LAPPEENRANTA–LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Energy Systems
Department of Environmental Technology
Sustainability Science and Solutions
Master's thesis 2019

Antonio de Jesús Bazán Colque

THE TECHNICAL, ECONOMIC AND ENVIRONMENTAL FEASIBILITY ANALYSIS OF IMPLEMENTING ELECTRICAL BASED HEAT PUMPS POWERED BY SOLAR PV SYSTEMS FOR THE COUNTRYSIDE HOUSEHOLDS LOCATED IN THE BOLIVIAN HIGHLANDS

Examiners: Professor, D.Sc. (tech) Risto Soukka
Associate Professor, Mika Luoranen

ABSTRACT

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The technical, economic and environmental feasibility analysis of implementing electrical based heat pumps powered by solar PV systems for the countryside households located in the Bolivian Highlands.

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119 pages, 24 figures, 45 tables, 1 appendix

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Keywords: Thermal circuit, heat loads, heat demand, heat pump, Photovoltaic System, Bolivia, Combined system, environmental assessment, CO_2 emissions avoidance, climate change, electricity generation, energy matrix, sustainability.

The absence of heating systems alongside with the adverse weather conditions of the Bolivian highlands, generate adverse living conditions for the rural population of the region, causing an over exigency of the national electrical system during the colder months of the year, thus increasing the emissions of CO2 emitted by combustion of natural gas in the thermoelectric plants of the country. Furthermore, Bolivian people living in the rural and suburban areas of the highlands still do not have complete access to basic services such as electricity. A combined system of heat pumps powered by solar panels has been designed to tackle this problematic. Tacking advantage of the Social Housing Program that the Bolivian Government implemented a combined heat pump & solar PV system was dimensioned for covering the calculated thermal demand of 7.1 kW of the prototype houses of the mentioned program.

The heat pump selected for the project has a maximum thermal power of 8,1kW and an electrical demand of 3,301 kWh was chosen for the heating period of 8 months.

An arrangement of 6 solar panels, with an efficiency of 19.3%, will generate 5,056 kWh per year, generating an excess of production (during the heating period) of 8.7 kWh/month which alongside with the complete covering of the non-heating period´s house demand, will generate 438 kWh/year/house ready to be reinjected into the National Interconnected System.

By implementing the project 4,730 tCO_2/year are avoided, representing a reduction of 34% of the current emissions generated by the total number of houses. An additional investment of 75% on the initial investment of 25,000 USD is needed for the implementation of the combined system.

ACKNOWLEDGEMENTS

Primarily I would like to thank my family, my parents Edgar and Katty, my brother Vladimir and my sister Carla, without whom I wouldn´t have been able to pursue and achieve my dreams and goals. I can only thank go**d** for being blessed with such beautiful beings.

To all the pe**r**sons that believed in me, in my hard work and my strong sense of responsibility and aptitudes, thank you so much for have been there, I really appreciate all of you.

Special gratitude to Prof. Risto Soukka for his guidance, patience and collaboration in the developing of the present work, as well as to all the teaching staff of Lappeenranta University of Technology, their support and teachings have been very meaningful throughout the entire year of studies.

Finally, the Sustainable Sciences and Solutions class of **2019** I will never forget you guys, nor your support nor your friendship.

In Lappeenranta 5th December 2019

Antonio de Jesús Bazán Colque

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LIST OF SYMBOLS

[°C]	Celsius Degrees
[K]	Kelvin Degrees
[W]	Watts
[m]	Meters
[m^2]	Square meters
[t]	Tons (mass)
[kg]	Kilograms (mass)
[l]	Liters (volume)
[m^3]	Cubic meters (volume)
[bar], [Pa]	Pressure

ABBREVIATIONS

COP	Coefficient of Performance
SCOP	Seasonal Coefficient of Performance
PV	Photovoltaic
GHG	Greenhouse gases
IEA	International Energy Agency
SIN	National Interconnected System of Bolivia
SA	Isolated Systems of Bolivia
IRA	Acute Respiratory Infections
LPG	Liquefied Petroleum Gas
NG	Natural Gas
ENDE	National Energy Company of Bolivia
TPES	Total Primary Energy Supply
SENHAMI	National Hydrology and Meteorology Center of Bolivia
USD	United States Dollar

List of chemical elements

CO_2	Carbon Dioxide

1. INTRODUCTION

The use of energy (in any of its forms) has undoubtedly been a milestone in the development of our civilizations. Representing the scientific and industrial development that propelled the human progress in almost every field of application. Given the advanced level of technological development that the use of energy has made on the planet, it is necessary to cover the world's energy needs in terms of electricity and heat. This holistic development could be seen interrupted without electrical and thermal energy generation systems, threatening our already energy dependent lifestyle.

Unfortunately for humans with a rapid and unsustainable development comes serious harmfulness to the environment in which they live. The consumption of natural resources such as the combustion of any kind of fuels, have been historically and directly linked with the production of energy worldwide. Leading us to extreme boundaries of the lack of the raw materials to conduct our energized world. Currently planet Earth goes through a delicate situation, due to the CO2 emissions from the different sectors of the human development.

The Paris climate agreement calls on the signatory states to reduce their greenhouse gas emissions to halt the rise in global temperature to a maximum of 2 ° C above pre-industrial levels. (STRECK ET AL., 2016). This requires rapid actions in several areas, including transport and industry, but also in residential properties, which are expected to become self-sustainable in terms of energy and emissions in the future. Tackling this way the need of sustaining a huge number of fossil fuel fired power plants (IEA, 2018).

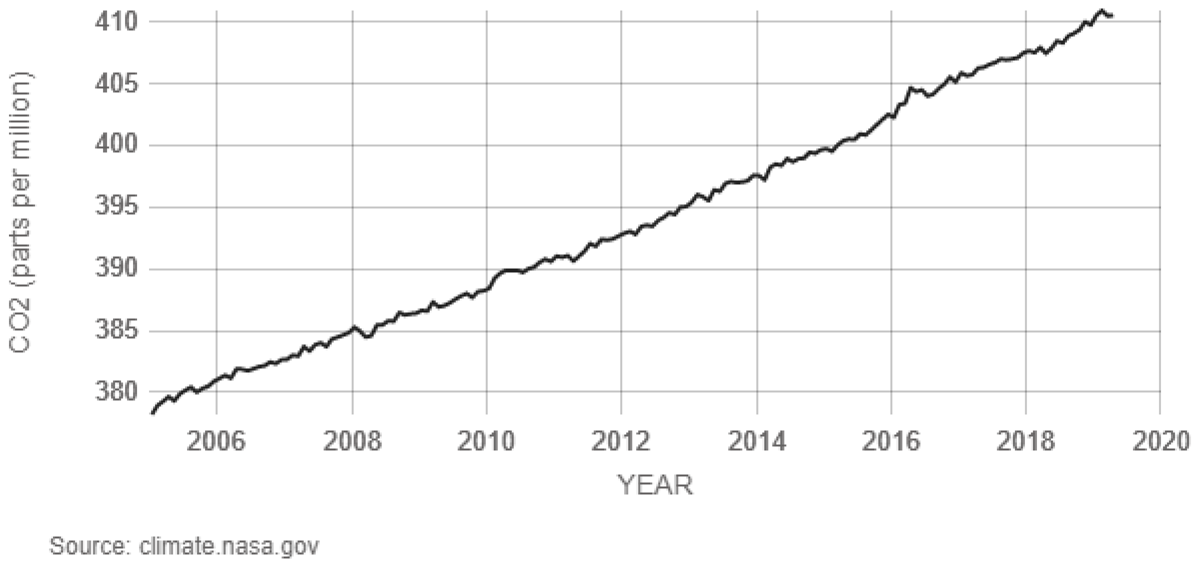


Figure 1. Yearly measurements of CO2 concentration in the atmosphere. (NASA, 2019).

The CO2 emissions rate all over the world are outrageous, surpassing this year the 410 ppm of CO2 in the atmosphere, causing the increment of the temperature of the earth. According to the latest report of NASA, the temperature has risen 0.8°C until June, 2019.

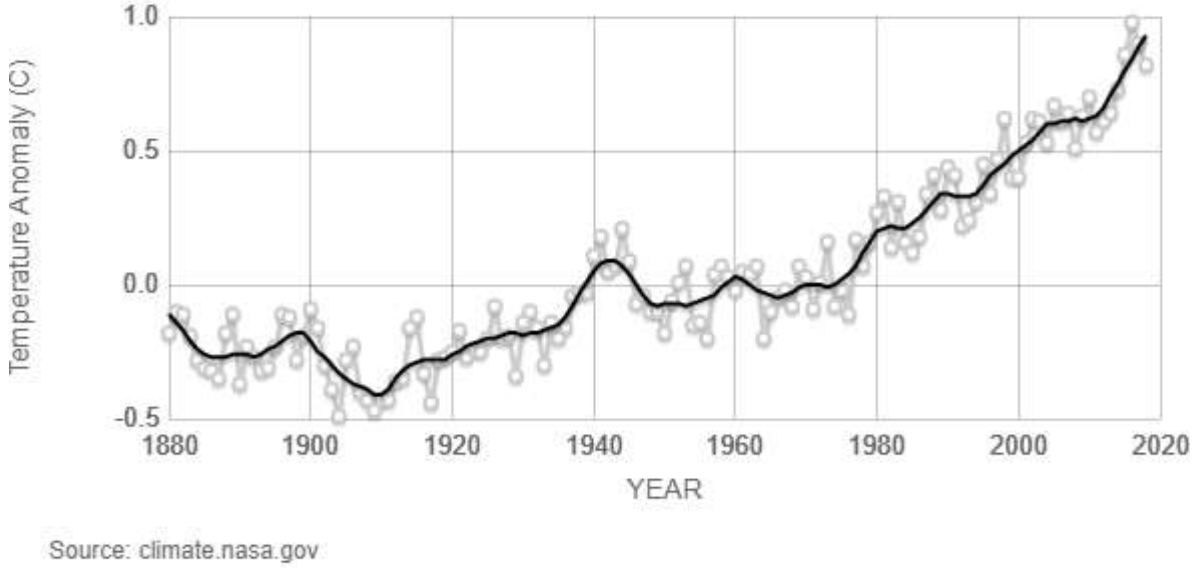


Figure 2. Yearly global land-ocean temperature measurements. (NASA, 2019).

The archaic systems of energy production are transforming and directing towards the change in the energy matrix and therefore using more and more renewable sources of energy (Könnölä, T. & Carrillo-Hermosilla, 2008).

Renewable energy projects applied to small scale projects are in this case an important and vital trend to follow in the pursuit of Paris Climate Agreement, especially when referring to the local self-production. By increasing support for the production of low greenhouse-gasses emission energy, progress in energy conversion and technology and storage (Chan & Kantamaneni, 2015).

The creation of technological systems, intelligent and sustainable have been the result of many years of trial and error in which as humans, realized that using natural resources in a measured way is not enough.

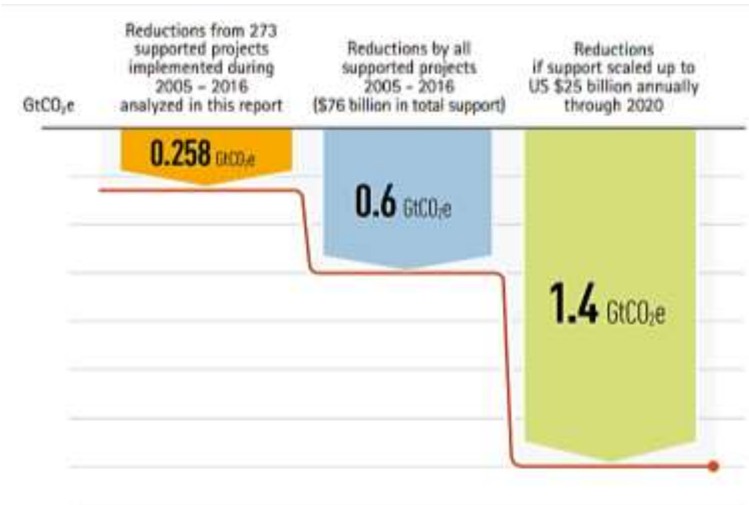


Figure 3. Emission reduction from renewable energy and energy efficiency projects by 2020 in developing countries. (UN Environment, 2017).

According to the latest renewable energy report of the International Energy Agency (IEA), the use of renewable energy will grow to reach 12.4% in 2023. Having its largest share in the electricity production sector providing around 30% of the global energy demand by 2023.

Electric heat pumps play an important role in trying to exclude carbon from energy production. According to the (IEA, 2019) it was estimated that since 2010 its participation in heat generation has increased by 7%. With the fastest increase in China, of 50%. The global potential for thermal energy production currently exists. The growth of the thermal residential sector has not yet reached the growth of the electricity sector. According to the projections made to reach the objective of the two degrees for 2025, the participation of renewable heat sources must have increased up to 32% by 2025.

In Bolivia, the situation is not so different than the rest of the world, in the present decade, it has experienced an increment of the net CO2 emissions of around 100% (IEA, 2019). This is linked to the economic development of the country that went from emitting 0.62 kg CO2/2010 USD in 2007 to emit 0.8 kg CO2/2010 USD in 2017 (The unit of measurement that IEA adopted comes from the value of the US dollar rate then year 2010) (IEA, 2019). But surprisingly different from other countries in the region the emissions rate was controlled, this thanks to the policies of the Bolivian Government which strict the environmental protection laws and continuously impulses renewable technology projects (Vice ministry of Renewable Energies, 2019).

Nonetheless, the results of the negative environmental impacts on the environment affect in a greater way to the most vulnerable population. In Bolivia, not only people in poverty situation suffers from the effects of the climate change but also people with a mid-class salary suffers them. The lack of houses for dwelling, the still incomplete access to basic services (electricity and potable water), the lack of district heating networks that provide heat during the coldest months of the year. In the rural and suburban areas, the droughts and the usage of native biomass for cooking and heating and all the health issues related to the topics previously detailed are of concern as well. Increasing this way, the need of rethinking all the possible solutions to get the Bolivian families the quality of life they deserve.

1.1. Objectives of the thesis work

The objective of the present work is to determine the technical feasibility of implementing a heat pump system powered by electricity from solar panels at the homes of the Bolivian Social Housing Program implemented by the national government. By calculating the demand for total heat and electricity per home, also considering the construction materials, environmental and climatic characteristics, and the number of inhabitants per dwelling and the geographical location of the site location of the houses.

Another objective to achieve is to perform the calculation of total emissions related to the implementation of the project, establishing scenarios for the implementation of the heat pump and the combined system. All this in order to compare the emissions that would be generated with real data on demand for heat and electricity, using data Real CO_2 emission per home in Bolivia, as well as CO_2 emissions related to the generation of electricity. Thus, generating information about the enormous potential environmental benefit of the implementation of decentralized self-production systems of the National Interconnected System (SIN).

Finally, the last main objective is to carry out the economic analysis about the costs and economic benefits of the implementation of the combined system, and its economic impact beneficial not only to the national government in terms of fuel savings and extension of the national power line. But also in the low-income people economic resources belonging to the Social Housing Program of the National Government of Bolivia.

1.2. Scope of the thesis work

The thesis work is limited to the calculation of the heat demand of a typical household of the Bolivian countryside that belongs to the Social Housing Construction Program for the people living in the Bolivian Highlands. All the representative and required parameters for calculating the heating demands are taken for this section of the country, this since Bolivia has a wide range of regions with their own correspondent characteristics.

The thesis is focused on analyzing the feasibility of the energetic coverage of the heating demand of a selected type of household by designing a combined electrical based heat pump system fed electrically by photovoltaic panels. Considering the environmental assessment of the tons of CO_2 emissions/avoidances produced by electricity consumption or auto-generation. Finally, an economic assessment was carried out, considering the costs of implementation of the project, internalizing the costs of tons of CO_2 emissions, and the benefits from avoiding consuming electricity from the network but instead self-producing it, and consequently avoiding the emissions of tons of CO_2.

1.3. Justification of the project

Article 33 of the Political Constitution of the Bolivian State indicates that "All inhabitants of the Bolivian State have the right to a healthy, protected and balanced environment ...". The new electricity law, in turn, establishes a change in the paradigm of the vision of the Bolivian State with respect to carrying out a restructuring of the electricity sector, proposing directives directed towards the incentive for the installation of power plants prioritizing alternative and renewable sources of energy. Energy. Shifting the generation of energy through the combustion of fossil fuels by cleaner energy. However, according to the guidelines of the Bolivia Development Plan 2025 (GUZMAN 2010), which responds to a long-term government strategy, based on which all projects of social order are directed, there are two extraordinarily important points that are:

- "Eradication of extreme poverty, as well as social inequalities among the population".
- "Universalization of basic services with sovereignty ...".
- "Environmental Sovereignty with integral development ...".

The Bolivian Constitution also establishes a direct mandate to the rulers towards the reduction of extreme poverty, establishing political and economic reforms that help to combat the situation of extreme, moderate poverty; as well as generating conditions of "decent and sustainable housing". When referring to "Living Well" or “Vivir Bien”(in Spanish), the Bolivian State collects ancestral knowledge, fundamental rights of people, constitutional-legal regulations, as well as institutional plans such as "Bolivia 2025 Development Plan", and compiles them in the definition that the Bolivian population has the fundamental right to live with dignity, equality in access to all their fundamental rights.

It is here that the development of the "national energy system" and the right to a "dignified housing with adequate living conditions for the development of the daily activities of the population", becomes relevant, especially the population living in poverty, which coincidentally is in its majority the population that lives in the rural area of the country ".

1.3.1. Urbanization Degree in Bolivia.

Housing in Bolivia maintains a marked difference when talking about the Urban Area and Rural Area. The urban area reflects 64.14% of the total housing in Bolivia, while the rural area represents 34.86% of the total housing. Clearly reflecting still nowadays, a marked difference between the housing conditions of people from rural and more urbanized areas (INE, 2017).

1.3.2. Social Household's Construction Program

Since 2005, the Bolivian Government has propelled a "Social Households Construction Program", this to fight against the lack of available housing for low-income families (State Housing Program, 2019).

The program divides itself into six categories:

1) "Qualitative household", which improves and enlarges the existing households under the drive of the Bolivian Government.

2) Buying and financing of the household, under this program the beneficiaries will eventually buy themselves a house under the supervision of their incomes and possibilities, allowing them to apply for this kind of house.

3) The self-construction of the new household under assisted supervision, this is the construction of the communities by themselves, with the technical help of government technicians, in order to develop the growing of the communities.

4) Extraordinary attention, this part of the program benefits handicap persons or people with a low-income, who would not be able to buy or construct their own house without the intervention of the governmental help.

5) Attention to disasters or emergencies, this part of the program helps people in need of help, whom have lost their houses due to natural disasters.

6) Urban communities, this refers to the construction of households shaped as communities, meaning the construction of a determined prototype of household developed by the government and approved by the future beneficiaries. The house is the same for all of them and are constructed by a number of one hundred.

1.3.3. Social and Health Component of the Project

The implementation of heat in the homes of low-income families is also related and has a strong health and hygiene component, given that, according to data from the National Institute of Statistics of Bolivia, the months in which cases of Infections intensify Respiratory Acute (IRAs) are precisely the months belonging to the winter period (Ministry of Health , 2017), which incidentally, extends and mesmerizes with the autumnal as well as the spring period in the sense that average and low temperatures decrease and the number of cases of infections respiratory rises. The precarious thermal insulation conditions of the houses of the Bolivian Altiplano favor the descent and almost direct exposure of the inhabitants of the Altiplano to the surrounding environment.

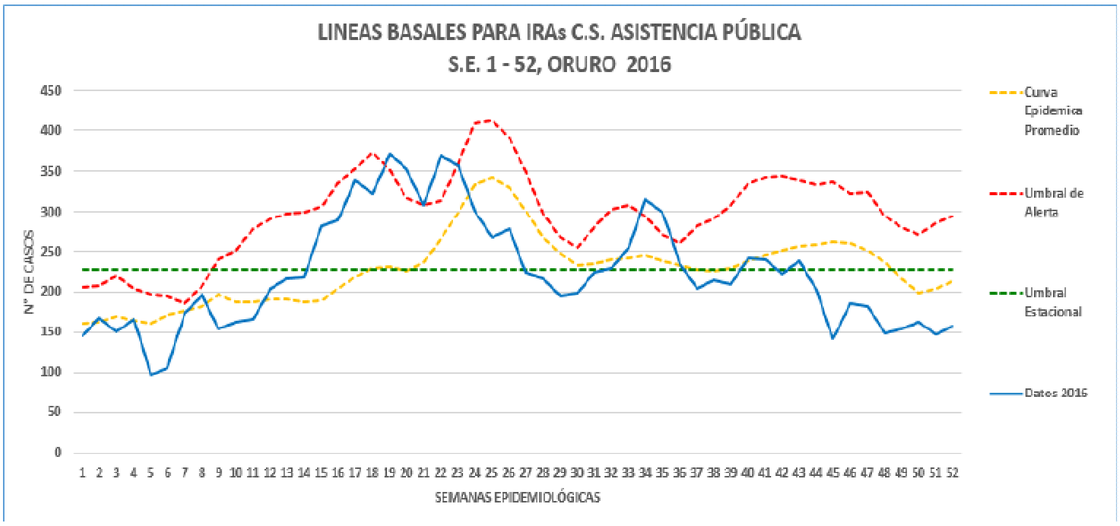


Figure 4. Baseline for Acute Respiratory Infections (IRA´s) (Ministry of Health, 2016).

1.3.4. Biomass utilization by the middle to low income families in Bolivia

According to Gomez, E. (2011) in Bolivia the gap in the access to public services, as important as electricity for heating or natural gas for cooking, has driven the middle to low income families to use different means of biomass to cover these needs. Although, the most used fuel in the Bolivian houses is the Liquid Petroleum Gas (LPG), due to the lack of distribution channels, many families opt for biomass burning. The residential sector in Bolivia currently consumes 44% of LPG, 5% of natural gas, 20% of electricity and 31% of biomass for cooking and heating their homes. Out of the 31% of biomass represents 46.51% of the total biomass consumption in the country (Ministry of Environment, 2016) and 69% of the countryside houses and 6.5% of the urban areas´ houses use firewood and/or brushwood (Gomez, E. 2011).

In the Following table it can be appreciated the shares of fuels used in the rural and suburban areas for heating and cooking purposes.

Table 1. Different fuels used for heating and cooking purposes in the rural and urban areas

Fuel type	Rural areas [%]	Urban areas [%]
Brushwood/firewood	46.51	2.77
LPG	45.24	82.27
Guano/manure	6.57	0.03
Electricity	0.28	0.7
Natural Gas (network)	0.14	10.82
Kerosene	0.33	0.02
Others	0.93	3.33
Total	**100**	**100**

1.4. Definition of the problem

The lack of a home heating system throughout the Bolivian territory generates adverse living conditions for the inhabitants of the highlands, the Social Households Construction Program faces directly the lack of housing of the most vulnerable population, but due to the harsh environment conditions of the Andes, especially the radical changes in temperature throughout the year and a poorly isolated housing design, it directly and indirectly encourages the use of organic material or demanding the use of electric heaters to cover the environmental heat demand of dwellings in the Bolivian Highlands. Exposing almost directly the inhabitants of the aforementioned region, to the adverse conditions of the Andes' own climate, pollution of the surrounding environment due to incomplete combustion of organic matter, damage to health, possible fires, deforestation of native tree species, increased respiratory infections during the winter period, increased tons of carbon dioxide emitted into the atmosphere due to the overuse of electrical energy from the electric power distribution network, which has as a major generation from the combustion of natural gas for the electricity generation (thermoelectric plants).

2. THE BOLIVIAN ENERGY MATRIX AND HOUSING CONDITIONS

2.1. Plurinational State of Bolivia

Bolivia is located between 57º26 'and 69º38' of longitude West and 9º38 'and 22º53' of South latitude and counts on a surface of 1.098.000 Km². Bolivia is a country that is divided into three differentiated regions (Montes de Oca, 1997):

1) The western or Andean region, which occupies 28% of the territory, with almost constant heights of around 3000 m.a.s.l. and with twelve peaks over 6000 m in height.
2) The sub-Andean zone that corresponds to the belt between the eastern mountain range and the tropical plains. It includes the valleys that are located at an average height of 2,500 m.a.s.l. which constitute agricultural areas par excellence, as well as the exuberant vegetation of the yungas.
3) The tropical plains of the east, lowland areas at a height of between 200 and 300 m.a.s.l. which cover about 60% of Bolivian territory. The latter are made up of extensive pastures, savannahs, humid and semi-humid forests of precious woods and numerous navigable and flowing rivers.

Due to its physiographic characteristics Bolivia has a variety of climates which are determined by the humid tropical influence of the Amazonian Equatorial Current and the cold air masses of the Southern Current, by the latitudinal gradient and by the altitudinal gradient from the West to the East.

Bolivia has been characterized for being a producer of hydrocarbons which has made the energy framework in which the country develops becomes vital for the national economy.

2.2. Bolivian Energy Matrix

In Bolivia, the energy matrix, or at least the source of energy supply in the country, is provided by the National Electricity Company (ENDE, 2019). Bolivia is a country rich in natural and energy resources. The primary energy consumption matrix (Total Gross Domestic Supply, OIBT) of the country indicates that 69.72% comes from natural gas, 4.45% comes from diesel, 24.97% from hydroelectric power plants, 0.67% from Eolic power, 0.012% and from solar power. Being 66% of the total energy produced, destined to exports (94% in the form of natural gas) and 33% destined to the internal consumption (transport 59%, industry 21% and residential 18%) (Ministry of Hydrocarbons & Energy, 2019).

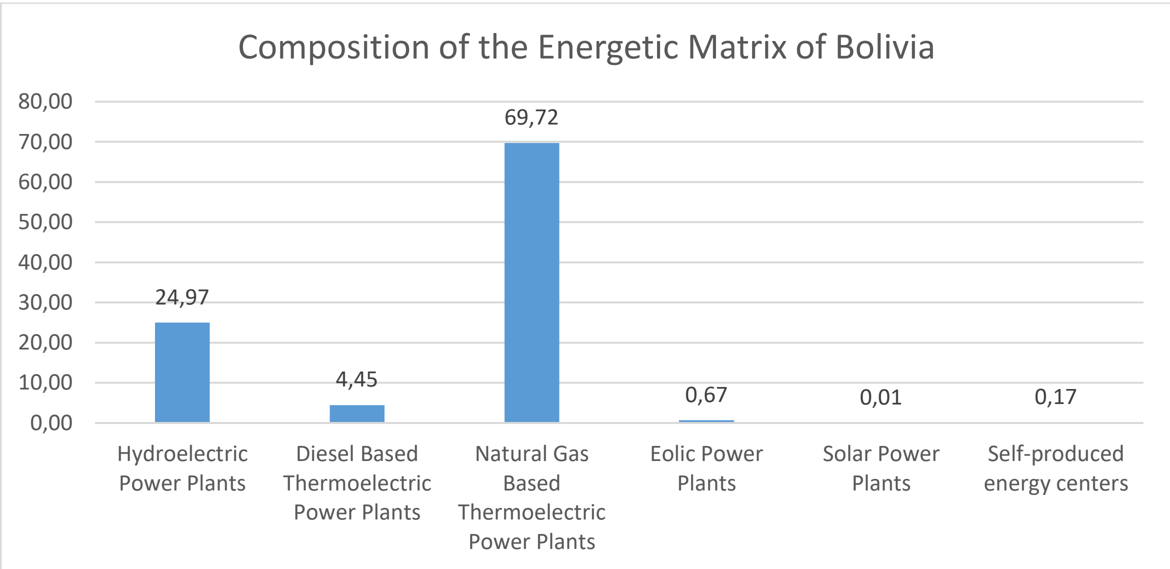


Figure 5. Composition of the Energy Matrix of Bolivia. (%) (MINISTRY OF HYDROCARBONS & ENERGY, 2019).

2.2.1. National Interconnected System (SIN)

The Bolivian Interconnected System is made up of the National Interconnected System (SIN), which provides electricity to the main cities of the country, the isolated systems that supply the smaller and distant cities of the trunk axis of the country. The SIN was constituted by the National Electricity Company (ENDE) and consists of generation, transmission and distribution units that operate in a coordinated manner to supply electricity consumption in the departments of La Paz, Oruro, Cochabamba, Santa Cruz, Beni, Potosí and Chuquisaca, which represent 90% of the total demand of the country. The operation of the SIN is based on the "Integral and Sustainable Use of Energy Resources, Generation Competition and Free Access to Energy Transmission". (Ministry of Energy, 2019).

Figure 6. National Interconnected System. (Ministry of Energy, 2019).

2.3. Bolivian Energy Consumption

Bolivia the year 2017 produced 244 TWh and consumed 86.45 TWh, the country possessed a Total Primary Energy Supply (TPES) of 104 TWh. The country has been growing its renewable energy share going from 2,020 GWh of electrical generation from renewables in 2005 to 2,573 GWh in 2017. The Andean country owns the electric network which also grow up to 100% coverage of urban areas and 77% of rural areas by 2019, representing a 91% of the country´s final users covered. In Bolivia there are six major electricity producers which are oil, natural gas, biofuels, hydro, solar and wind. Being the last two the ones with more initiatives for investment since 2016 (Ministry of Economy and Finances & Ministry of Environment, 2019).

As it can be appreciated in the Figure 7, the residential sector represents 37% of the total electric demand of the country.

2.3.1. Electric Power Consumption by Category in Bolivia

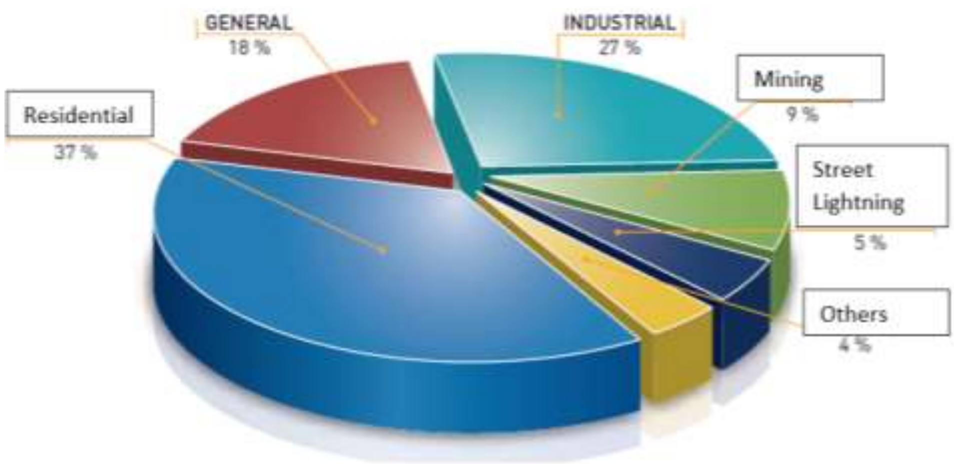


Figure 7. Electric Power Consumption by category in Bolivia. (Ministry of Energy, 2019).

2.4. Total Electricity Generation in Bolivia 2018

In Bolivia the electricity is produced in the National Interconnected System (SIN) and in the Isolated Systems (SA), the SIN currently is producing 74.49% of its electricity in thermal plants which work mainly with natural gas and diesel generators, from which 100% of the electricity supplied to the region conformed by Oruro, La Paz and Potosí; 24.83% of the total electricity comes from hydroelectric power and the remaining 0.68% from renewable energy sources such as wind and solar.

On the other hand, in the SA the renewables play a more important role with 11.58% of the total electricity production, 0.51% comes from hydro (mainly river systems for small communities) and 87.91% comes from small-scale diesel generators. It is important to clarify that the SA includes self-producers, which showed a increment of the renewables share of 100% since the encouraging renewables adoption policies came up in 2010 (Ministry of Energy - Statistic Journal, 2018).

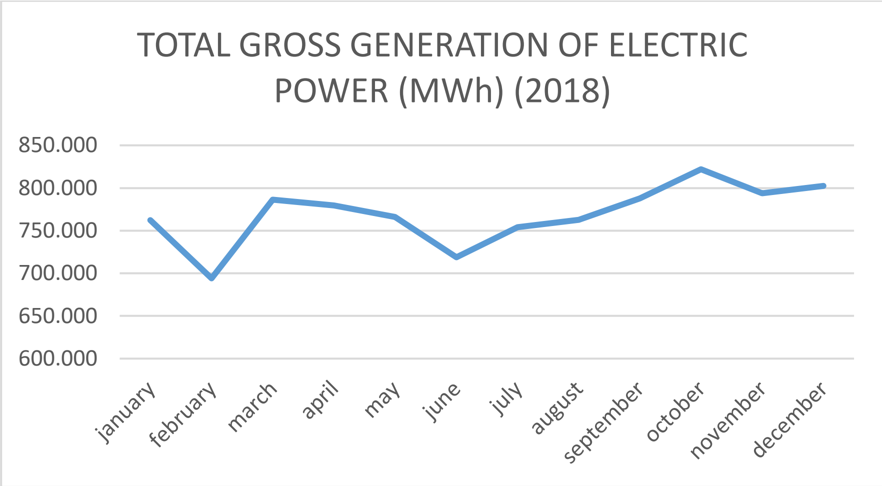


Figure 8. Total Electricity Generation in Bolivia (Ministry of Energy, 2019).

As it can observed in the figure 8, the total electric power generation in the country has a clear tendency to grow as the year goes by, showing a clear reduction in the electricity production during the coldest months of the year, the reason of this is due to the extremely low rain precipitations during these months (from march to September) the hydro capacity was reduced. Another important measurement to procure the electric reduction of the consumption during these months are the high tariffs, otherwise the system could collapse due to the intensity registered before these control methods were adopted in 2010.

2.5. Renewable energy projects in Bolivia

The continuous rise of the Bolivian installed capacity and production of electricity responds to the successful policy applied by the Bolivian Government that seeks transforming Bolivia into the "Energetic hearth of South America" (Bolivian Patriotic Agenda - 2025, 2016), encouraging this way all the energetic projects by funding or cofounding them alongside with international cooperation, all within the framework of the development of not only hydrocarbon projects but also having a strong presence in boosting up the renewable sources of energy such as hydro, solar, Eolic and geothermal. This way the Bolivian government highlights the importance of reducing the consumption of the Residential Sector through the introduction of isolated and self-productive systems. In 2018, Bolivia reported an annual generation from solar, wind and hydro of 2.67 TWh/y (Electric Charge Dispatch & Ministry of Energy, 2019).

Since 2016, the Bolivian Government is pushing 10 renewable projects that include 2 biomass plants, 4 wind farms and 4 solar power plants, that will ended up adding 210 MW to the SIN. A strong storage potential has been shown with respect to the last decade, increasing the pumped-storage in the country this way encouraging to the installation of more wind and solar projects in country.

2.5.1. Solar energy potential in Bolivia

In Bolivia, the regions of the Altiplano and the Inter-Andean Valleys receive a high rate of solar radiation; between 5 and 6 kWh / m2 day, depending on the time of year. In the Tropical plains area, the average radiation rate is between 4.5 and 5 kWh / m2 day. The high values of solar radiation in Bolivia are due to the geographical position of its territory, which is located in the tropical zone of the South, between the parallels 11 ° and 22 ° south. (Fernandez, 2010) Therefore, the radiation rate between winter and summer does not represent differences that exceed 25%. The presence of the Andes mountain range modifies to some extent the solar radiation, benefiting with a higher rate the high areas such as the Altiplano, which is our target beneficiary zone (Fundación Solon, 2015).

2.5.2. Advantages of implementing Photovoltaic Solar Energy projects in Bolivia:

- Clean, renewable, infinite and silent energy.
- It has economic advantages such as subsidies, reduced time of return on investment.
- Modularity, which allows users to replace or replace system components without having to renew it in its entirety.
- Extremely high solar irradiance throughout the Bolivian Territory, with a very small range of variations during the year.
- Availability of wide plane spaces on the Bolivian highlands and availability of wide areas in the roofs of the houses from the social housing program.
- Possibility of injecting the solar energy production excess to the electrical network.

3. HEAT TRANSFERENCE AND HEAT PUMPS

Heat pumps are thermal machines that are subject to the laws of thermodynamics, effectively transferring heat from a cold to a hot point. The capacity of these devices compared to other heat generation and utilization systems is that they have the capacity to use the energy (heat) of the environment to direct it towards indoor dependencies (hot focus) with relatively little work (electrical energy) by the compressor. (Staffell et al. 2012).

Heat pumps use refrigerant gases within a closed thermodynamic cycle that, thanks to the temperature differential between the contributing medium and the receiver (heat capture medium), heat is transported to the space intended for heating, currently varying widely. The heat pump system is being able to be used in industry or in-home heating.

Since the thermal energy can only go from one energy level to a lower one, the working fluid or refrigerant used in the evaporation phase of the pump must be at a lower temperature than the ambient temperature, the collection being of critical data for this part of the system design.

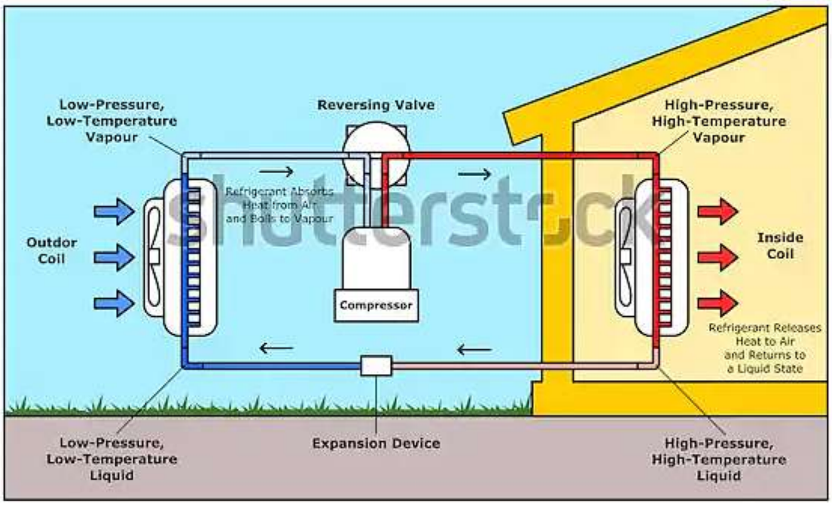


Figure 9. Air source heat pump – heating cycle. (Source: https://www.shutterstock.com)

3.1. Phases of the Heat Pump Cycle

1) Compression of the working fluid: The refrigerant fluid is compressed, in this process electrical energy is used for the operation of the compressor. This electrical energy is transformed into heat transmitted to the refrigerant, raising its pressure and at the same time its temperature. The compressor is the only device that requires electrical power for its correct operation within the cycle.

2) Condensation of the working fluid: Once hot, the working fluid is passed through the condenser, inside which heat is exchanged. The working fluid gives its heat to the "hot focus", once this happens, the fluid goes to condense (returning to a liquid state).

3) Expansion of the working fluid: The fluid, although it has given up its energy in the form of heat, is still quite hot and pressurized, which is why it is passed through an expansion valve (loss of load) reducing its pressure isenthalpic from the condensation pressure to the inlet pressure to the evaporator. Also reducing the temperature of the fluid.

4) Evaporation of the working fluid: The fluid passes through another exchanger located in the cold source where the fluid can absorb heat from the outside again and the cycle is restarted.

3.2. Coefficient of Performance of Heat Pumps (COP)

The efficiency of a heat pump system depends on the efficiency and thermal energy requirements of the building in which the heat pump is operating. The thermal efficiency of a pump is described by the Coefficient of Performance (COP). The COP of a heat pump is the ratio between the energy transferred to heat and the electrical input energy used in the process (European Heat Pump Association, 2018).

3.3. Seasonal coefficient of Performance of Heat Pumps

The seasonal coefficient of performance (SCOP) describes the heat pump´s average annual efficiency performance. Consequently, SCOP offers a description of how efficient a specific heat pump will be for a determined heating demand period (Danish Energy Agency, 2011). The SCOP offers a more realistic measure of the heat pump´s efficiency working on different climate zones. Different from the COP that is calculated for standard conditions in the laboratory, the SCOP is obtained from tests on-site and is determined using the European standard EN 14825.

3.4. Types of Heat Pumps

There exist several types of heat pumps such as the Air to air heat pump (aerothermal), in which the heat is taken from the air and transferred directly to the space you wish to heat. The air to water heat pumps (aerothermal) where the heat is taken from the air and directly transferred to a water circuit that will supply a radiant floor or ceiling, radiators, fan heaters or air heaters. Water heat pumps that are water to water (hydrothermal). In these systems the system takes heat from a water circuit in contact with an element that provides heat, this medium being the earth, water table, etc., to be transferred to another water circuit as in the previous case. In this type of systems, it is very common to use geothermal energy. Finally, the geothermal heat pumps; in this system the heat of the earth energy is obtained through a heat transfer fluid that absorbs heat from the ground and transmits it to the working fluid of the pump.

3.4.1. Aerothermy

The aerotermy obtains the heat of the ambient air for use in heating, cooling and domestic hot water production. One of the advantages of this system is the easy installation of the system, which leads us to reduce initial investment costs. (Aceituno, 2013). This type of heat pumps depend on the thermal jump or difference (differential between temperatures) and being the means contributing energy to the outside air the consistency in power supply can be affected due to the abrupt changes of temperature that usually occur outdoors.

3.5. Heat Transfer

Heat transfer is defined as the energy flow that exists due to a temperature difference between two points under study. Whenever there is a variation or temperature difference between two bodies, the heat transfer occurs, the energy in the form of heat, flows from the body of higher temperature to the lower temperature. There exist three types of heat transfer radiation, conduction and convection. The radiation is defined as the energy emitted by matter that is at a finite temperature. Radiation can come from all types of surfaces such as gases, liquids or solids. The radiation energy is communicated by electromagnetic waves and alternatively by photons. It is the only phenomenon of heat transfer that does not require the presence of a medium (materially speaking) for transport. Being more effective when it happens in a vacuum. The conduction of heat is a form of heat transfer between two systems under study, this type of heat transfer is based on the contact of the systems without there being a flow of matter, the purpose of the heat transfer is to equalize the temperature in both systems. Finally, in the convection the energy is transferred by a macroscopic phenomenon (fluid movement). The mentioned movement indicates the movement of large numbers of molecules collectively, and this in the presence of the temperature gradient finally contributes to the transfer of heat. There are two types of convection, natural convection and forced convection. The latter occurs when the fluid is induced by external agents, such as fans.

3.6. Equivalent Thermal Circuit

The method that is used for the realization of heat flow calculations through the elements that constitute the dwelling is the "Equivalent Thermal Circuit" method. For the modeling of the circuit, heat flow is considered in a one-dimensional way and without energy generation, besides the thermal properties of the materials that the heat flow goes through are constant.

4. CALCULATION OF THE HOUSEHOLD EQUIVALENT THERMAL CIRCUIT AND GLOBAL HEAT TRANSFERENCE COEFFICIENT

4.1. Global Heat Transfer Coefficient

The elements that make up the borders of the physical system studied are in the form of layers. For this, the global coefficient of heat transfer "U" is used. Which is related to heat by the following formula:

$$q_x = UA\Delta T \tag{1}$$

q_x = heat flux
ΔT = It is the total difference of temperatures, for this case it is the difference of interior and exterior temperature of the house
U = global coefficient of heat transfer [W/m^2*K]
A= heat transfer area [m^2]

The global coefficient of heat transfer maintains a relationship with the global thermal resistance in the following way:

$$UA = \frac{1}{R_{tot}} \tag{2}$$

U = global coefficient of heat transfer [W/m^2*K]
A= heat transfer area [m^2]
R_{tot} = Total resistance [m^2*K/W]

The total resistance is the addition of all the resistances analyzed within the limits of the studied system.

$$R_{tot} = \sum_1^n Ri \tag{3}$$

R_{tot} = Total resistance [m^2*K/W]

ΣRi = Sum of all the thermal resistances of the thermal circuit [m^2*K/W]

The resistances can be added in parallel or in series. Depending on how they are arranged. For reasons of calculation simplification, the resistances will be added in series. Once the formulas and implications required for the calculation of housing energy demand are detailed, the global coefficient of heat transfer of all the elements that make up the dwelling is calculated.

4.2. Heat Transfer Coefficient of the Wall

The first calculation that is made is for the wall of the house, because this is the one that has the largest area. Heat losses for the reason explained, would indicate a greater heat loss by this means.

To perform this calculation, it is necessary to know the materials that make up the wall. The wall of the house is formed by several layers of different materials. The composition of these layers from the outside of the house towards the interior is cement plaster, hollow brick and plaster as it can be seen in the following figure.

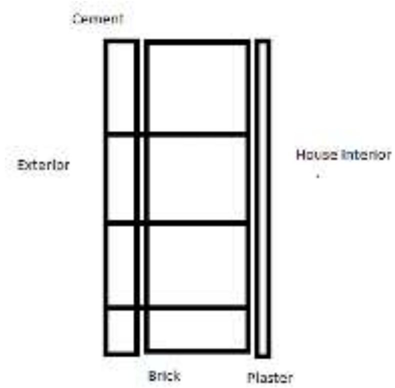
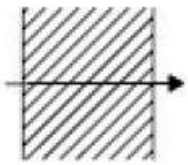


Figure 10. Structure of the wall of the houses from the Social Housing program. (Source: self elaboration).

To calculate the global coefficient of heat transfer of the wall, it is required to know the thickness and conductivity of these materials.

Table 2. Surface Thermal Resistances of enclosures in contact with the exterior and interior (for the wall) [m2 * K / W].

Enclosure position and direction of heat flow		R_{se} [m^2*K/W]	R_{si} [m^2*K/W]
Vertical enclosures or with slope over horizontal> 60 ° and horizontal flow.		0.04	0.13

- Temperature of the interior of the house for the winter period: 20 ° C.
- Temperature of the interior of the house for the summer period: 23 ° C.
- The temperature of the exterior of the house is determined by atmospheric measurements, carried out by the National Hydrology and Meteorology Service (SENHAMI, 2019).

Table 3. Circuit of thermal resistances of the wall.

Material	Cement plaster	Hollow or double brick	Plaster
Thickness (e) [m]	0.015	0.09	0.015
Conductivity (k) [W / m * K]	1.14	0.52	0.3

According to table 2, the values of the resistances due to convection are obtained:
R_{si}: 0.13 [m^2 * K / W]
R_{se}: 0.04 [m^2 * K / W]

Combining the equation (2) and (3) and using the data from the table 3, then the global heat transfer coefficient of the wall in question is:

$$U - wall = \frac{1}{Rsi + \frac{e-cast}{k-cast} + \frac{e-brick}{k-brick} + \frac{e-cement}{k-cement} + Rse} \quad (4)$$

$$U - wall = \frac{1}{0.13 \left[\frac{m^2 * K}{W}\right] + \frac{0.015[m]}{0.3\ \left[\frac{W}{m * K}\right]} + \frac{0.09[m]}{0.52 \left[\frac{W}{m * K}\right]} + \frac{0.015[m]}{1.14 \left[\frac{W}{m * K}\right]} + 0.04 \left[\frac{m^2 * K}{W}\right]}$$

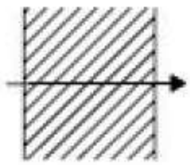
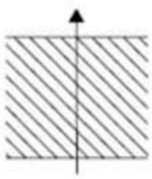
$$U - wall = 2.46\ [\frac{W}{m^2 * K}]$$

4.3. Heat Transfer Coefficient of the Roof

For the calculation of the heat transfer coefficient of the roof, a differentiation was made, with respect to habitable areas (A_{ui}) and non-habitable areas (A_{ue}). First is necessary to calculate the ratio of heat transfer between the habitable to the non-habitable areas. Once the ratio is known it is necessary to apply a Temperature Reduction Coefficient “b” for adjacent non-habitable spaces such as garages, storage rooms and spaces not conditioned under an inclined roof (Basic Energy Saving Document HE, 2009).

Following a similar calculus process as for the wall the heat transfer coefficient of the roof will be:

Table 4. Surface Thermal Resistances of enclosures in contact with the exterior and interior (for the roof) [m2 * K / W].

Enclosure position and direction of heat flow		R_{se} [m^2*K/W]	R_{si} [m^2*K/W]
Internal vertical enclosures or with slope over horizontal > 60 ° and horizontal flow.		0.13	0.13
Internal horizontal enclosures or with slope		0.10	0.10

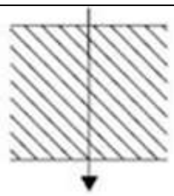
Enclosure position and direction of heat flow		R_{se} [m^2*K/W]	R_{si} [m^2*K/W]
over horizontal > 60 ° and ascendant flow (roof).			
Internal horizontal enclosures and descendant flow (roof).		0.17	0.17

Table 5. Circuit of thermal resistances of the roof.

Material	Galvanized steel cover	Light Wood	Plaster	Concrete Vault Cover
Thickness (e) [m]	0.0015	0.025	0.015	0.015
Conductivity (k) [W/m*K]	47	0.13	0.3	1.14

Living space area calculation

The living space areas are calculated because it is required to know the ratio between the habitable space and the non-habitable space for calculating the Temperature Reduction Coefficient "b".

$$A\ dinning\ room = base * height \quad (5)$$

$$A\ dinning\ room = 3.70\ m * 2.4\ m = 8.88\ m^2$$

$$A\ room = base * height \quad (6)$$

$$A\ room = 3\ m * 2.4\ m = 7.20\ m^2$$

Therefore:

$$A\ total\ living\ area - [Aiu] = A\ dinning\ room + A\ room \quad (7)$$

$$A\ total\ living\ area - [Aiu] = 8.88\ m^2 + 7.20\ m^2 = 16.08\ m^2$$

Non-habitable space area: Triangular vault area + 2* Small triangular vault area

$$A\ triangular\ vault = \frac{base*height}{2} \tag{8}$$

$$A\ triangular\ vault = \frac{3.30m * 1.05m}{2}$$

$$A\ triangular\ vault = 1.73\ m2$$

$$A\ small\ triangular\ vault = \frac{base*height}{2} \tag{9}$$

$$A\ small\ triangular\ vault = \frac{3.30m * 1.05m}{2}$$

$$A\ small\ triangular\ vault = 1.73\ m^2$$

$$A\ total\ small\ triangular\ vaults = 2 * 1.73\ m^2 = 3.47m^2$$

Therefore:

$$A\ total\ vault\ (not\ living\ area) - \ [Aue] = A\ triangular\ vault + A\ total\ small\ triangular\ vaults \tag{10}$$

$$A\ total\ vault\ (not\ living\ area) - \ [Aue] = 1.73\ m^2 + 3.47m^2$$

$$A\ total\ vault\ (not\ living\ area) - \ [Aue] = \ 5.20\ m^2$$

Relationship between areas of habitable and non-habitable spaces

$$\frac{Aiu}{Aue} = \frac{16.08\ m^2}{5.20\ m^2} \tag{11}$$

$$\frac{Aiu}{Aue} = 3.09\ m^2 = 3\ m^2$$

Table 6. Level of tightness of the enclosures.

Level of tightness	h^{-1}
1) No windows, no doors, no ventilation openings.	0
2) All components sealed.	0.5
3) All components well sealed, little ventilation openings.	1
4) Little tight, due to open joints or permanent ventilation openings	5
5) Little tight, due to many open joints or big permanent ventilation openings	10

In the following table, the Temperature coefficient of temperature reduction "b" for different Aiu/Aue ratios can be appreciated. There are two isolation degrees, in the case 1 the space is slightly ventilated, this case includes space with a tightness degree of 1, 2 or 3. From the table 6. The second case refers to a much-ventilated space with a tightness degree of 4 or 5 again from the table 6. Since the present project presents a case in which the house is poorly isolated between its enclosures the third and the fourth column are to be used of the table 7 are to be used. Furthermore, the sealing of the enclosures allows little ventilation openings the case 3 is selected. Now, since the case was chosen as the best representation of the house, case 1 of the third column should be chosen at the table 7.

Table 7. Temperature Reduction Coefficient "b".

	No aislado$_{ue}$- Aislado$_{iu}$		No aislado$_{ue}$-No aislado$_{iu}$		Aislado$_{ue}$-No aislado$_{iu}$	
A_{iu}/A_{ue}	CASO 1	CASO 2	CASO 1	CASO 2	CASO 1	CASO 2
<0.25	0,99	1,00	0,94	0,97	0,91	0,96
0.25 ≤0.50	0,97	0,99	0,85	0,92	0,77	0,90
0.50 ≤0.75	0,96	0,98	0,77	0,87	0,67	0,84
0.75 ≤1.00	0,94	0,97	0,70	0,83	0,59	0,79
1.00 ≤1.25	0,92	0,96	0,65	0,79	0,53	0,74
1.25 ≤2.00	0,89	0,95	0,56	0,73	0,44	0,67
2.00 ≤2.50	0,86	0,93	0,48	0,66	0,36	0,59
2.50 ≤3.00	0,83	0,91	0,43	0,61	0,32	0,54
>3.00	0,81	0,90	0,39	0,57	0,28	0,50

Once it was defined the columns to be used for the project, the ratio $A_{iu}/A_{ue} = 3$ was applied for the selection of the adequate b coefficient. The value of "b" would then be: 0.43, because the level of tightness of the non-habitable space is 1. Being Case 1 of the previous table. Combining the equation (2) and (3) and using the data from the table 5, then the resulting heat transfer coefficient of the roof is:

$$Up = \frac{1}{Rsi+\frac{1}{R\,plaster}+\frac{1}{R\,concrete\,vault}+\frac{1}{wood}+\frac{1}{steel}+Rse} \quad (12)$$

$$Up = \frac{1}{0.10\left[\frac{m^2*K}{W}\right]+\frac{0.015[m]}{0.3\left[\frac{W}{m*K}\right]}+\frac{0.015[m]}{1.14\left[\frac{W}{m*K}\right]}+\frac{0.025[m]}{0.13\left[\frac{W}{m*K}\right]}+\frac{0.0015[m]}{47\left[\frac{W}{m*K}\right]}+0.10\left[\frac{m^2*K}{W}\right]}$$

$$Up = 2.4661[\frac{W}{m^2*K}]$$

Therefore the heat transfer coefficient for the roof is:

$$U-roof = Up*b \quad (13)$$

b = coefficient of temperature reduction

$$U-roof = 2.4661\left[\frac{W}{m^2*K}\right]*0.43 = 1.0604\left[\frac{W}{m^2*K}\right]$$

4.4. Heat Transfer Coefficient of the Ground

Following a similar calculus process as for the wall the heat transfer coefficient of the ground will be:

Table 8. Circuit of thermal resistances of the ground.

Material	Ceramics	Concrete screed	Stone bed	Sand filler
Thickness (e) [m]	0.0075	0.45	0.30	0.45
Conductivity (k) [W/m*K]	0.81	1.63	2.33	0.58

$$R\,ground = \frac{e-ceramics}{k-ceramics}+\frac{e-concrete\,slab}{k-concrete\,slab}+\frac{e-stone}{k-stone}+\frac{e-sand}{k-sand} \quad (14)$$

$$R\ ground = \frac{0.0075\ [m]}{0.81\ \left[\frac{W}{m*K}\right]} + \frac{0.45[m]}{1.63\left[\frac{W}{m*K}\right]} + \frac{0.45[m]}{2.33\left[\frac{W}{m*K}\right]} + \frac{0.45[m]}{0.58\left[\frac{W}{m*K}\right]}$$

$$R\ ground = 1.2543\left[\frac{m^2*K}{W}\right]$$

To calculate the global coefficient of heat transfer for the soil, it is also necessary to know the buried wall has a deep length that varies from 1 to 2 meters and a characteristic length B', which is defined as follows.

$$B' = \frac{A\ household}{0.5*Perimeter\ of\ the\ house} \quad (15)$$

$$B' = \frac{53.9\ m^2}{0.5*31.02m} = 3.48m$$

Since our floor slab does not have any kind of thermal insulation, the resistance of the floor according to the characteristic length B' will be taken from the following table (Basic Energy Saving Document HE, 2009). By interpolation of data between B´=3.48 m and Rground = 1.2543 m2*K/W:

Table 9. Thermal transmittance Us [W/m2*K] (Basic Energy Saving Document HE, 2009)

		D = 0.5 m					D = 1.0 m					D ≥ 1.5 m				
	R_a	R_a (m² K/ W)					R_a (m² K/ W)					R_a (m² K/ W)				
B'	0,00	0,50	1,00	1,50	2,00	2,50	0,50	1,00	1,50	2,00	2,50	0,50	1,00	1,50	2,00	2,50
1	2,35	1,57	1,30	1,16	1,07	1,01	1,39	1,01	0,80	0,66	0,57	-	-	-	-	-
2	1,56	1,17	1,04	0,97	0,92	0,89	1,08	0,89	0,79	0,72	0,67	1,04	0,83	0,70	0,61	0,55
3	1,20	0,94	0,85	0,80	0,78	0,76	0,88	0,76	0,69	0,64	0,61	0,85	0,71	0,63	0,57	0,53
4	0,99	0,79	0,73	0,69	0,67	0,65	0,75	0,65	0,60	0,57	0,54	0,73	0,62	0,56	0,51	0,48
5	0,85	0,69	0,64	0,61	0,59	0,58	0,65	0,58	0,54	0,51	0,49	0,64	0,55	0,50	0,47	0,44
6	0,74	0,61	0,57	0,54	0,53	0,52	0,58	0,52	0,48	0,46	0,44	0,57	0,50	0,45	0,43	0,41
7	0,66	0,55	0,51	0,49	0,48	0,47	0,53	0,47	0,44	0,42	0,41	0,51	0,45	0,42	0,39	0,37
8	0,60	0,50	0,47	0,45	0,44	0,43	0,48	0,43	0,41	0,39	0,38	0,47	0,42	0,38	0,36	0,35
9	0,55	0,46	0,43	0,42	0,41	0,40	0,44	0,40	0,38	0,36	0,35	0,43	0,39	0,36	0,34	0,33
10	0,51	0,43	0,40	0,39	0,38	0,37	0,41	0,37	0,35	0,34	0,33	0,40	0,36	0,34	0,32	0,31
12	0,44	0,38	0,36	0,34	0,34	0,33	0,36	0,33	0,31	0,30	0,29	0,36	0,32	0,30	0,28	0,27
14	0,39	0,34	0,32	0,31	0,30	0,30	0,32	0,30	0,28	0,27	0,27	0,32	0,29	0,27	0,26	0,25
16	0,35	0,31	0,29	0,28	0,27	0,27	0,29	0,27	0,26	0,25	0,24	0,29	0,26	0,25	0,24	0,23
18	0,32	0,28	0,27	0,26	0,25	0,25	0,27	0,25	0,24	0,23	0,22	0,27	0,24	0,23	0,22	0,21
≥20	0,30	0,26	0,25	0,24	0,23	0,23	0,25	0,23	0,22	0,21	0,21	0,25	0,22	0,21	0,20	0,20

$$Uground = 1.0604 \left[\frac{W}{m^2 * K}\right]$$

4.5. Heat Transfer Coefficient of the Doors

The house for which this study is carried out, has two main double wooden doors, varnished and measuring: 0.85 m (width), 2.15 m (height) and 75 mm thickness. Then, the thermal equivalent circuit of the door will be:

Table 10. Circuit of thermal resistances of the doors.

Material	Oak wood
Thickness (e) [m]	0.075
Conductivity (k) [W/m*K]	0.209

$$Udoor = \frac{1}{Rsi + \frac{e-wood}{k-wood} + Rse} \tag{16}$$

$$Udoor = \frac{1}{0.13 + \frac{0.075[m]}{0.209\left[\frac{W}{m * K}\right]} + 0.04}$$

$$U - door = 1.8909 \left[\frac{W}{m^2 * K}\right]$$

4.6. Heat Transfer Coefficient of the Windows

The thermal insulation of a glass enclosure, as well as for other parts of the house such as the walls, ceiling or floor, depends on its thermal conductivity of the component materials and their respective thicknesses. For the calculation of thermal transmission, 2 calculation methods were used, the first is based on the UNE EN 6946 standard:

- The thermal conductivity (λ) of the glass is: 1.4 W/m*K.
- The thermal resistance of a transparent glass of 6 mm thickness is R: 0.19 m^2*K/W.
- The coefficient of thermal transmission will be: 5.88 W/m^2*K.

- Thermal resistance of the air inside R_{si}: 0.13 m^2*K/W.
- Thermal resistance of the air outside in contact with the enclosure material R_{se}: 0.04 m^2*K/W.

For the second method in the form of corroboration, the thermal transmission simulation software of the window manufacturer Saint-Gobain (Consulting Information and Organization, 2019) was used.

Luminous Factor:

- Light transmission: 90%.
- External reflection: 8%.
- Interior reflection: 8%.

Energy factors:

- Energy transmission: 85%.
- External energy reflection: 8%.
- Interior energy reflection: 8%.
- Energy absorption: 7%.
- Nominal thickness: 6 mm.
- Weight: 15 kg/m^2.
- Thermal Transmission = 5.69 W/m^2*K

The thermal transmission does not vary too much from one calculation method to the other. For precision effects, the last result was taken into the study.

$$U - window = 5.69 \left[\frac{W}{m^2 * K}\right]$$

4.7. Heat Transfer Area

The flow of heat, depending on the difference of indoor and outdoor temperature, the global coefficient of heat transfer and the heat transfer area, it is now necessary to calculate the transfer area.

Table 11. Dimensions of the Heat Transfer Area of all the rooms of the House

Heat Transfer Areas	Dimensions	Units
Habitable space height	2.40	m
Door height	2.15	m
Door width	0.85	m
Door area	1.83	m^2
Large window height	1.20	m
Large window width	1.15	m
Large window area	1.38	m^2
Small window height	0.40	m
Small window width	1.05	m
Small window area	0.42	m^2
Housing area	53.90	m^2
Large roof area	32.70	m^2
Small roof area	26,753	m^2

Table 12. Heat Transfer Area of all the rooms of the House

Element	Walls	Ground	Cealing	Roof	Windows	Doors
Area [m^2]	59.045	53.9	53.9	59.453	5.94	1.8275

5. HEAT LOADS CALCULATIONS AND ENERGY DEMAND BY THE HEAT PUMP

In this chapter the power demands of an individual housing have for the heating period are presented. The total annual heat load is included in addition to seasonal variations.

For this study, the year was divided into two periods, the winter period and the summer period. To calculate the heat loads, it is necessary to know the global heat transfer coefficient of the surfaces arranged for it, so it is also necessary to know the area of the same, the variation of temperature and relative humidity between the inside and outside of the House.

The winter period is the period belonging to the heating period and the summer period being the “cooling” of the house season. It is also necessary to mention that the refrigeration period as well as the refrigeration process itself have been separated from this study since refrigeration will not be necessary. This is because the comfortable temperature suggested by the Internal Regulation of Thermal Installations of Buildings (Spain and Chile), suggests as temperature of comfort and comfort inside the house a temperature of cooling period of minimum 23 ° C, but taking into account that the highest recorded temperature in previous years in the Bolivian highlands was 20 ° C, indicating that the refrigeration season is not necessary.

5.1. Thermal Comfort

The temperature values and indoor relative humidity, as mentioned above, are based on "pleasant" or comfort temperatures. The thermal environment is defined by all those characteristics that condition the exchanges of the human body with the surrounding environment, depending on the activity of the inhabitants of the premises or establishment and the thermal insulation of their clothing and that affect the feeling of well-being of the occupants of the property.

These characteristics are:

- The temperature of the air.
- The average air speed of the enclosure.
- The average air speed in the occupied area.
- Relative humidity of the environment.

Table 13. Interior Design Conditions (in accordance with UNE-EN ISO 7730, Regulation of Thermal Installations Chile).

Season	Operating Temperature	Average Air Speed [m/s]	Relative Humidity [%]
Winter	23 – 25	0.18 – 0.24	40 – 60
Summer	20 – 22	0.15 – 0.20	40 – 60

Since the objective of the calculation of the heat pumps is to identify the temporal variation of the energy demand in kWh due to temperature variations within the dwelling under study.

5.2. Variations of temperature in the studied areas of the Bolivian highlands

The temperatures at which the houses of the Bolivian Highlands are exposed in real conditions, the maximum, minimum and average temperatures of each month of the year were analyzed for the areas of interest. SENHAMI data (2019) was used for this purposed.

5.2.1. Average maximum temperature outside the household

Table 14. Average Maximum Temperature (C°) – Outside the Household

SENHAMI Station	January	February	March	April	May	June	July	August	Septemb	October	Novemb	Decembe	Annual
Uyuni (Airport) (2017-2016)	20	20	19	18	14	12	12	14	17	19	20	22	17
Oruro (Airport) (2017)	19	21	19	20	18	16	17	20	21	21	22	22	20
El Alto (Airport) (2017)	15	16	14	15	14	15	15	16	17	16	17	17	16
Altiplano Average	18	19	17	18	15	14	15	17	18	19	20	20	17

5.2.2. Average minimum temperature outside the household

As it can be appreciated in the table below, the coldest period of the year in the three departments is between the months of April and October. During this period the radiation on the highlands increments as well due to the absence of clouds in the skies (SENHAMI, 2019).

Table 15. Average Minimum Temperature (C°) – Outside the Household

SENHAMI Station	January	February	March	April	May	June	July	August	Septemb	October	Novemb	Decembe	Annual
Uyuni (Airport) (2017-2016)	6	4	4	-1	-8	-12	-12	-14	-7	-3	-2	5	-3
Oruro (Airport) (2017)	7	6	6	2	-2	-6	-7	-7	-2	1	3	6	1
El Alto (Airport) (2017)	5	4	4	2	0	-3	-4	-3	-1	2	2	4	1
Altiplano Average	6	5	5	1	-3	-7	-8	-8	-4	0	1	5	-1

5.2.3. Average relative humidity outside the household

The relative humidity in the highlands happens during the rainy months of summer, which is between November and March.

Table 16. Average Relative Humidity (%) – Outside the Household

SENHAMI Station	January	February	March	April	May	June	July	August	Septemb	October	Novemb	Decembe	Annual
Uyuni (Airport) (2017-2016)	56	66	57	64	47	38	38	39	42	44	44	50	49
Oruro (Airport) (2015-2016)	41	65	57	56	39	37	43	44	45	46	44	47	47
El Alto (Airport) (2016)	54	69	53	52	29	25	27	29	38	44	31	49	42
Altiplano Average [%]	50	67	56	57	38	33	36	37	41	45	40	48	46

It is necessary to emphasize that the winter period in Bolivia begins the month of June culminating in the month of August. Clearly in the previous graphs, it is possible to visualize the low temperatures during those months in the Bolivian highlands.

5.3. Variation in Electricity Consumption According to the Time of Year

The data from the Bolivian Electric Power and Load Dispatch was also handled, allowing to know the maximum energy consumption during the year.

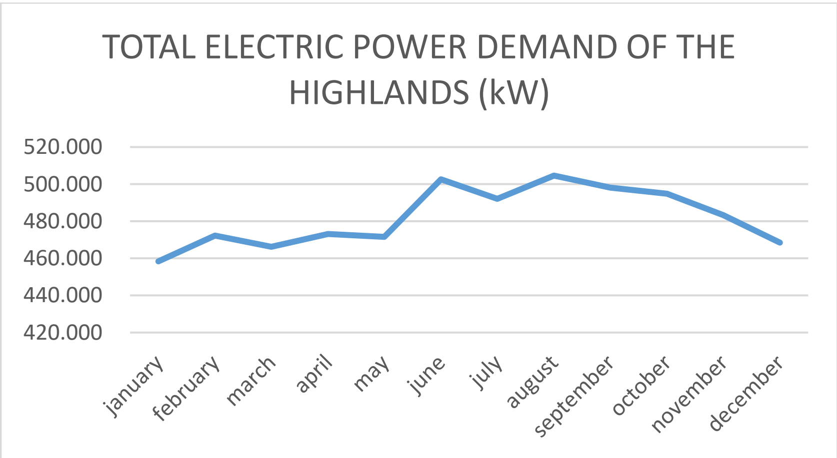


Figure 11. Total electric power demand od the Bolivian Highlands.

In this way it was possible to corroborate that in the Bolivian highlands, the demand for electric power is incremented due to the low temperatures throughout the year specially from April to November. It can be seen the highest electricity demand occurs during the coldest month of the year June.

5.4. Heat Loads for the Heating Period

Being the values chosen for the winter period based on the thermal comfort data suggested by standardized normative, the following designing parameters are used:

- Temperature inside the house: 20 ° C.
- Relative humidity: 45%.

5.5. Transmission Heat Load

This is the sensitive load that occurs due to the temperature difference, in which the heat loss originates from the inside of the house to the outside, this due to small cracks or holes present in the enclosures of the house.

$$Q_{transmission} = U_{enclosure} * A_{enclosure}(T_{in} - T_{out}) \quad (17)$$

$Q_{transmission}$ = Transmission heat load [MW]
$U_{enclosure}$ = [W/m^2*K]
$A_{enclosure}$ = [m^2]
T_{in} = Indoor temperature [°C]
T_{out} = Outdoor temperature [°C]

The transmission loads must be analyzed one by one (walls, floor, ceilings, windows and doors). The temperature differential will be the same for everyone. The global temperature coefficients and the area of each of the enclosures will vary. Since this calculation is only dedicated for the heating period, so all values for cooling are considered "zero".

Table 17. Calculation of the variation of the Transmission Heat through the enclosures with respect to the outdoor temperatures.

				Outdoor Temperature [°C]							
Enclosure	U enclosure [W/m²*K]	A - enclosure [m²]	Indoor Temperature [°C]	April	May	June	July	August	September	October	November
Walls	2.4616	59.045	20	9.3	6.07	3.9	3.5	4.5	7.47	9.13	10.37
Roofs	1.0604	53.9	20	9.3	6.07	3.9	3.5	4.5	7.47	9.13	10.37
Windows	5.69	5.94	20	9.3	6.07	3.9	3.5	4.5	7.47	9.13	10.37
Doors	1.8909	1.8275	20	9.3	6.07	3.9	3.5	4.5	7.47	9.13	10.37
Ground	1.0604	53.9	20	21.6	14.2	9.3	8.4	10.7	17.5	21.3	24.1

Table 18. Variation of the Transmission Heat through the enclosures with respect to the outdoor temperatures.

Transmission Heat Load	April	May	June	July	August	Septemb er	October	Novemb er
Qt [MW] - Walls	1.56	2.02	2.34	2.40	2.25	1.82	1.58	1.40
Qt [MW] - Roofs	0.61	0.80	0.92	0.94	0.89	0.72	0.62	0.55
Qt [MW] - Windows	0.36	0.47	0.54	0.56	0.52	0.42	0.37	0.33
Qt [MW] - Doors	0.04	0.05	0.06	0.06	0.05	0.04	0.04	0.03

Transmission Heat Load	April	May	June	July	August	Septemb er	October	Novemb er
Qt [MW] - Ground	-0.09	0.33	0.61	0.67	0.53	0.15	-0.07	-0.23

In following figures, the results from the calculations done in table 18 can be observed, as it was expected the heat transmission through the enclosurements reaches its peaks during the coldest period of the year, confirming the flow towards outside from the inteior of the house, this could be mainly for two reasons, poor isolating materials and lack of sealing of the enclosures.

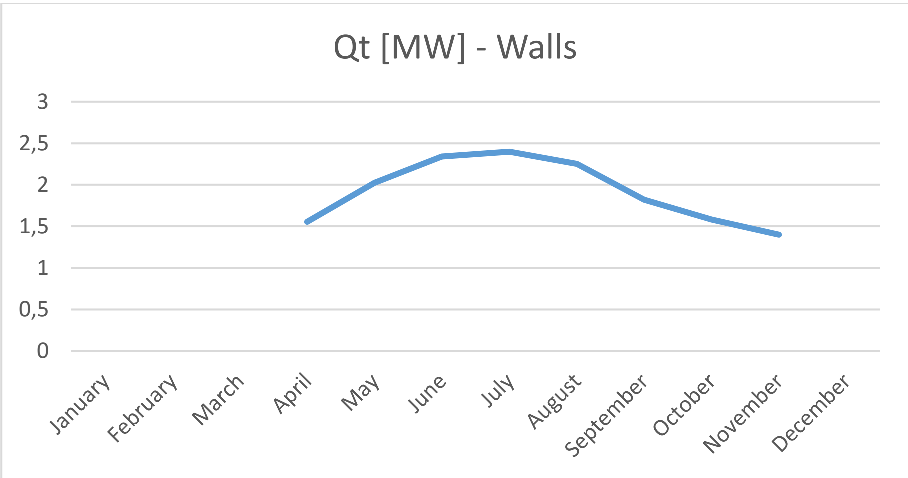


Figure 12. Transmitted Heat through the walls during the heating period.

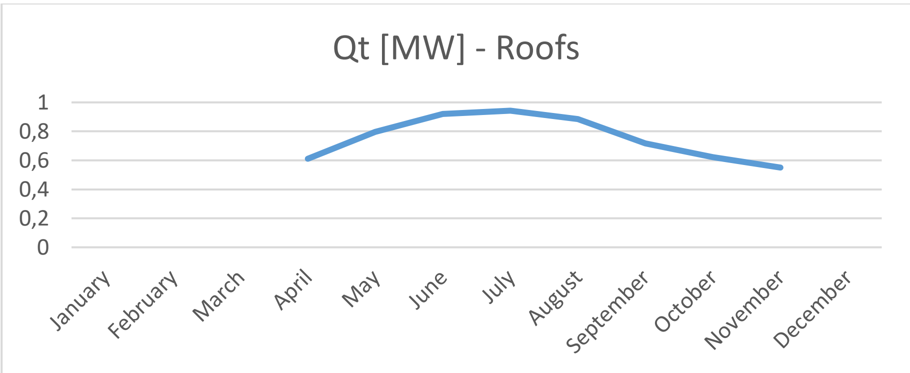


Figure 13. Transmitted Heat through the roofs during the heating period.

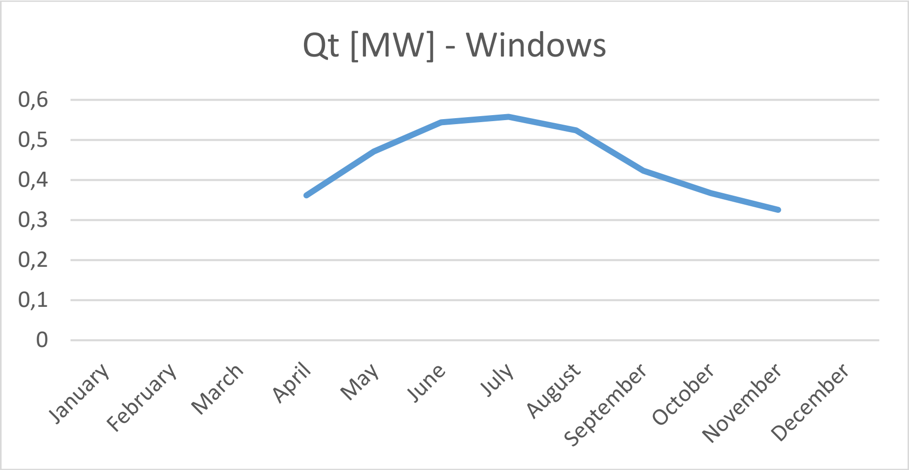


Figure 14. Transmitted Heat through the windows during the heating period.

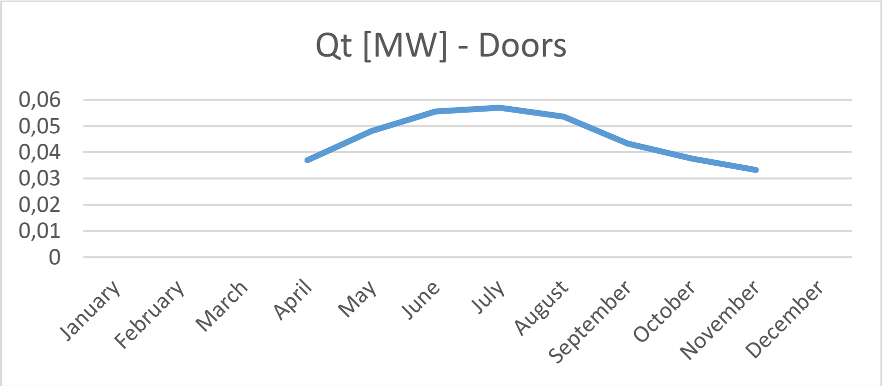


Figure 15. Transmitted Heat through the doors during the heating period.

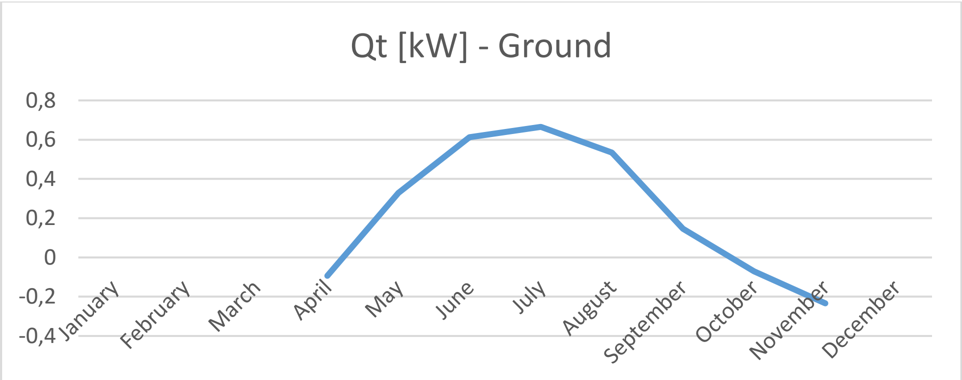


Figure 16. Transmitted Heat through the ground during the heating period.

In the figure 15, referred to the total transmitted heat through the ground, is the only curve in which there exist three months where there is no need for heating due to the inexistent heat transference through the ground. This happened because as it can appreciated in the table 17, the ground outdoors temperature is higher than the temperature of the air (Smith C. et al, 1998) causing this way this temperature difference and therefore the negative values in some months of the year. According to Smith C. et al (1998) the temperature difference that exist when measuring the air surrounding the ground would be 127% lesser than the ground´s temperature.

It could be observed that of the five different types of enclosures, the one with the highest transfer load are the walls, this is very logical because the transmission surface is very large. The doors on the contrary, reflect the lower transfer load, this given that they have a very small area and the overall heat transfer coefficient of the wood is low. The total heat load transmitted during the heating period is calculated using the following formula.

$$Q_{tot-heating} = Q_{-walls} + Q_{-roof} + Q_{-ground} + Q_{-windows} + Q_{-doors} \quad (18)$$

$Q_{tot-heating}$ = Total heat load during heating period [MW]
Q_{wall} = Total heat load conducted through the walls [MW]
Q_{roof} = Total heat load conducted through the roof [MW]
Q_{ground} = Total heat load conducted through the ground [MW]
$Q_{windows}$ = Total heat load conducted through the windows [MW]
Q_{doors} = Total heat load conducted through the doors [MW]

Table 19. Total Heat Load Transmission during the heating period.

	April	May	June	July	August	September	October	November
Qt Total [MW]	2.47	3.67	4.47	4.62	4.25	3.15	2.53	2.08

Finally, the total heat load transmission was calculated taking into account the previos results. As expected the total sum of the results provided a similar behavioral curve of heat load transmision for the house.

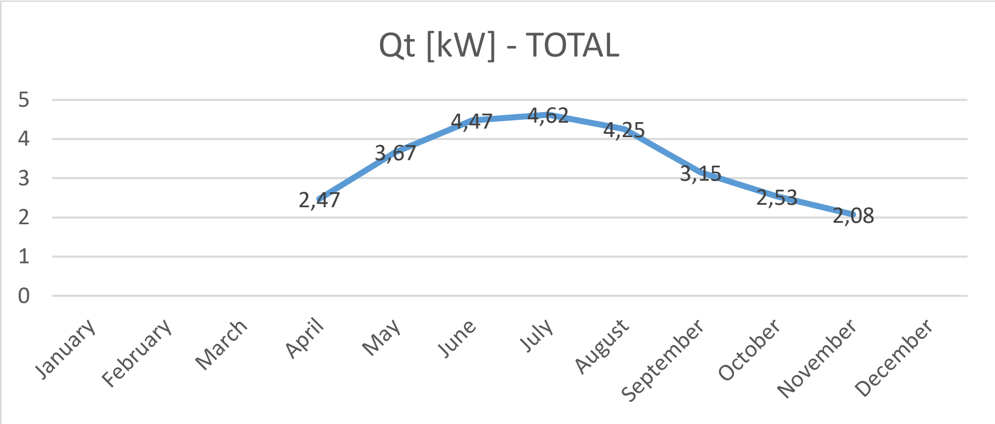


Figure 17. Total Heat Load Transmission during the heating period.

5.6. Heat Load of Ventilation and Infiltrations

The house requires ventilation to avoid discomfort related to "stale" air, this process is known as ventilation, which together with infiltrations (caused by pressure differentials between the interior and exterior of the house) make up an air flow of entry and exit of air. The different types of infiltrations that are generated in winter in the Bolivian Altiplano are due to the dynamic pressure of the wind and the chimney effect that is generated inside the homes (with the outside air that penetrates the lower areas of the house), it is heated inside and leaves the building by the upper parts.

The calculation of the heat load of ventilation and infiltrations is carried out jointly for both sensible and latent heat calculations.

Sensible Heat calculation

The sensible heat is the amount of heat required to heat or cool a body independently of the mass of the object. In the present case would be the amount of heat required to warm up the temperature of the volume of air inside the house, which will vary depending upon ventilation and infiltrations.

$$Q_{-sensible\ heat\ (V+I)} = \left(V_{air(vent)} + V_{air(infi)}\right) * \mathrm{Cp}_{-air} * \mathrm{r}_{-air} * (\mathrm{T}_{ind} - \mathrm{T}_{out}) \tag{19}$$

$Q_{sensible\ heat\ (V+I)}$ = Sensible heat load from ventilation and infiltrations [kW]

$V_{air\ (vent)}$ = Ventilation of air [l/s]

$V_{air\ (infi)}$ = Infiltration of air [l/s]

$Cp_{(air)}$ = Specific heat of air [kJ/kg*K], [W*month/kg*K]

$\rho_{(air)}$ = Air densitity [kg/m^3]

T_{ind} = Temperature indoors [°C], [K]

T_{out} = Temperature outdoors [°C], [K]

Table 20. Minimum natural ventilation airflow required according to the Technical Building Code - RITE standard (CTE-DB-HS-3).

		Minimum ventilation airflow required (qv) [l/s]		
		By Inhabitant	By useful m^2	With respect to other parameters
Premises	Bedrooms	5		
	Living room / Dinning room	3		
	Bathrooms			15
	Kitchens		2	50
	Common areas		0.7	
	Garages			120

		Minimum ventilation airflow required (qv) [l/s]		
		By Inhabitant	By useful m^2	With respect to other parameters
	Residues warehouses		10	

Table 21. Calculated natural ventilation airflow of the house for the project.

Part of the house	Area [m^2]	Air flow [l/s]
Room 1 (2 persons)	11.10	10
Room 2 (3 persons)	11.10	15
Dinning room	12.21	15
Bathroom	3.12	15
Kitchen	7.40	14.8
Hall	1.19	0.83
TOTAL		70.63

For the calculation of the infiltration flow rate, the infiltration flow through the doors will be 2.5 $m^3/h*m^2$ and through the windows 1.8 $m^3/h*m^2$.

Table 22. Calculation of the ventilation air volume for the heating period.

Parameter	Amount	Unit
Air Specific Heat (23°C)	1.006	kJ/kg*K
	0.0004	W*month/kg*K
Air density (20°C)	1.2041	kg/m^3
Area Windows	5.94	m^2
Area Doors	1.8275	m^2
Monthly days	30	days
Monthly hours	720	hours/month

Parameter	Amount	Unit
Infiltrations airflows - doors	2.5	m^3/hour*m^2
Infiltrations airflows - windows	1.8	m^3/hour*m^2
Total airflow ventilation	70.63	l/seg
	0.07063	m^3/seg
Ventilation air volume for heating period	183,072.96	m^3/1month
Heating period	From April to November	8 months

In the following table, the sensible heat was calculated for the heating period from April to November.

Table 23. Sensible heat calculations based on the differential of temperature between outdoor and indoor temperatures.

	April	May	June	July	August	September	October	November
Average Temperature outdoors (°C)	9.3	6.07	3.9	3.5	4.5	7.47	9.13	10.37

	April	May	June	July	August	September	October	November
Average Temperature outdoors (K)	282.5	279.2	277.1	276.7	277.7	280.6	282.3	283.5
Indoor Temperature	293.2	293.2	293.2	293.2	293.2	293.2	293.2	293.2
Temperature Difference	10.7	13.9	16.1	16.5	15.5	12.5	10.8	9.6
Q sens [kW]	0.97	1.26	1.46	1.50	1.41	1.14	0.99	0.87

The results obtained from the calculation can be seen in the figure 20, the curve of sensible heat responds to the total heat transmitted during the coldest period of the year.

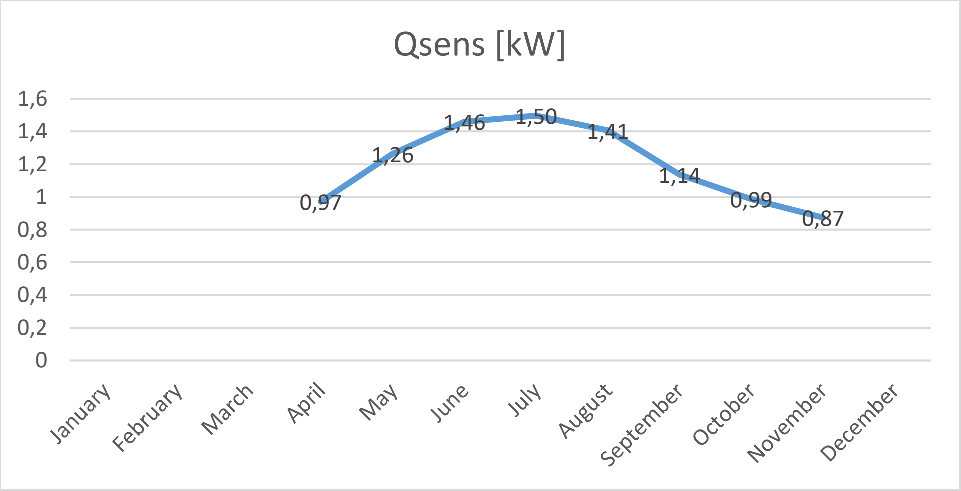


Figure 18. Total Sensible heat transmited through ventilation of the house.

As it can be appreciated, the sensible heat of ventilation and infiltrations in the study house, it is much higher in the months of June, July and August, reflecting the logical sense since they are the coldest months of the year.

Latent heat calculation

The latent heat in the present case would be the amount of heat necessary for the change of the physical characteristics of the air contained into the house, taking into account the density of the air and the relative humidity of the heating space since the changing of phases is involved into the latent heat transference in the air.

To calculate the latent heat of the dwelling in the heating period, it is required to deduce the formula that includes the thermal load for ventilation and latent infiltration.

$$Q_{-latent\ heat\ (V+I)} = \left(V_{air(vent)} + V_{air(infi)}\right) * \mathrm{r}_{-air} * \mathrm{Hfg} * (\mathrm{w}_{\ ind} - \mathrm{w}_{\ out}) \tag{20}$$

$Q_{latent\ heat\ (V+I)}$ = Latent heat load from ventilation and infiltrations [kW]
$V_{air\ (vent)}$ = Ventilation of air [l/s]
$V_{air\ (infi)}$ = Infiltration of air [l/s]
$\rho_{(air)}$ = Air densitity [kg/m3]
Hfg = Relative humidity of the air [%]
W_{ind} = Specific humidity of the air indoors
W_{out} = Specific humidity of the air indoors

To do this, it is known that air-vapor particles coexist inside the house, which is why the relative humidity must be considered. To obtain the variable "w", it begins with the analysis of Dalton's Law:

$$w = \frac{m_v}{m_a} \tag{21}$$

w = specific humidity

The humidity is defined as:

$$\text{Ø} = \frac{P_{pv}}{P_{sat}(T)} \tag{22}$$

Ø = humidity [%]

P_{pv} = partial pressure of water vapour [kPa]

P_{sat} (T) = saturation pressure in function of a temperature [kPa]

Therefore:

$$P_{pv} = \text{Ø} * Psat\ (T)$$

If the atmosphere is formed by air and steam particles:

$$Patm = P_{pa} + P_{pv} \qquad (23)$$

Patm = atmospheric pressure [kPa]

$$P_{pa} = P_{atm} - \text{Ø} * P_{sat}\ (T)$$

Finally:

$$w = 0.622 * \frac{\text{Ø} * P_{sat}\ (T)}{P_{sat} - \text{Ø} * P_{sat}\ (T)}$$

P_{atm} = atmospheric pressure [kPa]

P_{sat} (T) = saturation pressure in function of a temperature [kPa]

Ø = humidity [%]

Table 24. Calculation of the Ventilation involved in the heat transmistion by latent heat in the house.

Parameter	Amount	Units
Air density (20°C)	1.2041	kg/m^3
Area Windows	5.94	m^2
Area Doors	1.8275	m^2
Monthly days	30	days
Monthly hours	720	hours/month
Infiltrations airflows - doors	2.5	$m^3/hour*m^2$
Infiltrations airflows - windows	1.8	$m^3/hour*m^2$
Total airflow ventilation	70.63	l/seg
	0.0706	m^3/seg

Parameter	Amount	Units
Ventilation air volume for heating period	183,072.96	m^3/1month
Heating period	From April to November	8 months
Latent heat of water phase change (20°C)	2453.55	kJ/kg
Atmospheric pressure	1	atm
Partial pressure saturated vapor (20°C) - INDOOR	2.3361	kPa
	0.0231	atm

Table 25. Calculation of the Latent Heat of the house for the heating period.

	April	May	June	July	August	September	October	November
Average Relative Humidity outdoors [%]	57.43	38.3	33.33	36.03	36.93	41.43	44.67	39.87
Average Relative Humidity Indoors [%]	45	45	45	45	45	45	45	45
Partial pressure saturated vapor (T) [kPa] - Indoor	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Partial pressure saturated vapor (T) [kPa] - Outdoor	1.17	0.94	0.81	0.78	0.84	1.03	1.16	1.26

	April	May	June	July	August	September	October	November
Partial pressure saturated vapor (T) [atm] - Outdoor	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
w_{indoor}	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
$w_{outdoor}$	0.003	0.003	0.002	0.002	0.002	0.003	0.003	0.004
$w_{ind} - w_{out}$	0.003	0.004	0.004	0.004	0.004	0.004	0.003	0.003
Average Temperature outdoors (°C)	9.3	6.07	3.9	3.5	4.5	7.47	9.13	10.37
Indoor Temperature (°C)	20	20	20	20	20	20	20	20
Temperature Difference	10.7	13.93	16.1	16.5	15.5	12.53	10.87	9.63
Q lat (kW)	0.72	0.87	0.95	0.96	0.93	0.81	0.73	0.67

In the following figure, the results of the latent heat calculation carried out in the previous table can be appreciated, as the sensible heat requirementes, the latent heat demands of the household have similar tendency and form.

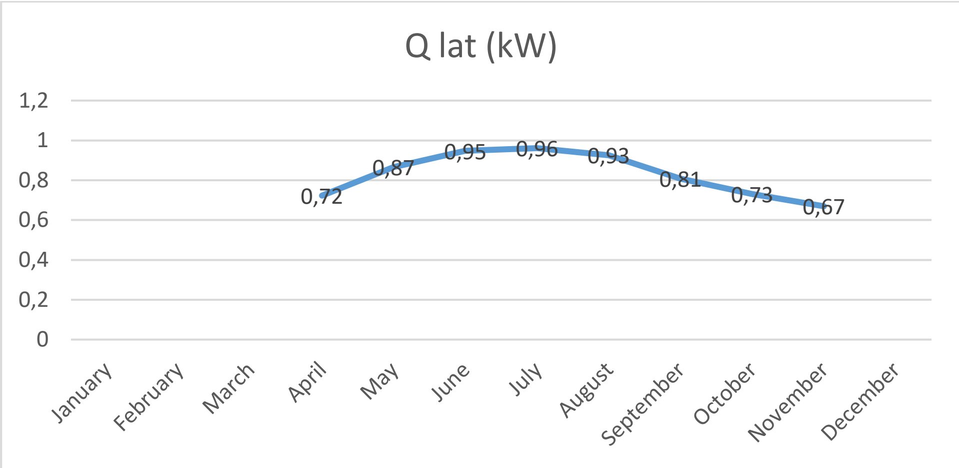


Figure 19. Total Latent heat transmited through ventilation of the house.

As it can see in the previous graph, the latent heat is higher in the months of lower temperatures, corroborating the result obtained for sensible heat.

5.7. Total Heat Load for the Heating Period

The total thermal load for the heating period is the sum of the heat of transmission of each one of the enclosures and the sensible and latent heat of the dwelling. Obtaining thus the heat required by the house in each of the heating stages established for the present study in the year.

Table 26. Total Heat Load for the heating period.

	April	May	June	July	August	September	October	November
Qt [kW] - Total Transmission	2.47	3.67	4.47	4.62	4.25	3.15	2.53	2.08

	April	May	June	July	August	September	October	November
Q_{sens} [kW]	0.97	1.26	1.46	1.50	1.41	1.14	0.99	0.87
Q_{lat} (kW)	0.72	0.87	0.95	0.96	0.93	0.81	0.73	0.67
Q Total (MW)	4.16	5.8	6.88	7.08	6.59	5.1	4.25	3.62

In the following figure, the total heat demand of the household calculated in the previous table can be seen.

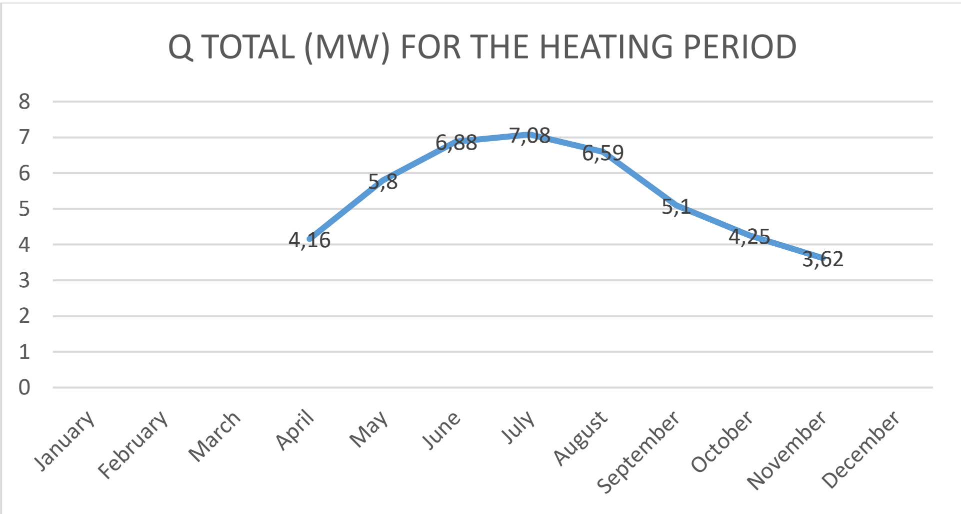


Figure 20. Total Heat Load for the heating period.

From the above graph the maximum value of heat that the house demands in the heating period that occurs in the month of July, the value required for heating is 7.1 KW.

Thus, the amount of heat required by the home: 7.1 kW. Now, for the present project the operational time of the heat pump has been set to be 8 months/year, which is according to the 22 the entire heating period in which the average temperatures would go below the comfort temperature.

Operation time of the heat pump: 8 h / day (during the heating period)

$$Operation\ time = 8\frac{hours}{day} * \frac{30day}{1month} * \frac{8months\ (heating\ period)}{1year} \quad (24)$$

$$Operation\ time = 1{,}920\frac{hours}{year}$$

Therefore:

$$Heat\ required = 7.1\ kW * 1{,}920\frac{hours}{year} \quad (25)$$

$$Heat\ required = 13{,}632\ \frac{kWh}{year}\ (annual\ heating\ period\ thermal\ demand)$$

5.8. Heat Pump Designing Selection and COP calculation

The procedure for selecting the right heat pump for the home was carried out using the heat demand of the house previously calculated in table 26.

Table 27. Technical Features of the Selected Heat Pump NEXURA FVXG50K+RXG50K (Daikin, 2019).

INDOOR UNIT				FVXG25K	FVXG35K	FVXG50K
Cooling capacity	Min./Nom./Max.		kW	1.3/2.5 /3.0	1.4/3.5 /3.8	1.7/5.0 /5.6
Heating capacity	Min./Nom./Max.		kW	1.3/3.4 /4.5	1.4/4.5 /5.0	1.7/5.8 /8.1
Seasonal efficiency (according to EN14825)	Cooling	Energy label		A++		A
		Pdesign	kW	2.50	3.50	5.00
		SEER		6.46	6.33	5.31
		Annual energy consumption	kWh	135	194	330
	Heating (Average climate)	Energy label		A+	A	A+
		Pdesign	kW	2.80	3.10	4.60
		SCOP		4.56	3.93	4.13
		Annual energy consumption	kWh	858	1,103	1,558
Nominal efficiency (cooling at 35°/27° nominal load, heating at 7°/20° nominal load)	EER			4.55	3.68	3.29
	COP			4.36	3.72	3.67
	Annual energy consumption		kWh	275	475	760
	Energy label	Cooling/Heating		A/A		
Casing	Colour			Fresh white(6.5Y 9.5/0.5)		
Dimensions	Unit	HeightxWidthxDepth	mm	600x950x215		
Weight	Unit		kg	22		
Fan - Air flow rate	Cooling	High/Nom./Low/Silent operation	m³/min	8.9/7.0/5.3/4.5	9.1/7.2/5.3/4.5	10.6/8.9/7.3/6.0
	Heating	High/Nom.	m³/min	9.9/7.8	10.2/8.0	12.2/10.0
Sound power level	Cooling	Nom.	dBA	54	55	56
	Heating	Nom.	dBA	55	56	58
Sound pressure level	Cooling	High/Nom./Low/Silent operation	dBA	38/32/26/23	39/33/27/24	44/40/36/32
	Heating	H/N/L/Silent operation/Radiant heat	dBA	39/32/26/22/19	40/33/27/23/19	46/40/34/30/26
Piping connections	Liquid	OD	mm	6.35		
	Gas	OD	mm	9.5		12.7
	Drain	OD	mm	18		
Power supply	Phase / Frequency / Voltage		Hz / V	1~ / 50 / 220-240		

OUTDOOR UNIT					RXG25K	RXG35K	RXG50K
Dimensions	Unit	HeightxWidthxDepth		mm	550x765x285	550x765x285	735x825x300
Weight	Unit			kg	34	34	48
Fan - Air flow rate	Cooling	High/Super low		m³/min	33.5/30.1	36.0/30.1	50.9/48.9
	Heating	High/Super low		m³/min	30.2/25.6	30.2/25.6	45.0/43.1
Sound power level	Cooling	High		dBA	62	64	63
Sound pressure level	Cooling	High/Silent operation		dBA	46/43	48/44	48/44
	Heating	High/Silent operation		dBA	47/44	48/45	48/45
Operation range	Cooling	Ambient	Min.~Max.	°CDB	10~46	10~46	10~46
	Heating	Ambient	Min.~Max.	°CWB	-15~20	-15~20	-15~20
Refrigerant	Type/GWP				R-410A/1,975	R-410A/1,975	R-410A/1,975
Piping connections	Piping length	OU - IU	Max.	m	20	20	30
	Level difference	IU - OU	Max.	m	15	15	20
Power supply	Phase / Frequency / Voltage			Hz / V	1~ / 50 / 220-240	1~ / 50 / 220-240	1~ / 50 / 220-240
Current - 50Hz	Maximum fuse amps (MFA)			A	16	16	20

(1) EER/COP according to Eurovent 2012

POSSIBLE COMBINATIONS	2MXS40H	2MXS50H	3MXS40K	3MXS52E	3MXS68G	4MXS68F	4MXS80E	5MXS90E	RXYSQ-P8V1
Maximum number of indoor units	2	2	2	3	3	4	4	5	6
FVXG25K	•	•	•	•	•	•	•	•	•
FVXG35K	•	•	•	•	•	•	•	•	•
FVXG50K		•		•	•	•	•	•	•

Acording to the technical descriptions of the heat pump NEXURA FVXG50K+RXG50K, accounts with an exceptional maximum heating capacity of 8.1 kW covering the average heating requirements throughout the entire heating period of 8 months.

Another equipment´s technical features have been consulted with respect to the capacity of covering the peak of consumption, but since the purpose and main target of this project is to reach low-income families in the highlands, the present proposal seems to fill the needed heat for the average range of temperatures through the entire winter season with a moderate range of prices.

5.8.1. Energy Demand of the Heat Pump

The SCOP of the selected heat pump for the heating period and according to the technical features described by NEXURA for the 8.1 kW of heating capacity is 4.13.

$$SCOP = \frac{Heating\ demand\ of\ the\ house\ during\ the\ heating\ period}{Electricity\ consumption\ of\ the\ heat\ pump\ during\ the\ heating\ period} \quad (26)$$

$$Electricity\ consumption\ of\ the\ heat\ pump\ during\ the\ heating\ period = \frac{Heating\ demand\ of\ the\ house\ during\ the\ heating\ period}{SCOP}$$

$$Electricity\ consumption\ of\ the\ heat\ pump\ during\ the\ heating\ period = \frac{13{,}632\ kWh/year}{4.13}$$

$$Electricity\ consumption\ of\ the\ heat\ pump\ during\ the\ heating\ period = 3{,}300.73\ \frac{kWh}{year}$$

Calculating the power needed by the heat pump using the full load hours during the heating period of equation 24.

Power required by the heat pump system:

$$P_{required\ by\ the\ HP} = 3300.73\ \frac{kWh}{year} * \frac{1\ year}{1920\ h\ (heating\ period)} \quad (27)$$

$$P_{required\ by\ the\ HP} = 1.72\ kW = 1{,}720\ W$$

The power required by the heat pump system is 1,720 W and applying a 15% of safety extra power in case of peak electricity demands during the winter period in Bolivia the power required by the heat pump would be 1.97 kW or 1,978 W.

6. PHOTOVOLTAIC SYSTEM AND ENERGY DEMAND OF THE HOUSE

6.1. Designing the Solar PV system based on the electrical demand of the Heat Pump

According to the total power required by the heat pumps calculated in the equation 27, the number of solar panels required to cover the design power of the heat pump that was proposed to be used in the present project that has a required power has been dimensioned and calculated for a 1.97 kW design (including the safety range of power for electric peaks demands during the winter).

For the sizing of the number of units and the amount of tentative energy to produce to cover the energy demand created from the implementation of the heat pump based on electricity for the home, data referring to the solar panel 375W TRINA SOLAR PANEL have been used MONO XL: TSM-375DE14 (II), manufactured by TRINA SOLAR. The choice of panel responds to its level of efficiency of transforming solar energy into electricity (19.3%), its competitive price, popularity within the market, competitive price per unit of solar panel and the guarantee provided by the company for up to 25 years. , besides that previous exports to the country have been identified of this brand of panels in particular, mostly for private projects, for the generation of energy in remote areas, providing positive results according to communications with the Bolivian Customs Office (2019) .

Table 28. Technical characteristics and calculation of the energetic production performance of the Selected Solar Panels System (Trina Solar - Solar Panel Model: TSM-375DE14 (II)).

Peak power	1,978	W
Solar irradiance -BOL	2,500,000	Wh/m2
Solar panel power generation capacity	347	W
Length	1.956	m
Width	0.992	m
Depth	0.004	m
Number of panels	6	panels
Total area	11.64	m^2
Panel efficiency	19.30	%
System performance efficiency	90	%
Annual electricity production of the arrangement	5056	kWh/year

Then, to cover only the annual energy demand of the heat pump throughout the year, it is required that 5 solar panels of the TSM-375DE14 (II) model be installed, representing an area use of 9.7 m^2. Additionally, this arrangement of panels (theoretically) would grant us as a net energy output produced by the 5,056 kWh / year system.

6.1.1. Verification of the Energetic Generation Calculation

In order to verify the net electricity production of the panel´s arrangement, the electricity production was calculated using only the technical provided by TRINA SOLAR as well as the average and peak solar hours available in Bolivia (SENAHMI, 2019). In the following table the calculation can be appreciated.

Table 29. Verification of the Energetic Generation Capability of the solar panels System.

Electricity generated annually by the solar panels of the system considering the technical features of the system		
Open circuit Voltage	48.5	V
Maximum power Voltage	40	V
Short Circuit Current	9.88	A
Maximum power Current	9.37	A
*Average Solar Hours throughout the year in Bolivia	12	h
*Peak Solar Hours	6.4	h
Arrangement of rows	1	row
Arrangement of panels	6	panels
Energy production annually	5,253	kWh/year

*(FLETES N. 2016).

As it can be appreciated in the previous table, if take into consideration the 5 panels estimated by the first approach and considering the technical features of the solar panel, a yearly production of 5,253 kWh/year is obtained, which is very close to the first electric production calculation done in table 29. Validating the calculation for its usage in the present project. The result of the net energy that the solar panels would produce annually is 5,056 kWh / year was calculated using only the panel and system performance efficiencies, the total panel area and the solar irradiance in Bolivia, therefore it has been decided to use this electricity production for further calculations in the present work.

The electric consumption of the heat pump system only during the eight months of scheduled operation during the eight months of the winter period is 3,300.73 kWh/year or 412 kWh/month. And the electricity generation is 5,056 kWh/year or 421 kWh/month. Granting a surplus of power generation of 72 kWh/year (during the eight months of heating period) and 1,621 kWh/year during the remaining 4 months of the year. Resulting in a total of 1,756 kWh/year of electricity to be used for domestic purposes.

6.2. Electricity Demand of the House

Now it is necessary to mention that the house, apart from the design consumption of the heat pump, has its own consumption of electricity, which is detailed below:

Table 30. Electricity consumption by electrical appliances.

Loads	Amount	Power (W)	N° daily hours	Wh/d
Refrigerator	1	90	24	2,160
Television	1	150	2	300
Light bulbs	5	75	5	1,875
Self-consumption regulator	1	1	24	24
Self-consumption invertor	1	2	24	48
Electric shower	1	3,000	1.5	4,500
Total daily energy consumption				8.91 kWh/d

Daily electricity consumption (including a security range of extra 15%) = 10.25 kWh/d.

The house has five inhabitants, so:

$$E_D = \frac{10.25\,\frac{kWh}{d}}{5\,hab} = 2.05\,\frac{kWh}{d*hab} \qquad (28)$$

Comparing with data obtained from the Bolivian Electricity Control and Inspection Agency (2018), which shows the average energy consumption per household for a middle – low class income family (INE, 2015) in Bolivia of 2.06 kWh / d * hab, the estimated estimate is obviously quite close to the actual consumption calculated of an inhabitant in Bolivia, in addition it must be taken into account that the average is of the whole country, the previous calculation is estimated for a house in the rural area, of people of low economic income.

The annual electricity demand of the house (with five habitants) without considering the inclusion of the heat pump will be:

$$Ed_{-year} = 2.05\,\frac{kWh}{d*hab} * \frac{365\,d}{year} * 5hab = 3{,}741.3\,\frac{kWh}{d*hab} \quad (30)$$

Now, it is necessary to indicate that the dwellings belonging to the Social Housing Construction Program, based on which the project is being dimensioned, have by law the provision of basic services such as drinking water, electric power of the network, sanitary sewer among others. Which indicates that the energy consumption of the house will be covered by electric power from the National Interconnected System (SIN), for which the dimensioning of the solar panels does not require expansion to cover the self-consumption of the inhabitants of the house.

Obviously, since the compressor of the heat pump is the device of the system that consumes electrical energy for its operation, it will be covered by the generation of solar energy during the day, so it is proposed to install a switch to change the power source, during the night hours. For the heat pump to have a highly productive cycle and use energy from the network as little as possible, it is necessary to analyze the hours in which the heat pump will be in operation.

Moreover, it should be noted that, given the designing conditions of the heat pump for air conditioning of the dwelling in question, the heat pump will only need to operate 8 months per year. Generating housing clean and productive energy the rest of the year for housing. Reducing the consumption of energy from the national network.

6.3. Energetic Balance

According to the results obtained, the solar PV arrangement will produce enough electricity to completely cover the energy demands of the heat pump during the eight months of the year it was set to work, generating an extra of 72 kWh/month during the heating period.

During the period of four months in which the heat pump is not required to work the solar PV arrangement will completely cover the electric energy demand of the house, generating an extra of 109.5 kWh of electric energy per month. Energy that can be reinjected into the grid.

During the heating period and given the electric demand of the heat pump, el solar PV arrangement will cover 8.7 kWh/month of the house demand, reducing it to 303.1 kWh/month (for the heating period).

Table 31. Energetic Balance of the house

	Amount	Units
Electric demand of the house of the project per year (without the combined system)	3741.3	kWh/year
Electric demand of the house of the project per month (without the combined system)*	311.8	kWh/month
Electric demand of the house of the project per year (with the combined system)	2424.8	kWh/year
Electric demand of the house of the project per month (with the combined system)	303.1	kWh/month
Electric energy injected to the net per year (during the non-heating period)	438	kWh/year
Electric demand of the heat pump per year (only during 8 months per year)	3300,7	kWh/year
Electric demand of the heat pump per month (only during 8 months per year)	412,6	kWh/year

Electricity Generated by the solar PV arrangement per year	5055,6	kWh/year
Electricity Generated by the solar PV arrangement per month	421,3	kWh/month

**The electric demand of the house will vary during the year, for calculation, to facilitate calculations the demand will be considered the same all throughout the year due to the fact that the monthly demand according to the Annual Statistical Yearbook published by the Ministry of Energy of Bolivia (2017) & the World Bank (2014), indicates that the monthly electric energy consumption of a suburban household varies from 280 to 314 kWh/year. Reaching the last one as a pick during winter seasons.*

7. ANALYSIS OF THE ENVIRONMENTAL IMPACT OF THE PROJECT

The implementation of the heat pump systems based on energy from photovoltaic solar panels represents the amalgam between two different types of technology, but together they make up an efficient and productive system for the beneficiary family.

The heat pump system requires a calculated power supply of 3,300.7 kWh / year. This amount has been obtained from the calculation of the heat of circulation required to maintain the interior of the house at a relatively constant temperature of 20 ° C (during the heating period), data also established due to standards of comfort and thermal comfort. The mentioned heat required and calculated for the dwelling is 7.1 kW of thermal power.

Now, an aerothermal pump system was chosen with a capacity to supply up to 8.1 kW of thermal power during the heating period, thus covering the demand calculated for the eight months of the winter period. The mentioned heat pump has a design electrical power of 1.72 kW, which was used to calculate the energy required to feed the heat pump during the period of one year of work during the winter period completely covered using photovoltaic panels.

The system of photovoltaic panels is sized to cover the annual energy requirement of the heat pump, using the average irradiation value of the Bolivian high plateau, with panels of 19.3% energy transformation efficiency requires 6 panels that will generate a total of 5,055.6 kWh / year.

The house from which it has departed to perform the calculations and design of heat supply, is intended for families with limited economic resources and located in the distant-urban (suburban) and rural areas of the country. The homes built and belonging to the Social Housing Construction Program as mentioned above, by law in Bolivia have the implementation of all basic services, including in these the connection to the National Interconnected System (SIN) which is the fundamental network of electric power distribution in the country.

Since the heat pump system requires a significant amount of energy for its operation, this in environmental terms would translate as consumption of indirect incidence in the emission of greenhouse gases. Given that in the country more than 70% of the electric power, and 100% of the energy produced for the Bolivian highlands (our target zone) is produced by the combustion of natural gas in thermal power plants. It is necessary to mention that the thermal energy that is generated in the aforementioned plants is released to the environment without any useful end.

The heat generated in the power plants in Bolivia is not used in HVAC processes. In Bolivia, there are no district heating distribution networks. According to the carbon dioxide emissions recorded in the last decade, in 2017, historical records of carbon dioxide emission were reached (table 32).

However, according to the records reached and measured of CO_2 emissions related to the coverage of basic services (electricity generation) for housing, commercial and residential buildings have a downward trend, which corresponds to an improvement in the quality of construction increasing and improving the thermal insulation of homes, the implementation of LED light bulbs, increase in electricity prices at peak hours, but also the reduction of the electricity consumption segment of buildings is also due to the growth of other sectors, as the manufacturing industry as well as the mining industry, and above all, the generation of energy through renewable sources such as wind and photovoltaic solar, given that precisely in 2010 they ventured into solar and wind projects in the country (Ministry of Hydrocarbons and Energy 2010).

Clearly, all these policies aimed at reducing electricity consumption and therefore the reduction of CO_2 emissions linked to the generation of energy, encourage the development of initiatives for the generation or self-generation of energy through the use and application of sustainable technologies and friendly to the environment.

Table 32. Registered CO_2 emissions of Bolivia during the last decade until 2017.

CO_2 emissions of Bolivia		
Date	CO_2 Total Kt	CO_2 t per capita
2017	22224	1,99
2016	21647	1,96
2015	20596	1,89
2014	20411	1,91
2013	18918	1,79
2012	18793	1,84
2011	16146	1,60

*Data obtained from: The World Bank, Trading Economics, CEPALSTAD (2019).

7.1. Environmental – Social Component of the Project

Bolivian families living in rural areas suffer from the consequences of environmental degradation, specifically suffering from scarce natural resources caused by the expansion of the agricultural frontier, the intensification of urban development, deforestation and climate change.

The decline of biomass in the highlands, is every time faster and faster, this caused by accelerated deforestation also due to inequities in access to energy sources, this way lacking efficiency in covering basic demands such as fuels for cooking and heating. Provoking the use of organic fuels such as wood or brushwood for combustion to cook their food and obtain heat for housing. Which ends up resulting in damage to health and generation of environmental pollution. Not only due to the combustion processes per se, but also due to the decrease of the natural carbon sinks, which potentiate the probability of occurrence of extreme climatic phenomena (such as droughts, floods, landslides) within the Bolivian territory.

The implementation of the combined system of heat pumps powered by photovoltaic energy systems, has a strong social and environmental component for families with limited economic resources in the Bolivian territory. The generation of heat for housing in the Bolivian Altiplano from renewable sources of energy is fundamental, because it provides the inhabitants of a house with the necessary shelter to withstand the incidents of the harsh climate that characterizes the highlands not only in the areas rural but also in urban areas.

By generating not only clean electricity, but heating in the home, reducing the use of organic fuels to cover the aforementioned need, in addition to greatly improving the living conditions of the beneficiary population, a change is generated not only environmental but social, in which they are reflected in equity in the access to services that allow people to enjoy a decent, pleasant home with a low dependence on the energy coming from the network. Allowing, in addition, more freedom and flexibility for the use of all types of electronic devices or simply the duration of the time of lighting of the light bulbs, not depending on the billing of amounts beyond the reach of the economy of the beneficiary population.

7.2. Methodology of Environmental Assessment

The environmental assessment is based on the generation of tons of carbon dioxide (CO_2) emitted into the environment using electrical energy from the fundamental energy network, based on the estimated energy calculation for a house with five inhabitants.

The CO_2 emissions generated from the electricity consumption of the house from the SIN have been estimated, these emissions were calculated based on a yearly electric demand. The CO_2 emissions were calculated a second time but considering the inclusion of the combined system (heat pump & solar PV arrangement) to see how much the emissions could be reduced while implementing the combined system, the lifecycle simulation software for sustainable products and / or services GaBi was used.

7.3. Proposed Scenarios to be analyzed

The first scenario represents the current situation of middle-to low class income families living in the rural and suburban areas of Bolivia, for which a total electricity consumption per year of 3,741.3 kWh/year was calculated. This scenario will reflect an estimation of how much CO_2 is being produced at the thermal power plants from the SIN to cover the need of a single house. The Result could be used for calculating a total CO_2 emissions caused by the totality of the houses from the Social Housing Program due to it is assumed they share important features such as number of inhabitants, electricity demand, the house has been built following a single model using the same materials and are located on the Bolivian highlands which would provide them similar temperature and humidity measurements, as well as a similar solar irradiation.

The second scenario was built based on the assumption of a completely installed combined system. Which has a solar PV arrangement that was dimensioned to provide enough electricity for the heat pump compressor during the heating period of eight months and provides electricity for the house during the four months in which the heat pump would not be required to work. The combined system generated a yearly electric energy of 5,055.6 kWh/year. There exist a surplus of electric energy during the heating period of 70 kWh. The solar PV system will provide enough energy for completely covering the electricity demand of the house during the non-heating period plus an extra that will be reinjected into the grid during four months of the year. Given that there won´t be any kind of electricity demand during four months of the year, the electricity demand of the house will be only the demand that occurs during the heating period which at the same time will be reduced to 2,424.8 kWh/year thanks to the self-generation of 8.7 kWh/month during the heating period.

To perform the simulations effectively, the thermoelectric plant of the database belonging to Brazil was used, given that the database is the plant with the most similarity with Bolivia. The limits of the system have been designed considering, within them, the electricity coming from the network, the flow of energy and the provisioned housing.

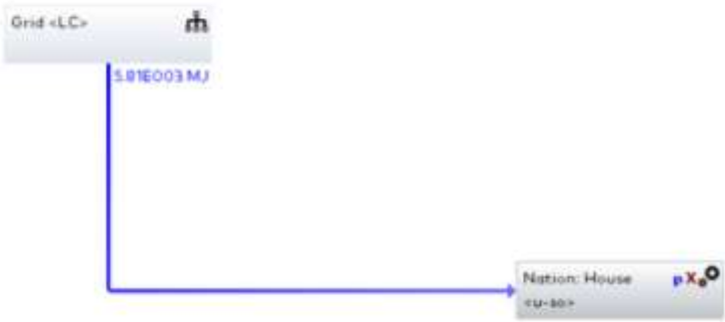


Figure 21. Simulation of the different Electrical demands in the project carried out by GaBi software.

In the following table the results of the calculation can be seen, the total CO_2 emissions from an annual electric consumption from the network are displayed.

Table 33. Scenario 1 for Environmental Analysis

Scenario 1		Unit
Annual electric consumption of the House	3,741.3	kWh/hab*year
Total Emission of Inorganic Carbon Dioxide generated for covering the house´s electricity demand.	0.8264	t CO_2

For the second scenario the conditions are the same as in the first one, but the implementation of the combined system (solar PV & heat pump) was considered, eliminating the electricity demand of the house during the non-heating period and reducing this way the electricity demand of the house during the heating period. This of course was reflected into the emissions of CO_2 related to the electricity demand from the grid.

Table 34. Scenario 2 for Environmental Analysis

Scenario 2		Unit
Reduced annual electricity consumption of the house due to the implementation of the combined system.	2,424.8	kWh/hab*year

Scenario 2		Unit
Total Emission of Inorganic Carbon Dioxide generated for covering the house´s electricity demand.	0.5434	t CO_2

In the table 35 and the consequent figure 22, the results of such modelling are shown, clearly depicting the incidence of the combined system in the reduction of the overall emission of CO2 related to the electricity demand of the targeted houses during the heating periods.

Table 35. Total CO_2 emissions of a house in the three different scenarios.

	Tons of CO_2 emissions / year	Unit
Total Emission of CO_2 generated for covering the current house´s electricity demand.	0.8264	t CO_2
Total Emission of CO_2 generated for covering the house´s electricity demand including the combined heat pump & solar PV system.	0.5434	t CO_2

In the figure 22, it can be seen that with the implementation of the combined system the emissions of CO_2 are even lower than if the system was not been used.

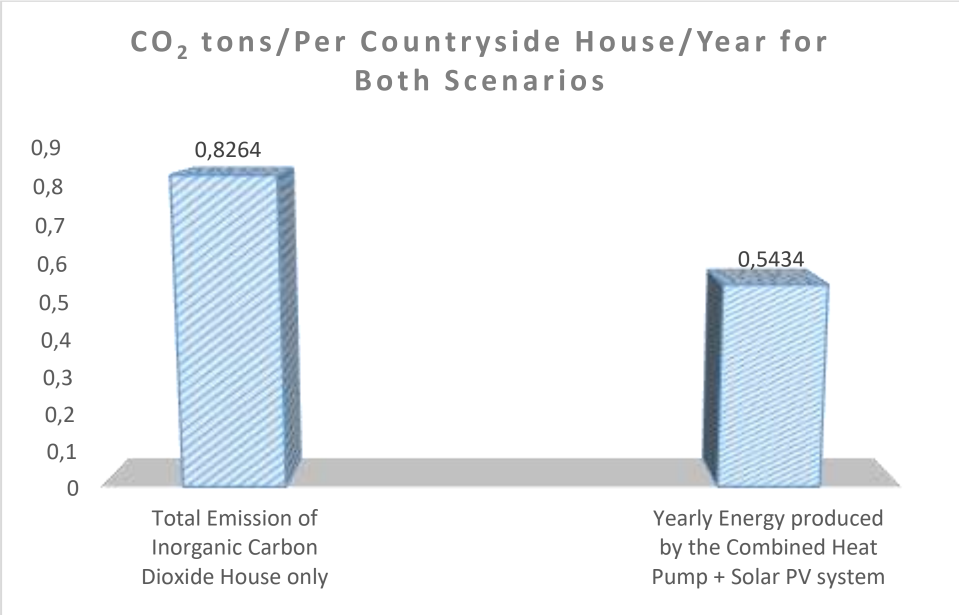


Figure 22. Total CO2 emissions of a countryside house in the two different scenarios.

It can be verified that the amount of CO_2 generated annually due solely to the consumption of the house is 826.4 kg of CO_2. Finally, when the solar PV system is added alongside with the heat pump, the tons of CO_2 emitted suffer a radical decrease, lower than when the heating system was not included and only the house demanded energy from the fundamental network.

Obtaining a total of 543.4 kg of CO_2 per year. According to the amount of tons of CO_2 generated and emitted to the air according to the different scenarios proposed for the analysis, it can be clearly seen the dependence of the heat pump system towards the joint implementation with the photovoltaic panel system, taking into account counts the amount of energy the compressor of the heat pump would demand during the work period established per year.

7.4. Potential emissions Caused by the Refrigerant

The selected refrigerant is R410a, according to the seller technical features it is described that the charge of the refrigerant inside the outdoor unit does not surpass the 4 kg, with an emission factor of 2.1. The refrigerant accounts with a GWP of 2,087.5, and every charge of 4 kg, during the entire lifecycle of the product it will produce 8.4 t CO_2 eq. The refrigerant additions to the overall CO_2 emissions can be avoided almost in its totality, since and adequate maintenance will prevent the refrigerant gas from leaking into the atmosphere. Since the CO_2 equivalent emissions are very low and preventable, they are therefore negligible.

7.5. Comparison of the calculated emissions and the emissions generated annually by the residential sector in Bolivia

Considering the emissions of carbon dioxide generated in Bolivia, only because of the burning and use of energy in buildings and houses in the country, the following graph can be seen.

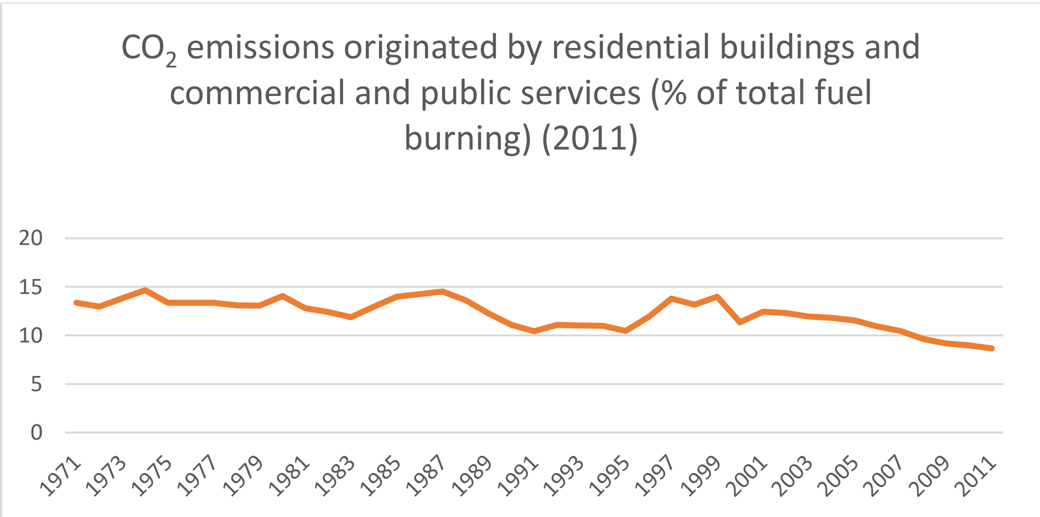


Figure 23. Total CO_2 emissions originated by residential buildings, commercial and public services of Bolivia (2011).

As can be seen in the graph above, the percentage share of CO_2 emissions corresponding to the burning of fuels in Bolivian households is 8.66%, which has been declining since 2006. Due to the there is not updated data available for the CO_2 emissions from the residential sector the CO_2 emissions are extrapolated until 2017, then there would be a percentage of participation of 8.3% of residential buildings and houses, therefore the calculation of the total amount of CO_2 generated from the residential sector only can be seen in the table 37.

Table 36. Total emissions caused by the share of simple constructed country-side houses of the Bolivian highlands.

	Calculation	Units
Total number of houses in Bolivia*	3,347,000	houses
Share of houses from rural areas*	33.3	%
Share of small size houses in rural and suburban areas*	80.2	%
Total number of small country-side houses of Bolivia	893,870	houses
Share of small countryside houses of Bolivia	26.7	%
Total Bolivian CO_2 emissions**	22,224,000	t CO_2
Share of residential, commercial and public lightning Sector from the total CO_2 emissions	8.3	%
Share of residential sector only***	61	%
Total Bolivian emissions originated by only the residential sector (2017)	1,125,201	t CO_2
Total emissions caused by the Share of small countryside houses of Bolivia	300,503	t CO_2

**Data obtained from the National Statistics Institute of Bolivia (2019).*

*** IEA statistics, 2019.*

**** Ministry of Energy of Bolivia, 2019.*

In the previous table, the total CO_2 emissions generated by the Bolivian residential and housing sector were calculated, obtaining that of the total of dwellings that exist in the country, which belong to the rural area of Bolivia (33.3%) and which are made up of Single-family houses of simple construction or of low budget (80.2%). Finally, 300,503 tons of CO_2 are generated annually by the share of small countryside houses in Bolivia.

7.5.1. Implementing the System vs Current Situation

The current CO_2 emission rate per houses from the rural and suburban areas of the country needs to be assessed in order to have comparable results. Therefore, the total CO_2 emissions per house without the combined system that belong to the Social Construction Program in the Bolivian highlands has been calculated. The total CO_2 emissions from the 16712 houses of the program are 13,810 tCO_2/year, which would represent 1.23% of the total residential emissions of the country.

Table 37. Total CO2 emissions per house and of the totality of the houses belonging to the Social Housing Program that have not installed the proposed combined system.

	Calculation	Units
1 Household without the combined solar PV + heating system	0.8264	t CO_2
Total houses of Social Housing Program	50,185	houses
Housing located in the Bolivian Countryside percentage	33.3	%
Total houses of social housing program that can potentially include the combined solar PV + heating system	16,712	houses
Emissions of the total houses of the social housing program without combined solar PV + heating system	13,811	t CO_2/year
Share of the emissions caused only by the total number of houses from the social housing program with respect to the total emissions caused by residential sector in Bolivia	1.23	%

According to the results obtained in the following calculation table, the total annual CO_2 generation of the house is 0.5434 tons of CO_2 per year, this amount was multiplied by the number of houses belonging to the rural area within the Bolivian highlands area, resulting in the Total emission of CO_2 into the atmosphere if the project were executed for all the 16,712 houses of the program, the result would be 9,081 tons of CO_2 per year, which represents 0.81% of the total emissions.

Table 38. Total CO2 emissions per house and of the totality of the houses belonging to the Social Housing Program that have installed the proposed combined system.

	Calculation	Units
1 Household with combined solar PV + heating system	0.5434	t CO_2
Total houses of Social Housing Program	50,185	houses
Housing located in the Bolivian Countryside percentage	33.3	%
Total houses of social housing program that can potentially include the combined solar PV + heating system	16,712	houses
Emissions of the total houses of the social housing program with combined solar PV + heating system	9,081	t CO_2/year
Share of the emissions caused only by the total number of houses from the social housing program with respect to the total emissions caused by residential sector in Bolivia.	0.81	%

To verify that the data obtained previously described would represent a clear reduction of CO_2 emissions that are generated in homes in the rural area of the country, the same calculation process is carried out as in the case of households that have the combined system. In the following picture can be appreciated the total emissions of CO_2 that are being produced for every scenario. If the project is implemented the CO_2 avoided emissions would reach the 4,729 tons of CO_2/year.

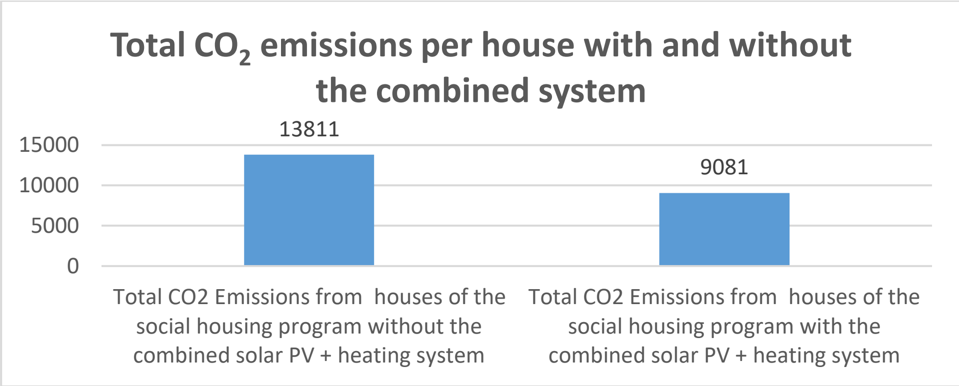


Figure 24. Summary of the emissions in the current situation vs the emissions reduction if the combined system would be implemented.

The dwellings in the rural area are not necessarily all efficient electricity consumers of the network. This added to the fact of the reduction of poverty in Bolivia, generates a varied electricity consumption and above the expected consumption for low-income families used in the present project.

8. ECONOMIC ANALYSIS

8.1. Breakdown of the costs and benefits calculation

The total costs which will be taken into consideration within this analysis will be the costs of the electric demand caused by the “prototype house” used in the present project and the total number of the houses belonging to the social housing program. The range of analysis will be 25 years because that is the designed useful lifespan for this project. Also, the costs associated to the emissions of carbon dioxide are considered in this chapter. Although, in Bolivia the taxation of carbon is something that won´t occur soon, the data regarding to the cost of emitting tons of carbon dioxide was taken from countries from South America for comparison purposes.

The costs also include the cost of building the house, as well as the implementation of the combined system (heat and electricity generation). In order to calculate the benefits of the project, the analysis has been directed from the avoidance of the carbon dioxide emissions by the implementation of “self-sufficient” systems, with practically null carbon dioxide emissions to the environment. Furthermore, the electricity generation took a big role while analyzing the project due to it was considered the “injection” of electricity surplus into the National Interconnected System, meaning a saving for the State in producing that amount of energy for the residential sector. Therefore, this amount of saved money is taken as an economical benefit, both environmentally and economic.

The reduction of the use of natural gas for the electricity generation through the use of the renewable energy based combined system in Bolivia, would represent a saving in economic terms very important for the country, being able to allocate that money for projects of social order or continue propelling renewable energy projects in the country.

8.2. Price of kWh in Bolivia

For the determination of an average price per kilowatt-hour of electrical energy, it is necessary to clarify that the prices from the departments belonging to the highlands were taken into account, it is also needed to mention that since the year 2012, in Bolivia the differentiation between the prices of providing electricity to the countryside have levelized, this following the social policies of equivalent access to the basic services, so the prices listed below are actually the real ones for both urban and rural areas of the Bolivian highlands.

Table 39. Electricity Tariffs of Bolivia – highlands regions (ELECTRICITY AGENCY, 2019).

Electricity rates 2019		
Department	Electricity rate [Bs/kWh]	Electricity rate [USD/kWh]
Oruro	0.86	0.120
La Paz	0.88	0.123
Potosí	0.90	0.126
Average		0.123

*Exchange rate (05/12/2019): 1 Bol = 0.14 USD.

According to the electricity consumption of a house without the combined system of electricity and heat, the house would demand a total of 3,741.3 kWh / year, and according to the average highland tariff of 0.123 USD / kWh, it would have a consumption of 460.2 USD /year. Calculating the cost of the electricity consumption given the case the combined system is implemented, for the 2,424.8 kWh/year of electricity demand of the house, it should pay 298.3 USD/year.

Analyzing the total number of simple construction social housing belonging to the rural area of Bolivia, there would be a total of 16,712 houses if it were estimated that all would express the same energy consumption as previously estimated would be a total of 7,690,862.4 USD that the inhabitants would pay to the State for the annual electricity consumption. On the other hand in the case the combined system is applied the total costs for energy consumption would reduce to 4,985,190 USD/year for the entire houses of the program. Showing a total saving of 2,705,672.4 USD/year of electric energy.

Finally, the injection of 438 kWh/year of electric energy reinjected into the grid per household, represented in monetary terms represents 53.9 USD/year per house. For the total 16712 houses of the program, it will represent 900,342.3 USD that would be subtracted from the electric bill of the houses leaving the total energy consumption of 6,790,520.1 USD/year.

Table 40. Costs and economic benefits of electricity demand and generation

	[kWh/year]	Tariff [USD/kWh]	Total number of houses of the program	Total costs [USD/year]
Electric demand per house without the combined system	3,741.3			7,690,862.4
Electric demand per house without the combined system	2,424.8	0.123	16,712	4,985,190
Reinjection of energy back into the grid	438			900,342.3

8.3. Costs and benefits of avoidance of CO2 emissions

The analysis of the emission costs of the tons of carbon dioxide emitted was made, considering a cost parameter for the emission of tons of carbon dioxide, the aforementioned parameter was obtained by comparing similar tax rates in countries of the region such as Chile, Argentina and Colombia. Obtaining thus, a rate by ton of carbon of 10 USD / tCO_2 (Balderrama J., 2018).

In the following table is possible to appreciate the total costs related to the emission of CO_2 calculated for both scenarios. In the first scenario without the combined system) the total cost of emission is 138,108 USD and in the case of applying the combined system the costs are being reduced to 90,813 USD. Representing this way a saving of 47,295 USD for Bolivia.

At the same time, the total savings from the avoidance of the 4,730 tons of CO_2 per year, calculated by the taxation method used so far, would result in the saving of 47,300 USD/year for the Bolivian Government.

Table 41. Calculation of the total costs of CO2 emissions by the total houses of the program.

	Electric demand [kWh/year]	CO_2 tons emitted per house per year [tCO_2/year]	Total houses of the program	CO_2 tons emitted per year by the totality of the house of the program [tCO_2/year]	CO_2 emissions tax rate of the region per ton of CO2 emitted [USD/tCO_2]	Total Cost of CO_2 emission based on the regional tax price [USD/year]	Total savings from the implementation of the combined system [USD/year]
House without the combined system	3741	0,83	16,712	13.811	10	138,108	47,300
House with the combined system	2425	0,54		9.081	10	90,813	

8.3. Costs of the Implementation of the Solar Photovoltaic System

Table 42. Calculation of Costs of the Implementation of the Solar PV System

	Cost [USD]	Lifespan [years]	Equivalent Annual Cost [USD/year]	Total Duration of the project [year]	Total Cost of implementing one Solar PV system [USD/year]
6 Solar PV panels	1,680	25	67	25	1,680
Inverter	480	10	48	25	1,200
Battery	720	4	180	25	4,500
Costs for the supervision + Previous studies + engineering	576	1	576	1	576
Wires, electric protections, network	144	10	14	25	360
Pole + structure	480	25	19	25	480
Transport + Installation	720	1	720	1	720
Total cost of the implementation of the solar PV system					9,516
Total cost of implementing the solar PV system to the 16,712 houses of the program					159,031,392

8.4. Costs of the Implementation of the Heat Pump System

Table 43. Calculation of Costs of the Implementation of the Heat Pump System.

Equipment/Expenditure of the system	Cost [USD]	Lifespan [years]	Equivalent Annual Cost [USD/year]	Total Duration of the project [year]	Total Cost of one heat pump system [USD]
Heat pump (outdoor unit)	1,014	25	41	25	1,014
Heat pump (2 indoor units)	2,213	25	89	25	2,213
Transport	1,383	1	1,383	1	1,383
Cost of supervision + Installation	2,582	1	2,582	1	2,582
Wires, electric protections, network	461	10	46	10	461
Structure	1,568	25	63	25	1,568
Total cost of implementing the heat pump system					9,221
Total cost of implementing the heat pump system to the 16,712 houses of the program					154,108,037

8.7. Total Costs of the Project

For the total costs of the project calculation, the costs related to the implementation of the system in all the houses of the program, the cost of energy demand of all the houses in Bolivia and the cost of releasing CO_2 emissions to the environment were taken into consideration. The results are displayed in the following table.

Table 44. Calculation of the Total Costs of the Project

COSTS OF THE PROJECT	**Units [USD]**
Total Cost of the total energy demand of all the houses of the social program	6,790,520
Cost of implementation the combined system for all the houses of the social construction program (solar PV & heat pump)	313,139,429
Cost of emissions of CO2 of the totality of houses to the atmosphere	138,108
Total [USD]	320,068,057

8.8. Total Benefits of the Project

For the economic benefits calculation, the total savings from the avoidance of the release of the CO2 emissions was considered and the total savings from energy consumption related to the fossil fueled power plants for the highlands was also considered. The savings are considered in economic terms due to the nature of the Benefit to Costs ratio. The results are displayed in the following table.

Table 45. Calculation of the Total Benefits of the Project

BENEFITS OF THE PROJECT	**Units [USD]**
Total savings from the avoidance of CO_2 emissions to the atmosphere per year	47,300
Total savings from the energy consumption per year	2,705,672,4
Total [USD]	2,752,972,4

8.9. Benefit/Cost Ratio

$$\frac{\boldsymbol{B}}{\boldsymbol{C}} = \frac{2{,}752{,}972.4 \text{ USD}}{738{,}768{,}399.2 \text{ USD}} = 0.008 \qquad (31)$$

B = Total economic benefits of the project [USD/year]

C = Total costs of the project [USD/year]

The results from the benefit/cost ratio show that the project has bigger costs than benefits, which indicates that the, in this case, economic benefits of the project will not surpass the inversion, but here it is highly necessary to mention the nature of the project. The Social Housing Program initiated by the Bolivian Government has a roof for the investment in each house of 25,000 USD. The total investment cost of one combined system is 19,198 USD, which would represent 77% of the initial investment for its application alongside with the houses.

9. DISCUSSION OF THE RESULTS

The heat transfer loads between the different series of enclosures of the dwelling, such as walls, roof, floor, windows, doors, as well as the movement of air due to architecturally generated ventilation, as well as the infiltrations of air inside the house, were calculated. The comfort conditions established for the design were 20 ° C as indoor temperature and relative humidity of 40%. Finally, the thermal demand of the house of 7.1 kW was calculated. Once the annual demand for thermal energy in the home was obtained, an air / air aerothermal heat pump model has been selected that covers the energy cost of the home (8.1 kW).

The model of heat pump has an outdoor unit (NEXURA RXG50K) and two indoor units (NEXURA FVXG50K), which will be arranged for each room of the social housing. It has been chosen only to use two indoor units due to the cost they represent, in addition to the fact that the house has two rooms for the inhabitants, thus prioritizing the rooms where the beneficiaries sleep over where they carry out other activities. According to the guidelines of multi-split heat pumps, it indicates that heat generation, although concentrated in the room where they are installed, would spread heat to other spaces in the home.

Once the model of the aerothermal heat pump to be used was settled, the electric power demand of the pump (1.98 kW) was used to determine the annual electric energy consumption of the heat pump. With the energy demand of the pump, the appropriate photovoltaic panel system to supply power to the heat pump system during the heating period was sized and that is 3,300.7 kWh / year.

To supply the required electrical power, 6 solar panels will be required, taking advantage of the fact that Bolivia has a solar irradiation of 2,300 to 2,700 kWh / m^2, with an average of 12 hours / day of sunshine per day and an average of 6.2 hours / day sun peak. The panels have an area of 11.6 m^2, with an efficiency of 19.3%, representing a use of roof area of 21.6%. The arrangement of solar panels will generate 5,055.6.4 kWh / year. The use of solar panels to boost the heat pump system during the winter period has been dimensioned in such a way that enough energy must be generated for the eight hours of work corresponding to the heat pump on a daily basis. In turn, surplus production margins have been calculated that can be used by the household in daily consumption, further reducing the direct consumption of the basic electricity distribution network.

The economic analysis was carried out from the perspective of consumption and generation of electricity over a year and during the total duration of the project, considering the average price of kWh of electricity in the Bolivian highlands, including the injection of electrical energy into the network. In this way, it was possible to identify the savings in economic terms that would represent the self-generation of electrical and thermal energy. A total of USD 7,690,862.4 was identified that represents the total electricity consumed by the 16,712 homes. In contrast to the 2,705,672.4 USD that would be saved by the beneficiaries of the project from implementing the combined system proposed in the project.

The Bolivian Government currently finances 100% of the construction of social housing, the cost per dwelling has a limit of up to USD 25,000. The cost of implementing the project per dwelling is USD 18,737.4, representing an increment of 75% on the original house investment.

9.1. Project response to the defined problematic

The present project found a feasible solution to the problematic defined in the Definition of the Problem Section. Stablishing the heat and electric demands of houses belonging to the Social Housing Construction Program that currently is carried out by the Bolivian Government. The present project proposes to install a combined system that will provide electric and thermal energy, the first one throughout the year and the second one during the eight stablished months in which the rough decrements of temperature affect the most to the target population of this project. The implementation of the combined system composed by a NEXURA heat pump, solar PV panels' arrangement and the electric network belonging to the National Interconnected System (SIN) and Isolated Systems (SA) are more than suitable to tackle the problems related to uneven access to basic services. Supplying and dignifying at the same time the living conditions of the inhabitants of the Bolivian highlands. The reduction of the CO_2 emissions is a fundamental part of the justification of the present project, due to it has been successfully corroborated its high influence in the reduction of the consumption of fossil fuels for heating and cooking, as well as being part in reducing the electricity demand during peak demand months (winter seasons). Economically the project showed that a 75% increment of the current budget should be necessary in order to apply to proposed system, which considering the savings from the usage of natural gas for providing electricity to all the houses belonging to the program could be possible. That without taking into account the environmental and economic benefits of the avoidance of CO2 emissions.

10. CONCLUSIONS AND SUMMARY

For the present project, a housing model from the Social Housing Construction Program was selected and based on the energy demands of heat and electricity to be supplied on an annual basis during the 25 years of the project the total energy required by this aforementioned house was calculated. The housing model responds to the need to provide homes for low-income families throughout the country. The house has two bedrooms (11.1 m2 each), a living / dining room, a bathroom and a kitchen and is designed for families of 5 people. The roof of the house has an area of 53.9 m2.

The Bolivian Altiplano has been selected as the target design region due to the characteristics of temperature differentials (thermal jumps from 3.5 ° C to 12.4 ° C throughout the year) and relative humidity (differentials from 33.33% to 57.43% throughout of the year) between the exterior of the houses and the rough environment of the Bolivian highlands. The energy demand of the house has been calculated, based on the records of minimum and average temperatures recorded for the three most typical regions of the Bolivian Altiplano, which are the departments of Oruro, La Paz and Potosí.

The environmental feasibility of the project has been verified, focusing on the tons of CO_2 generated by the residential and housing sector in Bolivia and comparing the figures with respect to the total emissions registered at the national level of the housing sector. Given that the country generates 69% of its electric power from the combustion of natural gas, and 100% of the electrical energy consumed in the highlands comes from thermoelectric plants. The reduction in the power demand of part of all the beneficiaries of the social housing program (16712 houses), would generate savings of 118,237 tons of CO_2 per year, and a total of 2,955,925 tons throughout the duration of the project (25 years) considering a steady emission rate.

The taxation of the CO_2 emissions was a critical factor when analyzing the economical costs and benefits of avoiding the emissions of CO_2 from the residential sector.

Finally, an analysis of Benefits / Costs was carried out, in which a ratio of 0.008 was obtained, which, indicates that the project has many economical costs than direct economic benefits, considering it only from the investment point of view. Nonetheless, the nature of the project was never to generate cash flow towards the central government. The project itself was created to improve the living conditions of people that do not have access to a house, in that sense it´s strongly advised to analyze possible funding opportunities to finance the present proposal.

The creation of employment sources through the implementation of sustainable residential heat generation projects, contributes enormously to the social development of the country, generating a kind of new environment with potential for future development.

The implementation of heating systems based on heat pumps fundamentally attacks the inequality of access to a primeval service such as the provision of a pleasant environment to live at a comfortable temperature, with friendly power generation systems with the environment. Results in a synthesis of reduction of greenhouse gases per capita potentially evaded by the beneficiary population of the project, as well as represents a direct economic reduction with respect to the annual cost of electricity by combined self-generation together with heat for housing.

The heat pump powered by the solar PV arrangement has been calculated and proves the feasibility of its application in the weather conditions of the Bolivian highlands, although the results could be improved by changing the materials described in the calculation of the thermal circuit (thermal resistances used in the construction of the house). Because it clearly showed that they have a low degree of insulation, raising the demand for heat inside the home. The total heat demand of the house would be greatly reduced using better materials for its construction. Unfortunately, given the conditions and the nature of the construction of homes that respond more to a social demand, a budget ceiling has been established that would limit the implementation of better materials. As an alternative to this situation, it is proposed to do a better job of sealing the enclosures of the house as well as the use of double glazing in the windows, to somehow safeguard the thermal insulation without raising the prices of materials but by conducting a construction inspection stricter in the sense.

It is recommended the development of fundamental regulations regarding the heating of dwellings of all kinds within the Bolivian territory. Since heat generation is currently regulated for industrial use, in addition to measuring it and categorizing it as a contaminant also within the Environmental Regulation for the Industrial Manufacturing Sector (RASIM) belonging to Law N ° 1333 of the Environment (1992). The use of heat for the air conditioning of housing of any kind is contemplated. It is recommended that the regulations regarding the implementation of heat generation systems for residential air conditioning, prioritize systems partially or totally based on renewable energies, avoiding the maximum use of thermal energy from thermoelectric plants.

The total cost of implementing the combined heating and electricity generation system in the 16712 houses in the rural and suburban areas of the Bolivian highlands is USD 313,139,428.8. The total annual reinjection of electric energy of the combined systems of the totality of the houses is 900,342.3 USD. The total environmental benefits of avoiding the emissions of CO_2in the case of applying the combined system to the totality of the program represents 47,300 USD/year and the total savings from the energy consumption are 2,705,672.4 USD.

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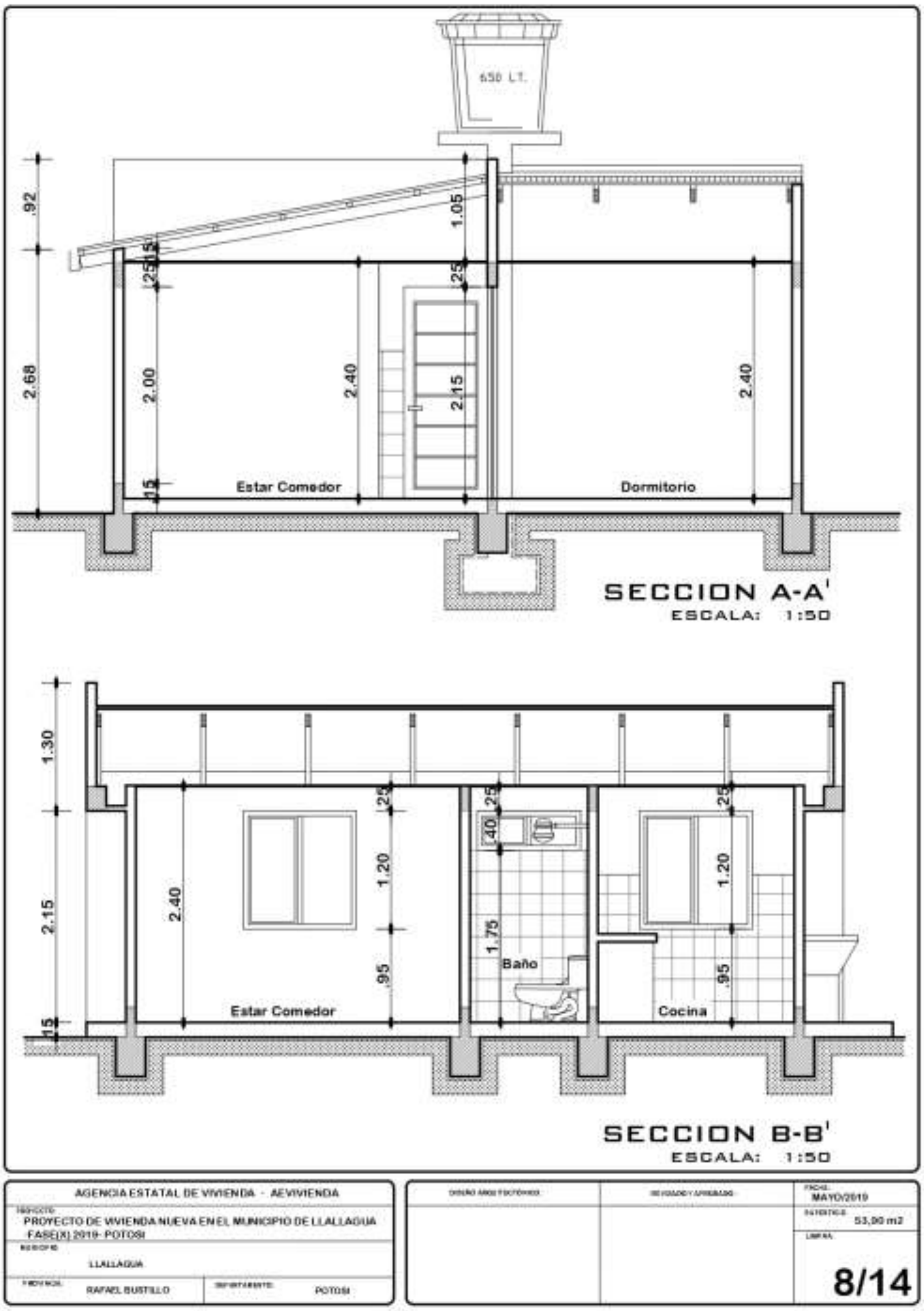
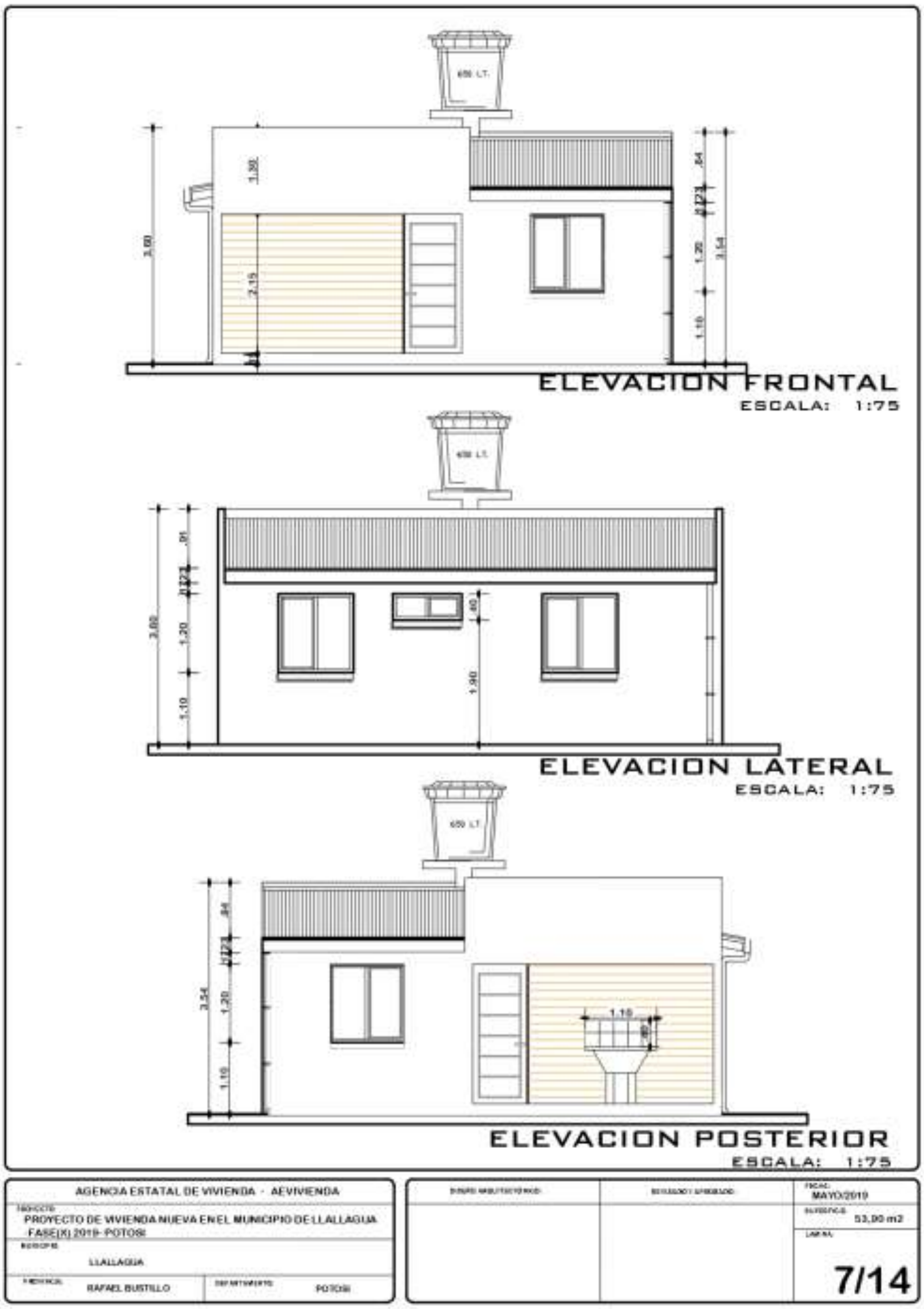
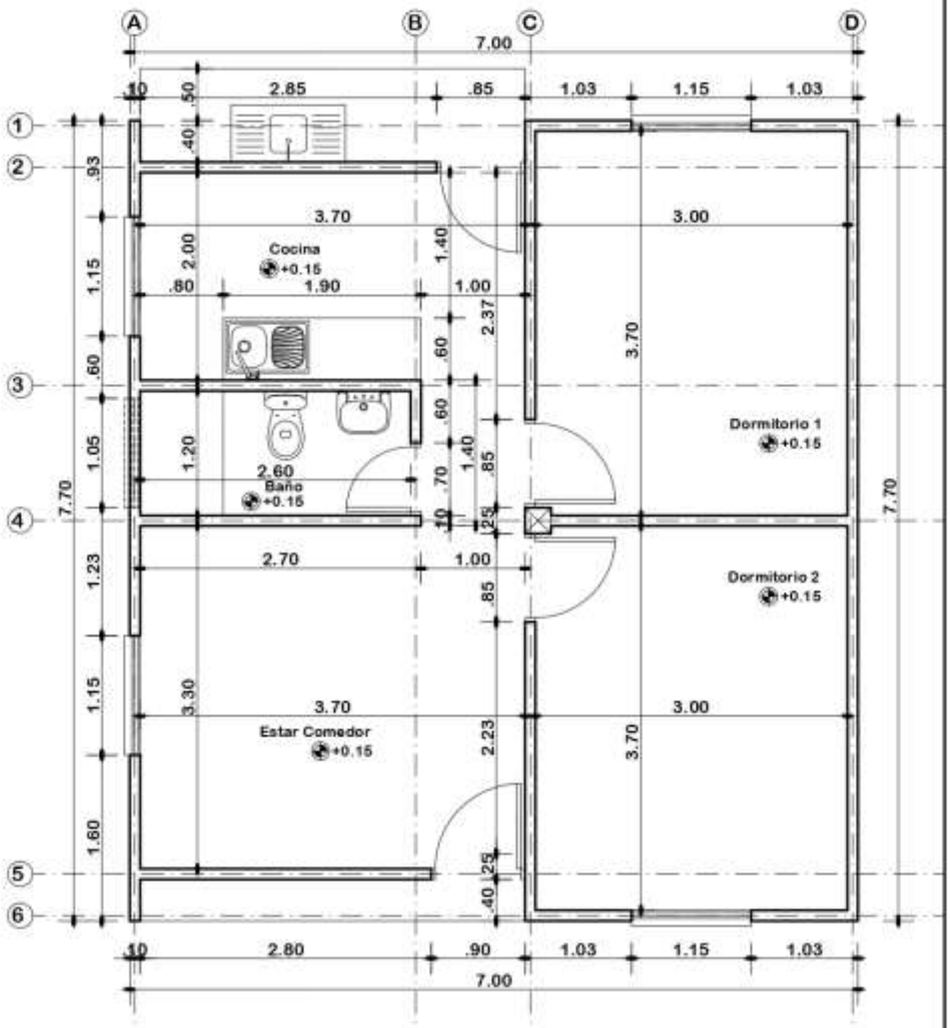
APPENDIX

HOUSING PLANIMETRY




650 LT.
ELEVACION FRONTAL
ESCALA: 1:75
650 LT.
ELEVACION LATERAL
ESCALA: 1:75
650 LT.
ELEVACION POSTERIOR
ESCALA: 1:75
AGENCIA ESTATAL DE VIVIENDA - AEVIVIENDA
PROYECTO DE VIVIENDA NUEVA EN EL MUNICIPIO DE LLALLAGUA
FASE(X) 2019- POTOSI
LLALLAGUA
RAFAEL BUSTILLO
POTOSI
MAYO/2019
53,90 m2
7/14



PLANTA ACOTADA
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AGENCIA ESTATAL DE VIVIENDA – AEVIVIENDA

PROYECTO DE VIVIENDA NUEVA EN EL MUNICIPIO DE LLALLAGUA -FASE(X) 2019- POTOSI

LLALLAGUA

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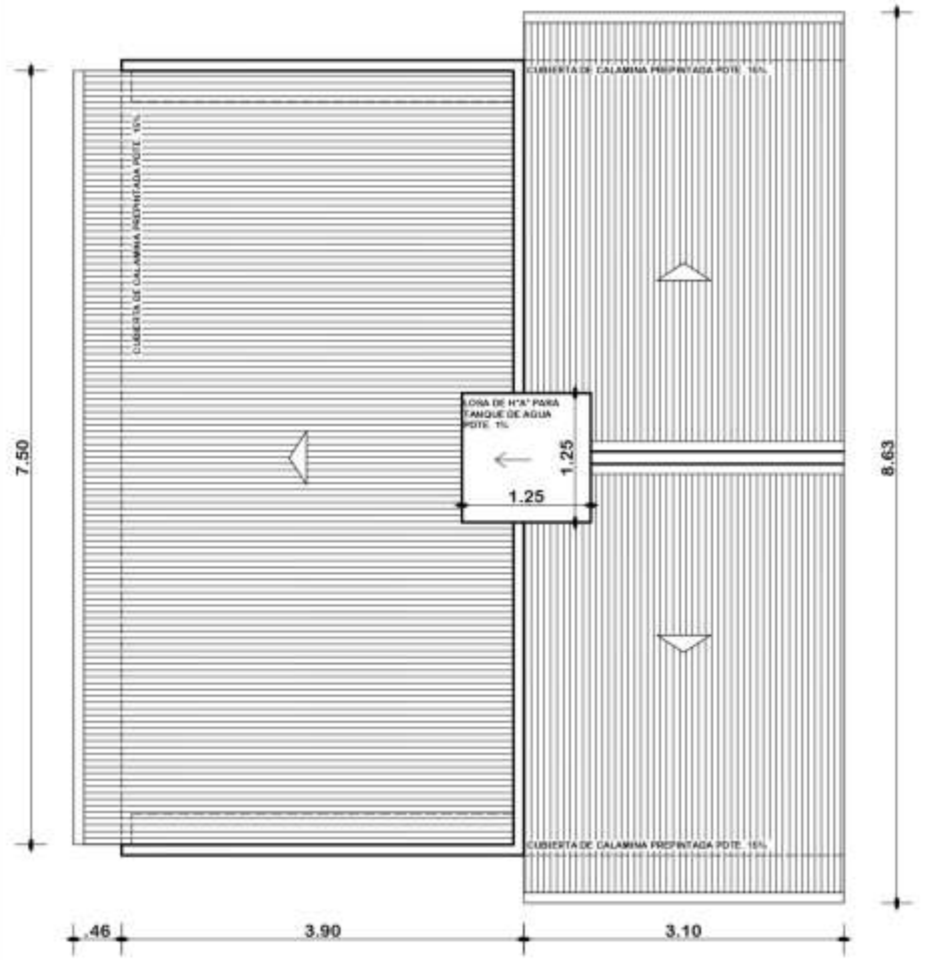

PLANO DE CUBIERTAS

ESCALA: 1:50

AGENCIA ESTATAL DE VIVIENDA - AEVIVIENDA

PROYECTO DE VIVIENDA NUEVA EN EL MUNICIPIO DE LLALLAGUA -FASE(X) 2019- POTOSI

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