used as base case for implementing the integrated multifunctional system and the optimization of the TFSMs. The energy-efficient model from Quebrada Blanca 2 shows an electricity consumption of 112.92 kWh/m^2 year, which counts 58%, 20%, 15% and 7% for electric equipment, DHW, heating and lighting consumption, respectively. The optimized building envelope and other energy related characteristics of the base case mining camp are detailed in Table 13. More detailed description of the design of the mining camp can be found in the results of section 2.

Table 13. Energy related characteristics of the optimized mining camp

Thermal resistances values	External Wall	U-value= 0.125 W/m2 K
	Roof	U-value= 0.125 W/m2 K
	Ground Floor	U-value= 0.125 W/m2 K
Thermal mass	none	
Window type	Aluminium Window	U-value = 1.5; SHGC = 0.52
Occupants	1,700 workers:	Day shift occupied from 19:30-7:30 Night shift occupied from 7:30-19:30 Offices occupied from 7:30-19:30 Dinning room occupied from 6:00-9:00; 12:00-15:30; 18:00-21:00 Kitchen occupied from 5:30-21:30
Setpoint temperatures	Bedrooms	Heating setpoint: 20°C
	Offices	Heating setpoint: 20°C, Cooling Setpoint: 24°C
Lighting	LED lamps with motion sensor	
Domestic hot water	Bedrooms A	3,600 l; Bedrooms A-1 3,000 l
	Bedrooms B	7,200 l; Bedrooms B-1 5,400 l
	Kitchen	120 l
	Gym bathrooms	800 l
HVAC system	Heat pump (COP = 2.2)	
Infiltration rate	0.25 ACH	

In the base case, the DHW is provided with electric water heaters, which are located in the bedroom buildings, the kitchen and gym bathrooms in the Central Building. The number of electric terms per bedroom building is calculated based on the average demand per person of 45 liters per day (See Table 14).

Table 14. Domestic Hot Water (DHW) existing parameters.

Electric terms	Number of building of each type	Capacity (liters)	Number of terms (units)	Water temperature (°C)	Number of people	persona por día
Bedroom A	3	600	6	60	80	45
Bedroom A-1	1	600	5	60	60	45
Bedroom B	8	600	12	60	160	45
Bedroom B-1	1	600	9	60	120	45
Sector 5 (Without HVAC)	1	200	4	60		
Sector 2 (Without HVAC)	1	30	4	60		

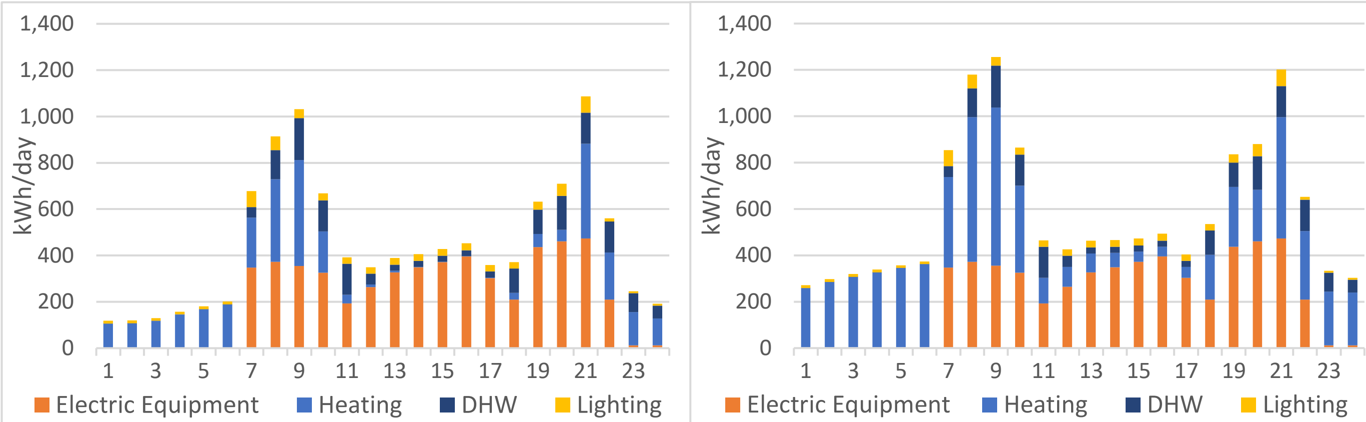

Figure 15. Hourly energy demand for equipment, heating, DHW and lighting in: a summer day (left) and, a winter day (right)

In Figure 15 is the hourly demand for equipment, heating, DHW and lighting for a representative summer and winter day, respectively. It is observed that the peak loads occur at 9:00 and 21:00 for each day. For the summer day, the peaks are 1,031 kW and 1,087 kW respectively and for the winter day are 1,256 kW and 1,201 kW respectively.

3.4.1.3 Multifunctional heat pump for DHW and HVAC

The same HVAC system used in the base case is integrated with the DHW to perform the least number of interventions in the design. The HVAC system is based on chilled beams as the distribution system in each bedroom and office with high efficient Heat Pumps (HP) as heat sources. The office building also has a free-cooling option available to avoid overheating. The cooling system consists in air induction units that inject external air to the chilled beams to take advantage of the low outdoor temperatures (free-cooling system). The temperature setpoints are set at 20°C for heating and 24°C for cooling based on TM52:2013 (CIBSE, 2013). Two design days were selected; (1) An extreme sunny cold day in July reaching -5.6°C and (2) an extreme sunny hot day in March reaching 10.7°C. The daily average dry bulb temperature and total solar insolation are used as basis for the selection of these days (Hong et al., 1999).

In the proposed system design, the previous described HVAC system is coupled with the DHW. The DHW is preheated through the heat generated by the high efficient heat pump (CH-01/02 in Figure 16), thus reducing the DHW energy consumption. A referential flow diagram is presented in Figure 16. The high efficient heat pump NRL550 generates hot water at 40°C to feed the heating inductors (Chilled beams); part of this water is redirected with a recirculating pump (Bi CH) to a plate heat exchanger (IP), where the heat is exchanged to the water for the DHW system. The DHW at 40°C is stored in hot water accumulators (AC). To minimize the risks of Legionella, the DHW must be above 50°C (Centers for Disease Control and Prevention, 2017). Due to the unavoidable occurrence of temperature drops in accumulated and transported water, the water should be ideally stored at 60°C and circulating water should be at 50°C or more (World Health Organization, 2011). To raise the DHW temperature from the 40°C to the 60°C required, the ACs have electric resistances (R1 and R2). When DHW is required, is taken from the ACs by means of a 3-way mixer valve to lower the temperature to the required user temperature by adding cold water.

In this way, the energy expenditure in DHW is equal to the consumption generated by the electrical resistance to increase the temperature from 40 °C to 60 ° C with a COP equal to 1. This system is also designed to increase the temperature by the electrical resistances in hours with presence of PV generation (9:00 to 17:00) in order to consume the electricity generated by the PV membranes instead of increasing the peak electricity purchased from the grid. The electric resistances mainly activate in hours with PV generation in order to maintain the temperature of the water in 60°C to prevent the legionella or any exceptional use of DHW.

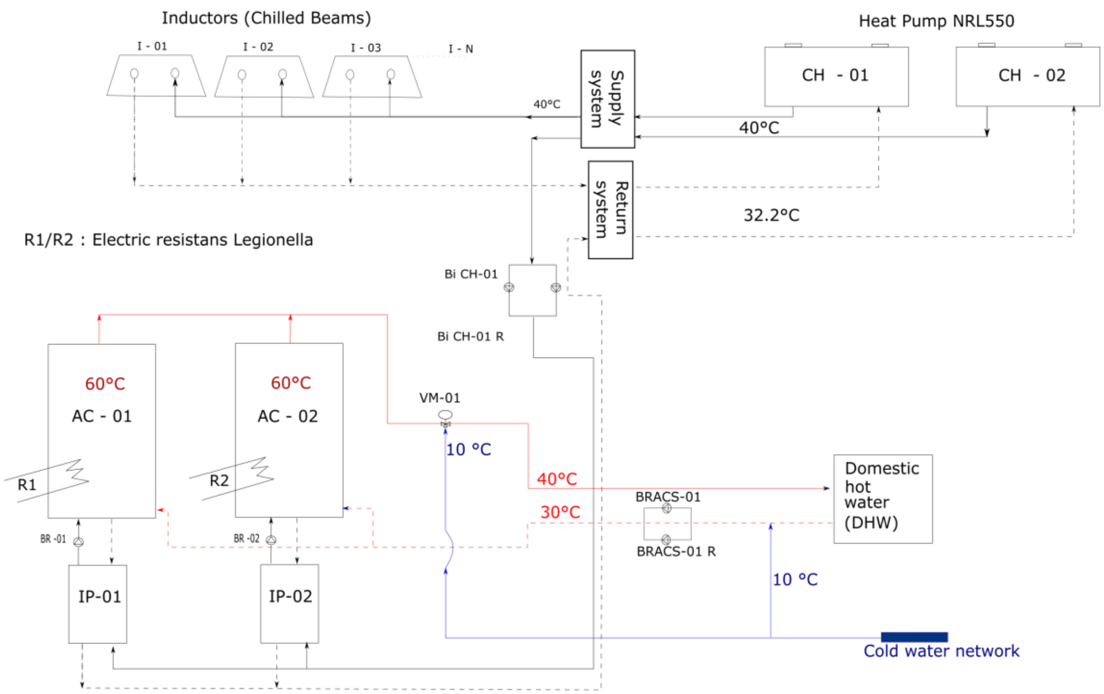

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Figure 16. Referential flow diagram of the proposed HVAC system for Quebrada Blanca 2. CH represent chillers, Bi CH represent recirculating pumps, BRACS represent hot water recirculating pumps, IP represent plate heat exchangers, AC are water accumulators and VM is the valve 3-way mixer.

3.4.1.4 TFSMs

The use of conventional PV panels was not considered because contradicts the main property of the modular construction, which is that the construction of the prefabricated buildings is completed on-site by only assembly the modules, while only minor installations are made on-site. Installing photovoltaic panels prior to assembly and transfer the modules is not feasible due to size constraints for transporting from manufacture to final site, the high probability of damage, and the requirement of an additional support structure for installation and tilting. TFSMs, unlike traditional panels, are characterized by being flexible, high adaptable and lightweight, which allows them to be installed in any place exposed to sunlight. Because of all the constraints, the TFSMs are directly installed in the module's roof, acquiring the inclination of the roofs to which it is attached. The predominant tilt is 1.5°, which is called as flat roof. The Quebrada Blanca 2 camp has a total built area of 18,408 m^2. Bedroom buildings have two floors and a flat roof with an available roof area of 12,825 m^2. All other areas have flat roof with a total available roof area of 3,777 m^2. The dining room and gymnasium have a roof slope of 35° and total available area of 3,034 m^2. Therefore, the camp has a total available roof area of 19,636 m^2 to install the flexible TFSM. The two TFSM technologies existing in Chile, amorphous silicon and CIGS technologies, will be included in the study through their characteristic efficiency. Tilt angle must be the same as the roof where the flexible TFSM is installed, because the current dimensions are based on the existing transportation size restriction for the prefabricated modules.

3.4.1.5 Integrated multifunctional system of HVAC, DHW and TFSMs

The integrated multifunctional system proposed is showed in Figure 17. The TFSMs supply all the electrical energy consumption of the mining camp, which includes electric equipment's, the HVAC system, DHW (electric resistances) and lighting. The surplus energy is exported to the grid and in the hours without PV generation, the electricity need is bought from the electricity grid.

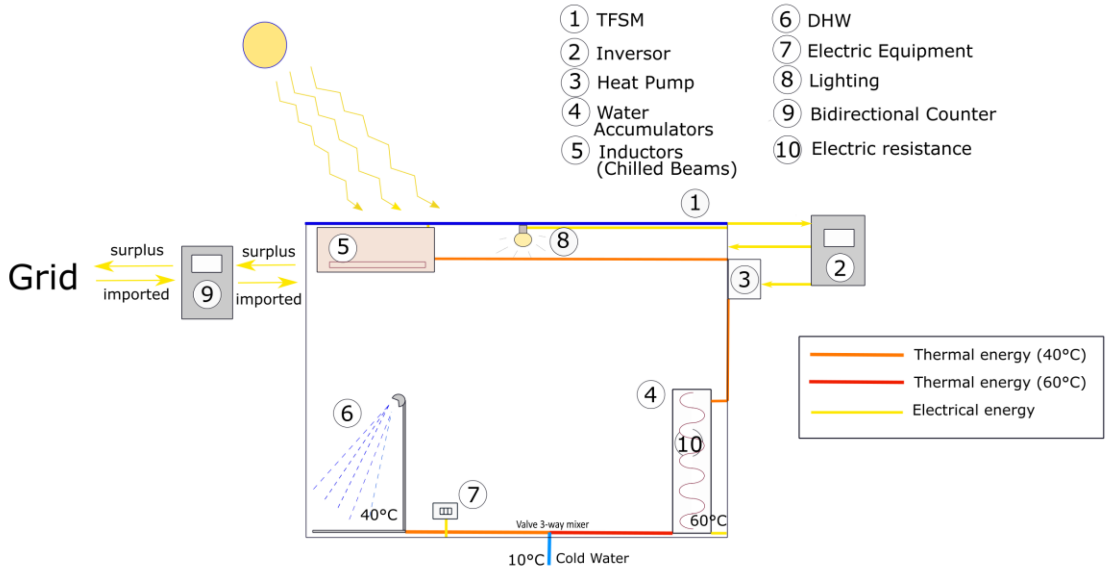

Figure 17. Conceptual scheme of the integrated multifunctional system applied in the mining camp.

3.4.2 Optimization Process

EnergyPlus (2010), a building simulation software, is employed as the simulation tool coupled with GenOpt as the optimization tool (Wetter, 2016).

3.4.2.1 Optimization algorithm

This paper will use the hybrid multidimensional optimization algorithm referred as GPSPSOCCHJ, which comprises the Particle Swarm Optimization (PSO) using a constriction coefficient (CC) and pattern search algorithm Hooke Jeeves (HJ) based on GPS algorithm (Wetter & Wright, 2003). We use GenOpt along with EnergyPlus to quantify the required TFSMs area and efficiency to achieve the net zero balance of the mining camp. This algorithm starts by performing PSO, which in a mesh for a specified number of generations. Then the HJ GPS algorithm is started exploratory movements around the minimal point found for the PSO algorithm to find the particle with the minimum value. Thus, the hybrid algorithm combines the global characteristics of the PSO algorithm with the probable convergence properties of the HJ GPS algorithm. For more information on this algorithm see GenOpt's User Manual (Wetter, 2016).

3.4.2.2 Optimization parameters

As mentioned in section 3.4.1, the optimized energy-efficient model of Quebrada Blanca 2 obtained in chapter 2 was used as base case. To maximize the potential of PV generation of the mining camp to reach net zero energy targets, this study explores scenarios with different percentage of TFSMs area integrated to the mining camps roof. The percentage of solar membranes areas varies between 20% and 90%. The initial PV system is assumed to cover 50% of the roof area, while the maximum amount of roof available for the installation of solar membranes is considered as 90%, due to installation difficulties, irregularities, and discontinuities. On the other hand, to include the options of TFSMs currently commercialized in the Chilean market, the TFSMs varies between 4% (amorphous silicon) to 17% (CIGS

Technology) with steps of 0.5%. The tilt angle is 1.5° because of construction constraints explained in section 3.4.1.4.

Table 15. Optimization parameters

Variable	Units	Initial	Min.	Max.	Step	Description
PV_area	%	50	20	90	1	Percent of PV area on roof
PV_eff	%	4	5	17	0.5	PV efficiency

3.4.2.3 Objective Function

The common definition of net zero energy buildings generated by the U.S. Department of Energy was used to address the objective function. The stated definition of zero energy buildings is "An energy-efficient building where, on a source energy basis, the actual annual energy delivered is equal to the on-site renewable exported energy" (U.S. Department of Energy, 2015). This means that a NZEBs produces enough renewable energy to meet its own annual energy consumption requirements and deliver to the grid the amount of energy that has been purchased. The building energy includes the energy used at the building site measured up to the site boundary. In this case, the site boundary condition defined is the camp perimeter. The energy consumed at the building includes heating, cooling, DHW, indoor and outdoor lighting and equipment. The delivered energy is electricity that is purchased to the grid. The exported energy is on-site renewable energy supplied through the site boundary and used outside as delivered energy. In these case, this electricity surplus is exported to supply mining processed. The on-site renewable energy production systems should supply a significant part of the buildings energy needs (Figure 18).

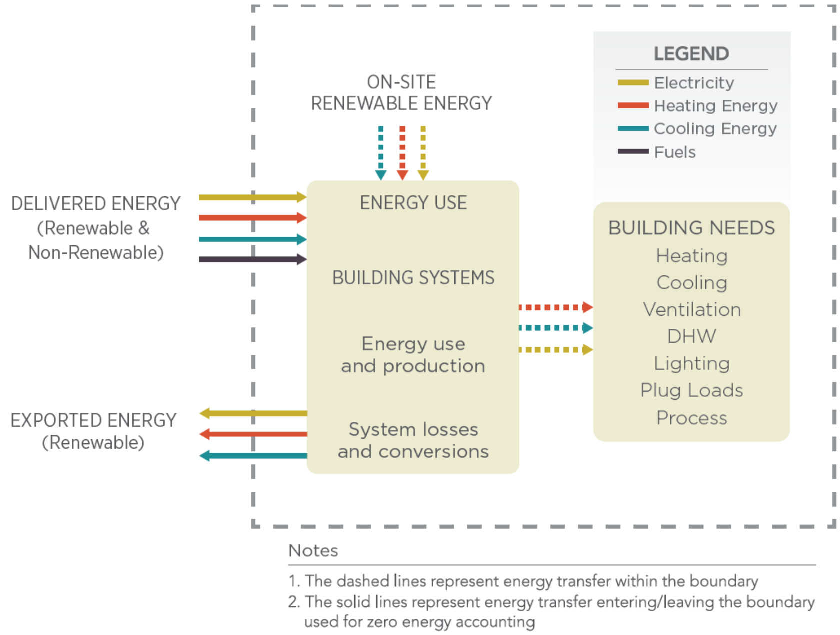

Figure 18. Site Boundary of Energy Transfer for Zero Energy Accounting (U.S. Departament of Energy, 2015)

If the building has varying fuel types, it is required to convert these into equivalent units of raw material and include the energy consumed in the fuel production process by weighting the relative efficiencies of the different fuel types (U.S. Department of Energy, 2015). Due to the lack of information about the efficiency of the Chilean power generation system, the national average source energy conversion factors from ASHRAE Standard 105were used (ASHRAE , 2014).

Based on the common definition of NZEB, the objective function is:

$$f(x) = \sum_i (E_{del,i} r_{del,i}) - \sum_i (E_{exp,i}\, r_{exp,i})$$

where $E_{del,i}$ is the delivered energy for energy $type_i$, $E_{exp,i}$ is the exported energy for energy $type_i$, $r_{del,i}$ is the source energy conversion factor for the delivered energy $type_i$ and $r_{exp,i}$ is the source energy conversion factor for the delivered energy $type_i$.

In this case, the energy $type_i$ is electricity for delivered and exported energy. Despite on-site renewable energy is a carbon free resource, in the NZEB accounting, the exported renewable energy displaces electricity that would be required form the grid, so the conversion factor to appropriately credit its displacement is the same as the delivered energy. Therefore, using the national average source energy conversion factors the objective function to be optimized is:

$$\min f(x) = min \left| 3.15\ (E_{delivered}) - 3.15(E_{exported}) \right|$$

The absolute value is included in the objective function in order that the optimization evaluates the greatest number of points around zero to obtain the set of possible combinations between the area and efficiency of the TFSM required. Finally, it is also carried out the optimization of the objective function without absolute value, in order to recognize if the mining camp has option of being a plus-energy mining camp.

3.5 Results and analysis

Firstly, this section shows the effectiveness of the implementation of the multifunctional system between the HVAC and DWH in terms of energy saving percentage in comparison with the base case. Secondly, the optimal configuration of TFSMs in terms of roof area and efficiency are presented with the daily fluxes of energy consumption to evidence the reduction of daily peak loads. The TFSMs generation is shown in terms of equipment, DHW, lighting and heating for the NZEB solution. Finally, the plus-energy is evaluated using 90% of the available roof and shown in the same graphics as the NZEB solution.

3.5.1 Multifunctional heat pump for HVAC and DHW generation

The energy savings in DHW generation are analyzed due to the integration with the high efficient heat pump for HVAC and according to the design system show in section 3.4.1.3. The analyzed configuration was compared with the base case, which use electric terms to produce DHW. The annual energy savings related to coupling DHW with HVAC system are shown in Table 16.

Table 16. Energy consumption and energy saving potential

kWh/m^2 year	DHW energy consumption	Energy saving potential	Energy saving percentage (%)
Electric terms (base case)	22.15	x	x
High-efficient pump	6.74	15.41	69.55

With the implementation of this system, the total energy consumption of Quebrada Blanca 2 is equivalent to 98 kWh/m^2 year, of which 62.4%, 20.9%, 9.82% and 6.88% respectively correspond to consumption of electric equipment, heating, lighting and DHW.

3.5.2 Optimization results

Prior the integration and optimization of the TFSMs with the multifunctional HP for HVAC and DHW, the mining camp electricity consumption was 98 kWh/m^2 year, which is the result of a very energy-efficient envelope, lighting and the multifunctional heat pump for HVAC and DHW generation. In this case, the integrated multifunctional system of HVAC, DHW and TFSM is implemented as described in section 3.4.1.5 and in Figure 17. For this configuration, the optimization was carried out in 169 simulations which results are shown in Figure 19.

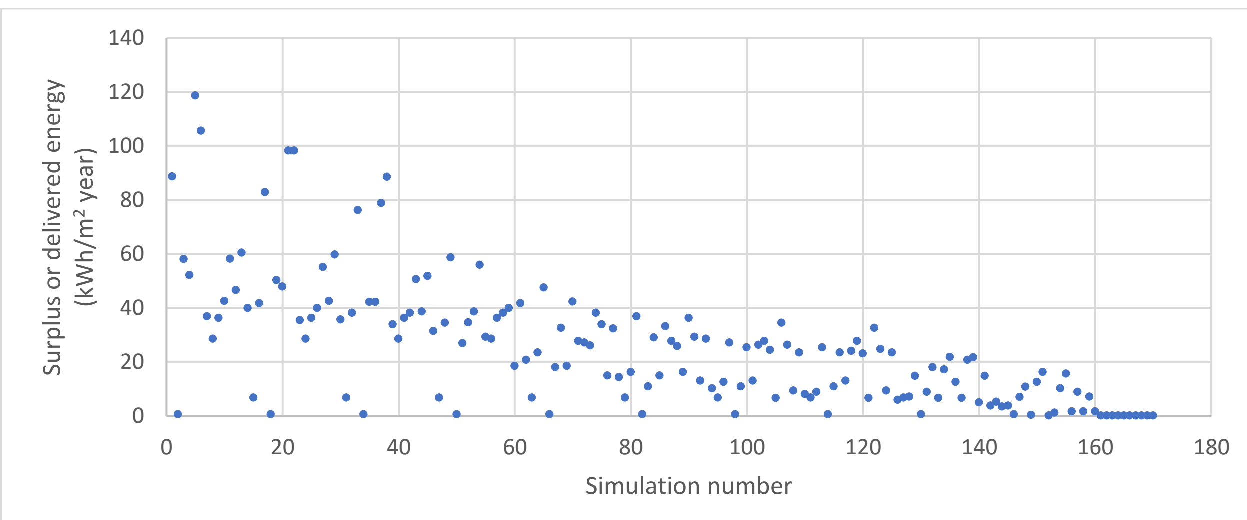

Figure 19. Optimization results with the integrated multifunctional system of HVAC, DHW and TFSMs.

According to the optimization problem, the closest solutions are achieved with an efficiency range between 10% and 14% and a percentage of the total roof area between 49% and 68%. The optimal solution is achievable with 11% efficiency of solar membranes and 62% occupied roof area, which is equivalent to 11,490 m^2. This case supplies 99.5% of the total consumption of the mining camp. As shown in Table 17, the factor between efficiency and PV area is constant between the optimal solutions. This factor allows to extrapolate the results to any PV area required to achieve the net zero target with any available TFSMs efficiency in the PV market between 7.5-17% as shown in Figure 20.

Table 17. Optimization results

Total energy consumption (kWh/m2 year)	Efficiency (%)	PV area (%)	PV area * efficiency
0.555	0.14	0.49	0.0686
0.358	0.1	0.68	0.068
0.051	0.11	0.62	0.0682
-0.05	0.12	0.57	0.0684

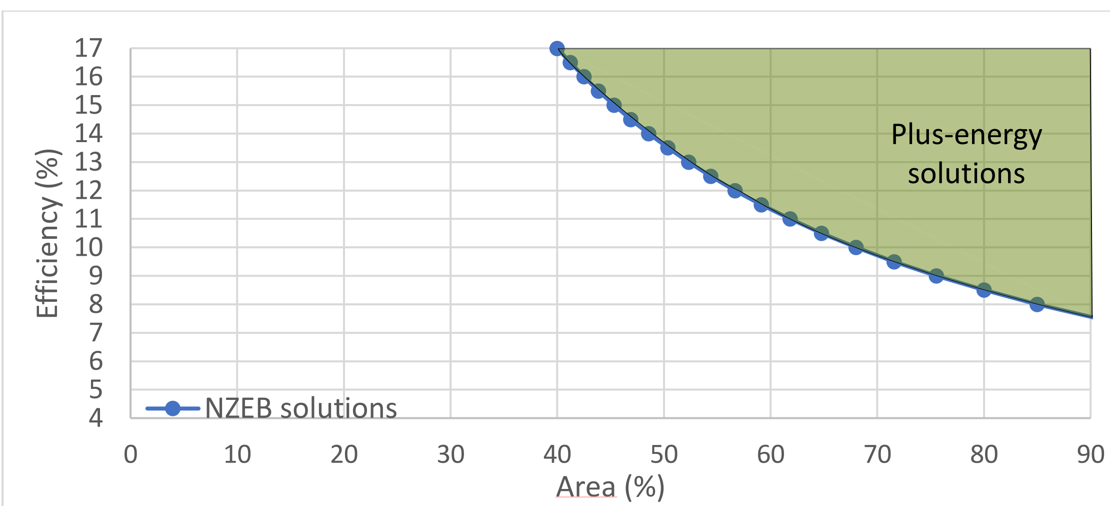

Figure 20. Set of possible solutions to reach NZEB or plus-energy target

3.5.3 NZEB solution

The previous section shows the best solutions of the optimization problem. The NZEB criteria requires a renewable energy generation equal or greater to the energy delivered from the electricity grid. Therefore, the solution that best complete these criteria is achieved with 12% efficiency and 57% of the total roof area occupied by TFSM (10,564 m^2), which allows to supply 100.1% of the electricity consumption of the camp (Table 18). This level of efficiency is achievable with the CIGS technology. The yearly NZEB balance is presented in Table 18.

Table 18. Yearly NZEB balance

Total electricity use	98	kWh/m^2 year
PV production	98.12	kWh/m^2 year
PV self-consumption	59.59	kWh/m^2 year
Energy surplus	38.53	kWh/m^2 year
Energy used from the grid	38.48	kWh/m^2 year

According to the annual energy consumption, PV generation and PV surplus, the monthly performance of the NZEB is shown in Figure 21. It can be observed that much of the energy generated by the solar membranes is consumed in the mining camp. In winter (May - August) the total energy consumption of the mining camp is greater than the generation of the TFSMs, which is consumed in 68% by the mining camp and only 32% of the renewable energy production can be exported to the grid to be used in mining processes. Of the 68% consumed by the camp, 24% correspond to heating, 43% corresponds to electrical equipment, 4% to lighting and 2.6% to DHW. This is because the TFSM generation is 27% lower in winter season than in summer season and the heating loads increases in 84% in respect with summer season. On the other hand, in summer (December – March), 60% of the production of TFSMs is consumed by the camp, while 40% can be delivered to be used in mining processes. The percentage of renewable energy self-consumption decreases due the heating load is lower in summer season and the TFSM increases the renewable energy production due to large solar radiation available (Figure 21). Of the 60% consumed by the mining camp in summer, 9% correspond to heating, 45% to electrical equipment, 3.6% to lighting and 1.5% to DHW.

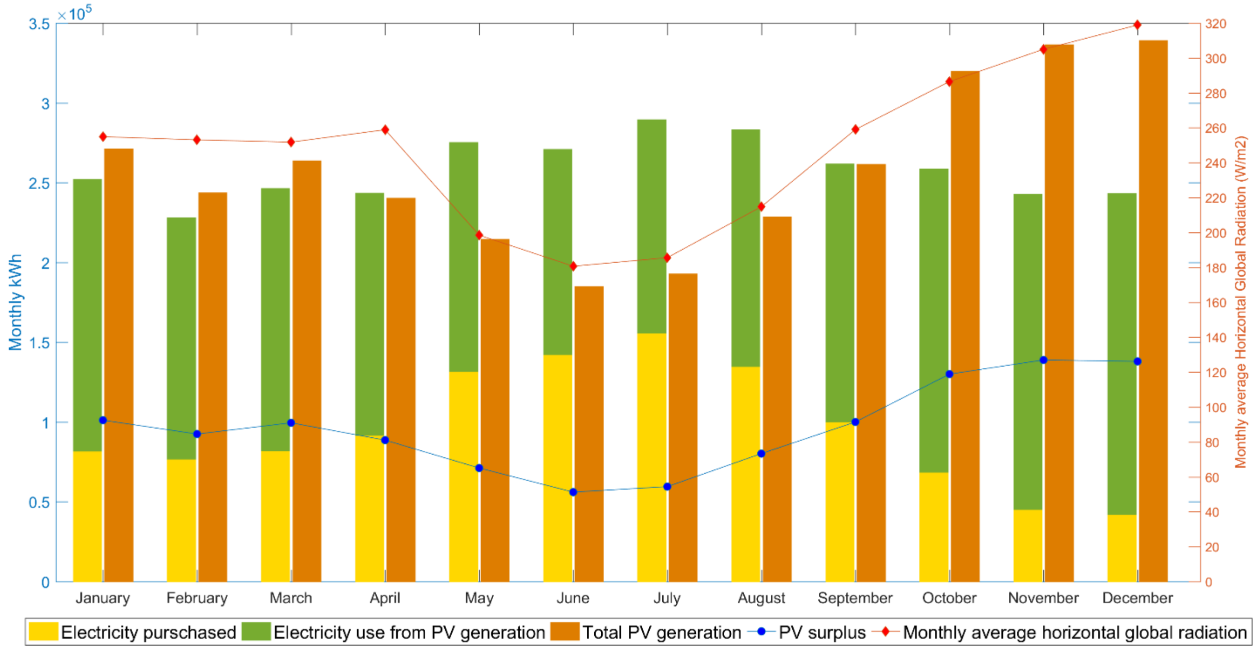

Figure 21. Annual electric energy consumption, PV energy production, energy purchased and PV surplus for NZEB QB2.

According to the integrated multifunctional system, the electric resistances are in operation during the periods when the TFSM system generates electricity to reduce the hourly power demand of electricity. Figure 22 and Figure 23 contain the energetic hourly flows of the camp for a representative summer day (March 2) and a representative winter day (July 7). As reported in Figure 22 and in comparison with Figure 15 of section 3.4.1.2, during summer season, the 85% of DHW energy consumption is supplied by photovoltaic energy. The morning peak loads in summer from the base case were 1,031 kWh at 9:00 hrs., which decreases in 17% with the proposed system. The afternoon peak load is of 1,087 kWh at 21:00 pm, which decreases in 11%.

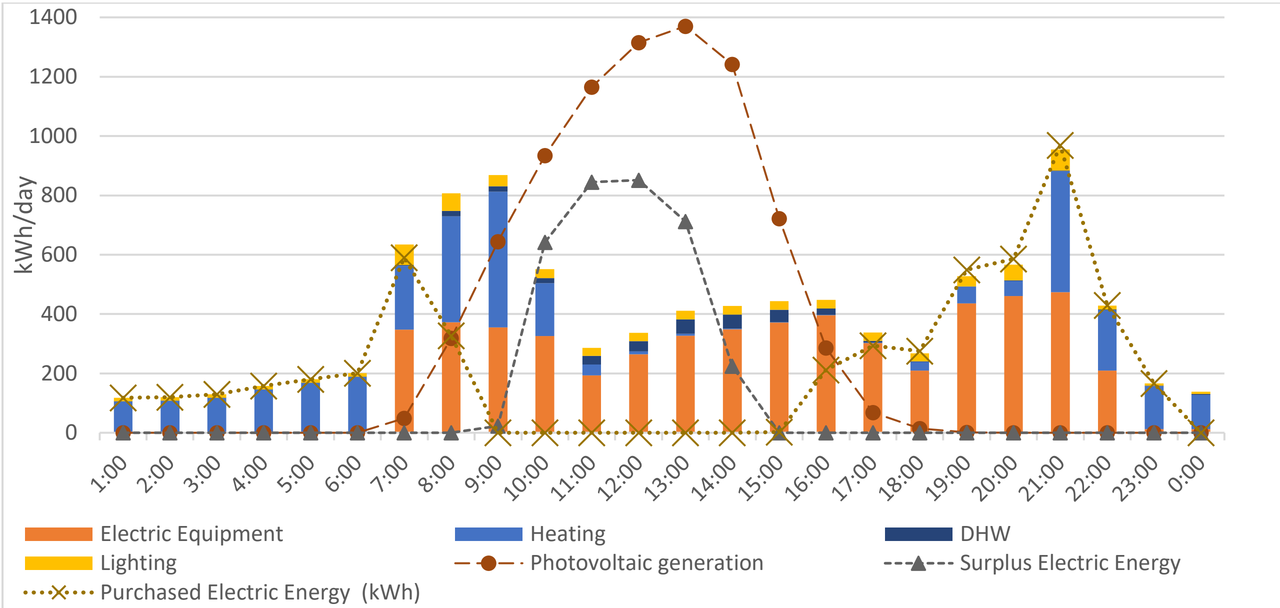

Figure 22. Hourly electricity fluxes in a typical summer day

On the other hand, during winter season (Figure 23) and in comparison with Figure 15 of section 3.4.1.2, the consumption of DHW is supplied 80% by photovoltaic energy. The morning peak load in summer for the base case were 1,250 kWh at 9:00 am, which decreases in 13% with the new system. The afternoon peak load was of 1,201 kWh al 21:00 pm for the base case, which decreases in 10% with the proposing integrated multifunctional system.

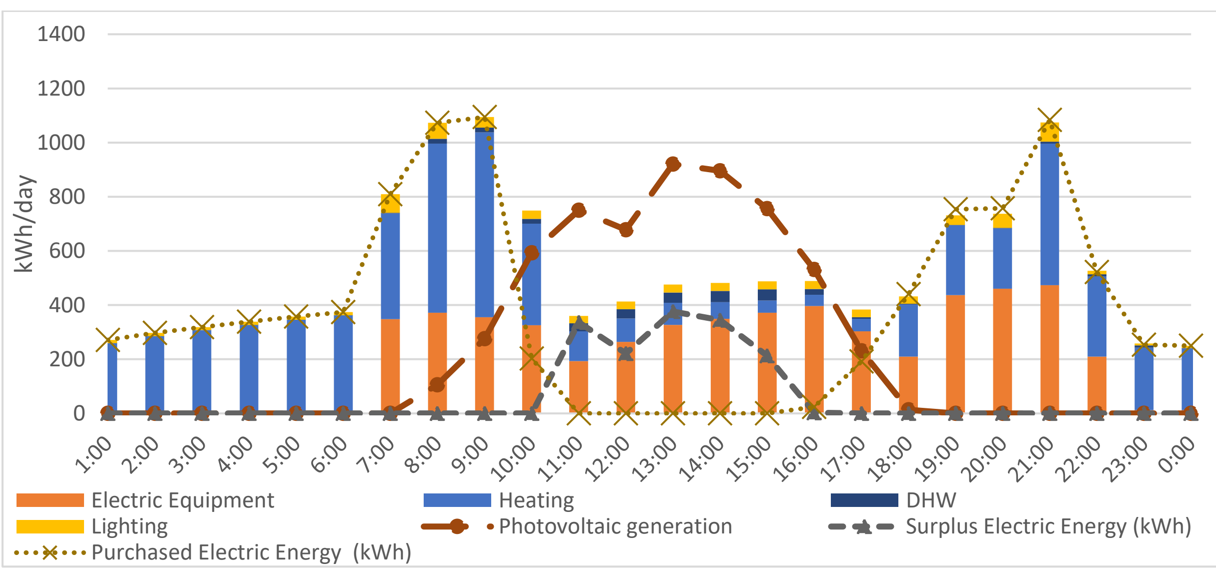

Figure 23. Hourly electricity fluxes in a typical winter day

3.5.4 Optimum solution to reach plus-energy mining camp target

It can be observed in section 3.5.3 that the maximum efficiency achievable by the TFSM using CIGS technology is 17% and the total available roof area is not being used. If the total available roof area and the maximum efficiency of the solar membranes were used, the solar installation of the camp generates a total of 225.3 kWh/m^2 year of renewable energy, which is equivalent to an energy surplus of 160.2 kWh/m^2 year that can be incorporated to the miming processes (Table 19).

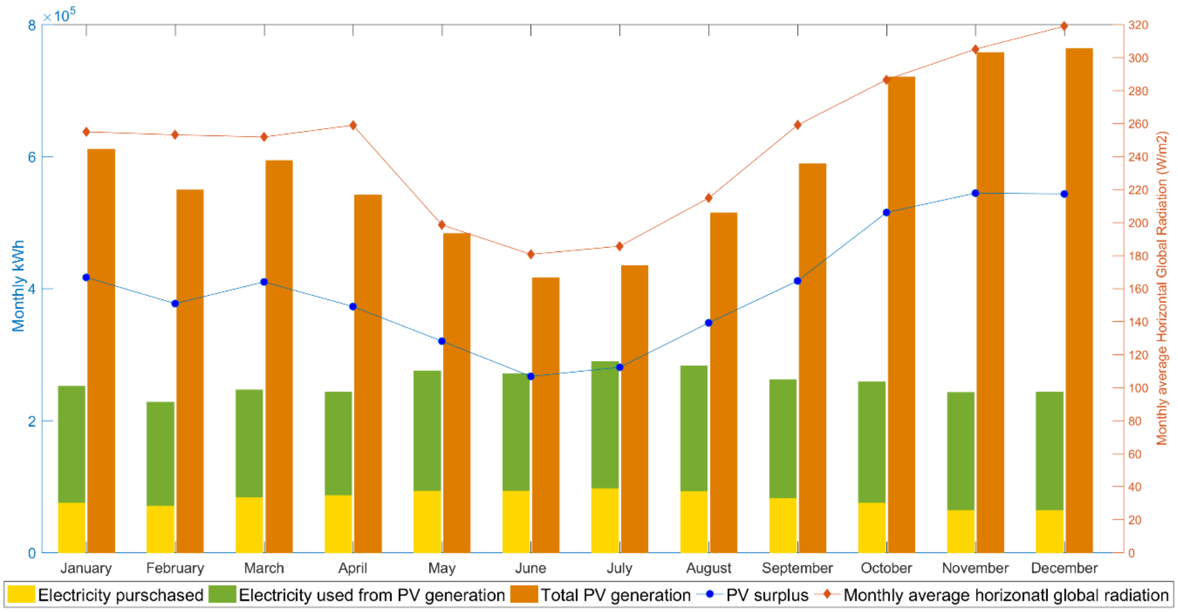

Figure 24 . Annual electric energy consumption, PV energy production, energy purchased and PV surplus in kWh/year in the EnergyPlus case.

The monthly energy consumption, PV energy generation, energy purchased, and PV surplus are summarized in Figure 24. It can be observed that the generation of renewable energy is greater than the mining camp' energy consumption during the whole year. The energy purchased from the grid is practically constant and is equivalent to the energy consumption generated at night, which is not possible to supply by the generation of the membranes. However, in Table 19, it can be observed that based on the annual balance the solar membrane plant completely covers the energy consumption of the camp, leaving a surplus of energy of 160.2 kWh/m^2 year. This energy can be used directly in mining processes.

Table 19. Yearly net plus energy camp balance

Total energy use	98	kWh/m^2 year
PV production	225.26	kWh/m^2 year
PV self-consumption	65.06	kWh/m^2 year
Energy surplus	160.20	kWh/m^2 year
Energy from grid	32.94	kWh/m^2 year

3.6 Conclusions

This paper aims to optimize a flexible TFSM configuration coupled with an integrated multifunctional system of DHW and HVAC to reduce the energy use and grid energy peak loads in a Chilean mining camp to reach the net zero energy goal. The multifunctional system is based on using a high efficiency heat pump for heating and also preheat the DHW, and thus reducing DHW energy use. In addition, the DHW is predefined to be heated in the periods of PV generation to reduce the grid electricity peak loads. An optimization is performed to evaluate which TFSM efficiency and roof area is required so that the actual annual delivered energy is equal to the on-site renewable exported energy. All the decisions are based on geographical, constructive and TFSMs market constraints. To include the market constraints of Chile, the efficiency of solar membranes implemented varies between 5-17% in response to solar membranes of amorphous silicon and CIGS respectively. The EnergyPlus option was evaluated to quantify the potential energy surplus of mining camps.

The main conclusions that can be drawn from this study are:

- The proposed multifunctional heat pump for HVAC and DHW generation is an effective solution to reduce the DHW energy use. This system reaches a decrease of 69.55% of the total energy consumption of DHW in comparison with the electric terms used in the base case.

- The integrated multifunctional system of TFSM, DHW and HVAC system can achieve the NZEB target with 57% of the available roof area and 12% efficiency of the TFSMs. The net zero energy balance is reached with 38,5 kWh/m^2 year PV surplus equal to the same amount provided from the grid.
- The integrated system of HVAC, DHW and TFSM reduces the daily peak loads in approximately 10% to 18% depending on the season time. Thus, the DHW energy consumption is satisfied almost the whole year in more than 80% by the TFSM production.
- In terms of the overall mining camp energy consumption, 60% of the generated renewable energy is self-consumed by the mining camp in summer season and 74% in winter season.
- Using the whole available roof area with 17% efficiency of the CIGS technology can generate 129% more energy than the required to supply the mining camp, which is equivalent to for 160.2 kWh/m^2 year. This energy can be harnessed to reduce energy consumption from fossil fuels to carry out mining processes, which responds directly to the provisions of the Chilean Energy Agenda.

This paper highlights the high potential of building net zero energy camps in Chile, taking advantage of the existing solar resource and the technology available in the commercial market to minimize the dependence on fossil fuels in mining and increase the resistance to power outages due to more renewable energy consumption and increase. This research can be used for both new mining camps and refurbishment of existing camps.

To encourage the construction of NZEB in Chile and develop accurate studies using different energy sources, future work should focus on creating the national average source energy conversion factors, to be able to convert the fuel types into equivalent units of raw fuel consumed in generating one unit of energy consumed on-site.

Future studies can also assess the economic feasibility to develop this solutions in future mining camps.

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APPENDIX

A. PHYTON SCRIPT FOR OVERHEATING CONSTRAINT

```
def clear_all():
    """Clears all the variables from the workspace of the spyder application."""
    gl = globals().copy()
    for var in gl:
        if var[0] == '_': continue
        if 'func' in str(globals()[var]): continue
        if 'module' in str(globals()[var]): continue

        del globals()[var]

clear_all()

import numpy as np

Datos=[4247,4249,4250,4252,4255,4256,4257,4259,4260,4262,4263,4265,4266,4268,4321,4323,4324,4326,
4328,4330,4331,4333,4334,4336,4337,4339,4340,4342,4343,4345,4346,4348,4349,4351,4352,4354,4355,43
57,4358,4360,4361,4363,4364,4366,4367,4369,4370,4372,4374,4375,4376,4378,4300,4302,4305,4304,4306
,4310,4307,4309,4381,4379,4382,4301,4303,4308,4380]

OverHeat1=np.zeros(len(Datos))
OverHeat2=np.zeros(len(Datos))
OverHeat3=np.zeros(len(Datos))
OverHeatTOT=np.zeros(len(Datos))
OverHeataux2=np.zeros(len(Datos))
TipoTurno=[0,0,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,1,1,1,1,1,
1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
#0 horario ( 7 -19 ), 1 horario (1-7) y (19-24)

HoraActual=0
Horamin=7
Horamax=19
diaT=0
Dtmax=4
dia=0
alpha=0.8
Trm=5.902
Tmax=0.33*Trm+21.8
ToutN=6
auxH1=0
fp = open('QB2aux.eso', 'r')
fp2 = open('QB2.eso', 'w')
while(True):
    aux=fp.readline()
    fp2.write(aux)
    if aux.find('1,UNTITLED (01-01:31-12)') >-0.1 :
        break
```

```
while(True):
    auxL=fp.readline()
    aux=auxL.split(',')
    OverHeatTOT=(OverHeat1/1460.0*100>3)+OverHeat2+OverHeat3
    if np.sum(OverHeatTOT>1)>1:
        while(True):
            auxL=fp.readline()
            aux=auxL.split(',')

            if aux[0].find('End of Data') >-0.1 :
                fp2.write('111,1\n')
                fp2.write(auxL)
                break
            fp2.write(auxL)

        break


    if aux[0].find('End of Data') >-0.1 :

        OverHeat1=OverHeat1/1460.0*100
        OverHeat1=OverHeat1>3
        OverHeatTOT=OverHeat1+OverHeat2+OverHeat3
        if np.sum(OverHeatTOT>1)>1:
            fp2.write('111,1\n')
            fp2.write(auxL)
        else:
            fp2.write('111,0\n')
            fp2.write(auxL)
        break

    fp2.write(auxL)
    if float(aux[0])==ToutN:
        Trm=(1-alpha)*float(aux[1])+alpha*Trm
        Tmax=0.33*Trm+21.8

    if float(aux[0]) == 2 :
        HoraActual= float(aux[5])
        if HoraActual == 1 :
            for i,Zone in enumerate(Datos):
                if OverHeataux2[i] >6:
                    OverHeat2[i]=1
            OverHeataux2=np.zeros(len(Datos))
        if float(aux[2])==1 or float(aux[2])==2 or float(aux[2])==3 or float(aux[2])==12:
            auxH1=1
        else:
            auxH1=0

    for i,Zone in enumerate(Datos):
        if float(aux[0])==Zone:
            if auxH1==1:
                if TipoTurno[i]==0:
                    if Horamin<=HoraActual and HoraActual<Horamax:
                        if float(aux[1])>Tmax:
                            OverHeat1[i]+=1
                            wf= float(aux[1])-Tmax
                            OverHeataux2[i]+=wf
```

```
                else:
                    if HoraActual<Horamin or Horamax<=HoraActual:
                        if float(aux[1])>Tmax:
                            OverHeat1[i]+=1
                            wf= float(aux[1])-Tmax
                            OverHeataux2[i]+=wf
            if float(aux[1])-Tmax>Dtmax:

                OverHeat3[i]=1


fp.close()
fp2.close()
```

B. PHYTON SCRIPT FOR LIGHTING CONSUMPTION VALUES

```
busqueda=['luces piezas','pasillo','bodega','cocina','comedor','gimnasio','lavado','sala de
reuniones','lavanderia','policlinico','control salida','oficina','sala','baños']

valoresAC=  [11.89,7.85,3.85,3.85,3.85,3.35,3.92,3.92,3.92,3.92,3.92,3.92,3.92,3.92]
valoresLED=  [5.71,3.78,2.86,2.86,2.86,2.38,2.20,2.20,2.20,2.20,2.20,2.20,2.20,2.20]
valoresLEDSM=[4.57,3.02,2.29,2.29,2.29,1.90,1.76,1.76,1.76,1.76,1.76,1.76,1.76,1.76]

FP = open('QB2.idf','w')
with open('QB2aux.idf', 'r')  as fp:
    lines = fp.read().split("\n")

for i in range(0,len(lines)):

    if lines[i].find('ACTxx')>-0.1 :
        for j,word in enumerate(busqueda):
            if lines[i-3].lower().find(word)>-0.1 :
                FP.write('    '+'%.2f' % valoresAC[j]+',                      !- Watts per Zone
                Floor Area {W/m2} \n')
                break

    elif lines[i].find('LEDxx')>-0.1 :
        for j,word in enumerate(busqueda):
            if lines[i-3].lower().find(word)>-0.1 :
                FP.write('    '+'%.2f' % valoresLED[j]+',                      !- Watts per Zone
                Floor Area {W/m2} \n')
                break

    elif lines[i].find('LEDSM')>-0.1 :
        for j,word in enumerate(busqueda):
            if lines[i-3].lower().find(word)>-0.1 :
                FP.write('    '+'%.2f' % valoresLEDSM[j]+',                      !- Watts per
                Zone Floor Area {W/m2} \n')
                break
    else:
        FP.write(lines[i]+'\n')

FP.close()
fp.close()
```

C. GENOPT SCRIPT FOR WINDOWS SIZE OPTIMIZATION

```
  Parameter{ //Delta alto Ventana Noreste
  Name    = DeltayNE;
  Min     = -0.5;
  Ini     = 0;
  Max     = 0.5;
  Step    = 0.25;
}

Function{Name = y1 ; Function= "add(%DeltayNE%,4.00390001)";}
Function{Name = z1 ; Function= "add(multiply(%DeltayNE%,-1), 2.92390001)";}
Function{Name = y2 ; Function= "add(%DeltayNE%,5.50390001)";}
Function{ Name = z2 ; Function= "add(multiply(%DeltayNE%,-1),4.42390001)";}
Function{Name = y3 ; Function= "add(%DeltayNE%,5.50390001)";}
Function{ Name = z3 ; Function= "add(multiply(%DeltayNE%,-1),4.42390001)";}
Function{Name = y4 ; Function= "add(%DeltayNE%,5.50390001)";}
  Function{Name = z4 ; Function= "add(multiply(%DeltayNE%,-1),4.42390001)";}
 Function{ Name = y5 ; Function= "add(%DeltayNE%,8.7955)";}
  Function{Name = z5 ; Function= "add(multiply(%DeltayNE%,-1),7.7155)";}
 Function{ Name = y6 ; Function= "add(%DeltayNE%,8.7955)";}
 Function{ Name = z6 ; Function= "add(multiply(%DeltayNE%,-1),7.7155)";}
 Function{ Name = y7 ; Function= "add(%DeltayNE%,7.2855)";}
  Function{Name = z7 ; Function= "add(multiply(%DeltayNE%,-1),6.2055)";}
 Function{ Name = y8 ; Function= "add(%DeltayNE%,5.63)";}
  Function{Name = z8 ; Function= "add(multiply(%DeltayNE%,-1),4.55)";}
  Function{Name = y9 ; Function= "add(%DeltayNE%,2.325)"; }
  Function{Name = z9 ; Function= "add(multiply(%DeltayNE%,-1),1.25)";}
  Function{Name = y10 ; Function= "add(%DeltayNE%,4.00390001)";}
  Function{Name = z10 ; Function= "add(multiply(%DeltayNE%,-1),2.92390001)";}
 Function{ Name = y11 ; Function= "add(%DeltayNE%,7.2855)";}
 Function{ Name = z11 ; Function= "add(multiply(%DeltayNE%,-1),6.2055)";}
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  Function{Name = z12 ; Function= "add(multiply(%DeltayNE%,-1),2.92390001)";}
  Function{Name = y13 ; Function= "add(%DeltayNE%,7.2855)";}
 Function{ Name = z13 ; Function= "add(multiply(%DeltayNE%,-1),6.2055)";}
 Function{ Name = y14 ; Function= "add(%DeltayNE%,4.00390001)"; }
 Function{ Name = z14 ; Function= "add(multiply(%DeltayNE%,-1),2.92390001)"; }
  Function{Name = y15 ; Function= "add(%DeltayNE%,7.2855)";}
 Function{ Name = z15 ; Function= "add(multiply(%DeltayNE%,-1),6.2055)"; }
 Function{ Name = y16 ; Function= "add(%DeltayNE%,4.00390001)"; }
 Function{ Name = z16 ; Function= "add(multiply(%DeltayNE%,-1),2.92390001)";}
 Function{ Name = y17 ; Function= "add(%DeltayNE%,7.2855)";   }
 Function{ Name = z17 ; Function= "add(multiply(%DeltayNE%,-1),6.2055)";   }
 Function{ Name = y18 ; Function= "add(%DeltayNE%,4.00390001)"; }
 Function{ Name = z18 ; Function= "add(multiply(%DeltayNE%,-1),2.92390001)";}
 Function{ Name = y19 ; Function= "add(%DeltayNE%,7.2855)"; }
  Function{Name = z19 ; Function= "add(multiply(%DeltayNE%,-1),6.2055)"; }
  Function{Name = y20 ; Function= "add(%DeltayNE%,4.00390001)";}
```

```
  Function{Name = z20 ; Function= "add(multiply(%DeltayNE%,-1),2.92390001)";}
 Function{ Name = y21 ; Function= "add(%DeltayNE%,7.2855)";}
 Function{ Name = z21 ; Function= "add(multiply(%DeltayNE%,-1),6.2055)"; }
Function{ Name = y22 ; Function= "add(%DeltayNE%,4.00390001)"; }
Function{  Name = z22 ; Function= "add(multiply(%DeltayNE%,-1),2.92390001)";}
 Function{ Name = y23 ; Function= "add(%DeltayNE%,7.2855)"; }
 Function{ Name = z23 ; Function= "add(multiply(%DeltayNE%,-1),6.2055)";}
  Function{Name = y24 ; Function= "add(%DeltayNE%,8.7955)"; }
 Function{ Name = z24 ; Function= "add(multiply(%DeltayNE%,-1),7.7155)";}
 Function{ Name = y25 ; Function= "add(%DeltayNE%,5.50390001)";  }
 Function{ Name = z25 ; Function= "add(multiply(%DeltayNE%,-1),4.42390001)"; }
 Function{ Name = y26 ; Function= "add(%DeltayNE%,8.7955)";}
 Function{ Name = z26 ; Function= "add(multiply(%DeltayNE%,-1),7.7155)";
}

      Parameter{ //Delta ancho y alto Ventana Sur Poniente
  Name    = DeltayVSO;
  Min     = -0.5;
  Ini     = 0;
  Max     = 0.5;
  Step    = 0.25;
}

Function{
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 Function{ Name = z2s ; Function= "add(multiply(%DeltayVSO%,-1),4.42390001)";}
  Function{Name = y3s ; Function= "add(%DeltayVSO%,5.50390001)";}
 Function{ Name = z3s ; Function= "add(multiply(%DeltayVSO%,-1),4.42390001)";}
 Function{ Name = y4s ; Function= "add(%DeltayVSO%,5.50390001)";}
  Function{Name = z4s ; Function= "add(multiply(%DeltayVSO%,-1),4.42390001)";}
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 Function{ Name = y6s ; Function= "add(%DeltayVSO%,8.7955)"; }
 Function{ Name = z6s ; Function= "add(multiply(%DeltayVSO%,-1),7.7155)"; }
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  Function{Name = z7s ; Function= "add(multiply(%DeltayVSO%,-1),6.2055)";   }
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 Function{ Name = z8s ; Function= "add(multiply(%DeltayVSO%,-1),4.55)";}
 Function{ Name = y9s ; Function= "add(%DeltayVSO%,2.325)";}
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 Function{ Name = y10s ; Function= "add(%DeltayVSO%,4.00390001)"; }
 Function{ Name = z10s ; Function= "add(multiply(%DeltayVSO%,-1),2.92390001)";}
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 Function{ Name = z11s ; Function= "add(multiply(%DeltayVSO%,-1),6.2055)"; }
 Function{ Name = y12s ; Function= "add(%DeltayVSO%,4.00390001)";}
  Function{Name = z12s ; Function= "add(multiply(%DeltayVSO%,-1),2.92390001)";}
```

```
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Function{ Name = z13s ; Function= "add(multiply(%DeltayVSO%,-1),6.2055)";}
 Function{Name = y14s ; Function= "add(%DeltayVSO%,4.00390001)"; }
Function{Name = z14s ; Function= "add(multiply(%DeltayVSO%,-1),2.92390001)";   }
Function{ Name = y15s ; Function= "add(%DeltayVSO%,7.2855)"; }
Function{ Name = z15s ; Function= "add(multiply(%DeltayVSO%,-1),6.2055)";}
Function{ Name = y16s ; Function= "add(%DeltayVSO%,4.00390001)"; }
Function{ Name = z16s ; Function= "add(multiply(%DeltayVSO%,-1),2.92390001)";}
Function{Name = y17s ; Function= "add(%DeltayVSO%,7.2855)"; }
Function{  Name = z17s ; Function= "add(multiply(%DeltayVSO%,-1),6.2055)"; }
Function{ Name = y18s ; Function= "add(%DeltayVSO%,4.00390001)";}
Function{ Name = z18s ; Function= "add(multiply(%DeltayVSO%,-1),2.92390001)";}
 Function{Name = y19s ; Function= "add(%DeltayVSO%,7.2855)";}
 Function{Name = z19s ; Function= "add(multiply(%DeltayVSO%,-1),6.2055)"; }
Function{Name = y20s ; Function= "add(%DeltayVSO%,4.00390001)"; }
 Function{Name = z20s ; Function= "add(multiply(%DeltayVSO%,-1),2.92390001)";}
 Function{Name = y21s ; Function= "add(%DeltayVSO%,7.2855)";   }
Function{ Name = z21s ; Function= "add(multiply(%DeltayVSO%,-1),6.2055)"; }
Function{Name = y22s ; Function= "add(%DeltayVSO%,4.00390001)";}
Function{ Name = z22s ; Function= "add(multiply(%DeltayVSO%,-1),2.92390001)";}
 Function{Name = y23s ; Function= "add(multiply(%DeltayVSO%,-1),7.2855)"; }
Function{ Name = z23s ; Function= "add(%DeltayVSO%,6.2055)";}
Function{ Name = y24s ; Function= "add(multiply(%DeltayVSO%,-1),8.7955)"; }
Function{ Name = z24s ; Function= "add(%DeltayVSO%,7.7155)"; }
Function{ Name = y25s ; Function= "add(multiply(%DeltayVSO%,-1),5.50390001)"; }
Function{ Name = z25s ; Function= "add(%DeltayVSO%,4.42390001)";}
 Function{Name = y26s ; Function= "add(multiply(%DeltayVSO%,-1),8.7955)";}
Function{ Name = z26s ; Function= "add(%DeltayVSO%,7.7155)";
}

        Parameter{ //Delta alto oficinas
 Name   = DeltayOFICINA;
 Min    = 0;
 Ini    = 0;
 Max    = 1;
 Step   = 0.5;
}

Function{ Name = z1v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67490001)";}
Function{ Name = z2v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67490001)";}
Function{ Name = z3v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";}
 Function{Name = z4v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";}
 Function{Name = z5v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";   }
Function{ Name = z6v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)"; }
 Function{Name = z7v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";   }
Function{ Name = z8v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";}
 Function{Name = z9v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)"; }
Function{ Name = z10v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";}
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 Function{ Name = z11v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)"; }
  Function{Name = z12v ; Function= "add(multiply(%DeltayOFICINA%,1),1.676900011)";}
 Function{ Name = z13v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";}
 Function{Name = z14v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";  }
 Function{ Name = z15v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";}
 Function{ Name = z16v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";}
Function{  Name = z17v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)"; }
 Function{ Name = z18v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)"; }
  Function{Name = z19v ; Function= "add(multiply(%DeltayOFICINA%,1),1.676900011)";}
 Function{ Name = z20v ; Function= "add(multiply(%DeltayOFICINA%,1),1.67690001)";}
 Function{Name = z21v ; Function= "add(multiply(%DeltayOFICINA%,1),1.71490001)";  }
 Function{ Name = z22v ; Function= "add(multiply(%DeltayOFICINA%,1),1.71390001)"; }
 }
```