UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ
FACULTADES DE CIENCIAS QUÍMICAS, INGENIERÍA Y MEDICINA
PROGRAMAS MULTIDISCIPLINARIOS DE POSGRADO EN CIENCIAS AMBIENTALES
AND
COLOGNE UNIVERSITY OF APPLIED SCIENCES
INSTITUTE FOR TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS

DESIGN OF A LOW-COST ACCLIMATIZATION SYSTEM FOR SUSTAINABLE SOCIAL HOUSING IN A TEMPERATE-DRY CLIMATE IN MEXICO

THESIS TO OBTAIN THE DEGREE OF
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MASTER OF SCIENCE
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IN THE SPECIALIZATION: RESOURCES MANAGEMENT
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SAN LUIS POTOSÍ, MÉXICO AUGUST 2014

Fachhochschule Köln
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Universidad Autónoma de San Luis Potosí
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Abstract

Conventional construction systems used in social housing in Mexico are based on high environmental impact materials that directly affect the thermal behavior of housing units. Sustainable social housing is a recent topic in Mexico, with tangible efforts dating from 2007 with the pilot launch of the INFONAVIT *Hipoteca Verde* (Green Mortgage) program. Despite the usage of eco-techniques derived from this program, social housing developments usually don't achieve internal comfort levels due to the repetition of a single housing prototype over a piece of land without consideration of the environmental conditions.

This research project focuses in the design of a low-cost acclimatization system for social housing in a temperate-dry climate in Mexico, specifically in the city of San Luis Potosí. This system, known as an *earth-to-air heat exchanger*, will help achieve thermal comfort in the interior of the housing units, which implies a reduction in the energy consumption required for cooling or heating with active devices. The design is based in the convection principle, where the external air is injected underground through a pipeline and directed inside the house with the help of a fan and a solar chimney. The air will become more temperate due to the energy exchange with the soil, considering that the variation of the temperature of the earth decreases with depth, reaching the annual average temperature of the site in depths greater than five meters. This way, the earth-to-air heat exchanger can help pre-cool the ambient air in summer and pre-heat it in winter.

Keywords: Sustainable social housing, eco-techniques, thermal comfort, earth-to-air heat exchanger, solar chimney.

Resumen

Los sistemas constructivos convencionales utilizados en los desarrollos de vivienda de interés social en México, están basados en la utilización de materiales con alto impacto ambiental, los cuales afectan directamente el comportamiento térmico de la edificación. Los programas de vivienda sustentable son relativamente nuevos en México, con los primeros esfuerzos tangibles realizados en 2007 con el lanzamiento piloto del programa *Hipoteca Verde* del INFONAVIT. A pesar del uso de ecotecnias derivadas de este programa, la mayoría de los conjuntos de vivienda de interés social no alcanzan niveles adecuados de confort interior debido a la repetición indiscriminada de un prototipo de vivienda sobre el terreno, sin considerar las orientaciones óptimas para cada espacio ni las condiciones del clima del lugar.

El presente proyecto de investigación se enfoca en el diseño de un sistema de climatización de bajo costo para vivienda de interés social en un clima templado-seco en México, específicamente en la ciudad de San Luis Potosí. El sistema, conocido como intercambiador de calor tierra-aire, ayudará a conseguir un confort térmico en la vivienda, lo que deriva en una reducción del consumo energético requerido para sistemas activos de calefacción o enfriamiento. El diseño está basado en el principio de convección, donde el aire exterior es inyectado al subsuelo a través de una tubería y dirigido al interior de la vivienda por medio de un ventilador y una chimenea solar. El aire será más templado debido al intercambio de energía con el subsuelo, considerando que la variación de temperatura del mismo disminuye con la profundidad, llegando a alcanzar la temperatura media del sitio a profundidades mayores a cinco metros. De tal manera, el intercambiador de calor tierra-aire ayudará a pre-enfriar el aire en verano y pre-calentarlo en invierno.

Palabras clave: Vivienda de interés social sustentable, ecotecnias, confort térmico, intercambiador de calor tierra-aire, chimenea solar.

Zusammenfassung

Die konventionelle Bauweise von Sozialwohnungen in Mexiko verwendet Materialien mit hoher Umweltbelastung, die sich unmittelbar auf die thermischen Eigenschaften des Gebäudes auswirken. Nachhaltige Wohnbauprogramme sind in Mexiko relatives Neuland. Das erste konkrete Pilotprojekt war im Jahr 2007 das Programm „Hipoteca Verde“ von INFONAVIT. Trotz der Verwendung von grünen Technologien, die von diesem Programm abgeleitet werden, erreichen die meisten Sozialwohnungen wegen der wahllosen Wiederholung eines Prototyp-Hauses ohne Berücksichtigung der Klimabedingungen oder optimalen Ausrichtung der Zimmer kein angemessenes Maß an Raumkomfort.

Dieses Forschungsprojekt konzentriert sich auf den Entwurf eines wirtschaftlichen Akklimatisierungssystems für Sozialwohnungen in einem warmen, trockenen Klima wie in San Luis Potosí, in Mexiko. Das System, das als Luft-Erde-Wärmetauscher bekannt ist, kann helfen, thermischen Komfort in der Wohnung zu erreichen, und dabei gleichzeitig den Energieverbrauch für die aktive Heizung oder Kühlung reduzieren. Das Design basiert auf dem Prinzip der Konvektion, bei der die Außenluft über ein Rohr in den Untergrund geblasen und anschließend mittels eines Gebläses in das Haus geleitet wird. Die Lufttemperatur wird durch Energieaustausch mit der Erde angepasst. Mit der Tiefe nimmt die Temperatur immer mehr ab. Die Durchschnittstemperatur wird in einer Tiefe von mehr als fünf Metern erreicht. So kühlt der Wärmetauscher die Luft im Sommer und heizt sie im Winter.

Keywords: Nachhaltige Sozialwohnungen, Öko-Techniken, thermischer Komfort, Erde-Luft-Wärmetauscher, Solarkamin.

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List of Abbreviations

AS	Atributos Sustentables del Conjunto Habitacional (Sustainability Attributes of the Housing Complex)
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CFE	Comisión Federal de Electricidad (Federal Electricity Commission)
CONABIO	Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (National Commission for Knowledge and Usage of Biodiversity)
CONAFOVI	Comisión Nacional de Fomento a la Vivienda (National Commission of Housing Promotion)
CONAVI	Comisión Nacional de Vivienda (National Housing Commission)
COP	Coefficient of performance
CoP17	17th Conference of the Parties
CMIC	Cámara Mexicana de la Industria de la Construcción (Mexican Chamber of Construction Industry)
CPA	Consumo Proyectado de Agua (Projected Consumption of Water)
CTF	Clean Technology Fund
DEEVi	Diseño Energéticamente Eficiente de la Vivienda (Housing Energetic Efficient Design)
DEP	Demanda de Energía Primaria (Primary Energy Demand)
DET	Demanda Específica Total (Specific Total Demand)
EAHE	Earth-to-air heat exchanger
FONHAPO	Fondo Nacional de Habitaciones Populares (National Fund for Popular Housing)
FOVISSSTE	Fondo de la Vivienda del Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado (Housing Fund of the Institute of Social Security and Services for the Government Workers)
GHG	Greenhouse gas emissions
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Agency for International Cooperation)
HVAC	Heating, Ventilation and Air Conditioning
IDB	Inter-American Development Bank
IDG	Índice de Desempeño Global (Global Performance Index)
INFONAVIT	Instituto del Fondo Nacional de la Vivienda para los Trabajadores

	(Institute of the National Housing Fund for Workers)
INIFAP	Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (National Institute of Forestry, Agriculture and Livestock Investigations)
INVIES	Instituto de Vivienda del Estado de San Luis Potosí (Housing Institute of the State of San Luis Potosí)
NAMA	National Appropriate Mitigation Action
NMX	Norma Mexicana (Mexican voluntary standard)
NOM	Norma Oficial Mexicana (Mexican official mandatory standard)
PECC	Programa Especial de Cambio Climático (Special Program on Climate Change)
PHI	Passive House Institute
PECC	Programa Especial de Cambio Climático (Special Program on Climate Change)
PHPP	Passive House Planning Package
PND	Plan Nacional de Desarrollo (National Development Plan)
PNV	Programa Nacional de Vivienda (National Housing Plan)
RUV	Registro Único de Vivienda (Single Housing Register)
SAAVi	Simulación del Ahorro del Agua en la Vivienda (Housing Water Saving Simulation)
SALUD	Secretaría de Salud (Health Secretariat)
SBS	Sick Building Syndrome
SCV	Sistema de Calificación de la Vivienda (Housing Rating System)
SEDESOL	Secretaría de Desarrollo Social (Social Development Secretariat)
SEGAM	Secretaría de Ecología y Gestión Ambiental Ecology and Environmental Management Secretariat
SENER	Secretaría de Energía (Ministry of Energy)
SHF	Sociedad Hipotecaria Federal (Federal Mortgage Company)
SISEVIVE	Sistema de Evaluación de Vivienda Verde (Green Housing Evaluation System)
UNFCC	United Nations Framework on Climate Change
VOC	Volatile Organic Compound
VSMMDF	Veces el Salario Mínimo Mensual del Distrito Federal (Times the Monthly Minimum Wage of Mexico City)
W	Watts; Also Wh (Watt-hour) and kWh (Kilowatt-hour)
WHO	World Health Organization

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1. Introduction

World population increases every year. It is estimated to reach more than eight thousand million people by 2030 (Dorian, et al., 2006), and almost twelve million by the end of the century (Nakicenovic, et al., 2009). Just in the past hundred years, we have witnessed the accelerated expansion of the cities over the world and its environmental effects, which have a direct impact in the quality of life of human population.

Nowadays, average people spend almost 80% of their time inside a built space, working, studying or performing another activity. Therefore, architecture is an activity that occurs unavoidably, in a constant and progressive way (Legorreta Stephen, 2009). If we consider that by 2007 50% of the population lived in urban zones (Dorian, et al., 2006) and that this trend is increasing, we see that construction sector has a very high impact in environmental degradation, being an activity that consumes between 40 and 50% of the world's energy and physical resources of the natural environment, and is responsible for 50% of CO_2 emissions (Edwards, 2004) (WBCSD, 2009).

As well, a high percentage of the global warming is caused by the usage of fossil fuels in the operation of buildings (WBCSD, 2009). Besides the energy consumption and the pollution caused by the production of construction materials, a building itself demands a vast amount of energy to operate in daily life, from water supply to electricity for appliances and equipment, and even acclimatization devices, depending on the climate conditions, the materials used, the design of the building and its orientation.

It is estimated that nearly 90% of the environmental impact of buildings is a result of the energy usage to operate during their lifetime (WBCSD, 2009). This energy is used to create conditions that provide wellbeing to the users and keep them healthy and efficient in the tasks they are developing. Several factors that affect human comfort can be distinguished, such as air quality, visual, acoustic and thermal comfort. Buildings can make use of active and/or passive devices, or a combination of both to create or maintain in a delimited space specific conditions of temperature, humidity, and ventilation. Bioclimatic architecture focuses, among others, on the right usage of available materials, orientation of buildings, and passive devices which require minimal dependency in fossil fuels to obtain a comfortable edification.

1.1 Problem Statement

According to the World Bank (2013), Mexico experienced an annual population growth of 1.2% in 2011, reaching 114.8 million inhabitants. If this trend continues, by 2030 it is foreseen that the number would increase up to 130 million. The Social Development Secretariat (SEDESOL) has estimated that in the last 30 years Mexico's urban growth reached an average of 50 hectares per day, and housing construction represents at least 60% of this expansion. Besides, it is foreseen that by 2030 Mexico will have over 20 cities with more than one million inhabitants, implying a social and economic challenge for urban planning, infrastructure and equipment supplying, land tenure, and transportation (Inter-American Development Bank, 2012).

The National Energy Balance 2008 from the Ministry of Energy (SENER) shows that the residential sector in Mexico consumes around 16% of the total energy consumed in the country, 11% of commercial energy and 26% of total electricity and represents 3% of the total amount of direct GHG emissions (Inter-American Development Bank, 2012). Conventional construction systems in social housing are based on the usage of high environmental impact materials such as brick and concrete blocks, which have a direct impact in housing's interior comfort levels, as their energy transfer and thermic qualities are very poor and no thermal insulation is considered in the design of the buildings, due to lack of knowledge, regulation or even interest from the constructors, incrementing the GHG emissions of the construction sector.

Mexico has committed to climate change mitigation by signing the United Nations Framework Convention in 1992. The Kyoto Protocol was signed by the country on June 9th 1998 and its ratification was approved by the Mexican Senate on April 29th 2000. Even if Mexico is not mandated to reduce its GHG emissions, it has adopted the "common but differentiated responsibilities" principle of the Kyoto Protocol, and is willing to reduce them to 340 Mt CO_2e by 2050, which represents an amount 50% below the levels found in 2002 (Inter-American Development Bank, 2012). Sustainable social housing is one of the targets presented by former president Felipe Calderon (2006-2012) to achieve this goal. Therefore, we can say that sustainable housing is a relatively new topic in Mexican housing history, with the *Green Mortgage* program as the first attempt in 2007.

This program is based in the in the integration of eco-technologies, including solar water heater, fluorescent lamps, water saving valves and toilets, and energy efficient appliances such as refrigerators and washing machines. The usage of eco-technologies has been increasing ever since and, depending on the climate zone, it may also include efficient air conditioning systems and envelope insulation.

Despite the usage of eco-techniques, social housing developments usually have a lack of internal comfort due to the repetition of a housing prototype over a piece of land, without any consideration of the optimal orientation for each space. If we consider that the housing deficit in Mexico is projected to rise up to 20 million housing units upon 2030 (Beele, 2012), improvements made in the design of upcoming dwellings can make a big difference in the energy consumption and in the environmental impact of residential sector.

Recently, a program to contribute Mexico's efforts to reduce GHG emission of the residential sector has been developed. The *Mexico Energy Efficiency Program "EcoCasa"*, in which investment capital and technical cooperation funds are provided by the Clean Technology Fund (CTF), Inter-American Development Bank (IDB), commercial banks, donors, and bilateral agencies (Inter-American Development Bank, 2012). This program is pursuing to increase the production of low-carbon housing by financing developers through the Federal Mortgage Corporation (*Sociedad Hipotecaria Federal*, SHF), and to increase the supply of mortgages for low-carbon housing, by providing resources for local financial intermediaries (Inter-American Development Bank, 2012).

This program follows the Nationally Appropriate Mitigation Action (NAMA), presented by Mexico in 2011 in the 17th Conference of the Parties (CoP17) to the United Nations Framework on Climate Change (UNFCC) in Durban. Its main objective is to promote the use of energy-efficient appliances and sustainable building design, based on the whole-house approach. Initially, it only considered three different climatic areas in Mexico (hot and dry, hot and humid, temperate and semi-cold) and three levels of energy efficiency for standard housing units (Inter-American Development Bank, 2012):

1) EcoCasa I: In the first stage Implementation of eco-techniques described in Green Mortgage program.
2) EcoCasa II: Targeting energy efficiency in new buildings, including insulation in roof and walls, reflective paint, energy saving windows, among others.
3) EcoCasa Max: It was first projected as the *Passive House Level*; this stage is in developing process, based on the Passive House Planning Package (PHPP) from the German Passive House Institute (PHI).

In order to calculate the energy efficiency of the housing units, the Institute of the National Housing Fund for Workers (INFONAVIT), along with the German Agency for the International Cooperation (GIZ) and the British Embassy in Mexico, developed the Model of the Green Housing Evaluation System (Sisevive-Ecocasa). This model pretends to grade the energy performance of a housing unit through the *Housing Energetic Efficient Design* tool (DEEVi) and the *Housing Water Saving Simulation* tool (SAAVi). Combining these tools, a *Global Performance Index* (IDG) is obtained with a scale from A to G, being A the most efficient and G the less efficient compared to a baseline house (SENER, GIZ, 2013).

Besides, we can find several standards for the construction sector to achieve certain degree of energy efficiency regarding efficient appliances and lighting, water efficient equipment, insulation and envelope. There are two types of standards: the Official Standards (NOM), which are mandatory for everyone to fulfill, and the Mexican Standards (NMX), which are voluntary. Even if they are not fully applied nor regulated, some of them are valid since 2001. The most significant for this research project are listed in Table 1.

Table 1. Mexican standards for energy efficiency and sustainable criteria in buildings

OFFICIAL STANDARDS	NAME	DESCRIPTION
NOM-008-ENER-2001	**EFICIENCIA ENERGÉTICA EN EDIFICACIONES, ENVOLVENTE DE EDIFICIOS NO RESIDENCIALES** (ENERGY EFFICIENCY IN CONSTRUCTION, ENVELOPE OF NON-RESIDENTIAL BUILDINGS)	This standard was published in the Official Federation Gazette (Diario Oficial de la Federación, DOF) on April 25 2001 takes into account the energy efficiency in construction and envelope of non-residential buildings.
NOM-018-ENER-2011	**AISLANTES TÉRMICOS PARA EDIFICACIONES** (THERMAL INSULATION FOR BUILDINGS)	This standard was published in the DOF on December 14 2011 sets standards and values for thermal insulation for buildings, as well as characteristics and proof methods.
NOM-020-ENER-2011	**EFICIENCIA ENERGÉTICA EN EDIFICACIONES** (ENERGY EFFICIENCY IN BUILDINGS)	This standard was published in the DOF on August 9 2011 sets standards for achieving energy efficiency in residential buildings through the implementation of insulation in the envelope of the building.

VOLUNTARY STANDARDS	NAME	DESCRIPTION
NMX-C-460-ONNCCE-2009	**VALOR "R" PARA LAS ENVOLVENTES**	This standard was published in the DOF on August 18 2009 sets the "R" values for insulation in envelopes for residential buildings according the climate zone in the country. It is not an Official Mexican Norm (NOM), but a Mexican Norm (NMX) which is not mandatory to fulfill. Instead, it is open to the users or constructors decision if they want to use its values and recommendations to upgrade the construction.
	("R" VALUE FOR INSULATION IN ENVELOPES)	
NMX-AA-164-SCFI-2013	**EDIFICACIÓN SUSTENTABLE- CRITERIOS Y REQUERIMIENTOS AMBIENTALES MÍNIMOS**	This standard is the most recent publication in the DOF in 2013. Its goal is to make residential buildings more sustainable, giving some basic criteria and minimal environmental requirements in energy efficiency, materials, insulation and social responsibility.
	(SUSTAINABLE BUILDING- CRITERIA AND MINIMAL ENVIRONMENTAL REQUIREMENTS)	

Source: (DOF, 2014)

1.2 Justification

It is known that industrial growth is a factor that promotes mobility between populations. In the city of San Luis Potosí, urban growth was accelerated in the second half of 20th century due to the increasing investments in the industry. From 1970 to 1980 the population doubled, reaching 400 thousand inhabitants. By 2010 population reached 772,604 inhabitants, and a total of 1,040,443 if we take into account the conurbation with the municipality of Soledad de Graciano Sánchez (INEGI, 2013) (See Table 2).

Nowadays, San Luis Potosí has the goal of becoming one of the five more industrialized cities from Mexico (Tagle, 2013), which means that a significant population growth is expected in the short to mid-term. This new population will certainly require new living spaces, which will be reflected in an increment of housing demand and urban expansion. If these new dwellings continue to be built with the same construction patterns that have been used for over fifty years, with the same construction systems, materials and architectural typology and without considering the physical context nor taking advantage of the climate factors and qualities, the environmental impact will be greater. Instead, new projects should be conceived and materialized with a respectful approach towards the environment, optimizing the usage of natural resources and renewable energies.

Table 2. Population growth SLP-SDGS 1950-2010

Inhabitants per municipality	1950	1960	1970	1980	1990	2000	2010
Soledad de G. S.	10,208	12,591	29,061	64,414	132,979	180,296	267,839
San Luis Potosí	155,238	193,670	267,951	406,630	525,733	670,532	772,604
Total Conurbation	168,478	208,366	298,987	472,982	660,986	854,232	**1,040,443**

Source: (INEGI, 2013)

Aguillón Robles (2007) in his *Bioclimatic atlas for the State of San Luis Potosí* mentions some passive acclimatization systems that are suitable for the climate conditions of the State. Most of them are based on solar control to prevent or encourage solar radiation into the buildings; heat collection; special roof types; air movement through windows and special elements, among others. Most of these systems require special architectonic configurations and orientations to take advantage of the sun path or dominant winds. But there is one system that can have less dependency on the orientation, making it more suitable for social housing complexes: ventilation through subsoil.

This system, also known as an earth-to-air heat exchanger (EAHE), can help achieve a comfort temperature in the internal spaces in both summer and winter, reducing the energy consumption required for it with active devices, considering that the variation of the temperature of the earth decreases with depth, reaching the annual average temperature of the site in depths greater than five meters (Dubois Petroff, 2009) (Loyau, 2005) (Bansal, et al., 2011). Although Brown & DeKay (2001) mentions that “at depths greater than 0.6m below the earth’s surface, daily temperature fluctuations are negligible”, most of the authors agree that the best depth to install the system is between 1.2 to 3 meters (Badescu, 2007) (Chel & Tiwari, 2008) (Florides & Kalogirou, 2007) (Mihalakakou, et al., 1996).

This research project focuses in the design of a low-cost EAHE for a temperate-dry climate, in a 48m^2 social house located in *Ciudad Satélite*, San Luis Potosí. The design is based in the convection principle, where the external air is injected underground and directed through a pipeline, where it will become more temperate due to the energy exchange with the soil, pre-heating or pre-cooling it depending on the season of the year. The system would be hybrid, working in a passive way with help of a solar chimney, which uses the solar heat to reinforce the natural convection of the air through a metal or black material which heats the air beneath it, forcing it to expand and elevate, sucking the internal air through it and producing air movement inside the building. If necessary, it can be used a 230W fan to enhance the air suction.

1.3 Objective

The main objective is to demonstrate that the integration of an EAHE system in the design of social housing is suitable for the geographical context of the city of San Luis Potosí, Mexico, and that it can help achieve a comfort temperature in the internal spaces of a housing unit with low energy input, which can help reduce environmental impacts in the housing sector in the country.

1.4 Specific Objectives

This objective is pretended to be achieved through five specific objectives described below:

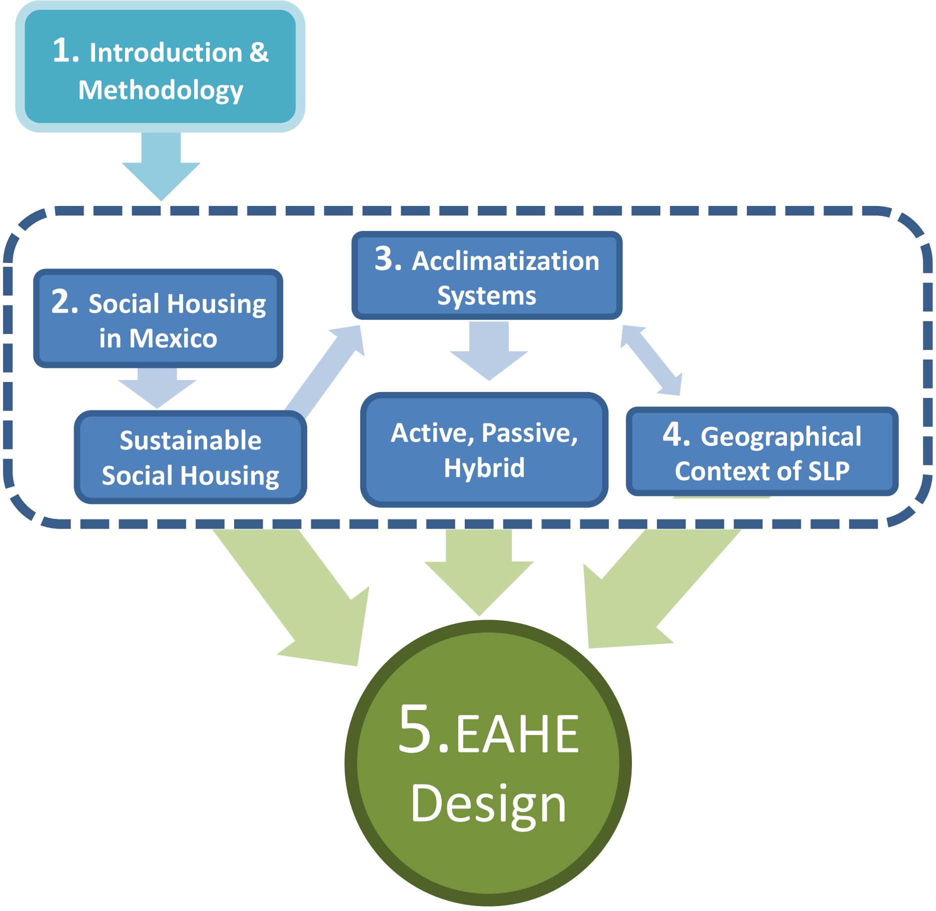
1. Explain how the social housing system works in Mexico, its background, and actual situation, as well as the actors that play a role in it.
2. Analyze the actual practices, norms, regulations and programs regarding sustainable construction and energy efficiency in the social housing sector in Mexico, their requirements, scopes and limitations.
3. Analyze the climate conditions of the study area (city of San Luis Potosí), its climate elements, soil types and bioclimatic environment.
4. Describe the different passive acclimatization systems commonly used in the residential sector, and analyze why the earth-to-air heat exchanger would be a feasible option to implement it in social housing.
5. Gather the previously analyzed data to create a design for the implementation of the EAHE system in a social housing unit, providing basic data as materials that should be used, dimensions, length and diameters.

This thesis project intends to give an overview of the sustainable social housing programs that are currently implemented in Mexico by the governmental institutions, their scopes and limitations, as well as how the regulatory framework and the existing standards on the topic that should be taken into consideration to achieve an energy-efficient housing unit. The analysis of the possible acclimatization systems and the geographical context will help decide the best options to rely as much as possible on passive systems.

One of the main intentions of this project is to measure the temperatures of the soil of a given terrain at different depths in order to determine the feasibility of applying the EAHE system. Due to the short amount of time, no experimentation on different configuration of an EAHE (vertical or horizontal) or different pipe diameters, lengths or materials is going to be performed. On the other hand, an existing unit of a housing complex is going to be analyzed to enhance its configuration according on its localization, to finally determine the best option for the layout of the EAHE and its complementation with a solar chimney for a hybrid usage.

The sequence of the chapters is presented on the diagram below. Chapter 1 includes the introduction with the problem statement, justification, objectives and methodology. Chapter 2 explains the legal framework on social housing in Mexico, to then explain the programs that are in development process or already implemented to achieve more energy-efficient housing units. In this case, the official and optional Mexican standards give some architectonic considerations to fulfill the requirements of the sustainable social housing programs; therefore, Chapter 3 explains the possible acclimatization systems to satisfy the thermal requirements given by the geographical context, described on Chapter 4, including passive, active and hybrid systems. At the end of Chapter 3, since passive systems usually rely on variable weather conditions, a hybrid system is proposed with the integration of an EAHE and a solar chimney.

Finally, Chapter 5 includes a summary of the climate conditions of the city of San Luis Potosí, described in four tables which represent the seasonal climate along the year. Then it explains the technical design considerations of an EAHE such as layout, materials, pipeline characteristics, drainage system, among others, and its implementation on a new housing unit, as well as the modifications the latter should consider to take advantage of the climate conditions and the system itself.



1.5 Methodology

This master thesis has an applied approach to design and implement a passive acclimatization system known as *earth-to-air heat exchanger* (EAHE) for sustainable social housing in the city of San Luis Potosí. The first chapters seek to provide an overview of the social housing framework in Mexico, as well as the programs and standards regarding sustainable social housing, the acclimatization systems commonly used to achieve comfort temperatures in a building, and the local context of the geographical location. The data gathered will help to perform simulations with specialized software on cooling and heating demands, as well as on the performance of the EAHE system.

Social Housing in Mexico

Literature review is usually the first step in a research project. Hart (2003) explains that the generation of information comes from critical evaluations, interpretative work and research. These methods will be used to understand the theories behind the project and the background of the housing situation in Mexico, as well as the state of the art respecting sustainable social housing in the country.

Interviews are used to obtain extended information in an oral and personalized way (Murillo Torrecilla, et al., 2005). They will help to understand the actual practices in sustainable social housing and to clarify doubts regarding the programs and funding. Open-ended standardized interviews (Blackstone, 2012) will be applied to actors and specialists of the construction sector to better understand the background, transitions, appreciation and success of the programs and recent developments.

Passive acclimatization systems

This chapter seeks to describe the passive acclimatization systems commonly used by bioclimatic architecture in the residential sector, and analyze why convective circuit would be a good option to implement it in social housing. In order to do so, the data needed will be a list of passive acclimatization systems and examples of their usage depending the climatic zones of the country, and psychometric charts for the climate conditions of the city of San Luis Potosí.

Local context

The local context of the geographical location is going to be analyzed, including mainly the climate conditions of the city of San Luis Potosí and the soil types found in the region, which are factors that will define the characteristics of the EAHE system. Climate data is partially reviewed in the literature, but data from weather stations near the city of San Luis Potosí is essential. This data has been obtained through the analysis of weather stations such as INIFAP, San Ignacio and La Purísima (See Table 3) and compared with the data obtained by Meteonorm (2007) (See Annex A) which is used in the simulation software. This information will help for setting the parameters for the temperature range and the desired comfort zone which is expected to be achieved inside the housing units with the acclimatization system.

Table 3. Weather stations near the city of SLP

Weather Stations San Luis Potosí				
No.	**Name of the Station**	**Latitude**	**Longitude**	**Location**
1	INIFAP	22.22	-100.99	San Luis Potosí
2	San Ignacio	21.95	-100.88	Vila de Reyes
3	La Purísima	22.08	-101.20	Villa de Arriaga

Source: INIFAP (2013)

Design

An experimental method (Sampieri, et al., 2003) will be used to analyze the temperature of the soil of a given terrain at different depths in the summer period. The measurements will be made on a time lapse of 15 to 30 minutes with 7 thermocouples type "J" buried every 30cm until the depth of 2.10m is reached. These measurements will be compared with the acclimatization requirements of the city of San Luis Potosí shown in Chapter 3, in order to give a particular response to a specific problem such as passive acclimatization for sustainable social housing in this region.

Comparative experiments are used to establish comparisons between objects which receive different treatments. In this case, the variables that affect the most the results of the behavior of the system will be controlled, such as diameter, materials, depth and length. Some factors, like the climate conditions cannot be controlled. Because of time constraints regarding the terrain usage, the month of June was used to take temperature measurements of the subsoil.

Due to these accessibility limitations, a deductive method (Sampieri, et al., 2003) was used to obtain a conceptual design of the EAHE system. The software GAEA 1.4.05 -specialized for analyzing the performance of earth heat exchangers (EHX) - was used to determine the optimal configuration of the system depending on the variables input.

Finally, by gathering the analyzed data, and through this simulation software, the design of the EAHE system for the city of San Luis Potosí integrated to a 53m^2 social housing unit of the urban development of *Ciudad Satélite* (See Annex C) was achieved, providing data of materials that should be used, optimal dimensions, length and diameter.

2. Social Housing in Mexico

Housing, including land, urbanization and basic services of infrastructure, is a vital need, but also an expensive good that not everyone can achieve. In Mexico it is a right granted by Law. In the Mexican Constitution, the first chapter of the Individual Guarantees (Garantías Individuales), Article 4° says: "Every family has the right to enjoy a decent dwelling. The law will establish the instruments and the required supports in order to reach that objective" (Constitución Política de los Estados Unidos Mexicanos, 2013).

To achieve this constitutional right, Mexican government relies on a welfare perspective of governance, where the State is responsible of providing dwellings to informal workers, which are the poorest sector of the population, through programs from SEDESOL. For workers affiliated to a social security, a managerial approach is followed, with a strong reliability of the government in institutions such as INFONAVIT and the Housing Fund of the Institute of Social Security and Services for the Government Workers (FOVISSSTE). These institutions manage private-sector companies to build social housing complexes to private and public sector workers.

The National Housing Commission (CONAVI) through its Housing Building Code (2010) classified social housing in six categories, being the most demanded the first three: *economic*, *popular* and *traditional*. This classification is made according to the surface, cost and number of rooms (See Table 4). For these three categories, the surface ranges go from 30 square meters to 62.5 square meters; the costs go from 118 to 350 times the monthly minimum wage (VSMMDF), equivalent to $2,045.61 MXN or $153.07 USD (April 2014); and the number of rooms varies from three to six. As we can see, all these definitions are based on quantitative criteria, not taking into account the needs for wellbeing and comfort of the users.

Private construction companies will try to take advantage of every opportunity to satisfy their economic interests. It is common that social housing complexes focus in minimum dimensions to increase the possible revenue from a given piece of land. Barely habitable small dwellings built with low quality materials and no considerations to the climatic environment are provided to the Mexican population in a massive scale. In average, the low-income developments that have been built until now have from 100 to 2,500 houses, but some of them can reach up to 15,000 (Beele, 2012).

Despite the construction of these massive developments, CONAVI expects that from the deficit of 20 million units for 2030, 56.5% (11.3 million) will be additional demand of new dwellings (Beele, 2012). A big constraint is the lack of affordable land close to the city centers, which promote disordered urban growth, land speculation and high costs in infrastructure, making it a difficult goal to achieve (CONAVI, 2007). As a result of this, it is common to find high-density settlements built in the peripheries of the cities, causing transportation conflicts and increasing the CO_2 emissions due to the usage of fossil fuel vehicles.

Table 4. Housing classification according to CONAVI

SOCIAL HOUSING TYPES IN MEXICO						
	Económica	**Popular**	**Tradicional**	**Media**	**Residencial**	**Residencial plus**
Built Surface (Average)	30 m2	42.5 m2	62.5 m2	97.5 m2	145 m2	225 m2
Cost (VSMMDF)	Up to 118	118.1-200	200.1-350	350.1-750	750.1-1,500	>1500
Number of Rooms	Bathroom	Bathroom	Bathroom	Bathroom WC	3-5 Bathroom	3-5 Bathroom
	Kitchen	Kitchen	Kitchen	Kitchen	Kitchen	Kitchen
	Multiple use area	Living-Dining room	Living-Dining room	Living room	Living room	Living room
				Dining room	Dining room	Dining room
		1-2 Bedrooms	2-3 Bedrooms	2-3 Bedrooms	3-4 Bedrooms	>3 Bedrooms
				Service room	Service room	1-2 Service rooms
					Hall	Hall

Source: (CONAVI, 2010)

2.1 Legal Framework

Since 1932 with the proclamation of the General Law of Credit Institutions (Ley General de Instituciones de Crédito) which included the construction of a Mortgage and Public Works Bank (Banco Hipotecario y de Obras Públicas), the Mexican framework for housing has been including a list of policies and financial institutions. In 1954 the National Housing Institute (Instituto Nacional de Vivienda) was created to study housing problems and to establish national policies to solve them, while constructing 14 thousand dwellings up to 1970 (Roux Gutiérrez, et al., 2010).

In 1972 the INFONAVIT and FOVISSSTE were founded. These institutions "provide loans to workers and guarantee the upfront payment to the developers" (Beele, 2012). The first one is dedicated to private sector employees, while the latter focuses on the workers of the public sector.

Nowadays, the housing scheme in Mexico is defined by a wide number of actors, including public and private sector financial institutions, housing developers and users. According to Roux Gutiérrez, et al. (2010), the State changed its role from constructor to mediator of institutional and financial policies that make possible the acquisition of a house built by private companies through mortgage credits. A list of institutions involved in legal policies and regulations for providing housing units and/or financial support are listed below.

A. **SHF:** On February 26th 2002, the Federal Mortgage Society (Sociedad Hipotecaria Federal, SHF) substituted the Bank of Mexico as an instrument for housing financing. It was established as a financial institution to promote the access of housing credits, designated mainly for construction, acquisition and improvement of social housing units. It doesn't serve the public directly, but through the support of financial intermediates. The latter are in charge of granting and administrating the credits from the aperture to the end (SHF, 2013).

B. **INFONAVIT:** On April 21st 1972 was promulgated the Law of the Institute of National Housing Fund for Workers (LINFO) as a solution to the housing problem through a three-way administration, integrated by the Federal Government, business sector and working sector (Valencia Salcedo, 2013). As it was mentioned before, the INFONAVIT is an institution that provides loans for housing construction or improvement, focusing in the private-sector workers that are affiliated to the social security system. It is one of the two largest public housing funds, which has been operating for over 30 years through a deduction of 5% from workers' salaries. According to IDB (2012) by 2011 it granted 501,292 loans, for a total amount of 156.2 billion MXN (over 12 billion USD).

C. **FOVISSSTE:** Created on December 28th 1972 as a specialized fund with financial resources that come from the State, the Housing Fund of the Institute of Social Security and Services (FOVISSSTE) is the second of the largest public housing funds. It is subordinated to the Health Secretariat (Secretaría de Salud, SALUD) and is the institution in charge of offering housing financing schemes for workers in the public sector.

D. **CONAVI:** Created in July 2001 with the name of National Commission of Housing Promotion (Comisión Nacional de Fomento a la Vivienda, CONAFOVI), it changed its name in 2006 to the National Housing Commission, (Comisión Nacional de Vivienda, CONAVI). It is a decentralized organization that designs, coordinates and promotes housing policies and programs to achieve the housing objectives dictated by the Federal Government, supervising that the housing actions are done within the framework of urban development, territorial ordinance and sustainable development (CONAVI, 2010).

E. **SEDESOL**: It is the secretariat in charge of creating policies for promoting social development and welfare. Its main objective is the overcoming of poverty in the country through inclusive and integral human development programs.

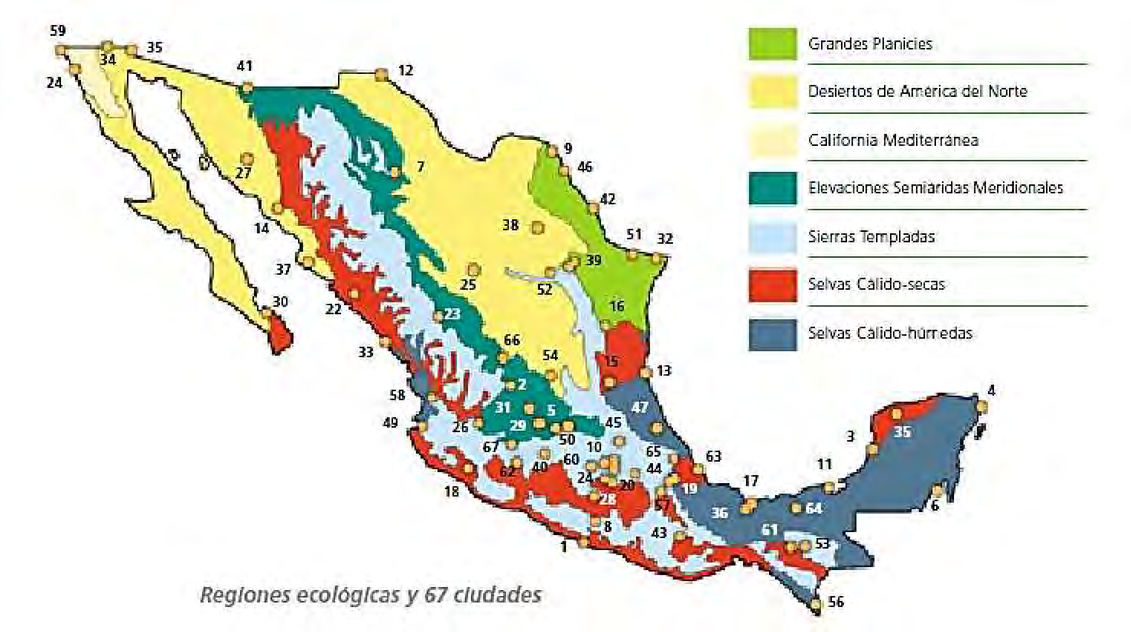
F. **FONHAPO:** As it was said before, informal workers do not have access to housing credits, making them more vulnerable. National Fund for Popular Housing (Fondo Nacional de Habitaciones Populares, FONHAPO) is subordinated to SEDESOL and is in charge of housing financing schemes for non-affiliated workers in poverty conditions.

2.2 Sustainable Social Housing

Sustainable housing is a relatively new subject in Mexican housing history. Construction sector has been relying in aggressive constructive systems, using materials with high environmental impact such as clay bricks and concrete block which require a lot of energy to be produced, and also emit high amounts of CO_2. Besides, these materials have low thermal and energy transfer qualities, and the lack of thermal insulation of any kind makes it even harder to achieve internal comfort in dwellings.

Furthermore, the typified scheme of housing developments increases the lack of comfort, with the same dwelling prototype being repeated over and over in a development without considering the orientation or even the climate zones of the site where it is going to be implemented. Due to the great extension of Mexico and its geographical location, a wide range of climate zones can be found (See Figure 1).

Figure 1. Climate zones in Mexico



Source: (CONAFOVI, 2006)

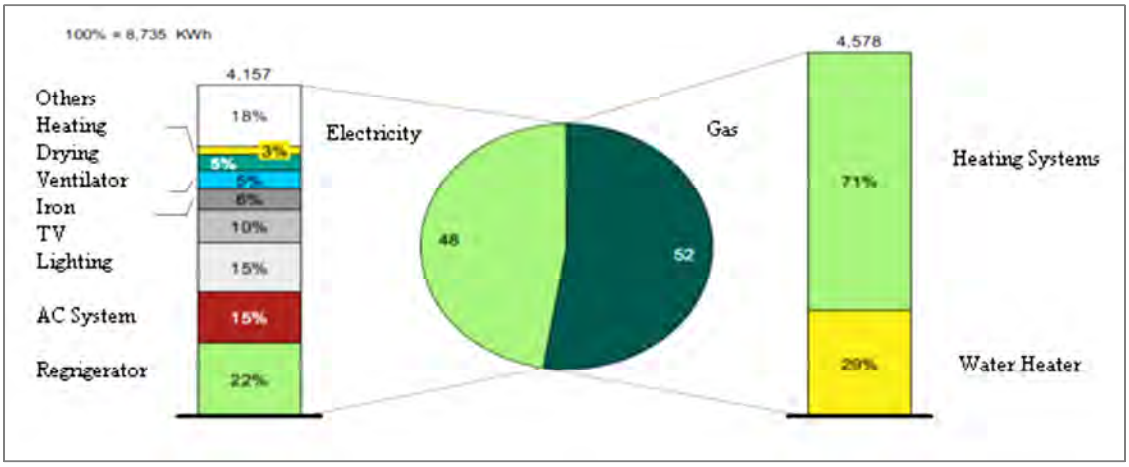
The Nationally Appropriate Mitigation Action (NAMA) considers just 4 climate zones for the calculations from the Passive House Institute (PHI) and the Housing Rating Systems (Sistema de Calificación de la Vivienda, SCV) by INFONAVIT. These zones are: 1) Hot dry, 2) Hot humid, 3) Temperate and 4) Semi-cold.

It seems obvious that different climate zones need different and specific design strategies, but constructors rarely consider the climate conditions in housing designs, leading to the installation of high energy-consuming equipment by the users such as air conditioning systems in climates that don’t require these kinds of acclimatization strategies, rising electricity demands (See Figure 2).

The subject of sustainability and energy efficiency in the housing sector was officially treated for the first time in the National Development Plan 2007-2012, and further developed in the National Climate Change Strategy (2007) and in the Special Program on

Climate Change (PECC 2009-2012). Co-benefits of mitigation and reduction of GHG emissions are supposed to "meet broader goals of increased energy independence, lower costs and higher quality of life" (PECC 2009-2012).

Figure 2. Residential energy consumption patterns in Mexico



Source: (Inter-American Development Bank, 2012)

2.2.1 National Development Plan 2007-2012

The Mexican Constitution in its Article 26° highlights the National Development Plan (Plan Nacional de Desarrollo, PND) which plays a very important role in the legal framework of the Government, being the guiding document for the executive power by specifying the national objectives, strategies and priorities for the integral and sustainable development of the country (Constitución Política de los Estados Unidos Mexicanos, 2013).

The first National Development Plan that talked about a sustainability approach was in the presidential period of Ernesto Zedillo (1994-2000). In its objective number 5, it promoted a "vigorous, sustained and sustainable economic growth for Mexicans" (Wikipedia, 2014). The National Development Plan 2001-2006 from the government of Vicente Fox specified in its objective number 11 the creation of "conditions for sustainable development" (op cit. 2014).

Specifically in the National Development Plan 2007-2012, in the presidential period of Felipe Calderón (2006-2012), we can find in the Axis 4 under the title of "Environmental Sustainability" the objective number 10 which proposes to "reduce greenhouse gas emissions (GHG)" (Gobierno de los Estados Unidos Mexicanos, 2007). Within this objective, strategy number 10.2 focuses in:

- Promotion of efficient use of energy in the domestic ambit based on policies of energy saving
- Encouragement of the use of energy efficiency lamps and thermal insulation in housing units
- The design of new housing units that integrate criteria for the efficient use of energy

To achieve the mentioned objectives, CONAVI created the National Housing Program (Programa Nacional de Vivienda, PNV 2008-2012).

2.2.2 National Housing Program 2008-2012

The National Housing Program 2008-2012, created as well in the presidential period of Felipe Calderón, promotes in its objective number 4 the "consolidation of a policy of federal support to enable the low-income population to funding access for housing, giving priority to the development of sustainable housing". Its main goal is that a higher number of families can be supported to build their own dwelling without falling in the informal market, irregularities, settlements in risk areas or with inadequate materials that represent a threat to their health, welfare and safety" (CONAVI, 2007).

The program has a strong focus in the density of cities, promoting re-densification and verticality. Verticality is one of the best responses to sustainable housing due to the less usage of land and less dependency on vehicles that use fossil fuels, reducing dramatically the CO_2 emissions. Nevertheless, it is well known that Mexican families are always seeking an appropriation of their own space, and having their own dwelling is very important to them as it is seen as a good that can be inherited to their children. Due to the low quality of materials, it is known that social housing have a lifetime of 40 years (Inter-American Development Bank, 2012), which may not make it feasible to inherit, but sometimes it is more valuable for Mexican people to own a piece of land than a floor in a high-density building.

In February 2013, the current president of Mexico, Enrique Peña Nieto announced the creation of the new National Housing Program. He said that this program will be focused on promoting the orderly and sustainable development of the sector. Alejandro Nieto, general director of the CONAVI informed that it will also promote the construction of vertical estate, and that the policies and operation rules will be the same as the past PNV 2008-2012, to offer the developers a "certitude framework" (El Economista, 2013).

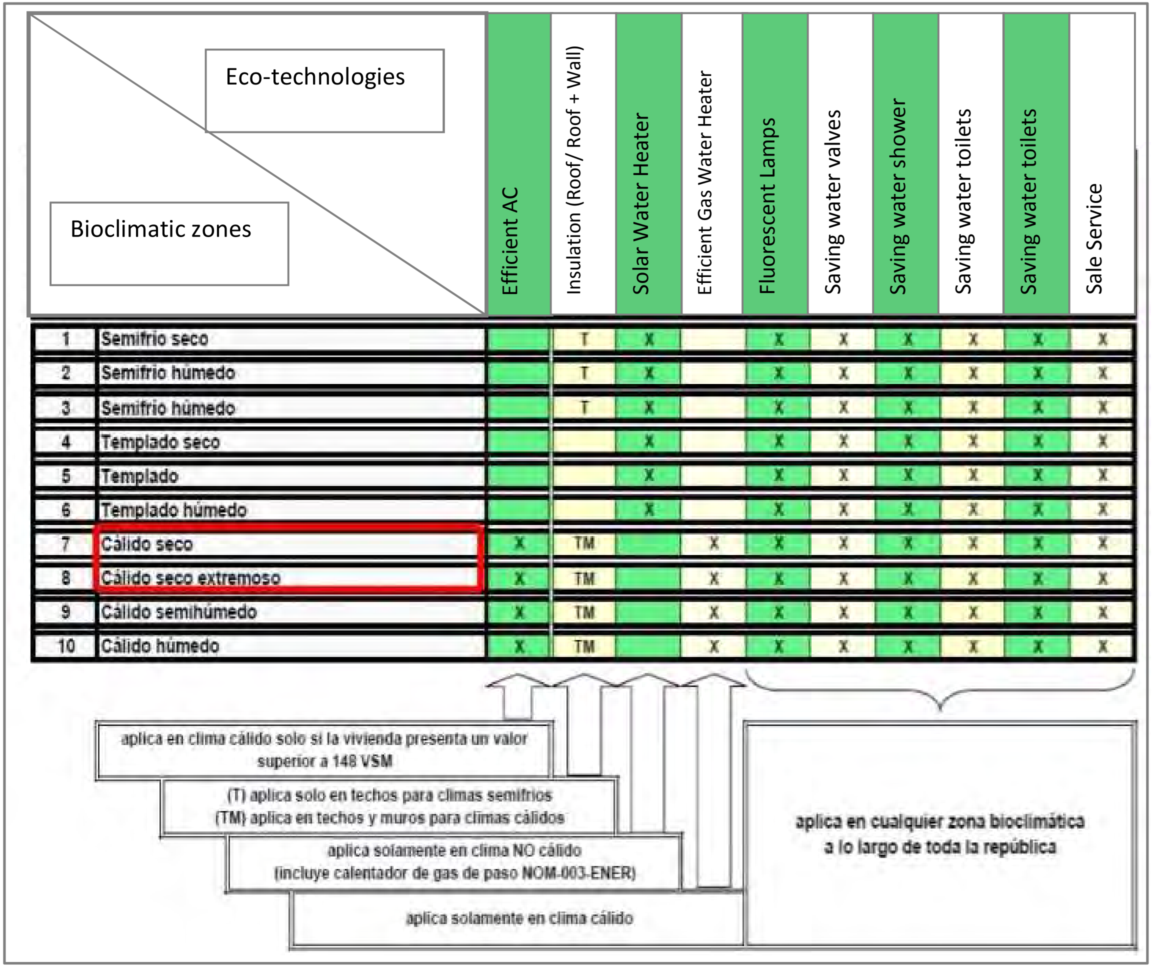
2.2.3 Green Mortgage (INFONAVIT)

Perhaps the most popular *green* program among the Mexican population, the Green Mortgage (Hipoteca Verde) is a loan provided by INFONAVIT that includes an additional subsidy for houses that are equipped with eco-technologies that, combined, allow a monthly monetary saving of minimum $215MXN (approx. $20USD) in the user's bills of electricity, water and gas. These eco-technologies include mainly solar water heater and high efficiency gas heater, energy efficient (fluorescent) lamps, and water saving valves and toilets. It also includes some energy efficient appliances as fridges and washer machines, and depending on the climate zone, it may also include efficient AC systems and wall or roof insulation (See Figure 3).

This initiative was created in 2007, but it was until 2009 that it was implemented at national scale. The first generation of the loans provided was for fixed packages of eco-technologies for the different climate zones. Since 2011, the eco-technologies stopped coming in fixed packages, instead, they became more flexible and actually took into account the different climate zones, housing unit and personal preferences of the user, who can use a simulation tool to determine the combination of technologies that can be acquired to achieve the required savings (Inter-American Development Bank, 2012). Each eco-technology has a number of points assigned so the user can choose a set of them to reach a determined number of points.

In 2011, INFONAVIT issued 376,815 Green Mortgages, from which 75% of the total number of mortgages were "green". That is over 650 thousand homes in the period 2007-2011 (Inter-American Development Bank, 2012). In 2010 the German Agency for International Cooperation (GIZ), collaborated with the INFONAVIT to develop a Housing Rating System (SCV) for social housing in Mexico. As a result, the Green Housing Evaluation System (Sistema de Evaluación de Vivienda Verde, SISEVIVE) was crated. Its main objective is to elaborate a certification system to establish a minimum efficiency level for housing in Mexico (Beele, 2012).

Figure 3. Eco-technologies promoted by the Green Mortgage program



Bioclimatic zones \ Eco-technologies		Efficient AC	Insulation (Roof/ Roof + Wall)	Solar Water Heater	Efficient Gas Water Heater	Fluorescent Lamps	Saving water valves	Saving water shower	Saving water toilets	Saving water toilets	Sale Service
1	Semifrio seco		T	X		X	X	X	X	X	X
2	Semifrio húmedo		T	X		X	X	X	X	X	X
3	Semifrio húmedo		T	X		X	X	X	X	X	X
4	Templado seco			X		X	X	X	X	X	X
5	Templado			X		X	X	X	X	X	X
6	Templado húmedo			X		X	X	X	X	X	X
7	Cálido seco	X	TM		X	X	X	X	X	X	X
8	Cálido seco extremoso	X	TM		X	X	X	X	X	X	X
9	Cálido semihúmedo	X	TM		X	X	X	X	X	X	X
10	Cálido húmedo	X	TM		X	X	X	X	X	X	X

aplica en clima cálido solo si la vivienda presenta un valor superior a 148 VSM

(T) aplica solo en techos para climas semifrios
(TM) aplica en techos y muros para climas cálidos

aplica solamente en clima NO cálido
(incluye calentador de gas de paso NOM-003-ENER)

aplica solamente en clima cálido

aplica en cualquier zona bioclimática
a lo largo de toda la república

Source: http://www.slideshare.net/mayelaguerra/hipoteca-verde-2549972

This rating system intends to provide the home owners with more information about energy efficiency in their homes, reduce the consumption of water and energy, encourage the use of more efficient and environmentally friendly materials and architectural designs and allow the housing institutions to share a common evaluation tool to focus the incentives in a more efficient way (Inter-American Development Bank, 2012).

The Green Mortgage has been internationally recognized as a successful case of implementation of an energy efficiency program, being awarded in 2012 with the Habitat Prize granted by the UN Habitat, UN University in Tokyo and Social Housing Foundation, for promoting the usage of energy efficiency systems and for benefitting since 2007 more than 900 thousand Mexican families (El Economista, 2013).

Nevertheless, the program might lack some specifications regarding the architectonic design. For example, it takes into account the usage of low-impact materials and health, but it never gives an option for alternative construction systems or specifies the so called low-impact materials. It seems that once again the criteria for achieving a sustainable housing rely on quantitative aspects that leave aside the final users.

Furthermore, targeting a low income sector might be counterproductive. It was very difficult to find an explanatory manual for the correct usage and maintenance of the eco-technologies, and these people might not be qualified enough to use them.

On the other hand, developers have the power of deciding which eco-technology they want to install in the developments to achieve the minimum requirements for the mortgage. This can lead to a selection of eco-technologies that might not be the best or the needed for a specific user. Besides, more effective strategies such as insulation in walls, roofs or both can also be put aside because of the economic implications that may affect the revenue of the construction companies.

2.2.4 NAMA

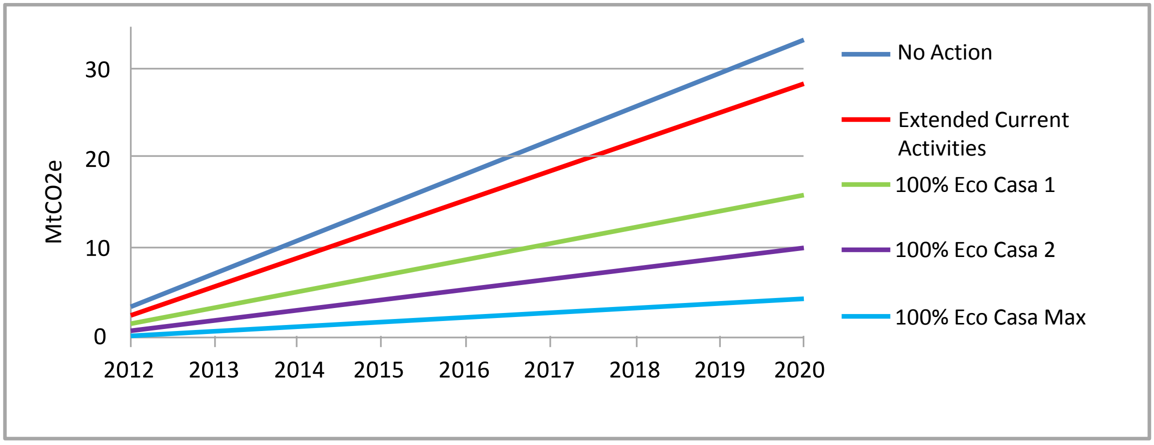
In 2011, the world’s first Nationally Appropriate Mitigation Action (NAMA) in the housing sector was presented at the 17th Conference of the Parties (CoP17) to the United Nations Framework on Climate Change (UNFCC) in Durban. Its main objective is to promote the use of energy-efficient appliances and sustainable building design. The NAMA for sustainable housing is based on the whole-house approach, not focusing on isolated energy efficiency and renewable energy measures in housing, but rather in performance. It has designed three levels of energy efficiency and renewable energy for standard housing units in the different climatic areas before mentioned (hot and dry, hot and humid, temperate and semi-cold) in Mexico: 1) EcoCasa I 2) EcoCasa II 3) EcoCasa Max.

An EcoCasa is considered as a housing unit that results in a reduction of a given amount of GHG emissions compared to the NAMA base case. It distinguishes three types of housing: 1) Single houses, 2) Row houses and 3) Apartment blocks. No insulation is considered for the base case and the electrical appliances are average to low energy efficiency. For the three levels of efficiency, measures can consist of a combination of insulation in roof and walls, reflective paint, efficient gas boiler, efficient refrigerator, solar water heater, energy saving windows, among others. The whole building approach intends to lead to an optimal solution for energy efficiency, comfort and cost effectiveness, as well as to provide flexibility in the design (Inter-American Development Bank, 2012).

The first phase of NAMA (2012-2016) targets new buildings, primarily for low-income families. During 2012 and 2013, the only standards foreseen are EcoCasa 1. However Eco Casa 2 is supposed to be introduced in the following years. The second phase (2016-2020) plan has not been scheduled yet but it will be extended to the existing housing stock. Pilot Passive House (EcoCasa Max) projects are planned to be built during both phases (Inter-American Development Bank, 2012).

Depending on the trend followed by the involved actors, several GHG emissions reduction scenarios can be observed. Figure 4 shows the emissions from newly built houses in Mexico if no action is taken compared to emissions of newly built houses under several mitigation scenarios, as described in the NAMA framework. The scopes of a 100% Passive House is set too high in the reduction of GHG emissions by 2020. Unfortunately, six years might not be enough time to fully introduce these sorts of dwellings, especially when the second phase (2016-2020) is not well defined yet and information about Passive House standards is not very clear, while the methods to achieve comfort, energy efficiency and flexibility in the design are still vague concepts without concrete recommendations.

Figure 4. Projected emissions scenarios under NAMA framework



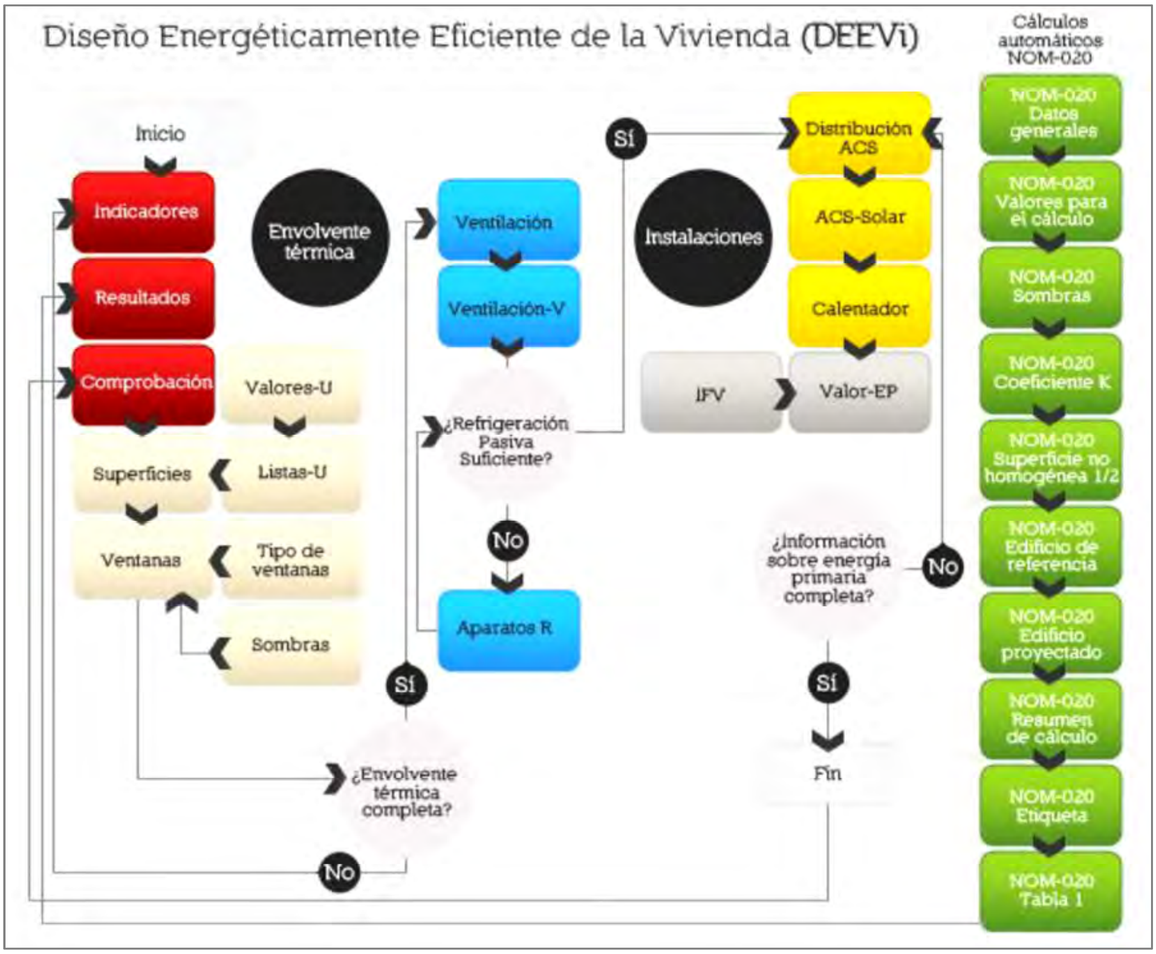
Source: (Inter-American Development Bank, 2012)

Mexican Government, with the support of German Government through the GIZ, the British Government and the Inter-American Development Bank, has developed an evaluation model to grade the energetic and environmental behavior of the EcoCasas. The project, known as Sisevive-Ecocasa, is based on the Passive House Planning Package (PHPP) from the Passive House Institute, but follows the framework of the Green

Mortgage Program. It calculates the efficiency of the dwelling through indicators of two Excel-based tools.

The first tool is known as Housing Energetic Efficient Design (Diseño Energéticamente Eficiente de la Vivienda, DEEVi) (See Figure 5), projected by the PHI based on the PHPP. It includes the possibility to verify the fulfillment of the NOM-020-ENER-2011 concerning the energy efficiency in buildings, although it doesn't certificate its compliance. It calculates the *Primary Energy Demand* (Demanda de Energía Primaria, DEP) and the *Specific Total Demand* (Demanda Específica Total, DET) of a house through indicators for gas and electricity consumption:

Figure 5. DEEVi calculation process



Source: (SENER, GIZ, 2013)

- DEP: It measures all the projected energy consumption, including projected consumption of lighting, gas water heater, appliances and acclimatization systems. It takes into account the input of renewable energies in both electric and thermic supply. The latter considers specifically the water heating from solar heaters.

- DET: It refers to the thermic demand of a dwelling, the energy used for heating and/or cooling, considering the climatic conditions of the emplacement. It measures the impact of the architectonic design and the specification of construction materials.

The second tool is the Housing Water Saving Simulation (Simulación del Ahorro del Agua en la Vivienda, SAAVi). It is a simulator that estimates the water consumption by dwelling and by occupant with the projected consumption of every device that uses water in the house, compared to the baseline house. In this tool are registered toilets, showers, bathroom faucets, kitchen faucets, washing machines and accumulated water in the hot water pipeline. It was created based on the current Mexican standards regarding water efficiency in appliances (See Table 5). Its indicator is called *Projected Consumption of Water* (Consumo Proyectado de Agua, CPA) and the consumption value is expressed as liters per person per day (l/p/d).

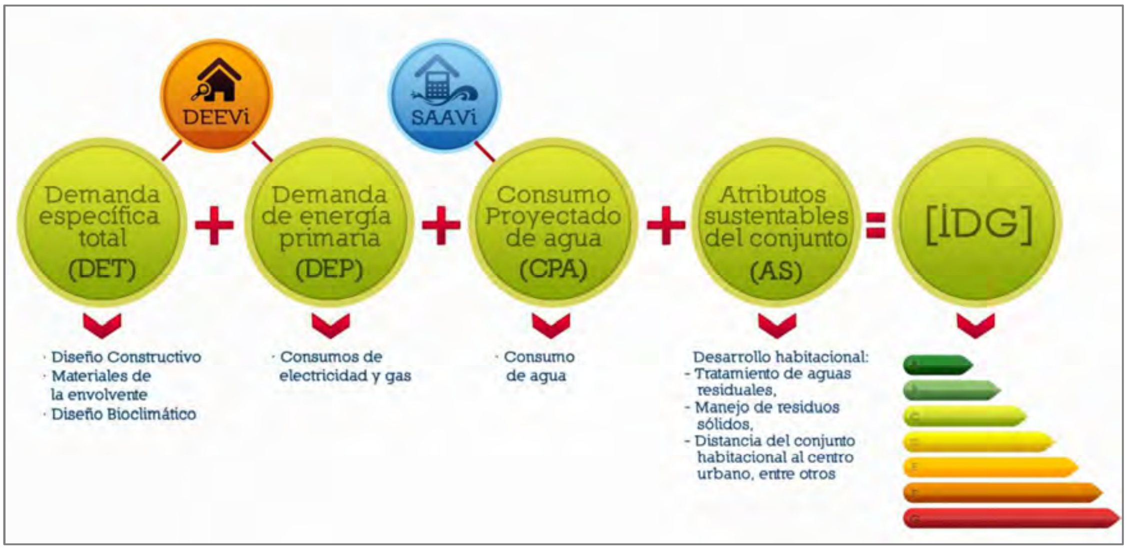
Table 5. Applicable Mexican standards for water efficient appliances

Device	Standard	Maximum permissible consumption
Toilets	NOM-009-CNA-2001	6l per flush
Bathroom Faucets	NMX-C-415-ONNCCE	8l per minute
Sink	NMX-C-415-ONNCCE	10l per minute
Shower	NOM-008-CNA-1998	10l per minute
Washing Machine	NMX-AA-158-SCFI-2011	Container volume= 107.6L 20.2L per washing cycle

Source: (SENER, GIZ, 2013)

Finally, another point is being developed in 2014, which focuses in *Sustainability Attributes of the Housing Complex* (Atributos Sustentables del Conjunto Habitacional, AS). These attributes will consider aspects such as water treatment, solid waste management, and the distance between the housing complex and the urban center, among others. The combination of DEEVi, SAAVi and AS, are used to create a *Global Performance Index* (Índice de Desempeño Global, IDG), which is the final grading of the house (See Figure 6).

Figure 6. Calculation of the Global Performance Index, IDG



Source: (SENER, GIZ, 2013)

Since all the elements considered by each tool are not expressed in the same units, the grade is weighted with indexes which vary depending on the climate zone. Besides, some variables have more weight than others in order to guide the projects towards more efficiently designed dwellings.

Once the information of the grading tools is generated, it is exported to the *Single Housing Register* (Registro Único de Vivienda, RUV) platform where the grading level will be calculated, emitting a pre-grade. Within the information exported to the RUV, a list of concepts to verify, such as materials and physical units, will be included for every registered project. When the housing units are verified, the final grade is emitted and published in the RUV and INFONAVIT platforms. At the end, all the new units will show a label in the main façade to indicate the possible efficiency levels and in which level is rated every specific unit. This way, new buyers can be aware of how efficient is the dwelling they are about to buy, affecting their demand towards more efficient units and causing that the developers focus in upgrading the energy efficiency of the housing complexes they offer in the market.

According to SENER (2013), some objectives in medium term are: to expand the system to other housing segments, such as existing dwellings, create competition among real estate developers, consolidate a national system of energetic and environmental certification for the housing sector, and to impulse the implementation of the Sisevive-Ecocasa program as a regulation for building codes in a municipal level.

2.2.5 Scopes and limitations

Social housing in Mexico includes a wide range of actors. Most of the times, construction companies seek to increase their revenue as much as possible, therefore, it is common that housing developments are conceived alien to their environment, with spaces without quality, and often not considering the climate zones or the orientation.

The urban expansion projected for the near future is something that should be considered for new dwellings, and the National Development Plan is targeting this specific issue with the promotion of denser, vertical housing. One of the main constraints of these programs is that they usually change with the next presidential period and, the lack of agreement between different actors at federal and state levels, leads to situations where every state and even every municipality has its own policies and development plans, which also may change along the incoming governmental periods, making it really difficult to regulate the housing conditions in the three governmental scopes.

Sustainable housing programs target the lower income sector. This can also be a constraint, since this sector of the population might not fully understand the concept of sustainability, and might have problems operating the eco-technologies applied in their new house and to giving them maintenance. Another constraint regarding low-income communities is that there have been found some vandalism acts, in which people steal the installed systems to resell them. At the beginning of the program, there were cases in which constructors did not install the eco-techniques in order to avoid these issues[1].

On the other hand, the Green Mortgage program relies in a minimum economic saving of \$215MXN, and not in consumption units. This way, constructors can apply the eco-technologies that best suit their own interests to fulfill the minimum requirements, but the housing projects tend to rely in the sustainability approach of these technologies instead of a bioclimatic design. Gaitán Lastras (2014) says that this *whole house approach* considers these economic saving has already an impact in CO_2 emissions reduction and water, gas and electricity savings, and that more complex eco-techniques are not suitable

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[1] Personal communication with C. E. Gaitán Lastras, Consultant IDB - Sisevive-Ecocasa, April 2014

for the program because they require maximum a two-year period to amortize the investment costs.

Even if there are official regulations and mandatory standards such as the NOM-020-ENER-2011 for energy efficiency in buildings, or the NMX-AA-164-SCFI-2013 for sustainable building and criteria for minimal environmental requirements, they still need to be reviewed, since the NOM-020-ENER-2011 only considers heat gain through the envelop, and not an energy balance (gains and losses). This way, Beele (2012) found that this official standard with its current requirements is not suitable for every climate zone in the country and its fulfillment can have negative consequences in some cases.

It is important to highlight that a mid-term objective from the Mexican Government is to include the Sisevive-Ecocasa program as regulation for building codes in a municipal level. In the first stages it will certainly be difficult to satisfactorily achieve the set goals, because the learning curve of the people involved in housing construction is somehow slow at the beginning, because it is necessary to deal with new construction systems, materials and providers. These involved actors will need to be in constant training to get used to these changes, as well as the certifications and grading systems.

INFONAVIT and the Mexican Chamber of Construction Industry (Cámara Mexicana de la Industria de la Construcción, CMIC) are in charge of providing the mentioned training packages to developers and people involved in construction[2]. Until now, INFONAVIT has only been able to train approximately 500 people[3], and, in general, the initial experience of these users is that the grading tools are not very *user-friendly*, since they are Excel-based tools which need a set of numbers and data, instead of being more visual as most of the common architectural design tools.

Nowadays, it is still perceived a lack of resources and interest from the regulatory organisms, because most of them are not yet capable to supervise the establishment and implementation of these kinds of standards. The lack of information on building energy use and energy efficiency building codes, and opposition from some private, well-established construction companies to follow them, causes a resistance from the construction industry towards *higher* investment costs and training of personnel in new techniques and materials, leaving behind the benefits of sustainable housing. On the other

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[2] Personal communication with M. Egea and A. Herrera, Experts in Sisevive-Ecocasa program, April 2014

[3] Personal communication with E. Gaitán Lastras, Consultant IDB - Sisevive-Ecocasa, April 2014

hand, there are smaller and more committed companies which are aware of the subject and find an opportunity to innovate and distinguish the products they offer, and are willing to help the housing market so that new buyers can demand more efficient dwellings.

If the grading tools are upgraded to be more flexible and user-friendly, some initiatives from these kinds of companies can be integrated to give a solution to specific demands of a local context. For instance, Gaitán Lastras states that new eco-techniques such as an EAHE can be considered as a good solution for achieving thermal comfort in Mexican social housing, if it if complies with the amortization period of two years, and if it fulfills Mexican standards of health and energy efficiency. He suggests that sometimes Mexican standards act as a filter for new systems and components, but that once you know the characteristics and thermal properties of the product, it can be integrated to the grading tools.

Finally, it is important to consider that the mortgage incentives are only available to affiliated workers, and the most vulnerable sector of the population cannot access the INFONAVIT program which has included *green* criteria. Besides, a great part of the subsidies provided by CONAVI are also channeled through INFONAVIT, so with a housing deficit as high as 11 million housing units for 2030, it is important to analyze whether if it's essential to focus on the expansion of sustainable requirements for all the dwellings, or on providing the missing dwellings to the people who need them, without considering any ecological conditions.

3. Acclimatization Systems

Human beings are not physiologically prepared for living in outdoor environments. The lack of this ability is compensated with clothing, which acts as a second skin, and buildings or other sorts of shelter which act as a third skin (Mermet, 2005). These measures let people develop in comfortable conditions, protected from the elements and allowing them to focus in their specific tasks and activities of the daily life. In order to maintain people within a comfort zone, buildings must fulfill certain qualities. The acclimatization of a building consists in creating or maintaining -in a delimited space- conditions of temperature, humidity, and ventilation necessary for the health, ease and wellbeing of the occupants of a building (RAE, 2001).

As it was mentioned before, the World Business Council for Sustainable Development (WBCSD, 2009) estimates that a high percentage of GHG emissions that contribute to global warming are caused by the usage of fossil fuels in the operation of buildings, mainly to achieve comfort conditions in the interior spaces, including electricity for artificial lighting, and active acclimatization devices for heating and cooling. Human comfort in general is affected by factors such as[4]:

- Indoor air quality: It must consider enough renovation rates for every sort of space and an adequate circulation through the spaces with the required humidity and temperature to achieve thermal comfort.

- Visual comfort: It means providing the users good lighting levels so they can satisfactorily develop their daily activities. It is based on the right illuminance, or lux per square meter for every sort of space. It also considers the connection of the internal spaces with the exterior, creating pleasant views for the users.

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[4] Autodesk Sustainability Workshop (http://sustainabilityworkshop.autodesk.com)

- Acoustic comfort: To achieve acoustic comfort, some internal spaces must be isolated as much as possible from disturbing noises, either from outside or inside the house. It must consider the tolerable decibel levels, reverberation time, and the damping qualities of construction materials.

- Thermal comfort: It includes the airflow, humidity, air temperature and the thermal radiation from surrounding surfaces. It is important to mention that the thermal sensation inside a space is the same as the average of the exterior temperature and the temperature from the internal surfaces (walls, floors and even furniture)

Before the industrial revolution, most of the constructions accomplished these requirements in a natural way, since they had to be designed and built linked strongly to their natural and physical context, using local materials such as wood, stone, earth, and straw, among others. The configuration of these buildings was determined mostly from these materials, creating high thermal mass elements, and taking advantage of the orientation to light and heat the spaces with the benefits from the sun, and cool it with natural ventilation.

With the development of artificial acclimatization and lighting, constructions became more detached from their natural context. With the ability of creating comfort conditions regardless the location, time of the day or period of the year, architects and constructors started to rely on these active devices to create architecture with high formal quality but with high environmental impact as well. After the energy and oil crisis that took place in the decade of the seventies, architects realized that energy consumption in buildings was too high, and the usage of tight, hermetic envelopes and elements insulation as energy-saving measures became more popular.

This tightness created to take advantage of the insulating materials to avoid energy losses and undesired gains, the restriction of natural ventilation, and the intensive usage of air conditioning systems, caused certain problems due to the lack of natural airflow, creating bad indoor air quality, mold and humidity, which affected the health of the occupants, causing what is known as the *Sick Building Syndrome*, where the users of air-conditioned offices developed respiratory disorders due to humidification systems contaminated with microorganisms, causing more serious illnesses such as the Legionnaire's disease (ECA, 1989).

With the emergence of these problems, organisms such as the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and the World Health Organization (WHO), have created regulations and standards regarding ventilation in buildings, from requirements in ventilation devices -including fresh air intake and air filters, among others- to ventilation rates which determine the air changes per hour depending on the room usage. In other words, natural ventilation, besides helping improve thermal comfort, also maintains acceptable indoor air quality, creating a positive impact in the health of the occupants of a building.

Nowadays it is common that architects and constructors insist in achieving human comfort through active systems, which are expensive and predatory, operated with energy produced, in most of the cases, with non-renewable energy. As it was stated in Chapter 2 with the Mexican example, new development models in the countries are trying to fight energy inefficiency, leaning to a usage of renewable energies and resources. With new standards, programs and regulations, construction sector in Mexico is now beginning to be regulated to help the government achieve these goals.

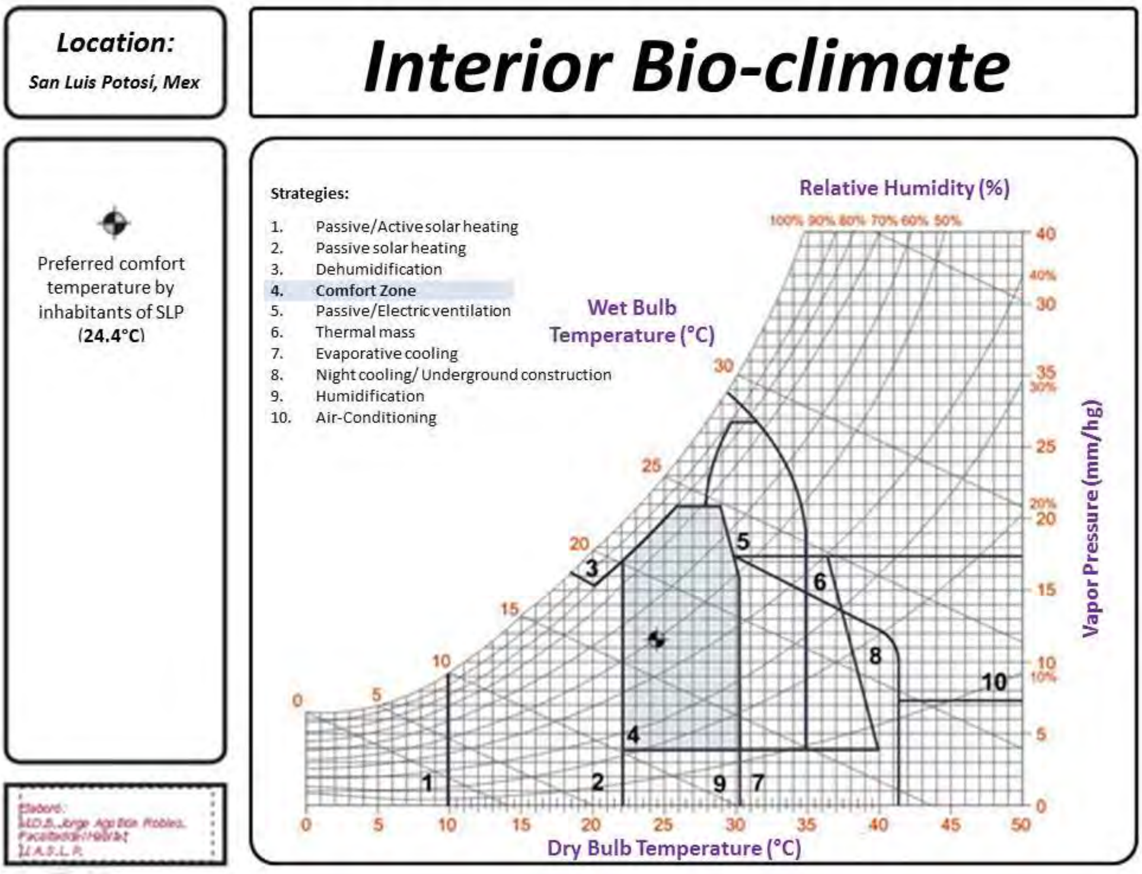
A good option for the actors involved in the construction sector to contribute with the sustainable development, and fulfill the requirements and demands from the official standards and programs, is to rely in *greener* architectural models such as bioclimatic architecture, which focuses on the right usage of local available materials, orientation of buildings and passive devices which require minimal dependency in fossil fuels to obtain comfortable levels, among others.

It is true that some extreme climate conditions will require active systems despite the passive considerations, but f architects "work out the passive design details, optimizing each space as appropriate to take advantage of natural ventilation and daylighting, and quantify thermal and visual comfort, they will also get a better understanding of the active systems needed to supplement the passive systems" (Autodesk, 2013). This way, instead of relying only in active devices, architectural configurations must focus on passive systems, or a combination of active and passive, to reach human comfort and reduce energy demand and, thus, the GHG emission and environmental impact in the construction sector.

3.1 Psychrometric Chart

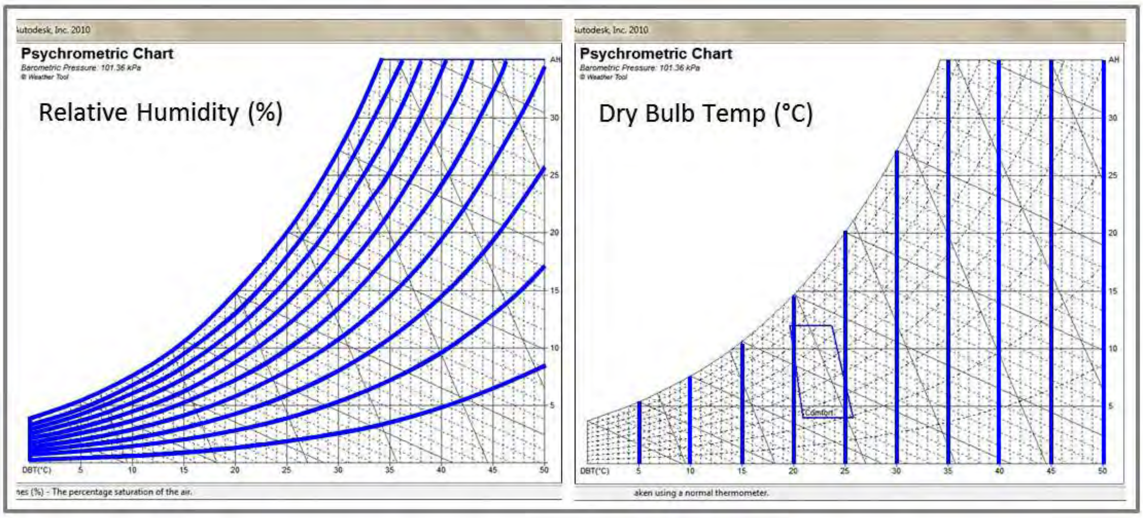
A useful tool to help decide the passive or active systems in a building is the psychrometric chart, proposed by de Steven V. Szokolay (Aguillón Robles, 2007)(See Figure 7). These charts, combine dry bulb temperature, relative humidity, wet bulb temperature and vapor pressure graphs. Aguillón Robles (2007) suggests performing the data analysis with an hourly basis of the average temperature and relative humidity of the site throughout the year. By finding the right position for the dry bulb temperature and relative humidity data (See Figure 8), the chart automatically indicates the rest of the information. Once the points are placed, it can be seen if they are located within the comfort zone box (number 4), or if they need a specific acclimatization strategy, either a passive or an active one.

Figure 7. Psychrometric chart for interior bio-climate



Source: (Aguillón Robles, 2007)

Figure 8. Relative humidity and Dry-bulb temperature in a psychrometric chart



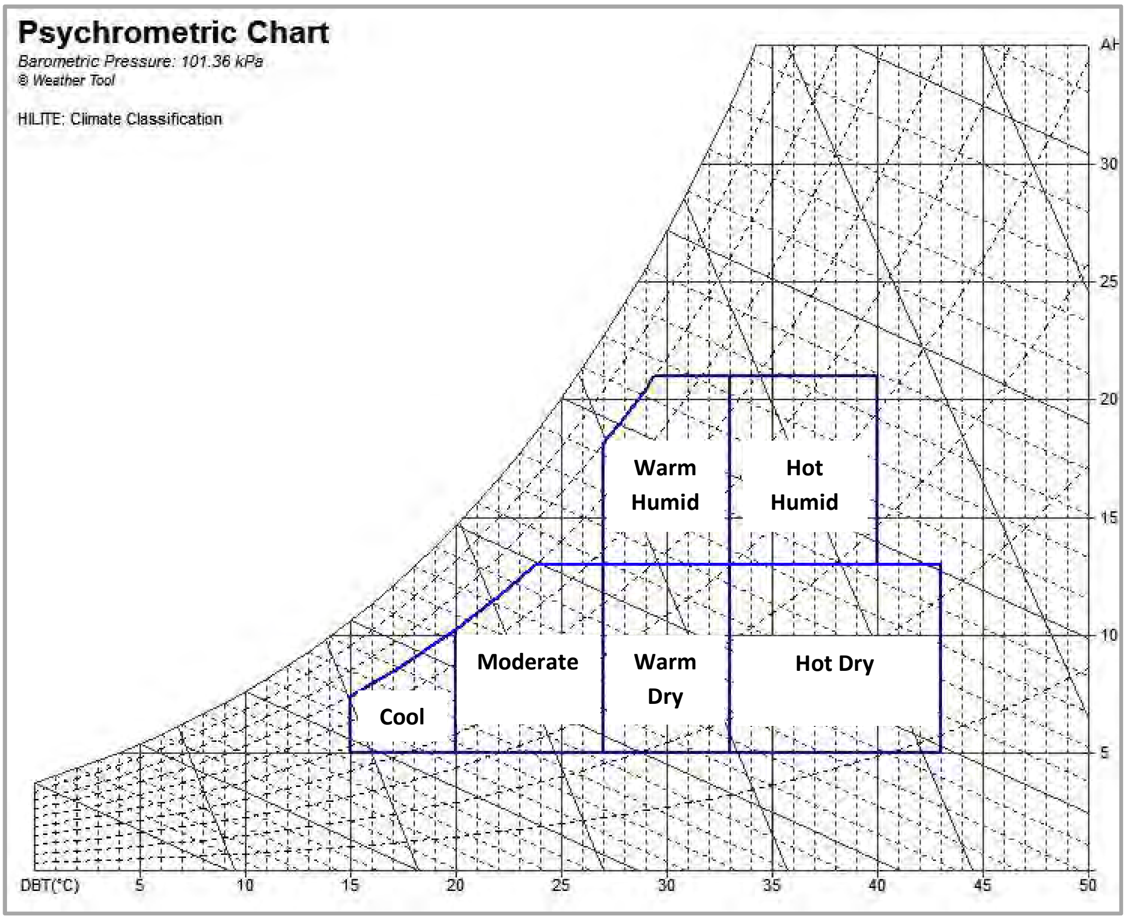
Source: (Autodesk Ecotect Weather Tool, 2014)

Dry bulb temperature is the ordinary air temperature, which can be measured with a regular thermometer. The relative humidity is the comparison of the amount of moisture present in a sample of air and the maximum amount of moisture that air can contain in a specific temperature. When relative humidity is 0 per cent, it means that the air is perfectly dry, and if it is 100 per cent, the air is fully saturated, meaning that it cannot accept any more moisture, resulting in condensation, mist or fog. The lines in the chart are curve because air can hold more moisture as it gets hotter. The bottom line represents 10% of humidity, increasing by 10% until the upper line, which represents 100% of humidity.

The relative humidity changes as the temperature of the air changes, therefore, heating the air lowers its relative humidity, while cooling the air increases it. It is convenient to maintain levels above 25% - to avoid affectations to the respiratory system, especially to the throat- and below 85% because above that level, people present difficulties to breathe (Rivera Vázquez, 2014).

Once the relative humidity and the dry-bulb temperature are graphed in the chart, the climate characteristics of the site can be determined. If the data lies in the upper part of the chart, it means that the weather is more humid; if it moves to the bottom, it means it is dryer. When it is located to the left, the weather is colder, while if it moves to the right, it is hotter. With these parameters, the Ecotect Weather Tool defines some climate classifications that can be seen in Figure 9.

Figure 9. Climate classification in Autodesk Ecotect Weather Tool

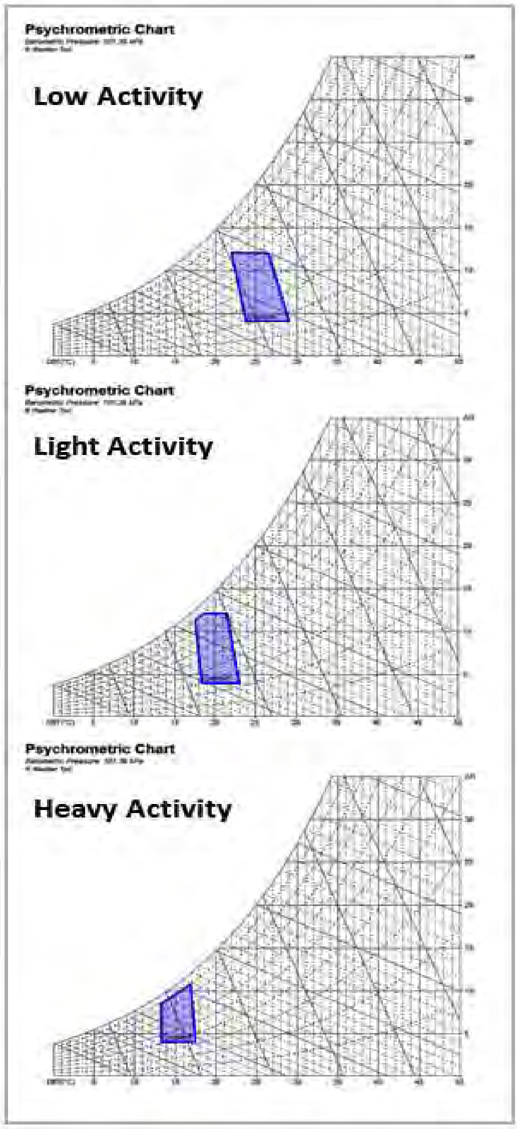


Source: (Autodesk Ecotect Weather Tool, 2014)

Among the possible acclimatization strategies presented in the chart, the following can be found:

1. Passive/Active solar heating
2. Passive solar heating
3. Dehumidification
4. *Comfort Zone*
5. Passive/Electric ventilation
6. Thermal mass
7. Evaporative cooling
8. Night cooling/ underground construction
9. Humidification
10. Air-Conditioning

Figure 10. Comfort zone relation with the activity level



Source: (Autodesk Ecotect Weather Tool, 2014)

It is important to mention that the comfort zone showed in Figure 7 highlights the preferred temperature of the inhabitants of the city of San Luis Potosí, México, within a sedentary activity. Some modelling tools, such as the Weather Tool of Autodesk Ecotect, allow setting the activity between low, sedentary, light, medium and heavy, and the movement of the comfort zone can be appreciated in real time (Figure 10).

As it can be seen in Figure 10, the comfort zone moves to the left with higher activity levels, meaning that the tolerable temperature is colder as the body gets warmer. This means that the activity intended to be performed in every internal space of a building, has an influence in the acclimatization requirement and, hence, in the design of the architectural components and acclimatization devices. For residential purposes, the considered activity levels are set between sedentary and light activity (Aguillón Robles, 1996).

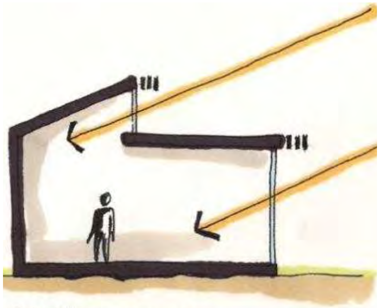
3.2 Passive Systems

A passive acclimatization system is a set of components that are related to the physical environment to give a solution to the problems that this could generate. These components make that an internal space of a building can reach a comfort temperature with minimum dependency on fossil fuels, as they are incorporated structurally to the building. They are product of an architectonic design appropriate for the climate conditions of the site, and they may include special devices for capture, distribution, storage and release of energy through radiation, thermal conduction or natural convection, helping reduce the final energy consumption of a building (Aguillón Robles, 1996). These systems are classified taking into account three aspects:

1. Structural configuration: defines the way they are incorporated to the structure of the building, integrating them into the architectonic design.
2. Acclimatization requirement: Depending on the climate conditions, the acclimatization requirements define whether the space requires heating, cooling, humidification, dehumidification and/or direct gain and solar protection.
3. Gender: it means if they are direct or indirect systems.

According to the structural configuration, some of the systems suitable for the climate conditions of the city of San Luis Potosí (Aguillón Robles, 2007) are:

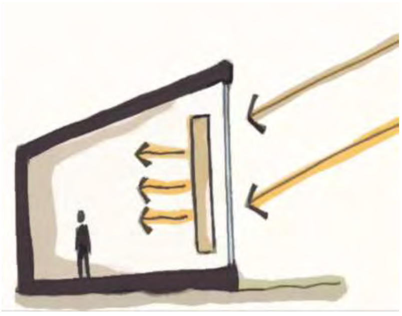
A. Direct Gain



This is the most basic principle of passive acclimatization systems and the easiest to handle, since it only requires the knowledge of the sun path to know where to let the sun inside the buildings and where to block it, depending on the requirements. This means that it doesn't require complicated components, other than the windows located in the right orientation, and their respective solar protection. With the right protection, windows obtain the maximum gains in winter, and minimal gains in summer due to the solar position in winter and summer solstices.

This way, in cold periods direct gain system takes advantage of the short-wave solar radiation that penetrates the spaces through a transparent cover-such as glazing- where it is absorbed by the internal surfaces, including walls, floors and furniture. The surfaces will absorb more radiation if they are made of a dark color. The heat is then dispersed as short-wave radiation through the air volume contained in the space, staying in the interior of the rooms.

B. Thermal Storage Wall



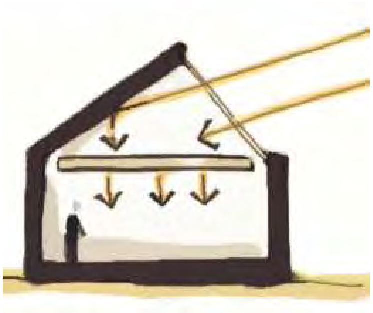
In this system, also known as *Trombe Wall*, the solar radiation passes through a transparent or translucent cover to the surface of a wall generally made of materials of high thermal mass such as concrete, brick, and water, orientated preferably to the south. Because of the greenhouse effect of the short wave radiation, the heat is captured in the space between the transparent surface and the wall. The latter absorbs the heat produced and stores it, releasing it to the interior spaces along the day. It can be equipped with openings on the top and bottom to help the circulation of the air.

If it gets too warm in the interior, the top opening allows the hot air go out the building by opening a window located on the transparent surface. In winter, the heated air flows to the space through the upper opening, sucking the cold air from the bottom opening and heating it with help of the glazing, creating this way a convective circuit. This way, thermal storage wall can be used for heating, cooling, dehumidification and to enhance natural ventilation.

C. Attached Solar Spaces

This system is also known as Indirect Gain, and it results from the combination between direct solar gain and the thermal mass wall. It consists of two thermal zones, being the first one a solar space for direct capture such as a greenhouse, and the second one, a space heated indirectly with the help of a thermal storage wall which divides both areas. Controllable openings on the greenhouse allow blocking the airflow and maintaining the warm air in cold periods, or enhancing the ventilation of the spaces in warm periods. The usage of vegetation helps improving the humidity of the spaces, the air quality, as well as the visual comfort, creating pleasant views for the users. A constraint for these kinds of systems is the space required to implement it, not making it suitable for social housing, which has strong space limitations.

D. Thermal Storage Roof and Heat Exchange



Thermal storage roof works with the same principle of the Trombe Wall, but in a horizontal position. The roof stores the solar radiation and transfers it to the interior spaces along the day. The advantage of this system is that, in hot periods, it can accumulate the heat produced in the interior of the building, since the warm air tends to rise, and dissipate it to the exterior through the windows located on the roof, in what is known as night cooling. Purging the excess heat can help cooling the building in a passive way. It requires good control of the openings to take advantage of free cooling but avoid overcooling.

E. Convective Circuit

It can be seen that in the previous systems, the convection principle is present as well. In this process, specific of the fluids –liquids and gases-, heat is transferred through a material by the bodily movement of particles, and it occurs when “a sample of fluid, such as air, is heated and so expands. The expanded air is less dense than the surrounding air and the cooler air displaces the warmer air causing it to rise” (McMullan, 1998). For buildings acclimatization, it can be achieved in a natural way in what is best known as the *stack effect*, or forcing it with active devices -such as a mechanical pump- to make the fluid flow faster.

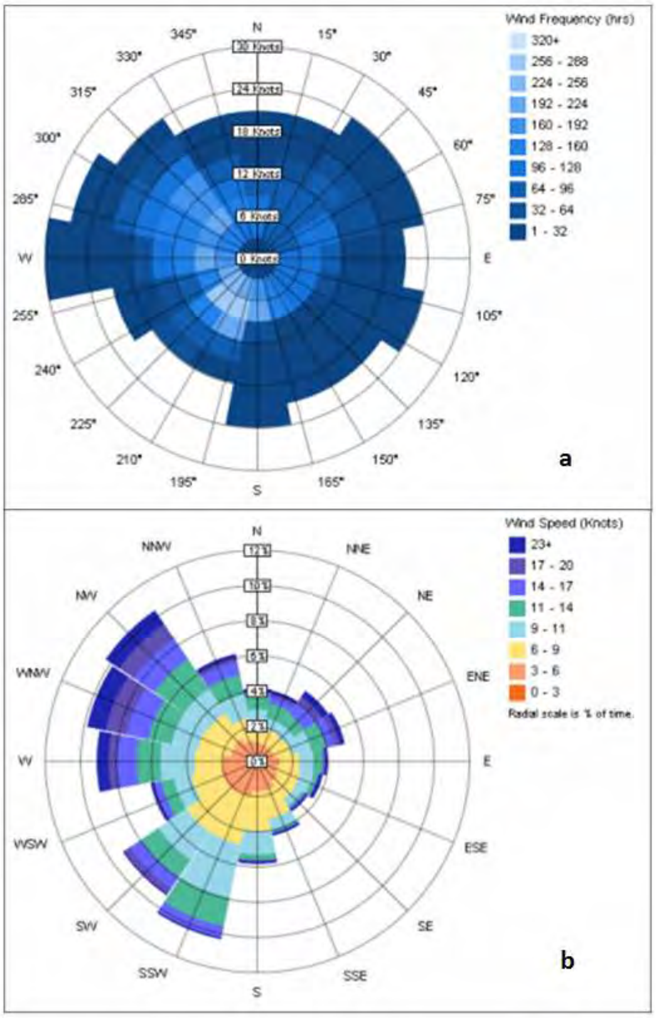
In this specific system, the solar collector and the thermal storage unit are separated areas, but they are connected by ducts, where, by natural convection, air is circulated from one space to another. This is the functional concept an EAHE.

F. Natural Ventilation

Wind is another source of energy that derives from the sun, since it is created by air currents produced in the atmosphere, principally by the difference of temperature caused by solar radiation (García Chávez & Fuentes Freixanet, 1995). The hot air tends to expand

and rise, while the cold air tends to sink due to its higher density. This produces a cycle characterized for having a direction, frequency and speed.

Figure 11 Wind roses representing frequency and speed



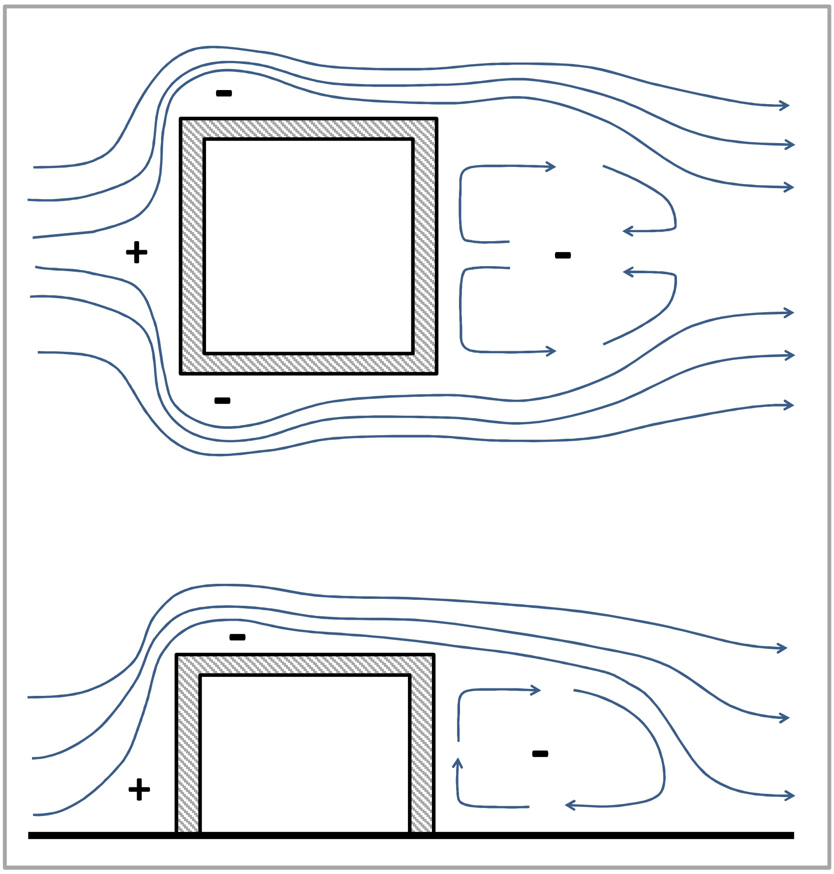
Source: (Autodesk, 2013)

The prevailing direction is that from where the wind blows with more frequency; the frequency is the percentage in which the air is presented in each one of the orientations; and the air speed is the distance covered by the airflow in a unit of time, usually expressed in the metric system as km/h or m/s, and in some cases in knots. These data is represented in a wind rose diagram as it can be seen in Figure 11. The direction is represented by the degrees as a compass, while the speed (Figure 11a) and frequency (Figure 11b) increase as they withdraw from the center.

"Wind cools buildings and people because it accelerates the rate of heat transfer" (Autodesk, 2013). Therefore, it is essential to understand its behavior to take advantage of the airflow and deliver natural ventilation in buildings in order to achieve passive cooling.

As the wind is a fluid, it behaves in the same way as water: when it meets an object, it will flow around it and continue with the same direction (Autodesk, 2013). As it hits a building, it creates a high pressure zone (windward) on the front façade; the wind goes around the building and increments its speed, creating zones of low pressure (leeward) on the side facades and on the back of the building (García Chávez & Fuentes Freixanet, 1995) (Mermet, 2005); (See Figure 12). This is helpful to know where to locate the windows, since air flows from high pressures to low pressures (Mermet, 2005). If solar control devices such as horizontal or vertical sunshades are placed, their location and configuration can create high or low pressure zones, which can affect the movement of the air on the inside.

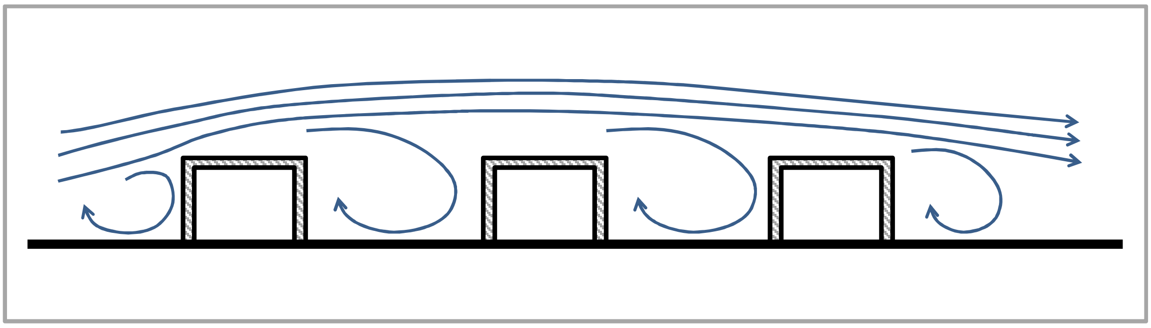
Figure 12. Wind behavior as it meets a building



Source: Self-construction based on García Chávez & Fuentes Freixanet (1995)

The big constraint of natural ventilation is that wind cannot be predicted in the same way as the sun path. In fact, wind direction and wind speed change within the same day and along the year, and it is highly influenced by the topography, vegetation and, in urban zones, by the layout of the buildings. If the layout of a housing unit is perpendicular to the prevailing wind, it can create *wind shadows* on the subsequent units (García Chávez & Fuentes Freixanet, 1995), which means that the air will flow above the rooftops, complicating the implementation of natural ventilation (See Figure 13).

Figure 13. Wind shadow on buildings layout



Source: Self-construction based on García Chávez & Fuentes Freixanet (1995)

With high buildings, maximum wind speed is achieved in greater heights; if the terrain is clear, it requires less height to achieve the same speed. Wind speed is a very important factor to consider for natural ventilation, since low speeds aren't able to cool the users, and high speeds can disturb them in their activities. Autodesk (2013) shows an adapted version of the *Beaufort Wind Scale* to compare wind speeds and their general effects (Table 6), while García Chávez & Fuentes Freixanet (1995) show the specific effects on the users of an interior space (Table 7).

Table 6. Beaufort wind scale: wind speed and its effects

Wind Speed	Description	Land Conditions
< 0.3 m/s	Beaufort #0 (Calm)	Smoke rises vertically
0.3 - 1.5 m/s	Beaufort #1 (Light air)	Smoke drift indicates direction; leaves are still
1.6 - 3.4 m/s	Beaufort #2 (Light breeze)	Leaves rustle; wind felt on skin
3.5 - 5.4 m/s	Beaufort #3 (Gentle breeze)	Leaves and small twigs moving; light flags extended
5.5 - 7.9 m/s	Beaufort #4 (Moderate breeze)	Small branches move; dust and loose paper rises
8 - 10.7 m/s	Beaufort #5 (Fresh breeze)	Moderate sized branches move; small trees sway
10.8 - 13.8 m/s	Beaufort #6 (Strong breeze)	Large branches move; umbrella hard to use
13.9 - 17.1 m/s	Beaufort #7 (High wind)	Whole tree moves; hard to walk against the wind

17.2 - 20.7 m/s	Beaufort #8 (Gale)	Twigs break from tree; extremely difficult to walk in wind
20.8 - 24.4 m/s	Beaufort #9 (Strong gale)	Branches break from tree; small trees blow over
24.5 - 28.4 m/s	Beaufort #10 (Storm)	Trees broken or uprooted; structural damage imminent
28.5 - 32.6 m/s	Beaufort #11 (Violent storm)	Widespread vegetation and structural damage
≥ 32.7 m/s	Beaufort #12 (Hurricane force)	Severe widespread vegetation and structural damage

Source: (Autodesk, 2013)

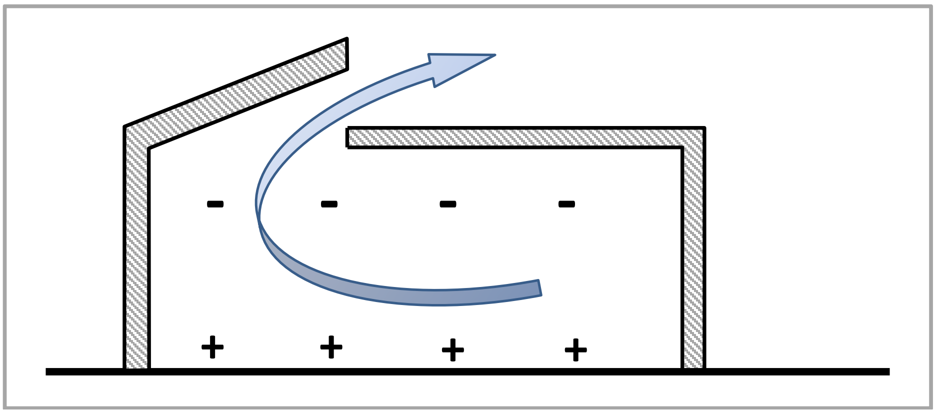
Table 7. Wind speed and comfort class for different activity levels

Speed (m/s)	Mechanical effect	Effect on users	Cooling effect on dry skin			
			15°C	20°C	25°C	30°C
0.10	Minimal in domestic level	Suffocation feeling	0	0	**0**	**0**
0.25	Cigarette smoke indicates movement	Air movement is imperceptible unless its temperature is low	2	1.3	**0.8**	**0.5**
0.50	Light a candle	It feels fresh in comfortable temperatures, but uncomfortable in low temperatures	4	2.7	**1.7**	**1.0**
1.00	Loose paper moves; equivalent to walking speed	Pleasant sensation in comfortable or warm temperatures; it causes high movement sensations. It is the maximum acceptable level for night comfort	6.7	4.5	**2.7**	**1.7**
1.50	Too fast for office work; paper flies	Uncomfortable in comfortable temperatures. Maximum comfort limit for interior activities	8.5	5.7	**3.5**	**2.0**
2.00	equivalent to the speed of walking fast	Acceptable only in very hot and humid conditions	10	6.7	**4.0**	**2.3**

Source: (García Chávez & Fuentes Freixanet, 1995)

Understanding the horizontal movements of the air is useful in order to give a passive solution to the acclimatization of buildings, taking advantage of the prevailing winds to allow or block the airflow towards its interior -depending on the seasonal requirements- and taking care on how the wind speed can affect the users and their performance. Nevertheless, the wind can also move vertically due to the convection principle in what is known as the chimney or stack effect. When speaking of convective winds, a reference is made to the ascending and descending movements of the air created due to the local temperature differences (García Chávez & Fuentes Freixanet, 1995). These temperature differences create a pressure gradient which forces the hot air with lower density to raise (buoyancy) and the colder, denser air to sink (See Figure 14).

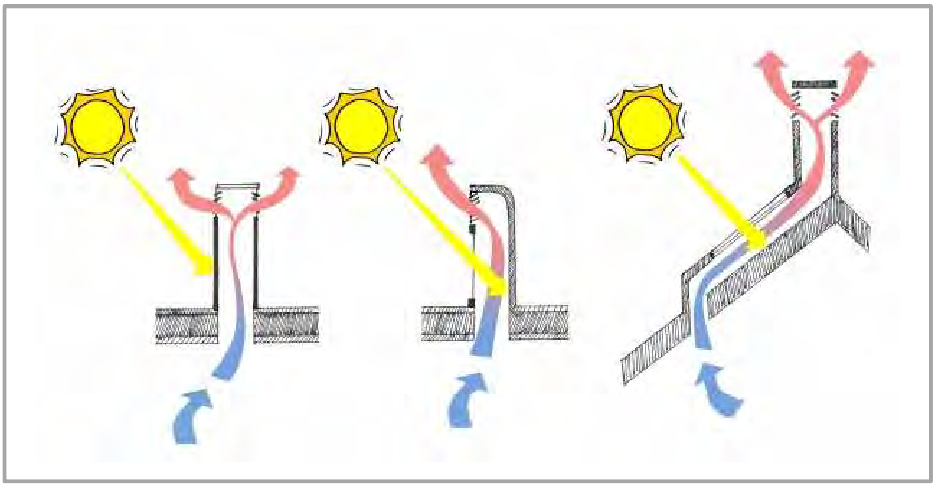
Figure 14. Air movement due to pressure gradients (Stack effect)



Source: Self-construction based on García Chávez & Fuentes Freixanet (1995)

The stack effect can be exploited with wind towers, solar chimneys or sloping roofs which can direct more effectively the ascending warm air towards a skylight or an opening on the top, where the external wind can pull it to the outside, enhancing the airflow in the interior of the building. “The most important consideration is to have a large difference in height between air inlets and outlets” (Autodesk, 2013). If the solar chimney is covered with a dark surface, such as black paint, it can take advantage of the solar radiation, heating the air underneath it and accelerating the airflow (See Figure 15).

Figure 15. Designs of solar chimney



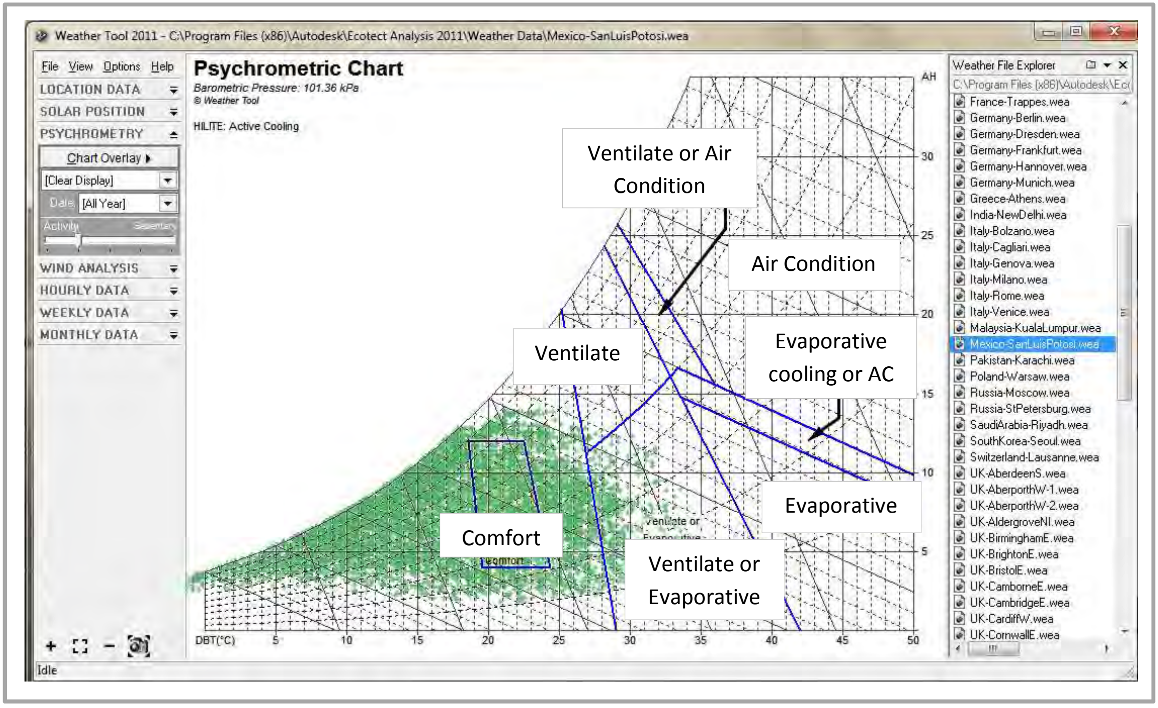
Source: (Autodesk, 2013)

3.3 Active Systems

In some regions of the world, especially outside the tropics, weather conditions are more extreme, and season changes are stronger, with colder winters and warmer summers. Under these conditions, it is almost impossible to heat or cool a building merely with natural, passive strategies, and the usage of active devices is crucial. These devices require an energy input, which usually comes from fossil fuels, increasing the energy consumption of a building and its GHG emissions. As it was said before, poor design decisions in buildings, such as incorrect materials, wrong space distributions and orientations, or bad sizing of elements such as glazing, can make that, even in moderate climates, buildings require these active devices to reach the desired temperature in a room.

Active devices for heating include radiators, radiant floor systems, electric or gas heaters, among others. Cooling devices can go from a simple fan to mechanical ventilation or complex air conditioning systems. Heat pumps are used for both, heating and cooling. A list of active strategies included in Ecotect's Weather Tool is shown in Figure 16. Engineers Specialized in heating, ventilation and air conditioning (HVAC) are in charge of calculating these systems depending on the demands of every room, taking into account its characteristics such as U-Values, dimensions and orientation.

Figure 16. Active systems in the psychrometric chart



Source: (Aguillón Robles, 2007) (Autodesk Ecotect Weather Tool, 2014)

Fans are highly used in residential sector, since they can solve problems regarding thermal comfort without requiring special architectural modifications, nor high investment in the appliance, although it increases the electricity consumption. The purpose of using a fan is to move the air of a room and create a wind-chill effect among its users, as the air in movement over the skin increases the evaporation, cooling the body. This means that fans don't cool rooms, but people. Therefore leaving a fan on when a room is empty not only will not cool the room, but its motor can act as a heat output that might rise the temperature of the room. If the air temperature is very high, even its movement won't be enough to cool the users, needing a more complex device such as an air conditioner.

Air conditioning systems have several components that allow controlling internal air temperature and humidity, despite the variation of the external air conditions (McMullan, 1998). These systems are equipped with an indoor coil called *evaporator* and a *condenser* -a hot outdoor coil- which releases the collected heat outside. These components are connected with a serpentine tube made of copper and surrounded by aluminum fins. With help of a pump known as compressor, it moves a heat-transfer fluid called refrigerant between the evaporator and the condenser. The refrigerant evaporates in the evaporator coil and pulls heat out of indoor air, cooling the internal spaces. The hot refrigerant gas is pumped out into the condenser where it returns to a liquid state, releasing its heat to the outside air (DOE, 2012). As McMullan (1998) states, “it is important to note that air conditioning plants use significant amounts of energy”.

Nowadays, the usage of air conditioning is increasing indiscriminately, with world sales that in 2011 increased 13 per cent over the registered in 2010, and a tendency of this growth to continue accelerating (Cox, 2012). Some devices are improving to be more energetically efficient such as the ENERGY STAR rated. “ENERGY STAR is a voluntary energy awareness program developed by the U.S. Department of Energy and the Environmental Protection Agency (EPA). These high-efficiency systems are labeled ENERGY STAR to identify products that are at least 15% more efficient than standard products (YORK, 2014).”

The release of more efficient air conditioning systems in the United States has incited the replacement of old units so that the users can comply with the new regulations and energy efficiency standards. A lot of the replaced units are sold in Mexican border cities at lower prices than those of the new and more efficient units. Because of this, a lot of low-income Mexican families acquire these air conditioning systems, which represent a saving in the initial investment, but, due to the inefficiency, in long term their energy consumption is higher and so are the electricity bills, the environmental impact and the health risk of these families.

3.4 Hybrid Systems

One of the most rigorous standards regarding energy efficiency in building acclimatization and energy efficiency is the PHPP, which dictates that a building’s heating and cooling demand should not exceed 15kW/m^2 per year each. These values can only be achieved if the building is designed properly with passive considerations to reduce the load of the active devices when they are necessary. The combination of passive systems with active devices to support them is known as hybrid or mixed systems. This combination allows more energetic efficiency, lowering the excessive usage of active systems ((Rivera Vázquez, 2014)

Givoni (1994) affirms that “the term passive does not exclude the use of a fan or a pump when their application might enhance performance. Even when mechanical devices are used, their coefficient of performance (COP) - the energy input per unit of cooling that is obtained within the building- is much higher than the common value in air conditioning”

(Givoni, 1994). Nevertheless, most of the literature regarding passive acclimatization focuses just in systems that are integrated to the structure of a building and which don’t require any external input.

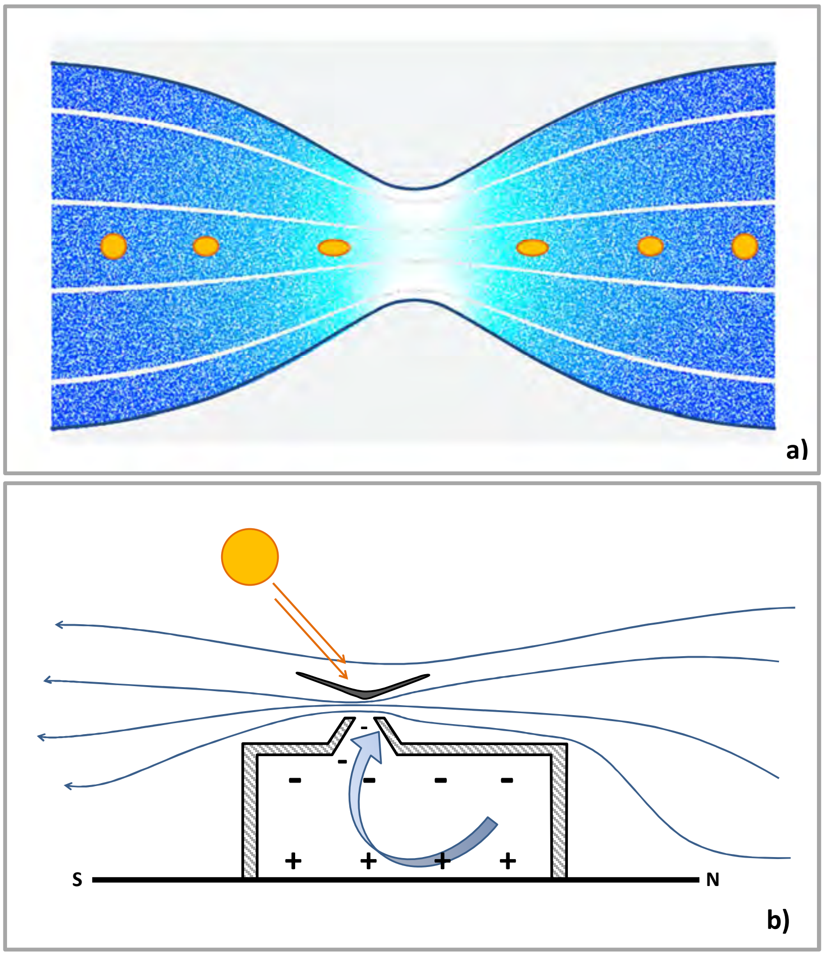
In this research project it is going to be considered a hybrid system as a combination of passive strategies and strategies which require an energy input. The proposal for the design of an acclimatization system for the city of San Luis Potosí contemplates to integrate an EAHE with another passive strategy such as the solar chimney to enhance the stack ventilation and, hence, the indoor airflow in social housing units to stimulate comfort ventilation in a natural, passive way.

The constraint of passive acclimatization systems is that they depend fully from the weather conditions, and, if a cloudy day avoids the full usage of the solar chimney, or the wind comes from another direction because of a special phenomenon, the desired ventilation effect won’t occur. Because of that, the design of the EAHE is thought as a hybrid system provided with a 230W fan which can extract the air from the underground ducts, enhancing the airflow when the natural conditions are not satisfactory to make the air flow in a specific velocity any time of the year.

Besides, if the wind shadow described on Figure 13 is considered, the solar chimney can take advantage of the wind flowing above the rooftops, directing it through the chimney’s outlet, in order to suck the interior air and enhance the indoor airflow inside the housing unit, stimulating comfort ventilation in a passive way to restrict the active usage of the fan when possible.

The proposed solution is to take advantage of the *Venturi* effect (See Figure 17a), which states that the wind’s velocity increases when the wind is directed and compressed by a reduced cross-section (García Chávez & Fuentes Freixanet, 1995) (McMullan, 1998). By Bernoulli’s principle, air with more speed has lower pressure (McMullan, 1998); therefore, the air coming from inside the house will flow from higher to lower pressure, helped by the low pressure of the air heated by the solar chimney and the low pressure of the air flowing through it with more velocity (See Figure 17b).

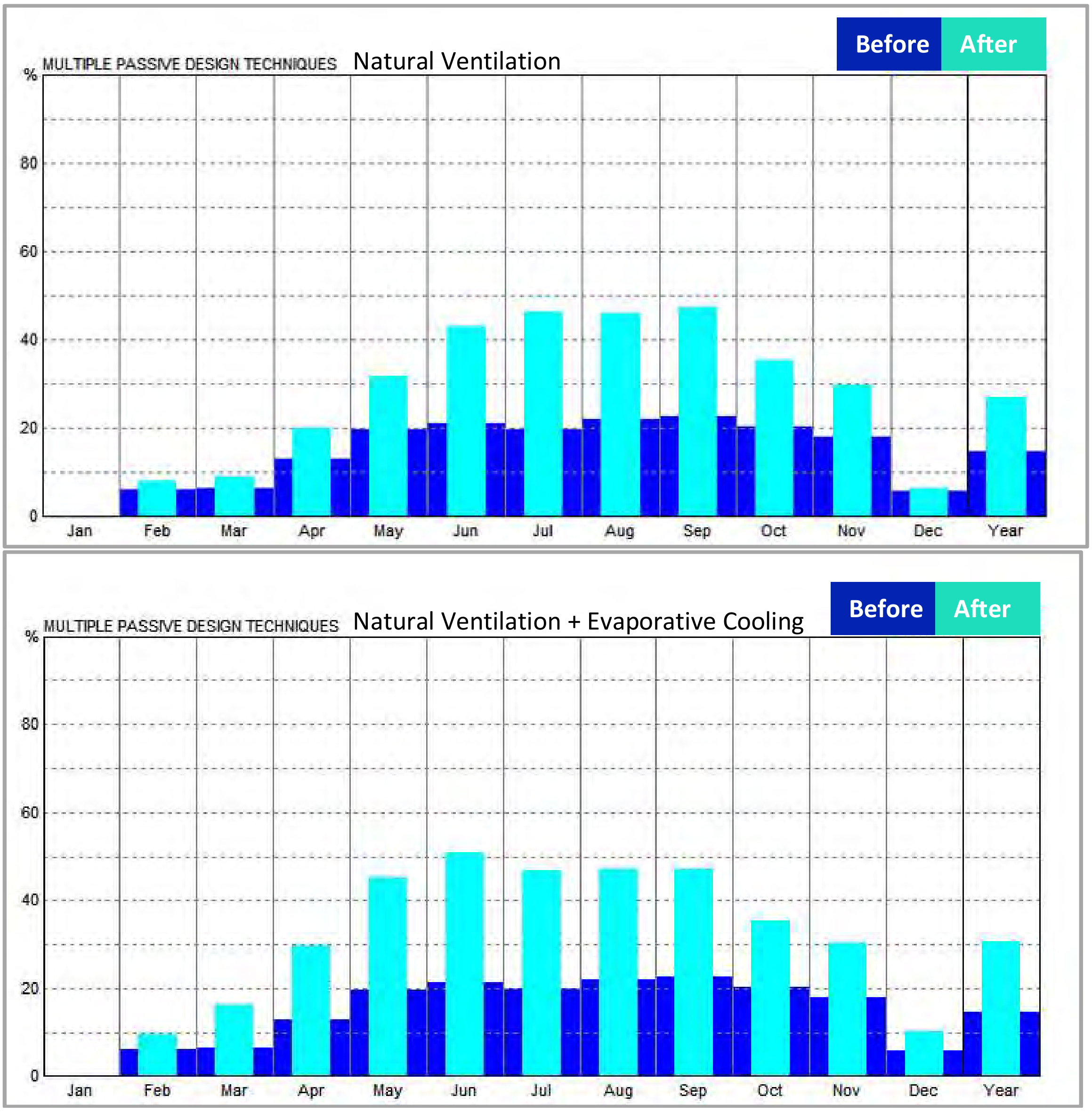
Figure 17. Venturi effect applied to a solar chimney



Source: (Wikipedia, 2014); Self-construction, 2014

Another possible combination of an active device with the EAHE –which is out of the scope of this master thesis-, is an evaporative cooler at the outlet, which is within the recommendations of Ecotect’s Weather Tool. Bansal, et al. (2011) proved that an EAHE itself could provide 4500 MJ of cooling effect in summer, while an additional 3109 MJ were achieved by integrating an evaporative cooling. A percentage of comfort along the year using only natural ventilation and natural ventilation combined with evaporative cooling is shown in Figure 18. As it can be seen, only with natural ventilation, the comfort is increased in summer by nearly 50%. The addition of evaporative cooling strategy increases the comfort especially in spring, in the months of April, May and June, which tend to be the hotter months in the city.

Figure 18. Comfort percentage before and after acclimatization strategies

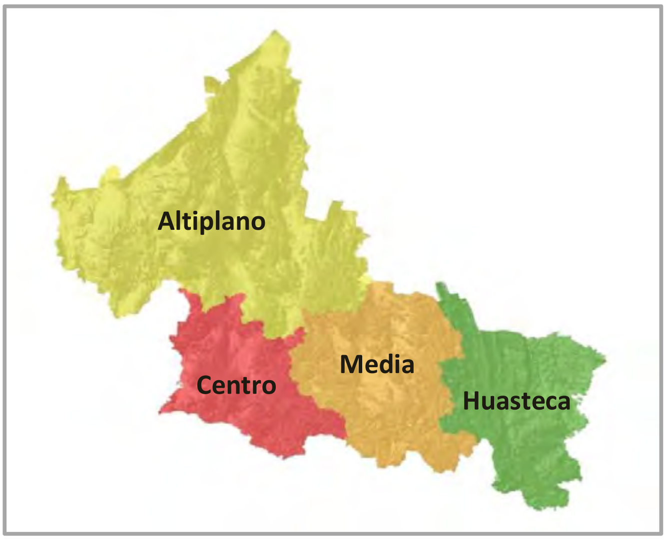


Source: (Autodesk Ecotect Weather Tool, 2014)

4. Geographical Context of the City of San Luis Potosí

The State of San Luis Potosí is located in the central-eastern part of the Mexican country, with a total extension of 61,137km2, representing the 3.22% of the national surface. Its geographic coordinates are: 24.48° N, 21.16° S, 98.33° E, and 102.3° W. It is divided in four regions: Altiplano, Centro, Media and Huasteca (See Figure 19). The mountain range called Sierra Madre Oriental crosses a great portion of its territory in a northeast-southeast direction. This mountain range blocks the rainfall from the northern Gulf coastal plain, located to the east of the State, causing a climate variation in its different regions because of the rainfall *shadow* effect created on the northern-western area, where precipitation is scarce and intermittent. The climate diversity in the State goes from dry, semi-dry, warm, and in some regions, very dry, temperate and semi-cold (Rivera Vázquez, 2014).

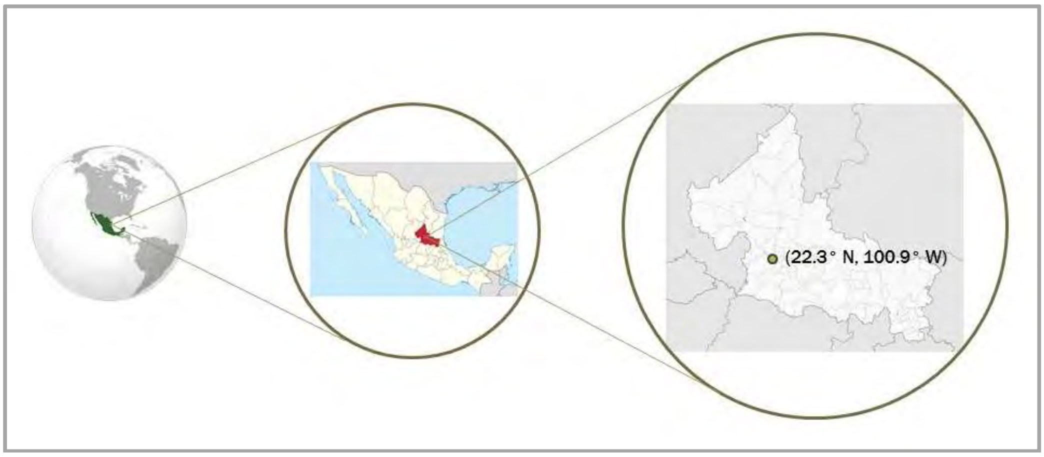
Figure 19. Regions of the State of San Luis Potosí



Source: http://cienciastierra.uaslp.mx/siia/siia.html#

The city of San Luis Potosí is the capital of the State, and it is located in the center region, with geographic coordinates of 22.3°N, 100.9°W (See Figure 20) and an altitude of 1887masl. This region is characterized by a temperate-dry climate with rainfall in summer. In this kind of climate, mean temperatures can range between 12°C and 18°C and the temperatures of the coldest month can be set between -3°C and 18°C, and the hottest month above 18°C. Total annual precipitation is approximately 300mm (Rivera Vázquez, 2014). The data presented in this chapter comes from weather stations from the Faculty of Engineering of the UASLP, the National Institute of Forestry, Agriculture and Livestock Investigations (Instituto Nacional de Investigaciones Forestales, Arícolas y Pecuarias, INIFAP) and the weather file from the Autodesk Ecotect software, obtained through the software Meteonorm.

Figure 20. Geographical location of the city of San Luis Potosí



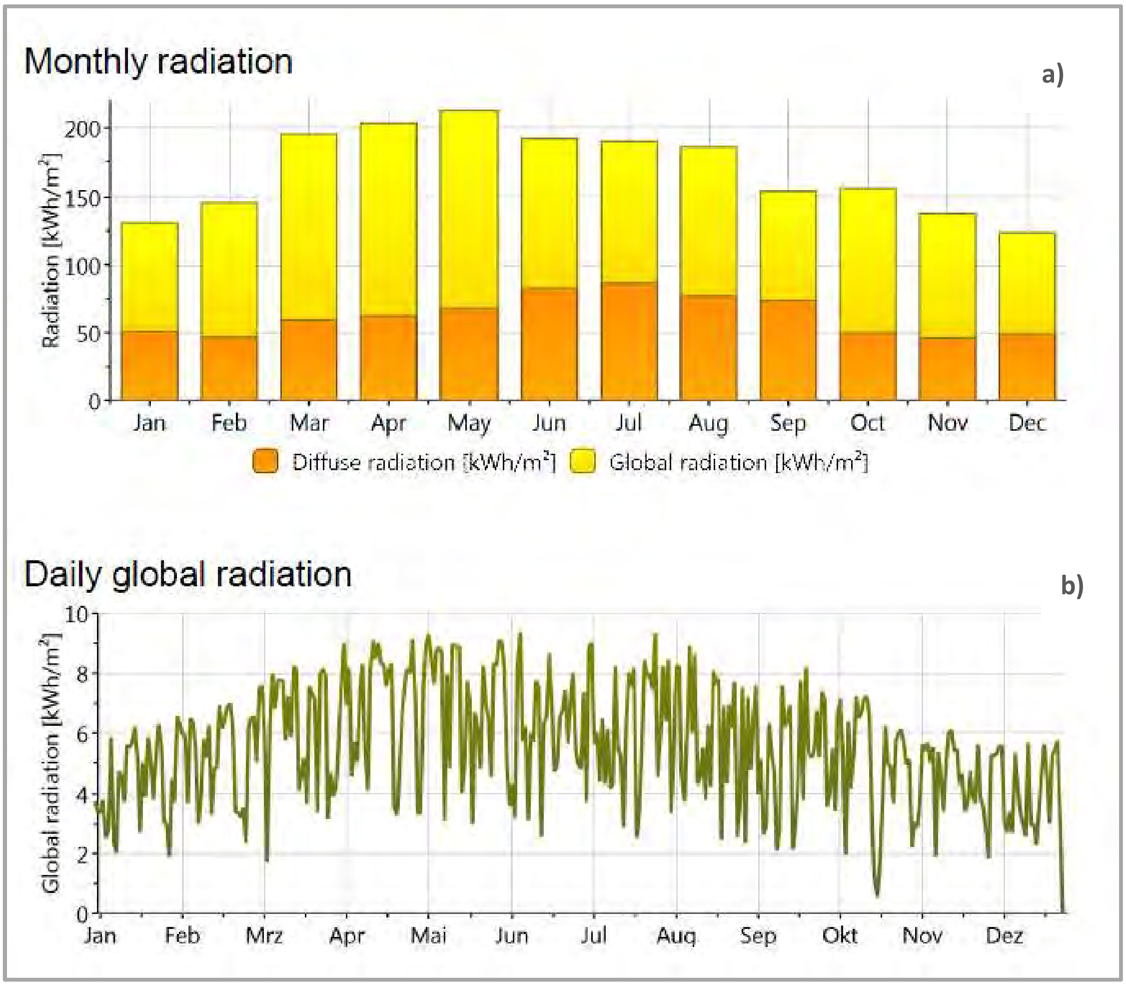
Source: Self-construction based on http://www.wikipedia.org/

4.1 Solar Radiation

Solar radiation is the amount of solar energy that receives a horizontal surface, although it can also be measured in vertical planes, or facades, depending on their orientation (N, S, E, and W). Solar radiation is measured in kWh/m^2, and it is divided in a) direct solar radiation, or the rays that come directly from the sun (solar rays) and b) diffuse radiation, when the direction of the solar rays is modified by atmospheric density or other particles (sky radiation). It can vary depending on the latitude, altitude, climate and cloudiness or atmospheric pollution. It is directly responsible on the temperature of a given location, since the latitude determines the incidence of the solar rays, being more perpendicular and more intense on latitudes near the equator and less intense on latitudes near the poles. It has many applications in the daily life, such as water heating, air heating and electricity production through photovoltaic panels.

Figure 21a shows the data registered by Meteonorm for the monthly global and diffuse radiation of this latitude, while Figure 21b shows its daily global radiation. Aguillón Robles (2007) states that an average of 6.3kWh/m^2 day is received in the territory of the city of San Luis Potosí. As it can be seen in Figure 21a, May registers the most solar radiation with more than 200kWh/m^2, which, divided by 31 days is consistent with the data of Aguillón Robles (2007). On the other hand, December receives the less solar radiation, with an average of 125kWh/m^2, or 4.03kWh/m^2 every day.

Figure 21. Monthly and daily global radiation in SLP

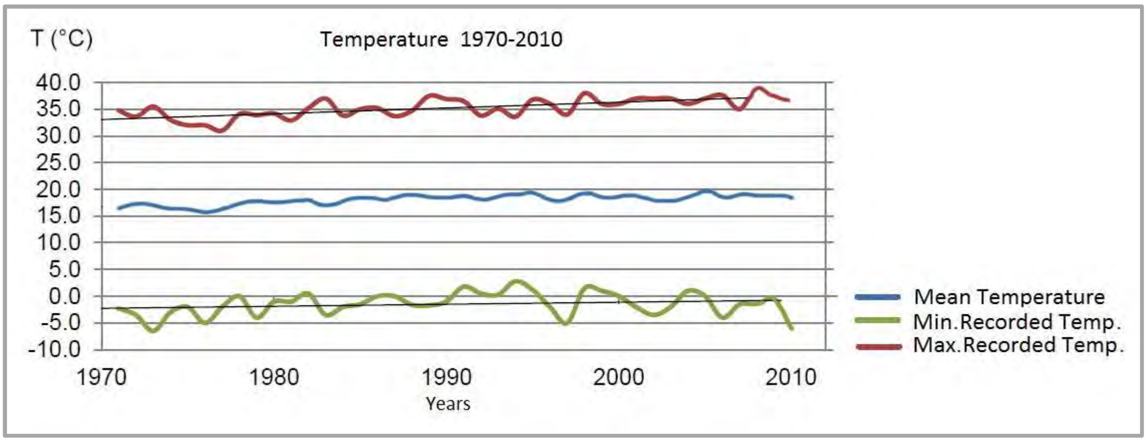


Source: Meteonorm (2014)

4.2 Temperature

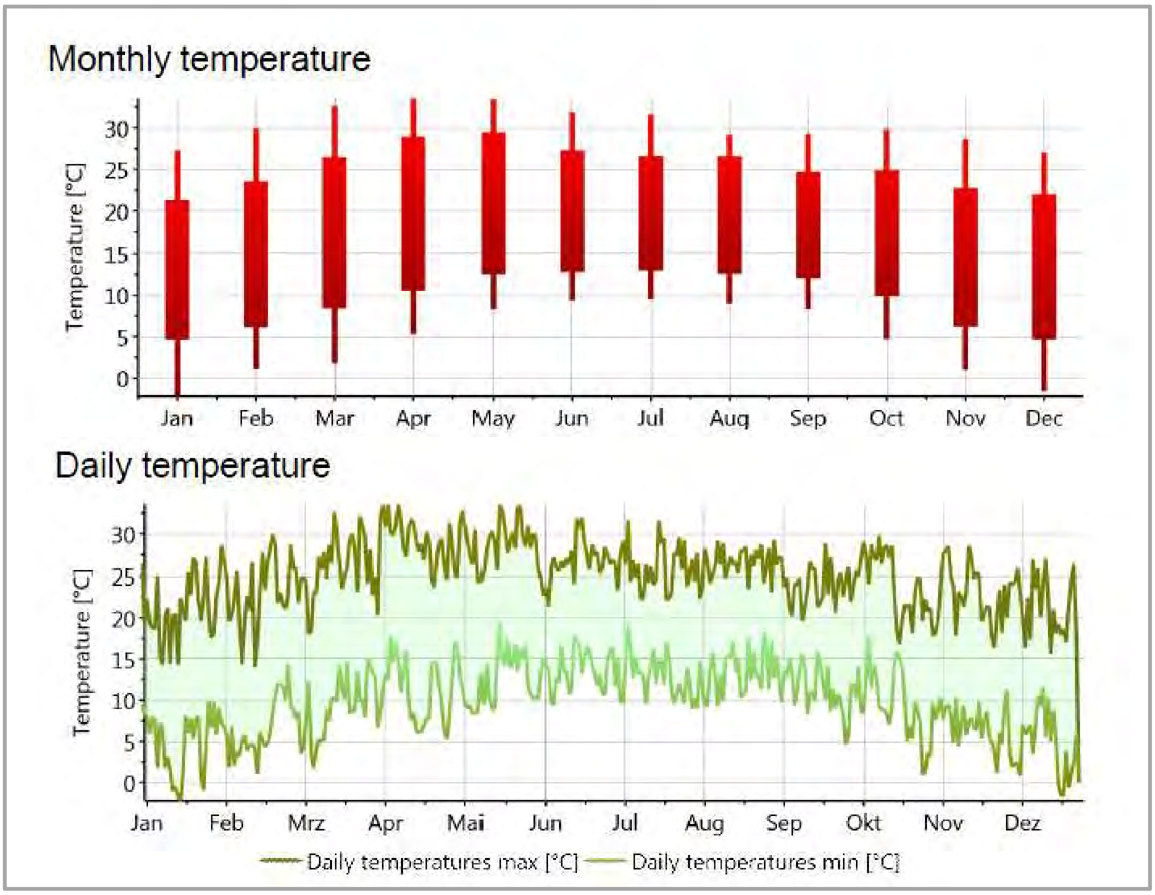
As it can be seen in Figure 22, historical records of temperature from 1970 show that the average temperature in the city is between 17 and 19°C, maximum recorded temperatures above 35°C and minimum recorded temperatures up to -5°C. According to Aguillón Robles (2007), the mean temperature of the city is 18.2°C and the mean annual thermal oscillation is 15°C. This means that in a day, a variation of temperature of an average of 15°C can be experienced. For inhabitants of San Luis Potosí it is normal to experience cold mornings, hot evenings and cool nights.

Figure 22. Historical records of temperature 1970-2010



Source: (Rivera Vázquez, 2014) with data from INIFAP and UASLP

Figure 23. Monthly and daily temperature data from Meteonorm

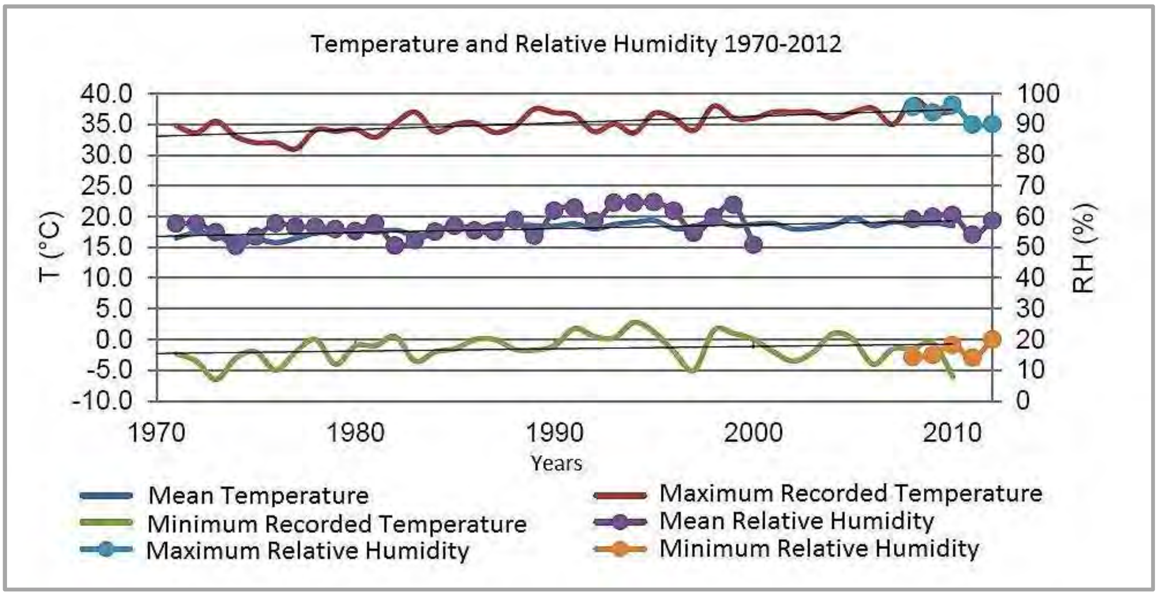


Source: Meteonorm 2014

4.3 Relative Humidity

García (2001) quoted by Rivera Vázquez (2014) affirms that for a thermal comfort zone, relative humidity must be between 30 and 70%, whereas the optimal zone is found between 40 and 60%. Levels under 30% make possible the growth of bacteria and viruses, and some respiratory issues such as asthma and infections in the respiratory system. Levels above 70% also enhance the growth of bacteria and viruses, but also mites and fungi. Figure 24 shows that the historical records of mean relative humidity set this value between 50-70%. The maximum and minimum values have been registered only since 2008 and some of the data shows values of above 90% and minimum values below 20%, ranges that are outside of the acceptable limits (Rivera Vázquez, 2014).

Figure 24. Historical records of temperature and relative humidity in SLP 1970-2010



Source: (Rivera Vázquez, 2014) with data from INIFAP and UASLP

4.4 Degree-Days in San Luis Potosí

“Accumulated degree-days” is a method used to know the heating or cooling requirements of a location. It is calculated with a base temperature -such as the minimum or maximum comfort temperature- as a reference to count the degrees outside the comfort zone and the number of days for which that temperature difference occur (McMullan, 1998). If the temperature registered is above the maximum comfort temperature, it counts as cooling degree-days, and if it is below the minimum comfort temperature, it is counted as heating degree-days. Two days with 1°C below the minimum comfort zone represent 2 heating degree-days, while one day with 2°C below, also represent 2 heating degree-days (McMullan, 1998).

Table 8 shows the heating degree-days below the 19°C minimum comfort temperature acceptable for the inhabitants of the city of San Luis Potosí and cooling degree days above the 27°C maximum comfort temperature in every season (See Table 11), as well as the accumulated heating and cooling degree-days along the year:

Table 8. Heating and cooling degree-days in the city of SLP

Season	Heating Degree Days	Cooling Degree Days
Spring	564	173
Summer	460	50
Autumn	919	0
Winter	1062	0
Annual	**3005**	**223**

Source: (Aguillón Robles, 2007)

As it can be seen, the city of San Luis Potosí requires heating strategies all the year with 3005 accumulated degree-days, against the 223 cooling degree days required just in spring and summer. Table 9 and Table 10 express the thermal sensation related to the temperature and the relative humidity combination. Sometimes the air temperature might be within a comfort zone, but the relative humidity might be too low or too high, creating the sensation of discomfort. These tables show that most of the uncomfortable sensations are below the minimum comfort temperature of 19°C, especially in the night, between 20h and 9h -even in summer period- while difficult environments or sultriness and dry heat are not found in any season.

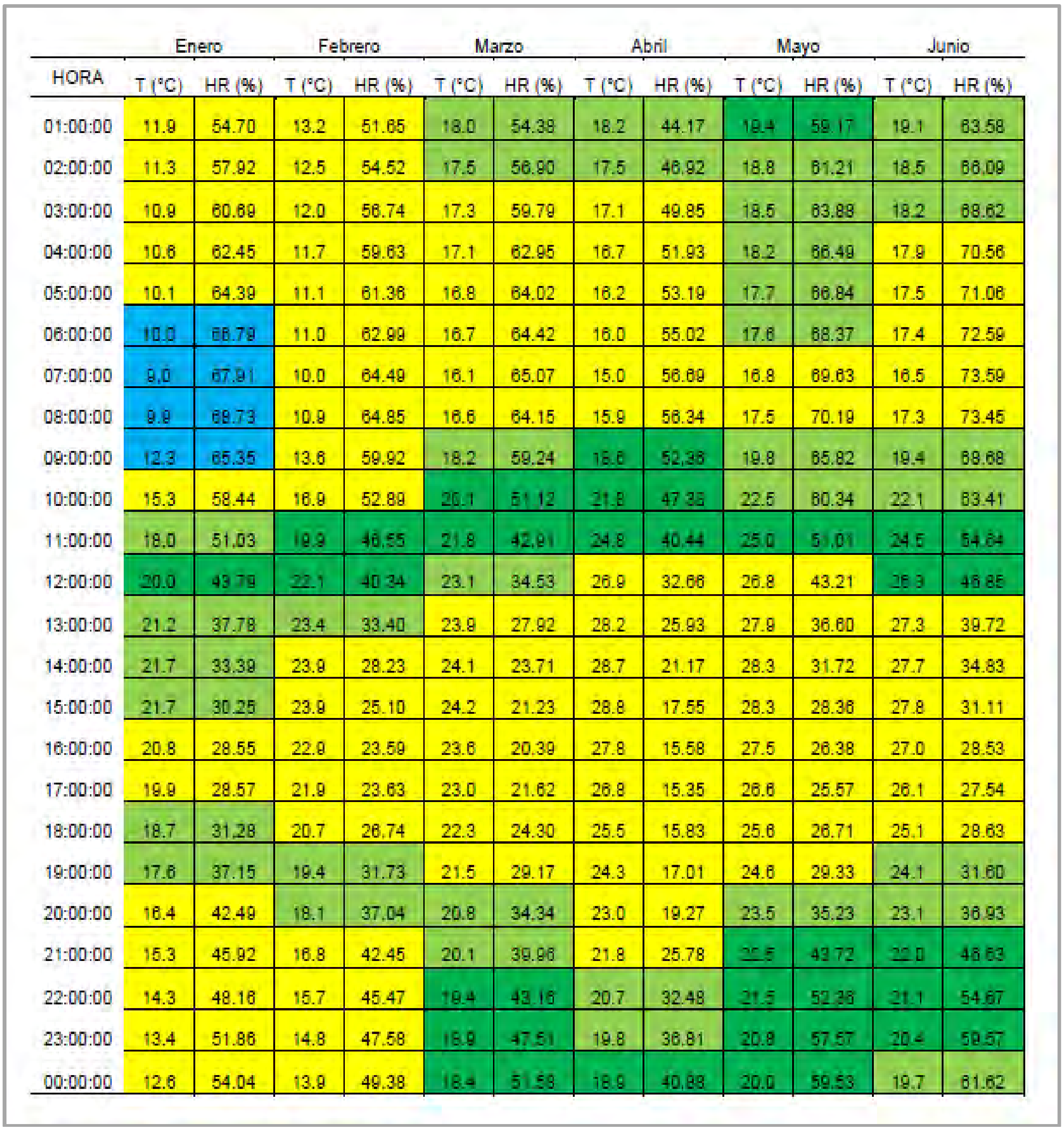
Table 9. Thermal sensation in relation with temperature and relative humidity

Thermal Sensation	T (°C)	RH (%)
Optimal Comfort (min. limit)	18.3 – 23.3	40 – 60
Optimal Comfort (max. limit)	21.0 – 26.6	40 – 60
Acceptable Comfort	17.4 – 23.3	30 – 40
Acceptable Comfort	21.0 – 26.6	60 – 70

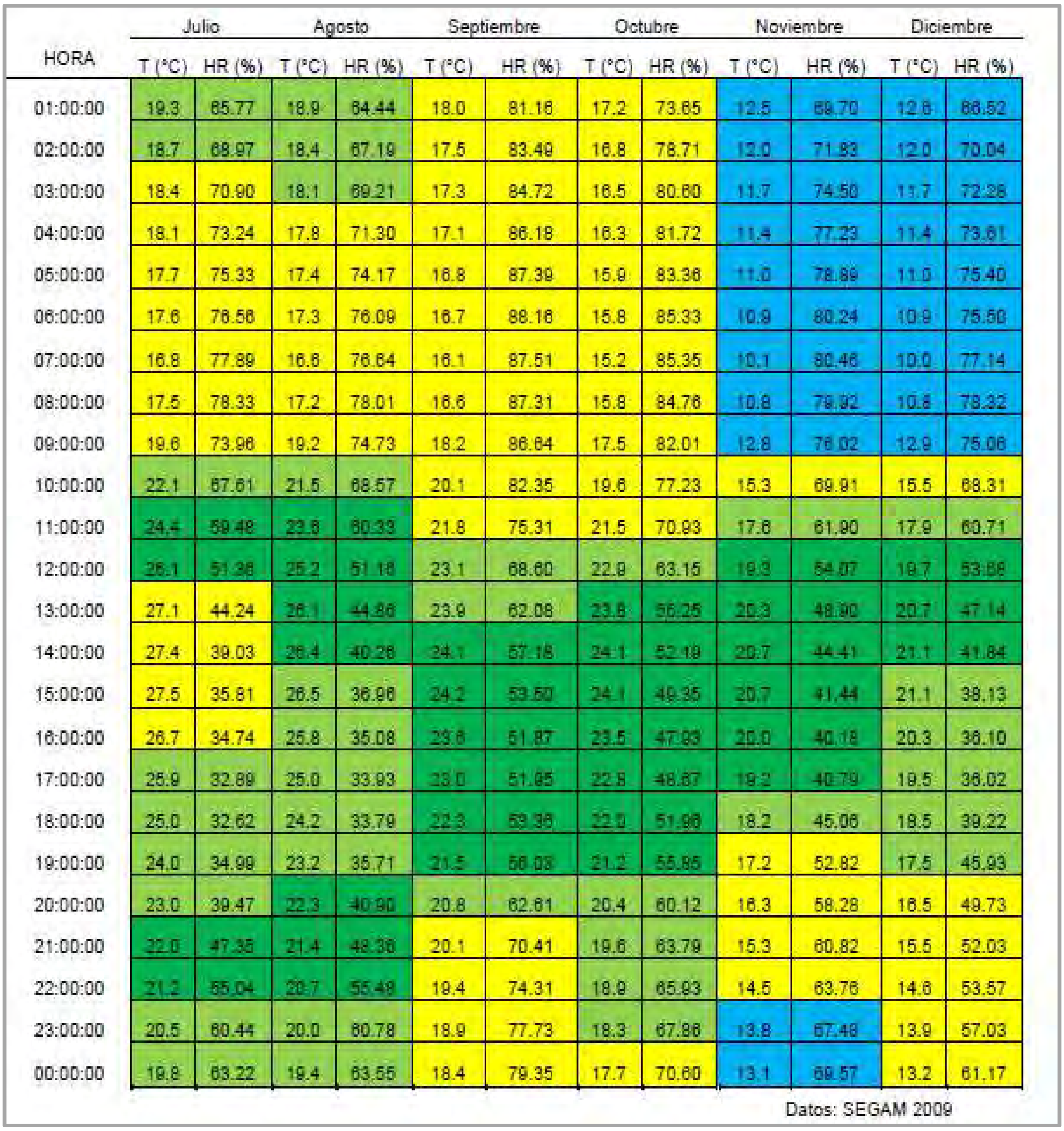
Uncomfortable	≠17.4 – 26.6	≠ 30 – 70
Difficult Environment	T > 37.5	70 <HR> 25
Cold and humid	T < 15	65 <HR> 25
Sultriness and Dry Heat	T > 35	70 <HR> 25

Source: (Rivera Vázquez, 2014)

Table 10. Monthly mean temperature and relative humidity of SLP



	Enero		Febrero		Marzo		Abril		Mayo		Junio	
HORA	T (°C)	HR (%)	T (°C)	HR (%)	T (°C)	HR (%)	T (°C)	HR (%)	T (°C)	HR (%)	T (°C)	HR (%)
01:00:00	11.9	54.70	13.2	51.65	18.0	54.38	18.2	44.17	19.4	59.17	19.1	63.58
02:00:00	11.3	57.92	12.5	54.52	17.5	56.90	17.5	46.92	18.8	61.21	18.5	66.09
03:00:00	10.9	60.69	12.0	56.74	17.3	59.79	17.1	49.85	18.5	63.89	18.2	68.62
04:00:00	10.6	62.45	11.7	59.63	17.1	62.95	16.7	51.93	18.2	66.49	17.9	70.56
05:00:00	10.1	64.39	11.1	61.36	16.8	64.02	16.2	53.19	17.7	66.84	17.5	71.06
06:00:00	10.0	66.79	11.0	62.99	16.7	64.42	16.0	55.02	17.6	68.37	17.4	72.59
07:00:00	9.0	67.91	10.0	64.49	16.1	65.07	15.0	56.69	16.8	69.63	16.5	73.59
08:00:00	9.9	69.73	10.9	64.85	16.6	64.15	15.9	56.34	17.5	70.19	17.3	73.45
09:00:00	12.3	65.35	13.6	59.92	18.2	59.24	18.6	52.38	19.8	65.82	19.4	68.68
10:00:00	15.3	58.44	16.9	52.89	20.1	51.12	21.8	47.38	22.5	60.34	22.1	63.41
11:00:00	18.0	51.03	19.9	46.55	21.8	42.91	24.8	40.44	25.0	51.01	24.5	54.64
12:00:00	20.0	43.79	22.1	40.34	23.1	34.53	26.9	32.66	26.8	43.21	26.3	46.85
13:00:00	21.2	37.78	23.4	33.40	23.9	27.92	28.2	25.93	27.9	36.60	27.3	39.72
14:00:00	21.7	33.39	23.9	28.23	24.1	23.71	28.7	21.17	28.3	31.72	27.7	34.83
15:00:00	21.7	30.25	23.9	25.10	24.2	21.23	28.8	17.55	28.3	28.36	27.8	31.11
16:00:00	20.8	28.55	22.9	23.59	23.6	20.39	27.8	15.58	27.5	26.38	27.0	28.53
17:00:00	19.9	28.57	21.9	23.63	23.0	21.62	26.8	15.35	26.6	25.57	26.1	27.54
18:00:00	18.7	31.28	20.7	26.74	22.3	24.30	25.5	15.83	25.6	26.71	25.1	28.63
19:00:00	17.6	37.15	19.4	31.73	21.5	29.17	24.3	17.01	24.6	29.33	24.1	31.60
20:00:00	16.4	42.49	18.1	37.04	20.8	34.34	23.0	19.27	23.5	35.23	23.1	36.93
21:00:00	15.3	45.92	16.8	42.45	20.1	39.96	21.8	25.78	22.5	43.72	22.0	46.63
22:00:00	14.3	48.16	15.7	45.47	19.4	43.16	20.7	32.48	21.5	52.36	21.1	54.67
23:00:00	13.4	51.86	14.8	47.58	18.9	47.51	19.8	36.81	20.8	57.57	20.4	59.57
00:00:00	12.6	54.04	13.9	49.38	18.4	51.58	18.9	40.88	20.0	59.53	19.7	61.62



HORA	Julio		Agosto		Septiembre		Octubre		Noviembre		Diciembre	
	T (°C)	HR (%)	T (°C)	HR (%)	T (°C)	HR (%)	T (°C)	HR (%)	T (°C)	HR (%)	T (°C)	HR (%)
01:00:00	19.3	65.77	18.9	64.44	18.0	81.16	17.2	73.65	12.5	68.70	12.6	66.52
02:00:00	18.7	68.97	18.4	67.19	17.5	83.49	16.8	78.71	12.0	71.93	12.0	70.04
03:00:00	18.4	70.90	18.1	69.21	17.3	84.72	16.5	80.60	11.7	74.50	11.7	72.26
04:00:00	18.1	73.24	17.8	71.30	17.1	86.18	16.3	81.72	11.4	77.23	11.4	73.61
05:00:00	17.7	75.33	17.4	74.17	16.8	87.39	15.9	83.36	11.0	78.89	11.0	75.40
06:00:00	17.6	76.56	17.3	76.09	16.7	88.16	15.8	85.33	10.9	80.24	10.9	75.58
07:00:00	16.8	77.89	16.6	76.64	16.1	87.51	15.2	85.35	10.1	80.46	10.0	77.14
08:00:00	17.5	78.33	17.2	78.01	16.6	87.31	15.8	84.76	10.8	78.92	10.8	78.32
09:00:00	19.6	73.96	19.2	74.73	18.2	86.64	17.5	82.01	12.8	76.02	12.9	75.06
10:00:00	22.1	67.61	21.5	68.57	20.1	82.35	19.6	77.23	15.3	69.91	15.5	68.31
11:00:00	24.4	59.48	23.6	60.33	21.8	75.31	21.5	70.93	17.6	61.90	17.9	60.71
12:00:00	26.1	51.38	25.2	51.18	23.1	68.60	22.9	63.15	19.3	54.07	19.7	53.68
13:00:00	27.1	44.24	26.1	44.86	23.9	62.08	23.8	56.25	20.3	48.90	20.7	47.14
14:00:00	27.4	39.03	26.4	40.26	24.1	57.18	24.1	52.19	20.7	44.41	21.1	41.84
15:00:00	27.5	35.81	26.5	36.96	24.2	53.50	24.1	49.35	20.7	41.44	21.1	38.13
16:00:00	26.7	34.74	25.8	35.08	23.6	51.87	23.5	47.93	20.0	40.18	20.3	36.10
17:00:00	25.9	32.89	25.0	33.93	23.0	51.95	22.8	48.87	19.2	40.79	19.5	36.02
18:00:00	25.0	32.62	24.2	33.79	22.3	53.36	22.0	51.96	18.2	45.06	18.5	39.22
19:00:00	24.0	34.99	23.2	35.71	21.5	56.03	21.2	55.85	17.2	52.82	17.5	45.93
20:00:00	23.0	39.47	22.3	40.90	20.8	62.61	20.4	60.12	16.3	58.28	16.5	49.73
21:00:00	22.0	47.35	21.4	48.36	20.1	70.41	19.6	63.79	15.3	60.82	15.5	52.03
22:00:00	21.2	55.04	20.7	55.48	19.4	74.31	18.9	65.93	14.5	63.76	14.6	53.57
23:00:00	20.5	60.44	20.0	60.78	18.9	77.73	18.3	67.86	13.8	67.48	13.9	57.03
00:00:00	19.8	63.22	19.4	63.55	18.4	79.35	17.7	70.60	13.1	69.57	13.2	61.17

Datos: SEGAM 2009

Source: (Rivera Vázquez, 2014)

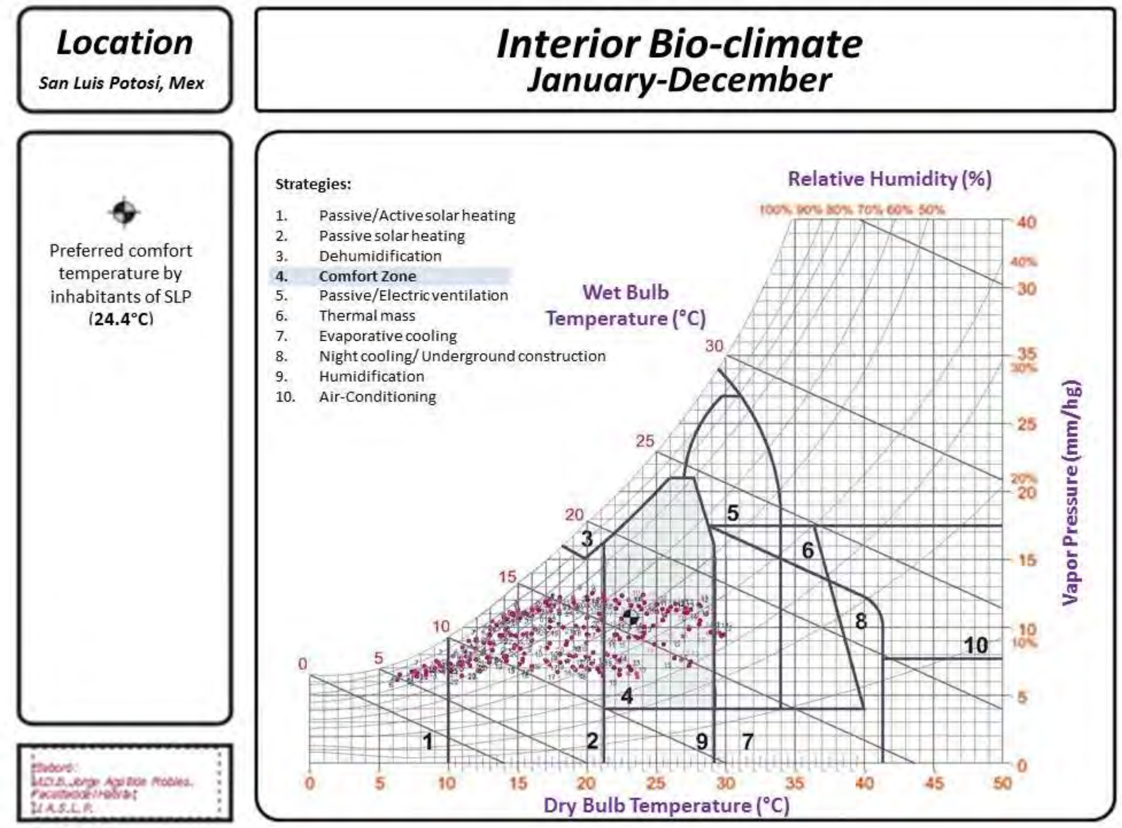
4.5 Psychrometric Chart of the City of San Luis Potosí

Since the software Autodesk Ecotect is going to be used to perform thermal models of the study unit, a comparison of the climate data of the psychrometric chart of Aguillón Robles (2007) and Ecotect's Weather Tool is presented in Figure 25. Even if the chart created by

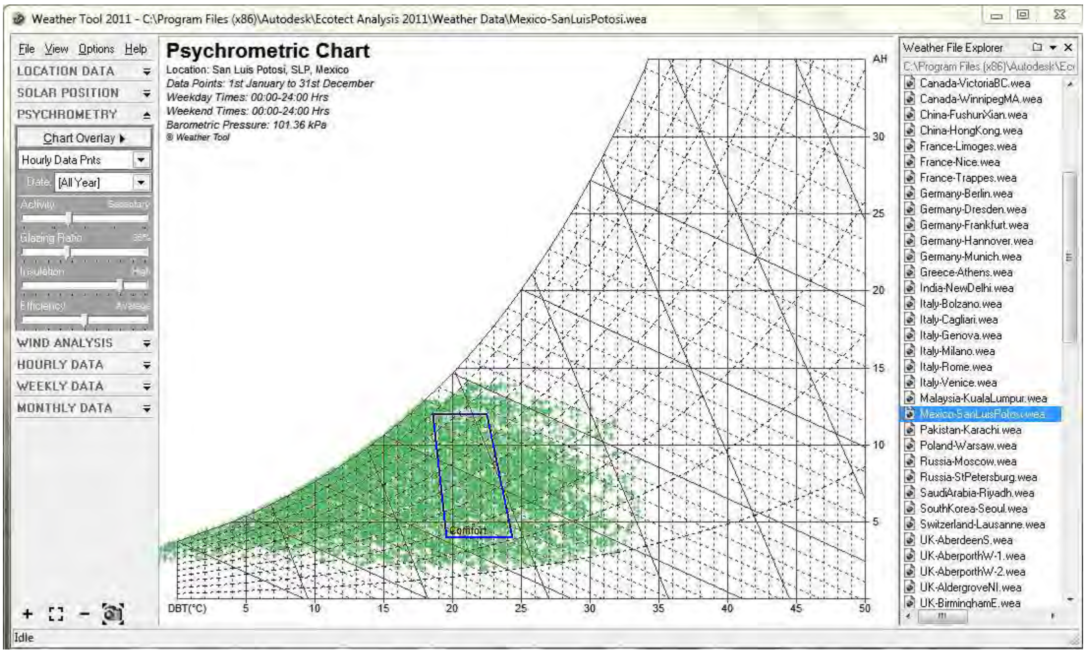
Aguillón Robles uses monthly average values, and the one obtained with the Weather Tool uses more detailed hourly values for every day of the year, it can be seen that both charts are consistent in the position of the data, defining the seasonal climate of San Luis Potosí between cool, moderate and warm-dry, depending on the season of the year. It is important to highlight that, in either case, active acclimatization strategies -such as air conditioning- are not essential to achieve thermal comfort.

As it can be seen in Figure 16 and Figure 25, climate conditions of the city of San Luis Potosí don’t require active systems such as air conditioning. Instead, good ventilation systems and evaporative cooling are enough to achieve thermal comfort in hot periods. The combination of passive systems with low energy-input devices can also be considered to enhance their performance.

Figure 25. Comparison between Aguillón Robles' and Ecotect's Weather Tool psychrometric chart for the city of San Luis Potosí



a)


Weather Tool 2011 - C:\Program Files (x86)\Autodesk\Ecotect Analysis 2011\Weather Data\Mexico-SanLuisPotosi.wea

Psychrometric Chart

Location: San Luis Potosi, SLP, Mexico
Data Points: 1st January to 31st December
Weekday Times: 00:00-24:00 Hrs
Weekend Times: 00:00-24:00 Hrs
Barometric Pressure: 101.36 kPa
© Weather Tool

Hourly Data Pnts
Date: [All Year]

b)

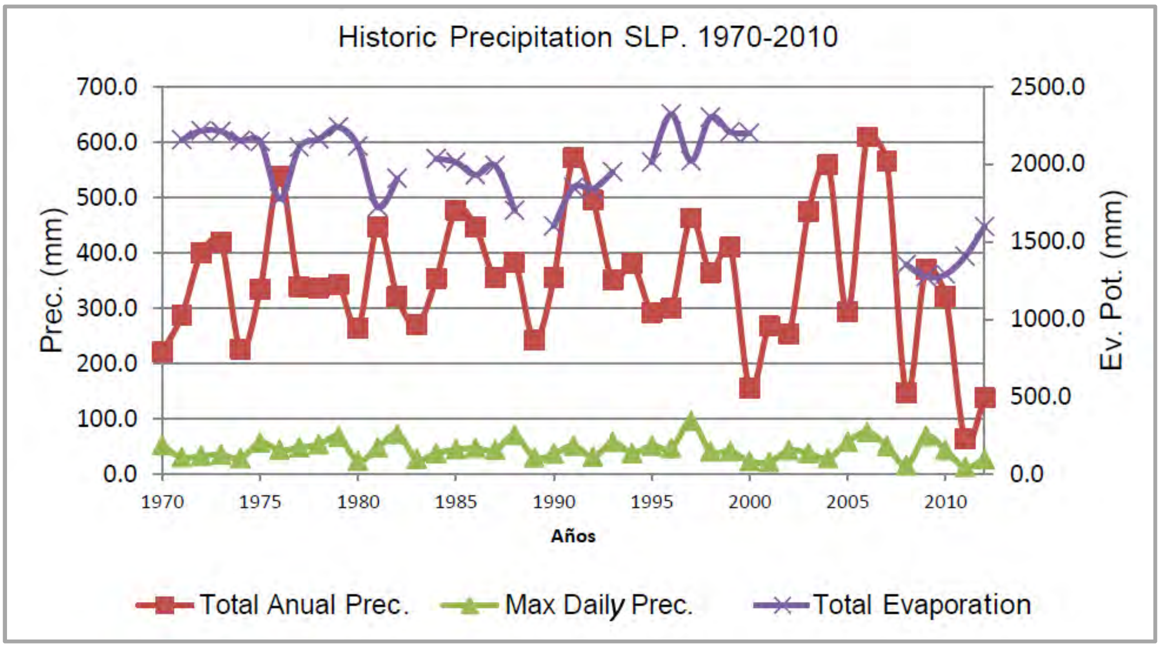
Source: (Aguillón Robles, 2007) (Autodesk Ecotect Weather Tool, 2014)

4.6 Precipitation

Annual mean precipitation in the city of San Luis Potosí is 315mm (Aguillón Robles, 2007), but some extreme years can be found in Figure 26. For example, in 2006 records of up to 600mm can be found, while 2011 barely registered 100mm. The low precipitation levels and high evaporation means that in the past years the city has experienced a drought period.

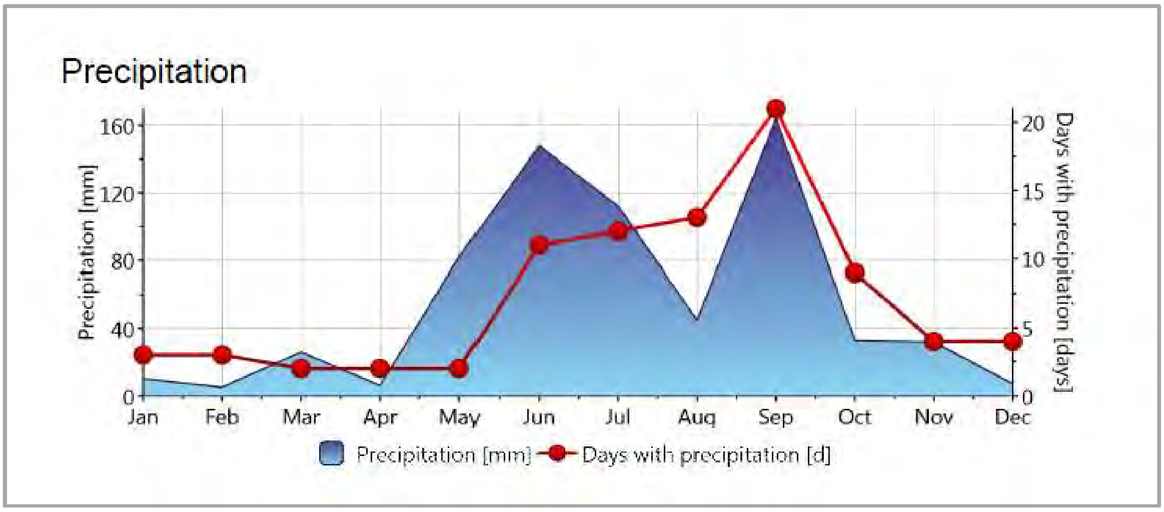
With these precipitation levels, water harvesting through the roofs is not feasible over the year. The city of San Luis Potosí, along with the municipalities of Soledad de Graciano Sánchez and Cerro de San Pedro, satisfy their water demands with the aquifer 2411, which is being overexploited, extracting more water than it can recharge with the scarce precipitation. Besides, new residential complexes located in what used to be natural reserves of the *Sierra de San Miguelito* in the western part of the city, have blocked important recharge areas, forcing the water to flow through the drainage and paved roads into the city instead of filtering into the soil, causing floods and severe damage to the infrastructure of the city (COTAS, 2005).

Figure 26. Historic records of precipitation and evaporation



Source: (Rivera Vázquez, 2014) with data from INIFAP and UASLP

Figure 27. Monthly precipitation according to Meteonorm

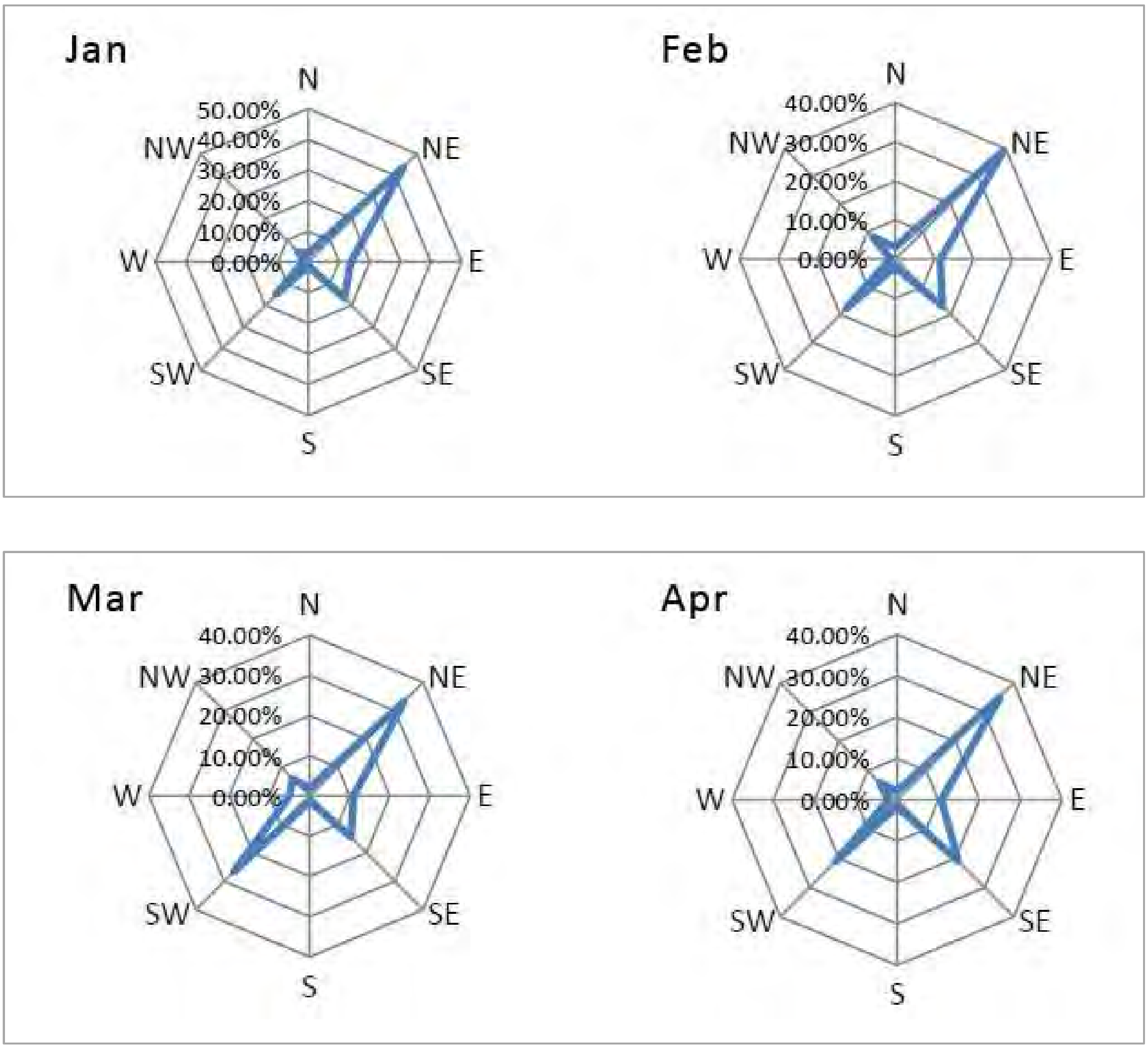


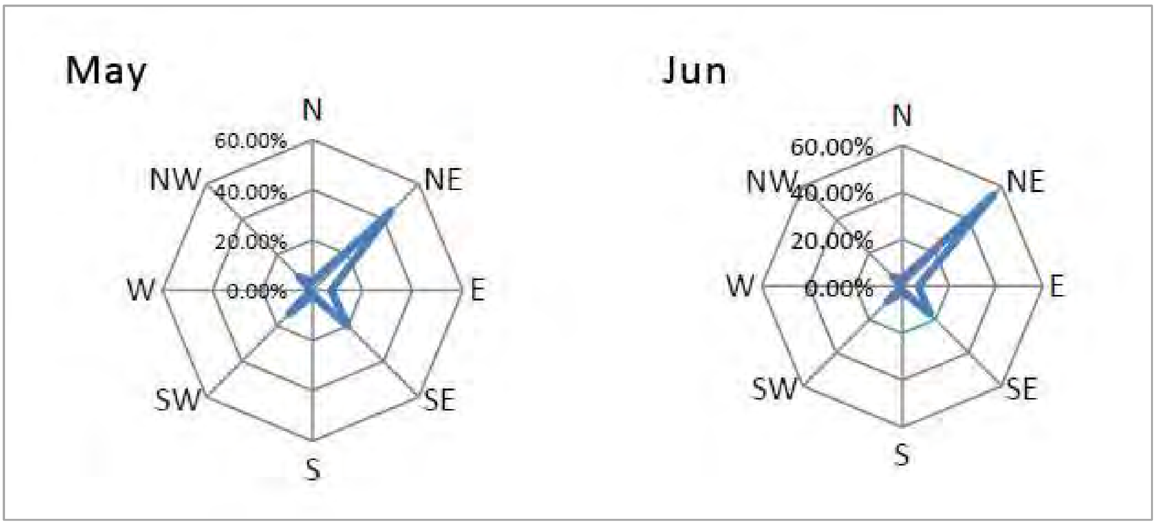
Source: Meteonorm (2014)

4.7 Wind

Unfortunately, wind data in the weather stations of the city of San Luis Potosí has only been registered in a consistent way since 2002 (Rivera Vázquez, 2014). As it can be seen in Figure 28, prevailing winds in the city come from the north-east. Nevertheless, from January to April wind can be registered from south-west and south-east. In the summer period, winds come mostly from north-east and, in a smaller frequency, from south east. In tables 12-15, Aguillón Robles (2007) shows that the average wind speed in the four seasons can vary from 3 to 4.6 m/s.

Figure 28. Prevailing winds of the city of San Luis Potosí by month




May
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NE
E
SE
S
SW
W
NW
60.00%
40.00%
20.00%
0.00%
Jun
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NE
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SE
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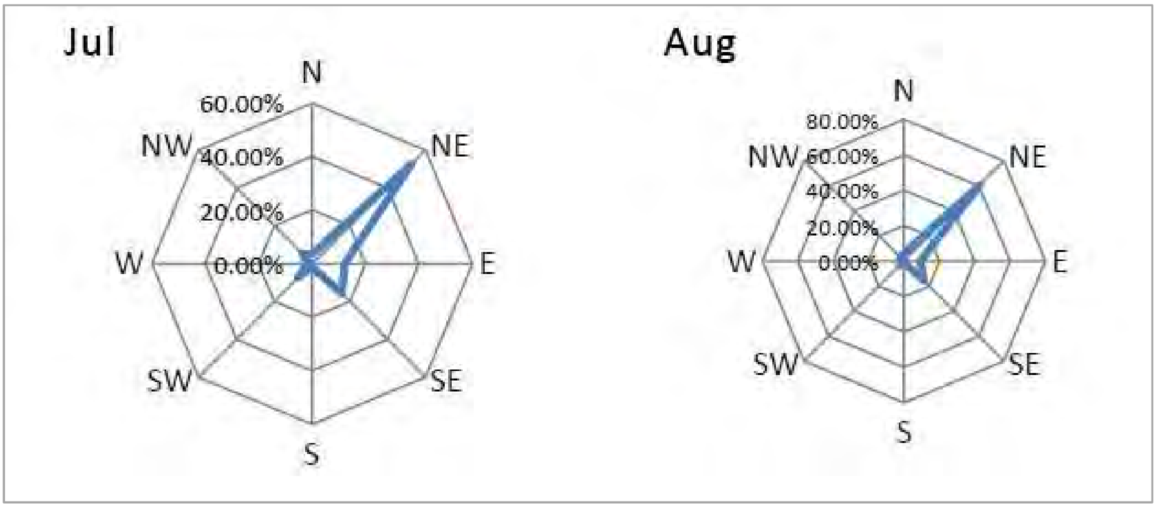
SW
W
NW
60.00%
40.00%
20.00%
0.00%


Jul
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NE
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SE
S
SW
W
NW
60.00%
40.00%
20.00%
0.00%
Aug
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NE
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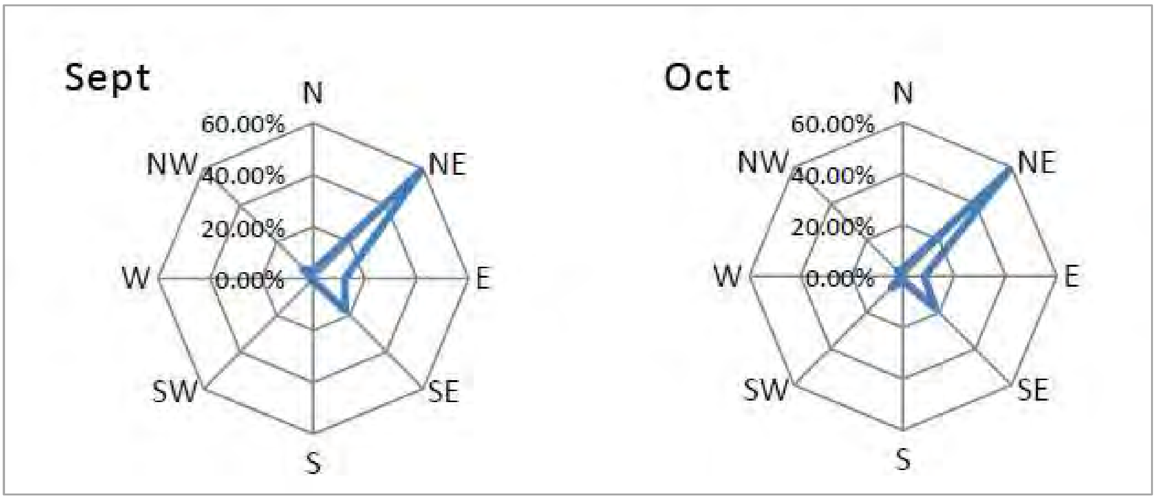
SE
S
SW
W
NW
80.00%
60.00%
40.00%
20.00%
0.00%


Sept
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NE
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SE
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60.00%
40.00%
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Oct
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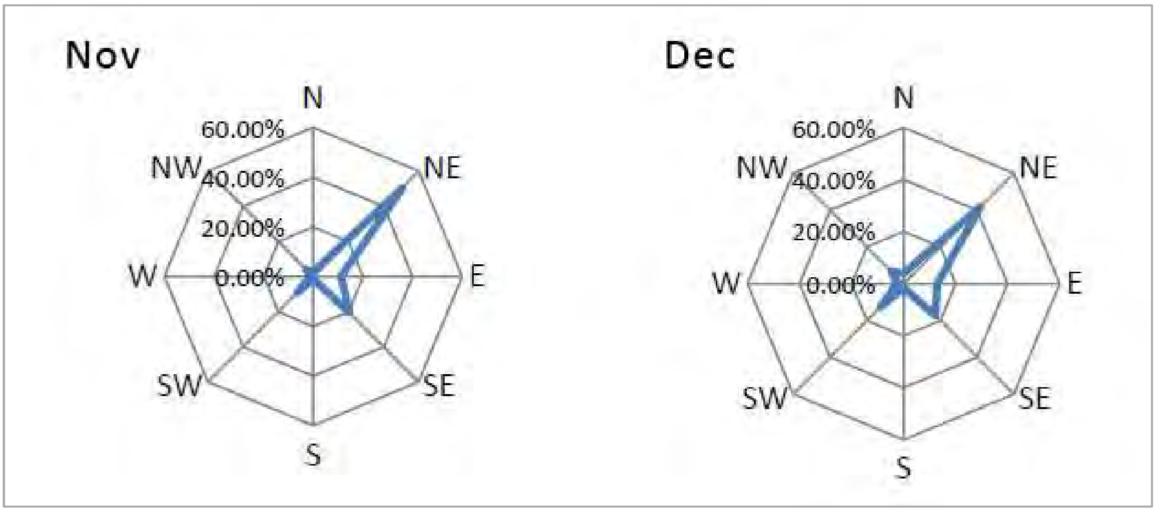


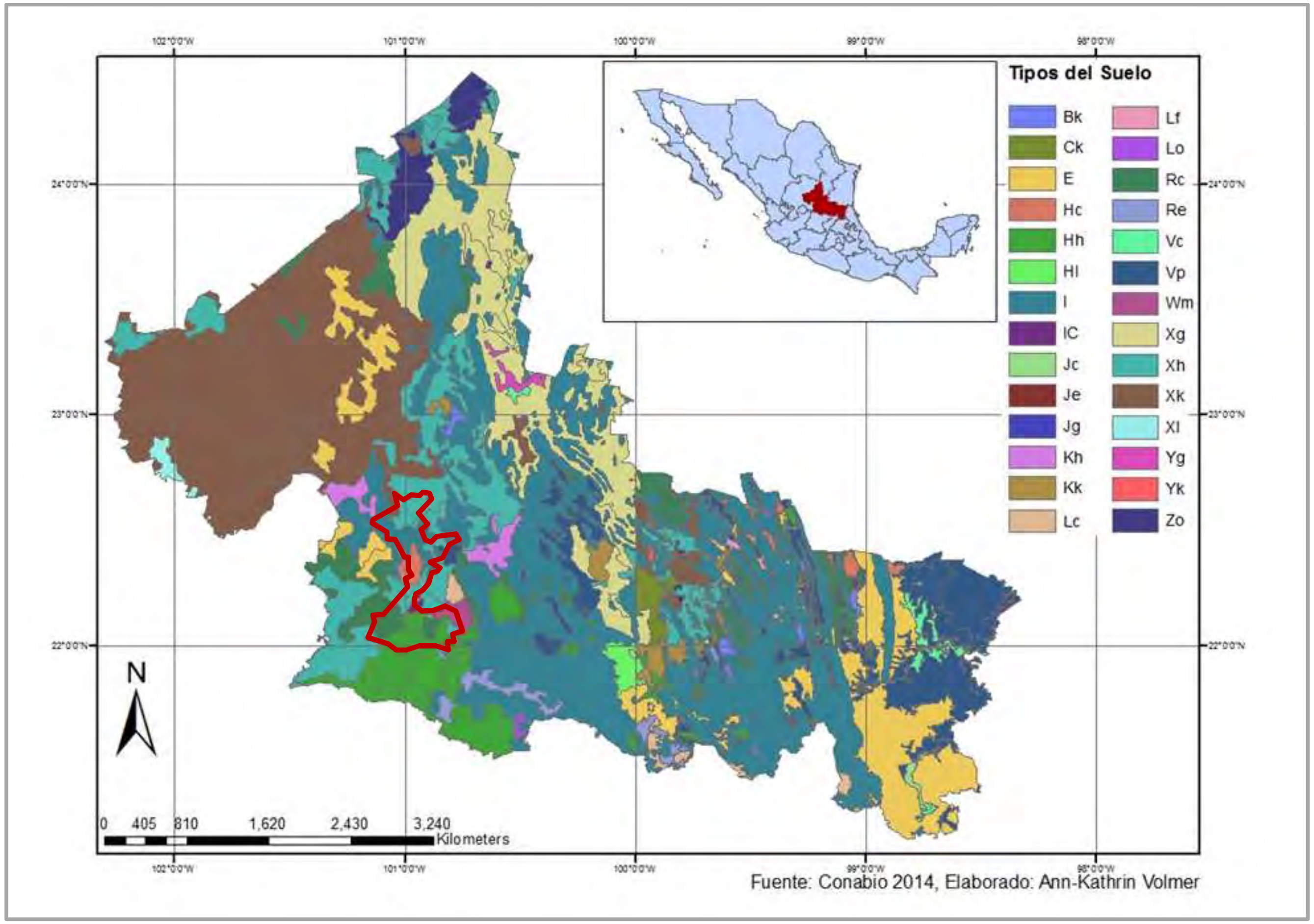
Source: (Rivera Vázquez, 2014)

As it was mentioned before, knowing the direction of the prevailing winds can help decide the location of windows, and -in this case- of the wind chimney which will help enhance the airflow in the interior of the house by sucking the internal air with the Venturi effect. As Mermet (2005) and García Chávez & Fuentes Freixanet (1995) affirm, natural ventilation is improved when the inlet window and the prevailing wind direction create a 45° angle. This means that for the specific case of the city of San Luis Potosí, the best location for inlet windows is on the North façade, in an E-W axis.

4.8 Soil types

Different soil types can be found in the *Centro* region of the state. According to their extension, the most common types are: Xerosol, Litosol, Vertisol, Feozem and Rendzina; and in less proportion, Castanozem, Regosol, Luvisol, Solonchak, Fluvisol, Chernozem, and very few Cambisol, Yermosol and Planosol. Approximately 77.5% of the soils in the state have physical limitations for use, most of the times at depths smaller than 100 cm. These limitations include petro-calcic (caliche), lytic (stone) and rocky and gravel limitations; 9% have chemical restrictions (saline, sodium and saline-sodium phases) within 125 cm depth. Only 13.5% are deep (greater than 100 cm) and without usage limitations (SEGAM, 2008). Figure 29 and Figure 30 show the soil distribution in the State and the City of San Luis Potosí, respectively.

Figure 29. Soil types in the State of San Luis Potosí



Fuente: Conabio 2014, Elaborado: Ann-Kathrin Volmer

Source: Ann-Kathrin Volmer with data from CONABIO (2014)[5]

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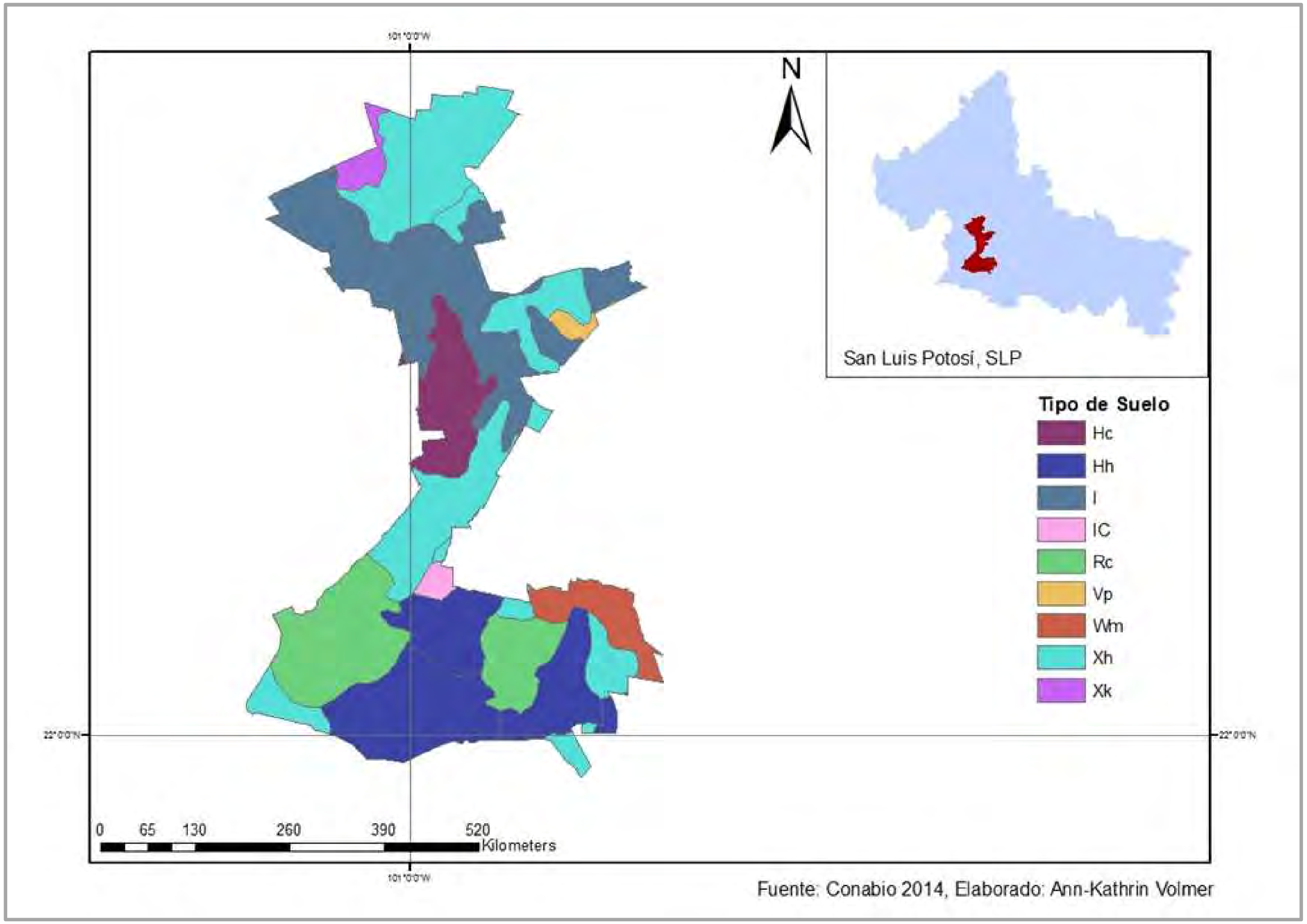
[5] See Annex B for edaphology nomenclature

Figure 30. Soil types in the City of San Luis Potosí



Source: Ann-Kathrin Volmer with data from CONABIO (2014)

5 Design of an Earth-to-Air Heat Exchanger

As it was stated on Chapter 3.2, the usage of natural ventilation in architecture has many benefits. It is a useful strategy to achieve adequate indoor air quality levels to create healthy conditions for the users of a building, as well as it can be used to achieve passive acclimatization of the interior spaces, reaching comfort temperatures and acceptable humidity levels. As García Chávez & Fuentes Freixanet (1995) state, a good control of the wind allows cooling a building through the airflow of natural ventilation, heating it through thermo-convective processes, enhance humidification through evaporative cooling or dehumidification through condensation. Nevertheless, the random behavior of wind creates difficulties to properly implement natural ventilation in an architectural project (Mermet, 2005).

On the other hand, under some climate conditions, the implementation of natural ventilation in a building can increase its energy consumption, due to the necessity of being heated, cooled or just circulated (Autodesk, 2013). The advantage of integrating a passive strategy such as an EAHE is that the energy transfer of the air and the soil not only helps pre-cooling the air in hot seasons, but it can also pre-heat it in cold seasons. Brown & DeKeys (2001), state that the massive properties of the ground allow its temperature peak to lag between 10 to 13 weeks behind the seasonal changes, making it feasible to be used as a heat sink (Larson, 2014). Therefore, “air may be passed through buried ducts and thus used to cool or heat incoming fresh ventilation air” (Brown & DeKay, 2001).

5.1 Bioclimatic Environment of San Luis Potosí

All the climatic elements mentioned on Chapter 4 give special characteristics to the bioclimatic environment of a specific location, which can create microclimates and specific weather conditions along the year, called the seasonal climate (See Table 12). As a summary, Aguillón Robles (2007) presents the climatic data of the city of San Luis Potosí in the following table:

Table 11. Bioclimatic environment of the city of SLP

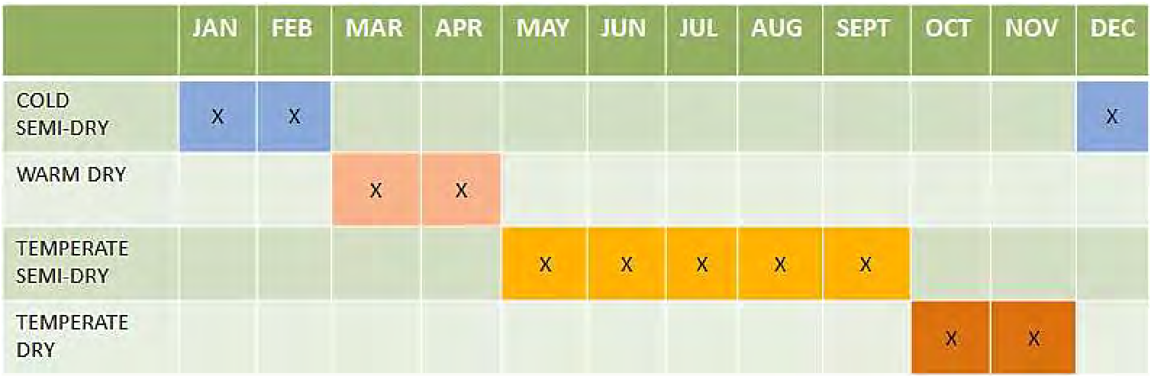
Bioclimatic Environment San Luis Potosí		
Latitude: 22.3° N	**Longitude: 100.9° W**	**Altitude: 1887 MASL**
Mean Annual Temperature………………………………………………………….		18.2° C
Mean Annual Thermal Oscillation …………………………………………….		15.0° C
Mean Annual Relative Humidity………………………………………………….		52 %
Mean Annual Precipitation………………………………………………………….		315 mm
Mean Annual Solar Radiation…………………………………………………….		6.3 kWh/m^2 day
Wind………………………………………………………………………………………....		4.8 m/s SW, 4.1 m/s NE
Comfort Temperature San Luis Potosí		
Comfort T°	**Min Comfort T°**	**Max Comfort T°**
23°C	19°C	27°C

Source: (Aguillón Robles, 2007)

Seasonal Climate

Over the year, the different proportion of climate elements in the bioclimatic environment causes different characteristics, creating four specific microclimates in the city of San Luis Potosí: Cold semi-dry; Warm-dry; Temperate semi-dry and Temperate-dry (See Table 12).

Table 12. Seasonal climate of the city of SLP



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
COLD SEMI-DRY	X	X										X
WARM DRY			X	X								
TEMPERATE SEMI-DRY					X	X	X	X	X			
TEMPERATE DRY										X	X	

Source: Self-construction based on Aguillón Robles (2007)

According to the previous table, Aguillón (2007) describes four primary acclimatization objectives along the year:

1. To control and optimize exterior heat gain: With the strategy of solar control, it is possible to let the solar radiation into the spaces or block it when necessary.
2. To avoid nocturnal heat dissipation: High thermal mass materials release energy more slowly over the night. Well sealed windows and elements as fabric curtains reduce heat dissipation outside the building.
3. To control and take advantage of exterior, natural ventilation: Natural ventilation must be avoided in cold seasons to prevent heat losses (See Table 13). In hot seasons, natural ventilation must be stimulated to cool the internal spaces.
4. To enhance humidification: In hot seasons, natural ventilation can be enhanced with humidification, letting the air pass through wet elements or even water fountains.

Tables 13 to 16 show the characteristics of each seasonal-climate found in the city of San Luis Potosí, as well as their specific acclimatization requirements. Since this research project focuses on an acclimatization/ventilation system for social housing, natural ventilation and humidification requirements are highlighted in every table.

Table 13. Cold semi-dry seasonal weather

COLD SEMI-DRY (January, February, December)						
Temperature	Maximum:	22.3°C	Minimum:	6.7°C	Average:	14.5°C
Relative Humidity	Maximum:	98%	Minimum:	11%	Average:	50%
Comfort Temperature	22.1°C					
Wind	Direction:	SW	Speed (m/s):	4.6		
Solar Exposure	9 hr/day		Sun's maximum height:		47°	
Solar Radiation	7.248 kW/m^2/ day					
Precipitation	Total:	5mm	Maximum:	48mm	Maximum in 24hrs:	17mm

Seasonal acclimatization requirements:

- Take advantage of internal heat production
- Take advantage of thermal gain, optimizing solar radiation, if possible, all day
- **Block exterior ventilation**
- **Humidification control between 11h -17h**
- Foster the usage of high thermal mass materials

Table 14. Warm-dry seasonal climate

WARM-DRY (March, April)						
Temperature	Maximum:	28.7°C	Minimum:	10.9°C	Average:	19.8°C
Relative Humidity	Maximum:	97%	Minimum:	6%	Average:	38%
Comfort Temperature	23.7°C					
Wind	Direction:	E	Speed (m/s):	4.3		
Solar Exposure	10 hr/day		Sun’s maximum height:	78°		
Solar Radiation	7.624 kW/m^2/ day					
Precipitation	Total:	8mm	Maximum:	32mm	Maximum in 24hrs:	13mm

Seasonal acclimatization requirements:

- Control internal heat production
- Block solar radiation to avoid heat gains between 11h and 18h
- **Incite humidification between 11h and 16h**
- **Control natural ventilation**
- High thermal mass materials

Table 15. Temperate semi-dry seasonal climate

TEMPERATE SEMI-DRY (May, June, July, August, September)						
Temperature	Maximum:	27.4°C	Minimum:	10.9°C	Average:	20.4 °C
Relative Humidity	Maximum:	97%	Minimum:	19%	Average:	57%
Comfort Temperature	23.9°C					
Wind	Direction:	NEE	Speed (m/s):	4.1		
Solar Exposure	11 hr/day		Sun’s maximum height:	98°		
Solar Radiation	10.851 kW/m^2/ day					
Precipitation	Total:	49mm	Maximum:	128mm	Maximum in 24hrs:	51mm

Seasonal acclimatization requirements:

- Control internal heat production
- Block solar radiation to avoid heat gains from 9h
- **Optimize humidification**
- Control rain infiltration
- High thermal mass materials

Table 16. Temperate-dry seasonal climate

Temperate-Dry (October, November)						
Temperature	Maximum:	23.5°C	Minimum:	9.4°C	Average:	16.5°C
Relative Humidity	Maximum:	98%	Minimum:	16%	Average:	60%
Comfort Temperature	22.7°C					
Wind	Direction:	E	Speed (m/s):	3.0		
Solar Exposure	10 hr/day		Sun's maximum height:		43°	
Solar Radiation	7.624 kW/m^2/ day					
Precipitation	Total:	18mm	Maximum:	55mm	Maximum in 24hrs:	34mm

Seasonal acclimatization requirements:

- Control and optimize internal heat production
- Control solar radiation, inciting heat gain from 11h to 16h
- **Incite humidification from 11h to 16h**
- **Stimulate and control natural ventilation**
- High thermal mass materials

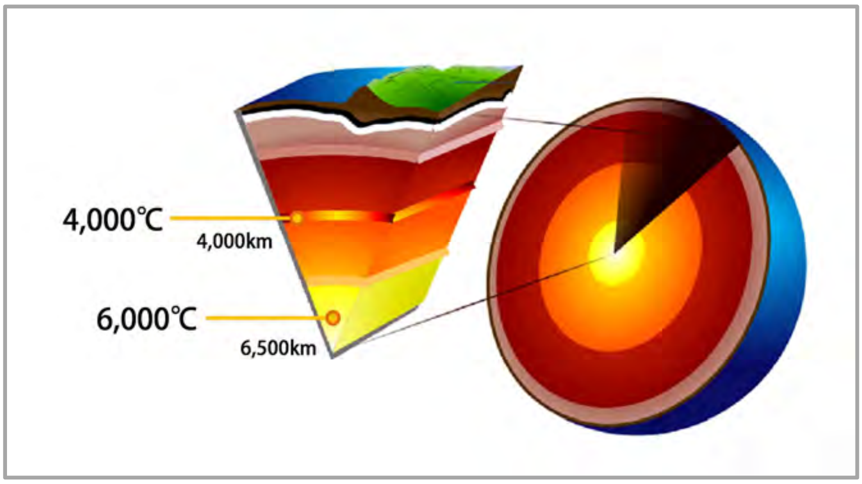
Source: (Aguillón Robles, 2007)

These tables give an overview on the specific time of every season where the EAHE must be turned on or stay off, or even enhanced with a humidification device to fulfill the acclimatization requirements, as well as the wind direction and speed registered along the year, which can help deduce the behavior of the wind on the housing unit. It is important to mention that, depending on the weather conditions, the 230W fan can be turned on or off as well. If the sky is clear, solar radiation will induce the air suction by the solar chimney, avoiding the usage of the fan. On the other hand, if the cloudiness doesn't allow the proper function of the solar chimney, the fan must be turned on to supply the air on the required spaces of the house.

5.2 Design and implementation of an EAHE system

Geothermal energy is the energy “available as heat emitted from within the earth’s crust” (OECD, 2002). The temperature of the inner core of the earth is approximately 6000°C, while in the outer core temperatures can reach 4000°C. This heat is transferred through the mantel and up to the crust of the earth. In the lithosphere the thermal gradient increases approximately 0.5°C for every 20 meters of depth. Geothermal energy is commonly used to produce electricity by the steam produced by the heated groundwater. Some perforations can go as deep as 3km (EPA, 2014) to reach the steam.

Figure 31. Geothermal heat



Source: Self-construction based on http://guykeulemans.com

Besides producing electricity, the geothermal energy can be used to heat or cool a building due to the inertia of the soil, which delays the seasonal changes in depths greater than 5m (Dubois Petroff, 2009) (Loyau, 2005) (Bansal, et al., 2011). Even if Brown & DeKay (2001) affirm that at 0.6m below the earth’s surface the daily temperature fluctuations are small, most of the authors agree that the best depth to install the system is between 1.2 to 3 meters (Badescu, 2007) (Chel & Tiwari, 2008) (Florides & Kalogirou, 2007) (Mihalakakou, et al., 1996). At greater depths, less thermal variation can be found, nearly reaching the temperature of the annual mean temperature of the location all over the year(Bansal, et al., 2011), but the excavation costs become greater, turning the system less cost-effective.

As a “one-way open-air system” (Larson, 2014), ambient air is injected into a network of buried pipes and released into the housing unit with help of a fan (Peretti, et al., 2013) or the stack effect. As the temperature below the surface is more constant than the outside air temperature, the soil acts as a heat sink in hot seasons, as the flowing air loses heat by convection and transfers it to the pipe’s internal surface, which then transfers the gained heat to the surrounding soil by conduction (Al-Ajimi, et al., 2005) (Peretti, et al., 2013). In cold seasons the process is reversed, and the warmer soil acts as a heat source, transferring its heat to the colder ambient air inside the pipes. Due to this heat exchange over the year between the earth and the air inside the pipes, this system is known as an earth-to-air heat exchanger (EAHE).

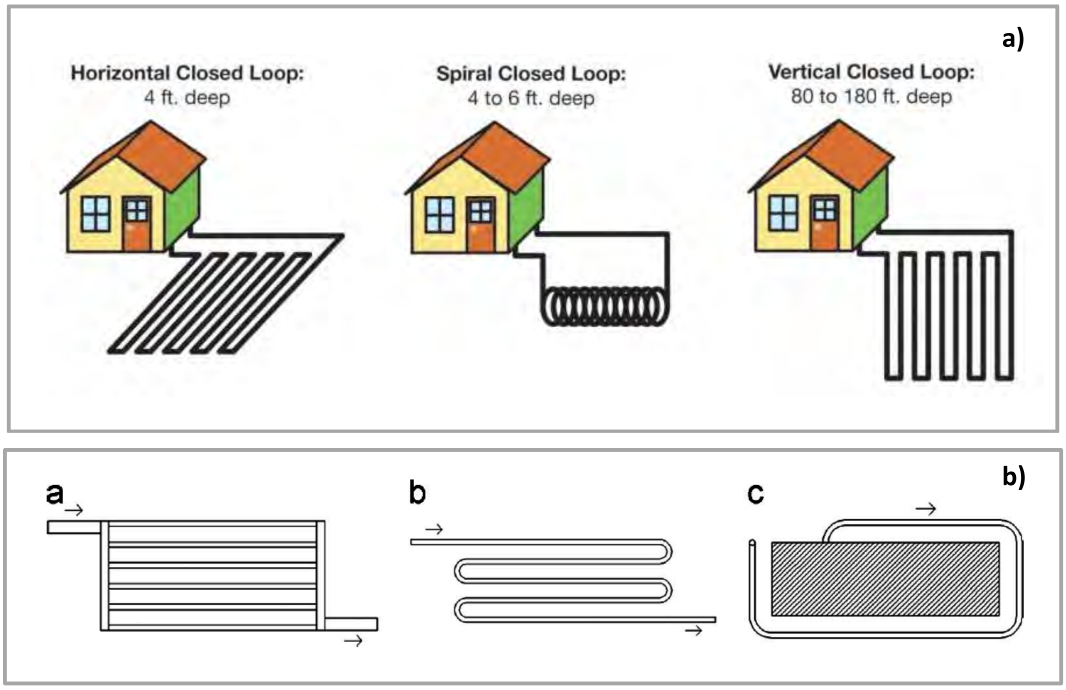
According to Bansal, et al. (20011), this ability of heating the air in cold seasons and cooling it hot seasons before using it for ventilation purposes, represents a good advantage over most passive systems. Nevertheless, Badescu (2006) found that “the heating flux it provides during the cold season is rather small”. Another advantage is that the EAHE “can be installed in different types of climate, such as hot desert, Mediterranean, humid subtropical and oceanic climates” (Peretti, et al., 2013). Moreover, if it is combined with other passive techniques and a bioclimatic design of the house, an EAHE “may eliminate the need for an air-conditioning system in many cases” (Paretti, et al., op. cit.).

Characteristics

There are several variables that influence the performance of an EAHE such as “humidity, ambient air temperature, ground surface temperature, ground temperature at burial depth, and air mass flow rate” (Maerefat & Haghighi, 2010), but the more important are “pipe length, pipe radius, air velocity inside the tube and the temperature at the depth of the buried pipe” (Mihalakakou, et al., 1996).

The layout of the pipes of an EAHE can vary depending on the project. Designers usually face restrictions regarding due to the limitation of “space and economic boundary conditions” (De Paepe & Jannssens, 2002). The most common layout of the buried pipes is in a horizontal configuration, but normally a big constraint of installing the EAHE in smaller housing units is the limited amount of space. This can be solved with a vertical configuration which can go as deep as 50m below the surface. This solves the issue of space, but definitely increases the cost and complexity of the system. Another solution is to install the pipes beneath the buildings, under the concrete slab in a ring or spiral design (Peretti, et al., 2013)(See Figure 32), and taking advantage of the existing excavation for the foundations in new constructions.

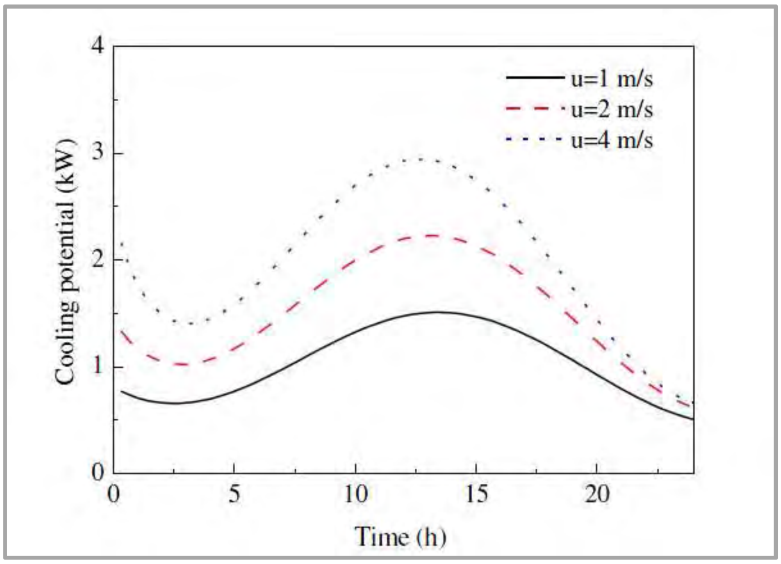
Figure 32. Layout of an EAHE pipes



Source: http://www.homepower.com/; (Peretti, et al., 2013)

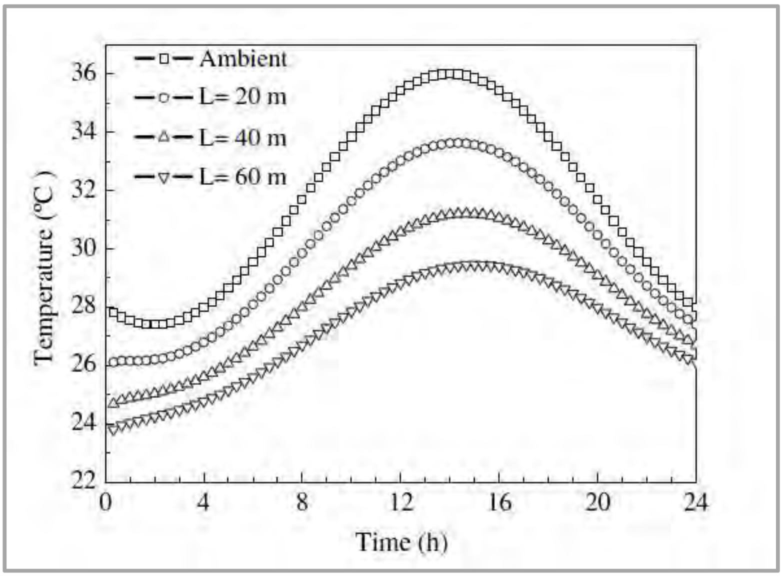
Loyau (2005) indicates that the air must flow inside the tube at least 20 seconds to successfully exchange heat with the soil. If an air speed of 2m/s is considered (See Figure 33), the total length of the system should be 40m. Dubois Petroff (2009) affirms that a length of approximately 35m is enough in most of the cases for diameters of up to 20cm. Wu, et al. (2007) present a graphic where they show the relation between the outlet air temperature and the length of the pipeline (See Figure 34). The length does not need to be continuous, as in the first example of (Figure 32b), where the ducts are separated and with a certain number to fulfill the required length (Brown & DeKay, 2001). In fact, De Paepe & Janssens (2003) found that “it is better to have several tubes of small diameter over which the flow rate is divided”.

Figure 33. Cooling capacity of an EAHE depending on the flow rate



Source: (Wu, et al., 2007)

Figure 34. Outlet air temperature depending on the length of the pipeline

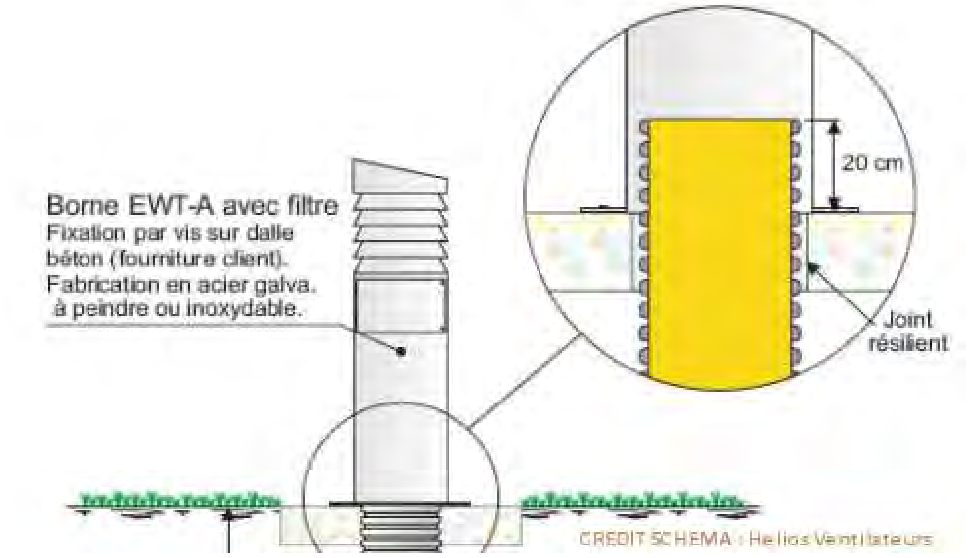


Source: (Wu, et al., 2007)

It must be taken into account that the surrounding soil can affect the performance of the contiguous tubes. Al-Ajimi, et al. (2005) affirms that "the thermal effect of soil surrounding the pipe is negligible after a distance of one pipe radius (r) from the outer surface of the pipe", while Florides & Kalogirou (2007) proved that "the influence of the pipe on the temperature of the surrounding soil is limited to a distance of twice its diameter”. Even though, Brown & DeKay (2001) recommend to space them 3m from each other to avoid any external influence.

Regarding the air inlet (See Figure 35), it is recommended place it under a shady place, away from additional heat gains from the solar radiation. It shouldn’t be too close to dense vegetation to avoid aspiration of CO_2 of the plants (Dubois Petroff, 2009) and with a minimum height of 1m to avoid pollutants which can be found within the first 30cm above the ground (Loyau, 2005). It must be equipped with a replaceable air filter which must be able to block dust, pollutants and even pollen. Materials such as PVC should be avoided, since they produce volatile organic compounds (VOC) if their temperature rises.

Figure 35. Example of an air inlet for an EAHE



Source: (Loyau, 2005)

Material

In heat transfer, the properties of a material are essential to know if it will be a good conductor or not. Nevertheless, some authors affirm that in the case of an EAHE, the material doesn't affect since "the thickness of the pipe is very small, making its thermal resistance negligible" (Al-Ajimi, et al., 2005), as well as its influence on heating and cooling energy provided by the heat exchanger (Badescu, 2006).

In this case, the right selection of the material is influenced by the health conditions. As a premise, the material shouldn't be toxic or produce VOC, but especially, it shouldn't encourage the production of mold and bacteria (Larson, 2014). Corrugated high-density polyethylene (See Figure 36) has proved to be the best material for this system, since it is also easier to install because of its flexibility and joint reductions. Besides, the corrugated texture forces the air to turbulate inside the pipe, mixing all the air (Larson, 2014).

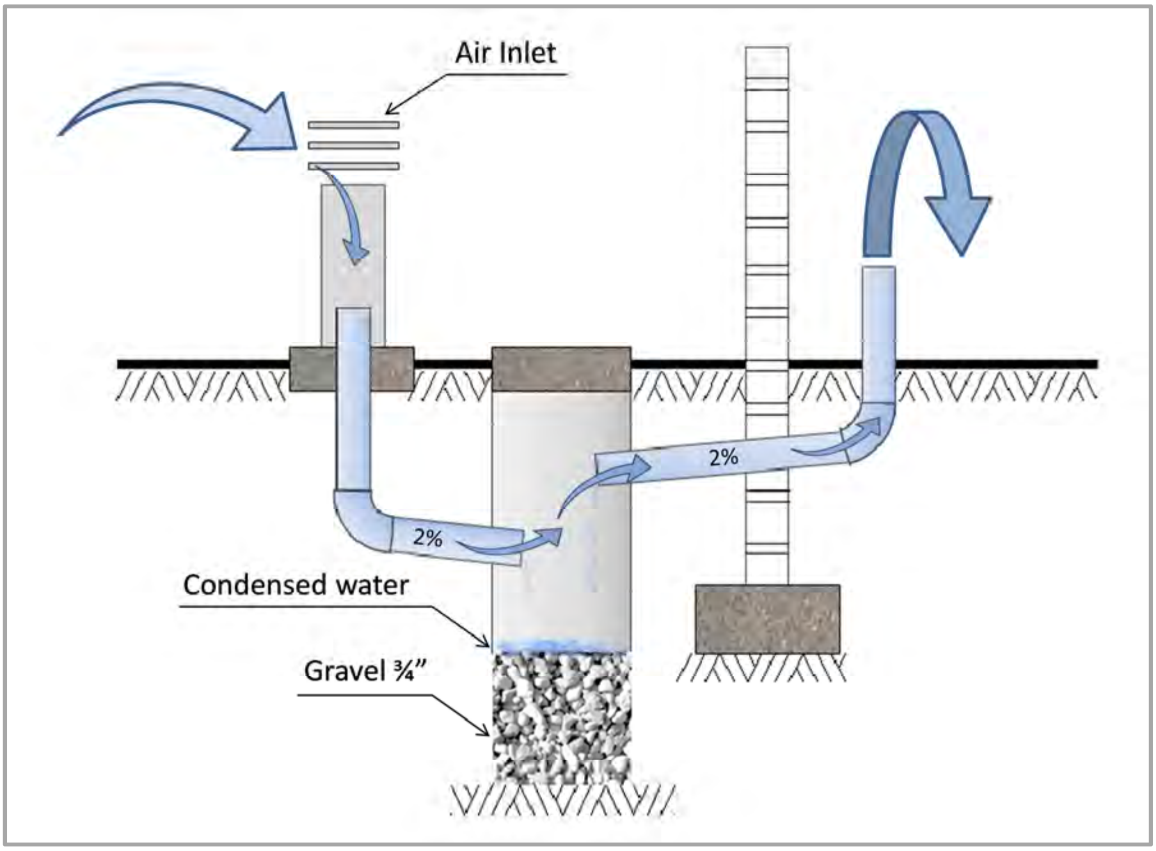
Figure 36. Usage of HDPE in an EAHE

Source: (Larson, 2014)

Drainage

Because of the pipe length and the difference of temperature between the ambient air and the ground, the internal surfaces of the pipes can reach the dew point temperature, resulting in condensation (Larson, 2014)(Peretti, et al., 2013). Therefore, it is important to install the ducts with a minimum slope of 2% to avoid stagnant water -which may stimulate the formation of mold and bacteria- and maintain an adequate air quality (Florides & Kalogirou, 2007). According to Larson Loyau (2005), a good drain system for an EAHE is a kind of cesspool where the pipe can be divided in two and drain the water, which should be then extracted with help of a water pump. In order to avoid this extra energy input, the drainage system is proposed to be perforated on the bottom and with a layer of gravel below it (See Figure 37) so that the water can be absorbed by the soil.

Figure 37. Drainage of an EAHE



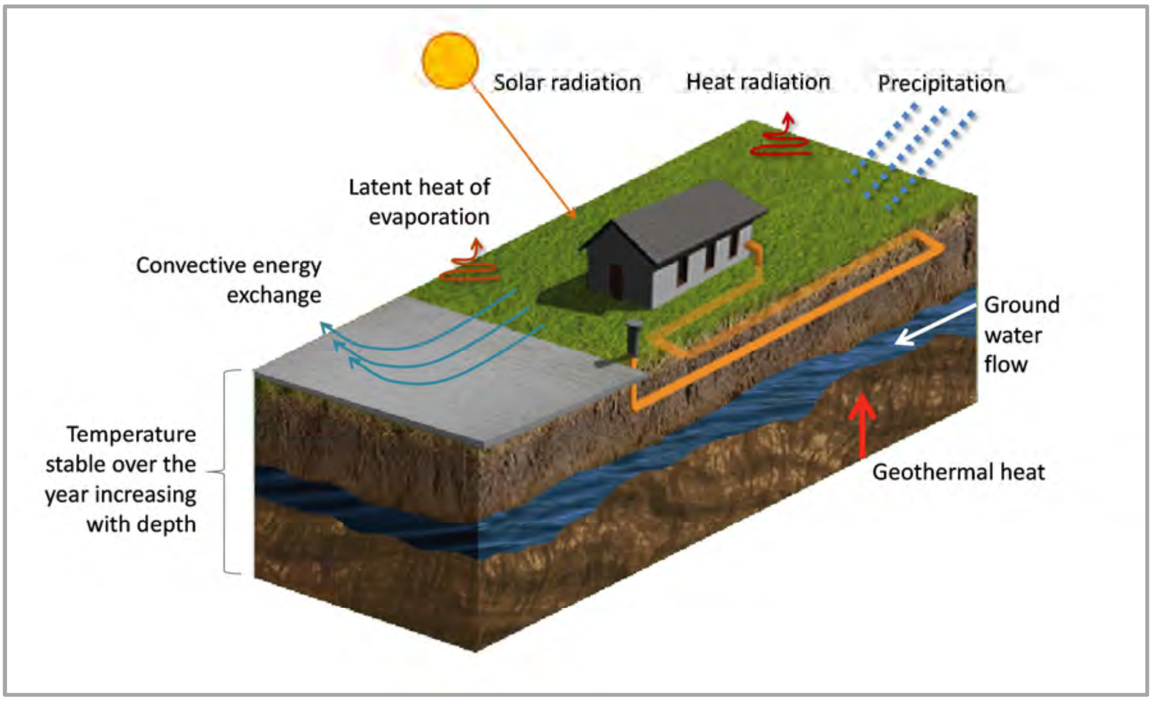
Source: Self-construction based on (Loyau, 2005)

Soil temperature

The thermal performance of an EAHE is highly influenced by the temperature of the soil of the location. Fourier's law explains that daily mean ground surface temperature follows a harmonic variation and that, in general, the temperature of the subsoil is close to the annual mean temperature of the place at sufficient depths (Bansal, et al., 2011) as well as its "yearly amplitude is similar to that of the air (…) as long as there is no anomalous gradient temperature or significant groundwater flow" (Peretti, et al., 2013). It can also be considered that these temperature fluctuations on the subsoil behave under a sinusoidal pattern (Al-Ajimi, et al., 2005) such as the outdoor ambient air (Wu, et al., 2007).

On the layers which are closer to the surface, thermal variations are higher because of the interaction of the ground surface with the climate elements (See Figure 38), affecting the heat transfer into its profile principally due to convection with external air, incident solar radiation and radiant heat exchange with the sky" (Peretti, et al., 2013). The soil type can also affect the behavior of its temperature, as "soils with more moisture contents have a higher heat exchange capacity than rocky, dry, or sandy soils" (Larson, 2014).

Figure 38. Interaction of the ground with the climate elements



Source: Self-construction based on (Florides & Kalogirou, 2007)

The ground cover can also have an influence on the heating potential of EAHE (Badescu, 2006). Mihalakakou, et al. (1996), compared the heating potential of a pipe buried under bare soil, under short-grass-covered soil and under asphalt-covered soil. The authors concluded that the bare soil surface can increase the system's heating capacity by +1.5°C. This means that for heating purposes it is better to bury the pipe network under bare soil. If the requirement is to cool, the pipes under the house's slab foundation or under grass-covered soil is the best option.

For the case of San Luis Potosí, some measurements were taken in a terrain of the metallurgy Faculty of the Autonomous University of San Luis Potosí (UASLP). A pipe with 7 type "J" thermocouples was buried to obtain thermal data of the soil every 30cm, until the depth of 2.1m was reached (See Figure 39). The characteristics of the soil revealed it to be sandy loam, with medium sized rocks. A big constraint is that a lot of rubble was found buried in the soil, such as pieces of concrete and brick, due to the usage of the terrain.

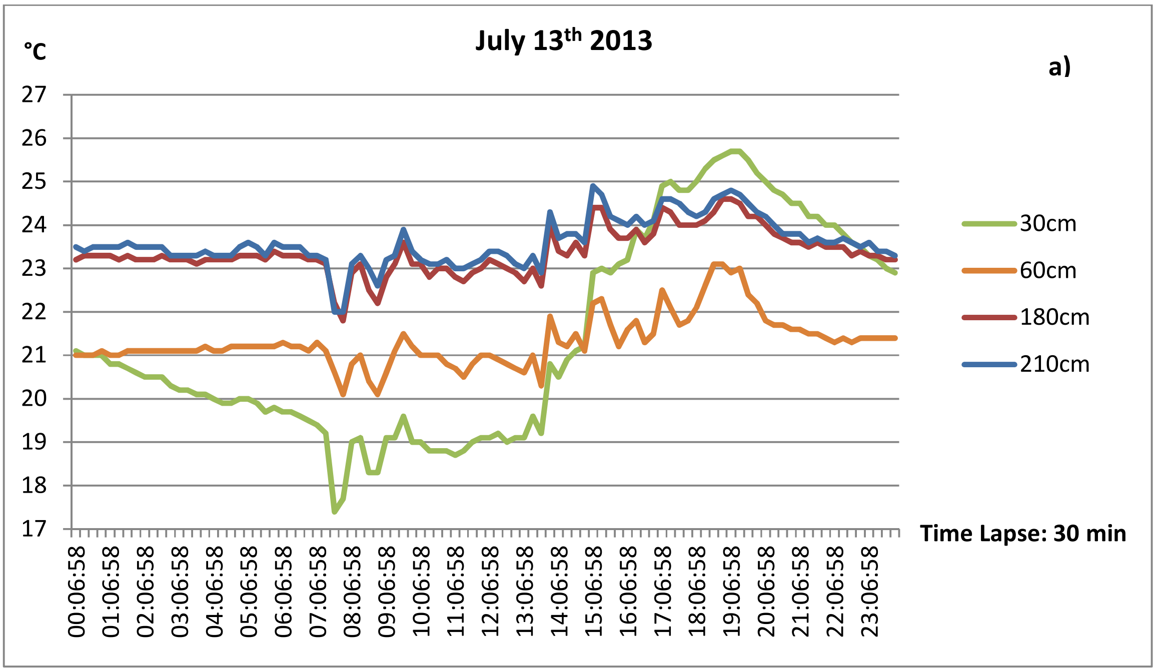
Figure 39. Thermocouples for subsoil temperature measurements

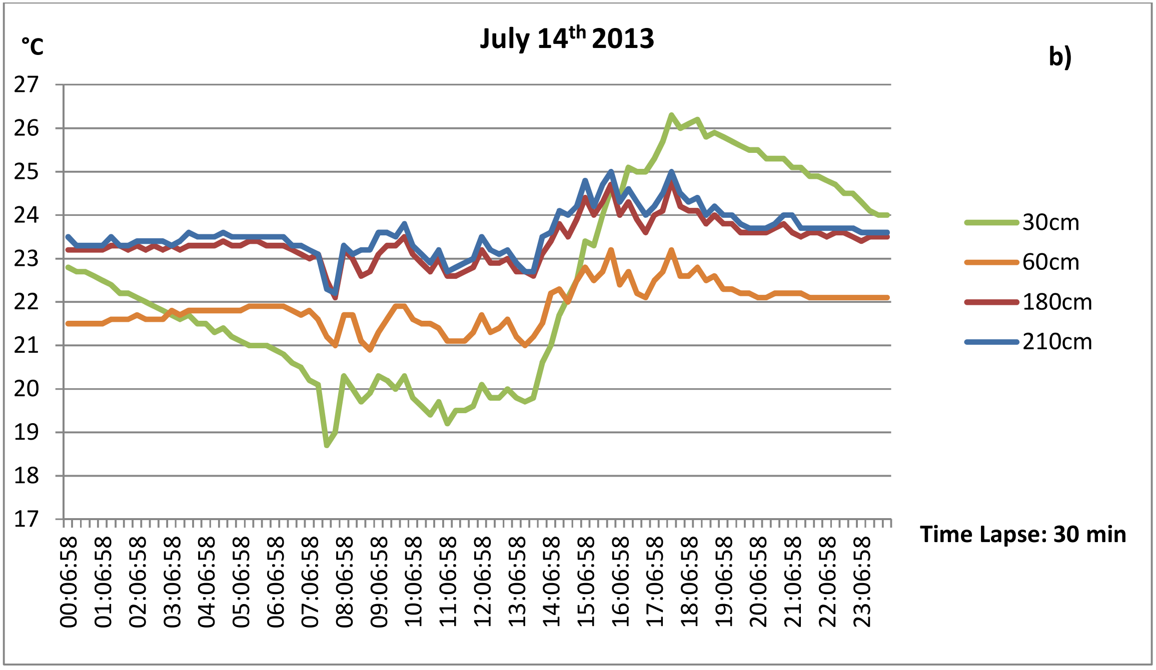
Source: Personal archive, 2014

The first measurements (Figure 40) were made by Dr. José Nieto Navarro, physicist of the UASLP, on July 2013. It is clearly visible a high temperature-variation along the day on the shallow surface of 0.3m, with a range from 17.5°C to 26°C. At 60cm the temperature was more stable, with a range from 20°C to 23°C. On the other hand, the temperatures from depths of 1.8m and 2.1m, which were expected to have lower temperatures, ranged between 22 and 25°C.

The second set of data (Figure 41) was taken on end June 2014. Since the thermocouples used where the same that those used one year ago, some of them registered extreme temperature data due to possible corrosion of the wires. The data of these thermocouples (depths 0.9m, 1.2m and 1.5m) had to be removed in both set of tables to maintain consistency. On the data of 2014, the temperature variation at 0.3m is evident, but it also revealed that depths of 0.6m and 2.1m also presented this variation. In Figure 41a, it was registered an extreme peak of 40°C between 18 and 19h. The most consistent depth was at 1.8m with an average of 22°C. It is possible that the rests of rubble may have affected the measurements of the thermocouples.

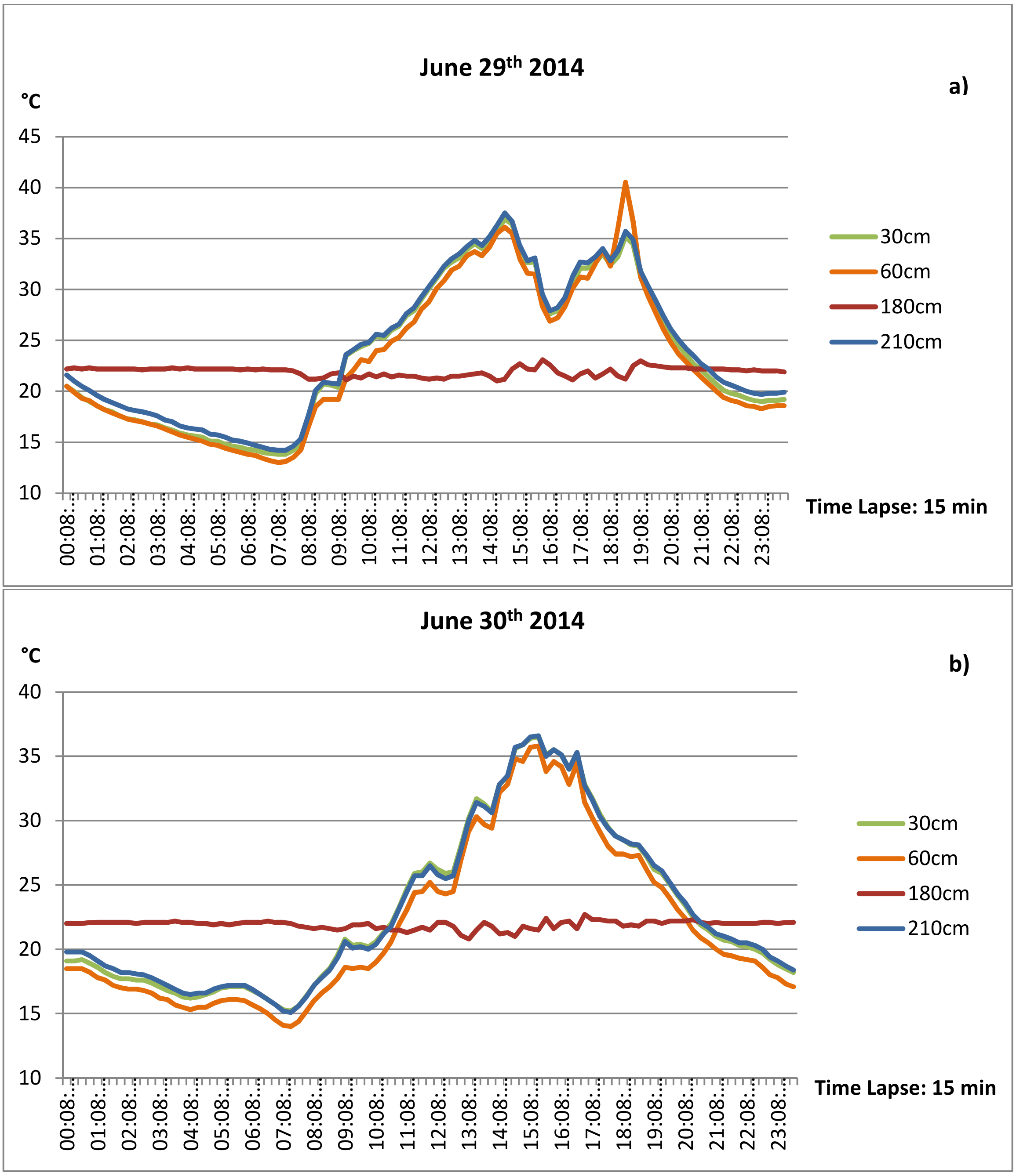
Figure 40. Daily variation of soil temperature 2013





Source: Self-construction with data from José Nieto Navarro, 2013

Figure 41. Daily variation of soil temperature 2014



Source: Self-construction, 2014

Low-Cost

Unlike active cooling and heating devices, an EAHE doesn't require complex equipment or technology to operate (Larson, 2014). It can be considered as a low-tech system since it can work just with a fan to inject the air in the pipeline, and, in some cases, with simply the flow created by the stack effect. The cost of a 12m piece of high density polyethylene is around $420.00MXN (Majum, 2014), and it is considered to use approximately 3.5 pieces per housing unit, so it would be $1,470 MXN of HDPE ($110USD).

As an EAHE can avoid the usage of air-conditioning, it implies a significant saving in electricity consumption (De Paepe & Jannssens, 2002) which would have been used for the acclimatization of a housing unit (Larson, 2014). The most commonly used air-conditioning systems in the market are the mini-splits, which have an average cost of $6000.00MXN ($450USD). Besides the initial cost of these systems, an average mini-split consumes 0.97kWh, while the proposed fan consumes only 0.23kWh.

As it is shown on Table 10, in the summer season uncomfortable thermal sensations are experienced from 12h to 19h, but where the temperature exceeds the maximum comfort temperature of 27°C is from 12h-16h. Therefore, if the air-conditioning system is activated these 4 hours every day for 4 months (488 hours), the consumption of the mini-split would be 488kWh for this period, while the fan would require 112.4kWh, less than a quarter the energy consumption. The "basic consumption" electricity rate as for August 2014 is $0.814MXN/kWh (CFE, 2014). Therefore, in one month the air-conditioning will spend $94.60MXN, while the EAHE only $22.40, representing a monetary saving of $72.00MXN, which is 1/3 of the required $200.00MXN monthly saving set by the Green Mortgage program.

5.3 Integration of the EAHE to a *Popular* Social Housing Unit

The EAHE layout was designed for a housing unit located in Ciudad Satélite (See Annex C), taking advantage of the excavation made for the foundations, and only requiring additional 13.3 m^3 (See Figure 44). The Housing Institute of the State of San Luis Potosí (Instituto de Vivienda del Estado de San Luis Potosí, INVIES) offers the possibility of donating one existing house (See Figure 42) and one unoccupied terrain to implement the design, but the donation is still in process. In the case of the constructed house, it is really difficult to implement a passive acclimatization system, since they are integrated to the design since the beginning, as it was mentioned in chapter 3.2. Nevertheless, this unit is helpful to take temperature and relative humidity measurements and use it as a baseline to compare it to the improved design to be built in the empty terrain.

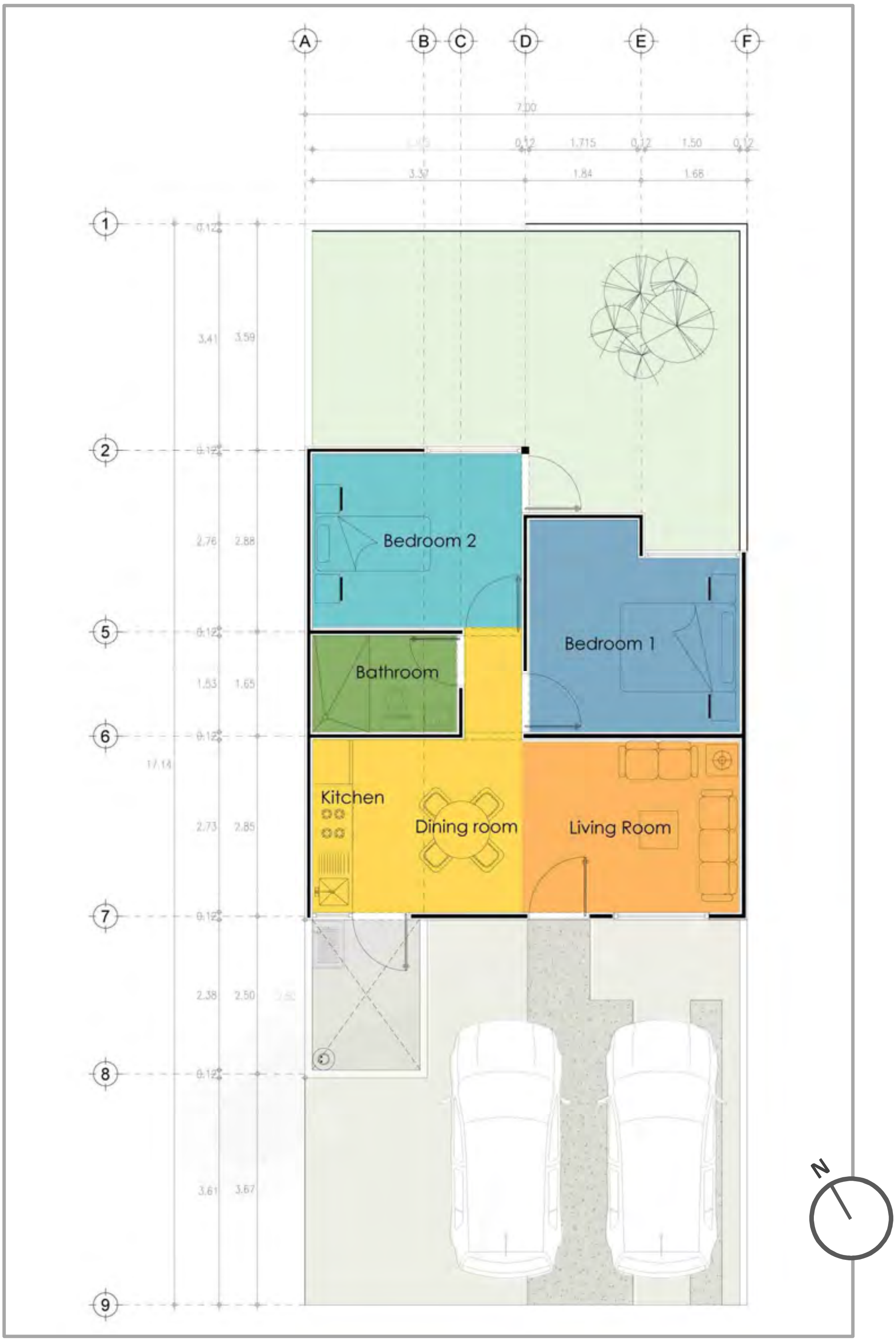
It was sought to maintain the same 48m^2 of the original project, but in order to integrate the solar chimney, an additional space was created (See Figure 43). This space -between the living room and the kitchen- serves as a multiple usage space, which can be used to place a linen closet, kitchen cabinets or a desk to use it as a working space. Besides, since the solar chimney is placed right above this space, it has the dimensions to locate a stair for a future extension of the house, allowing the placement of the chimney on the top of the vertical core, which will enhance its operation, since a larger distance between the inlet and the outlet of the air, increases the performance of solar chimneys (Autodesk, 2013) (García Chávez & Fuentes Freixanet, 1995).

Another major modification to the original design of the house was to switch the places of the living room and the second bedroom (Bedroom-2) to allow a continuous circulation to the backyard without crossing any private space. This also allows a cross ventilation, taking advantage of the prevailing wind from NE when the air temperature is not so high to require the cooling of the EAHE.

The floor area of this proposal is 54.34 m^2, staying in the “Popular” classification of CONAVI (See Table 4) which goes from 42.5-62.4 m2. If the floor plan of the first story is duplicated to the second story -in case of an extension of the house- the master bedroom (bedroom-1) and the living room area can be used as bedrooms, while the kitchen and bedroom-2 area can be used as a master bedroom with an integrated bathroom. This way, the air outlets can be extended to the second story to take advantage of the airflow of the EAHE.

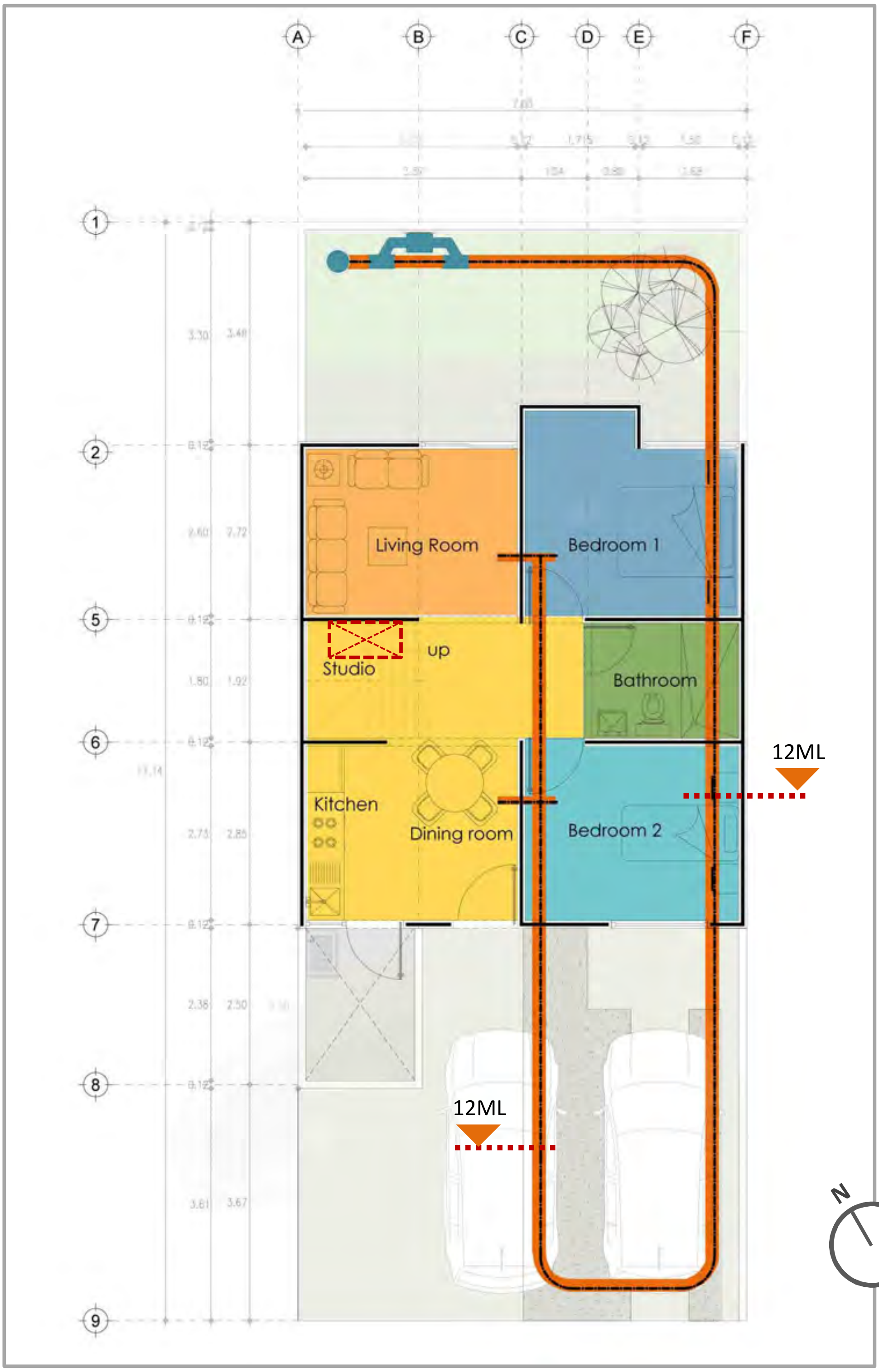
With this final layout, the EAHE is laid on the side of the perimeter foundations and on the foundation of the wall on the center, with a total extension of 33.3 linear meters (ML), consisting of two 12-meters pieces and a final section of 9.3m which enters the house (See Figure 43). Both air outlets can be placed at 0.8m height on the walls, with a “T” configuration to supply the temperate air to the bedrooms, the living room and the kitchen.

Figure 42. Original house floor plan of Ciudad Satélite housing unit



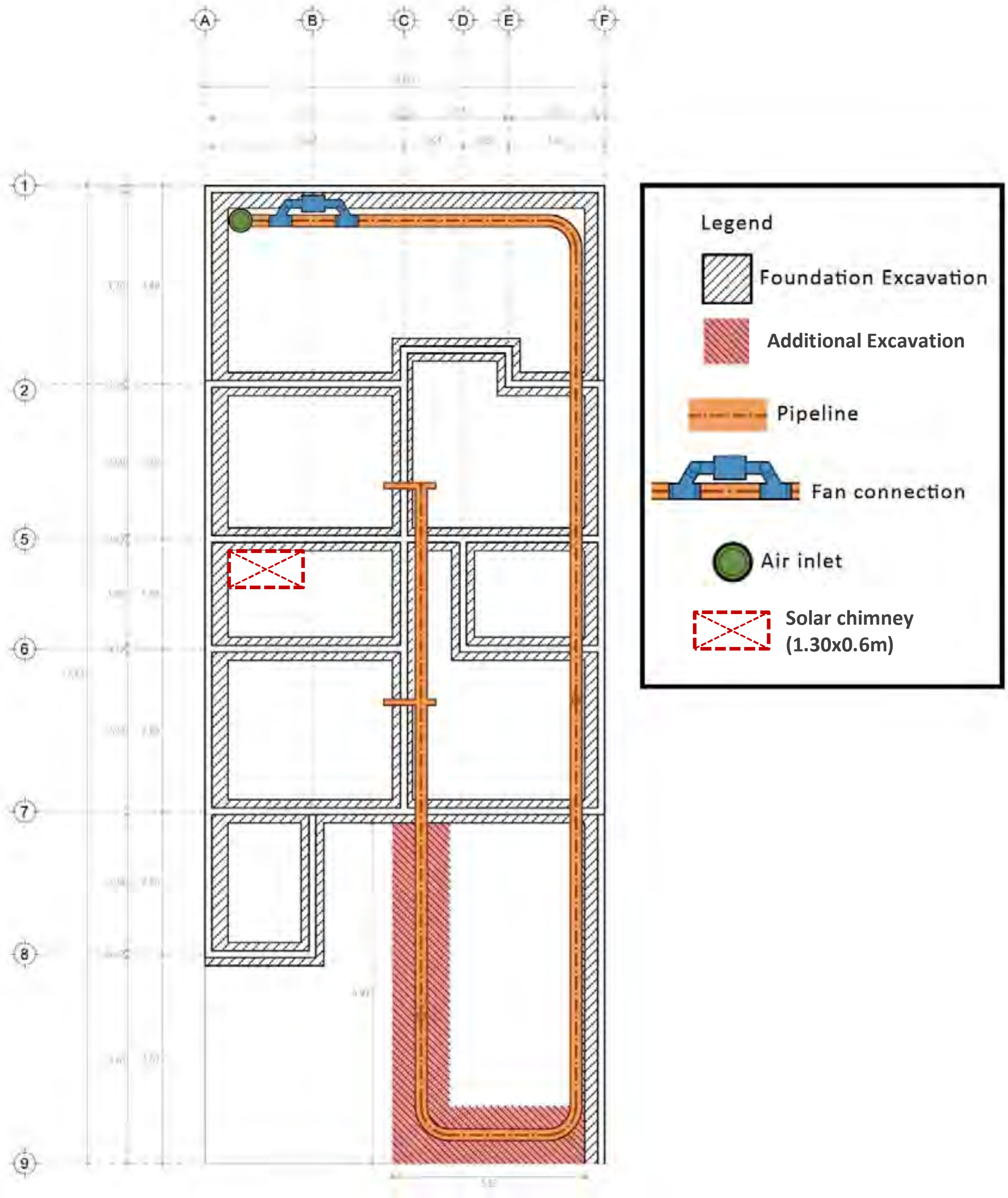
Source: Self-construction based on INVIES (2014)

Figure 43. Modified floor plan of Ciudad Satélite housing unit



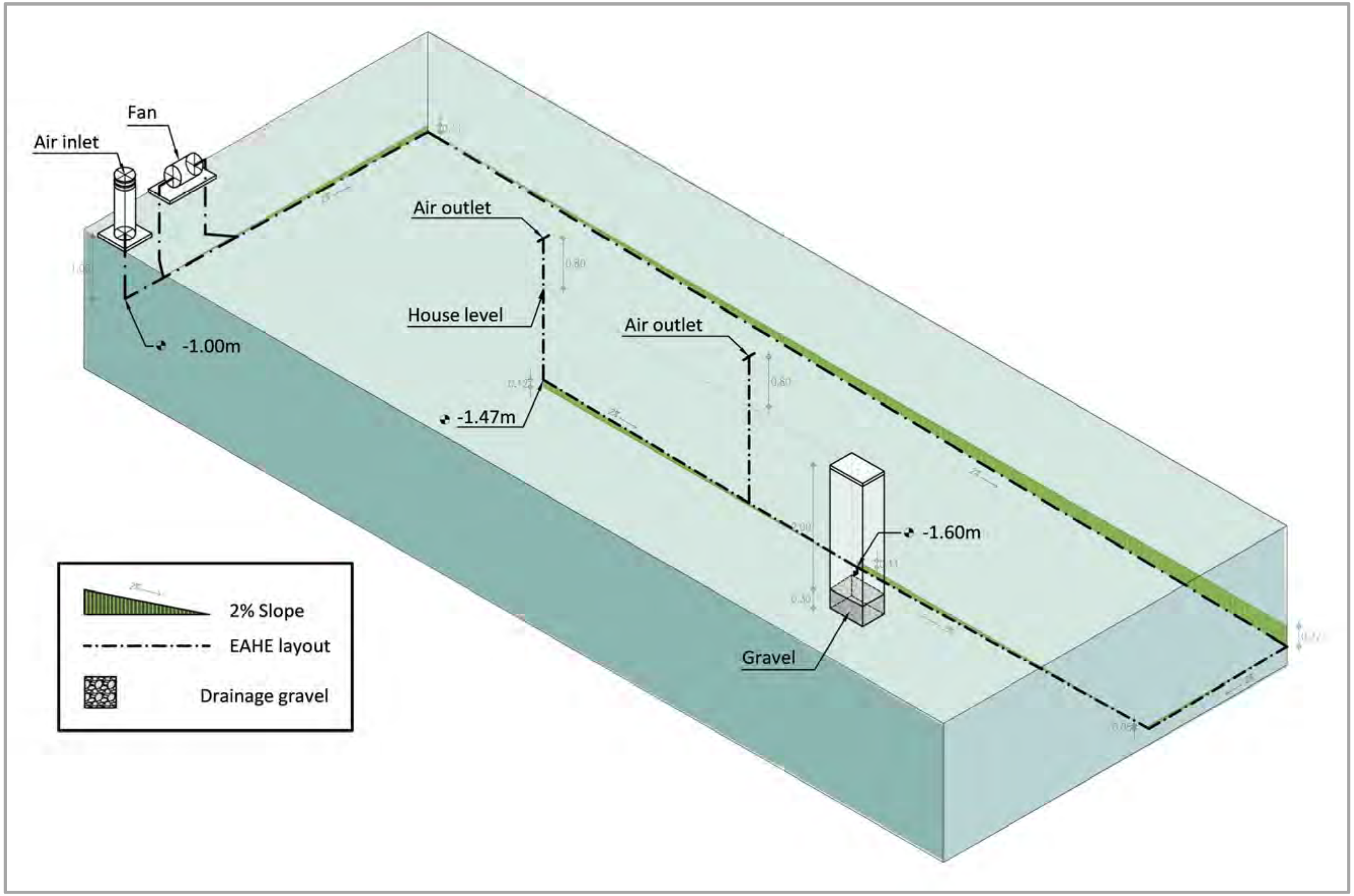
Source: Self-construction (2014)

Figure 44. Layout of the EAHE pipeline on the foundations



Source: Self-construction (2014)

Figure 45. Isometric of the EAHE layout



Source: Self-construction (2014)

Figure 45 shows the layout of the EAHE in an isometric view. The pipe from the inlet goes down to one meter, and then follows the perimeter of the terrain on the side of the foundations, considering a minimum 2% slope to drain the condensed water. A cesspool is located just before entering the house so maintenance works can be done without damaging the interior of the house. A 30 cm gravel layer is placed on the bottom to absorb the condensed water and drain it to the terrain (See Figure 37). At this point, the pipeline reaches the maximum depth of 1.6m. The following pipe which enters the house has a positive 2% slope so that the condensed water returns to the cesspool, rising 13cm to reach a depth of 1.47m. It is important to mention that the fan is located slightly back of the pipeline so it can be bypassed if it is not used, in order to profit from the stack ventilation, lowering the energy consumption.

With these characteristics defined mainly by the terrain, soil limitations and design of the house, the data was processed in the specialized software GAEA to determine the performance of the proposed EAHE (See Figure 46). First of all, Figure 46a shows that one spiral pipe of a length of 33.3m, a diameter of 0.2m and an average depth of 1.3m it is being considered. Then, Figure 46b shows the tab where different kinds of soils can be selected. In this case, the soil that was more consistent with the given terrain is the sandy soil, whose characteristics are set by default by the software. These values can also be manually defined by the user.

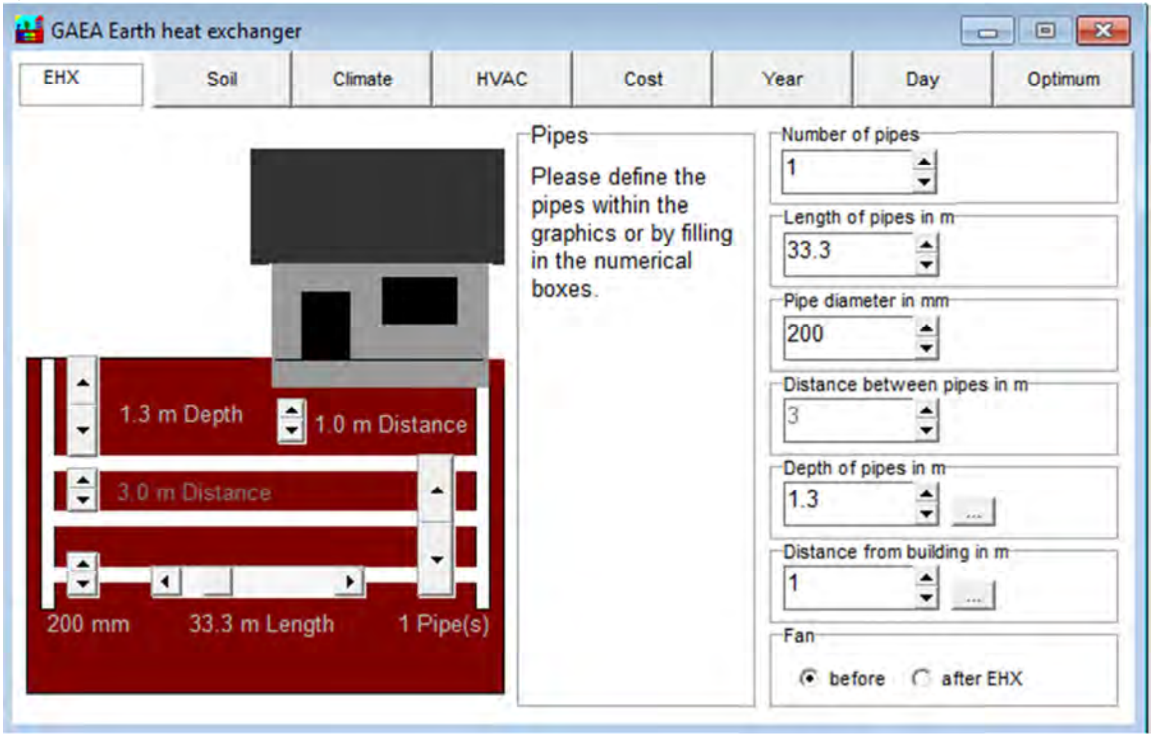
Figure 46c shows the climate with a sinusoidal pattern after setting the maximum monthly temperature and the yearly mean temperature. A weather station or a climatic region can be selected, but only for Europe. Therefore, a precise simulation cannot be performed; however, it can be used to have an idea of the performance of an EAHE on an early design stage.

The building volume and the air flow rate can be set on the HVAC tab (Figure 46d), as well as the operation of the EAHE, which can be set by a period of time or by a temperature range. In this case, the comfort temperature limits of the city of San Luis Potosí were considered; therefore, the EAHE would start operating above 27°C and below 19°C.

The annual analysis showed on Figure 46e shows that even if the maximum inlet air temperature goes up to 39.5°C, the maximum outlet air temperature is almost 10°C lower, and with a minimum inlet air temperature of -3.5°C, the outlet air temperature stays on 7°C. Even if in both cases the comfort temperature is not achieved, it is demonstrated that the usage of an EAHE can reduce significantly the usage of active devices to achieve it.

Figure 46. EAHE performance simulation with the software GAEA

a)



Pipes

Please define the pipes within the graphics or by filling in the numerical boxes.

Number of pipes: 1

Length of pipes in m: 33.3

Pipe diameter in mm: 200

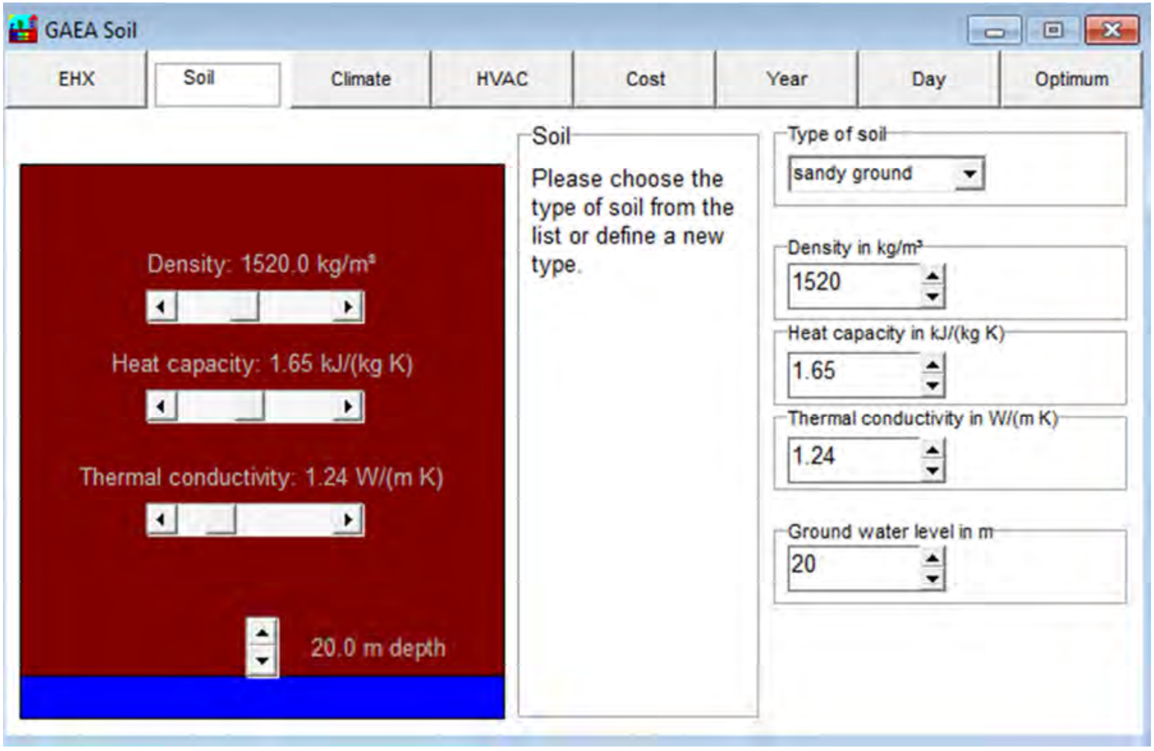
Distance between pipes in m: 3

Depth of pipes in m: 1.3

Distance from building in m: 1

Fan: ● before ○ after EHX

b)



Soil

Please choose the type of soil from the list or define a new type.

Type of soil: sandy ground

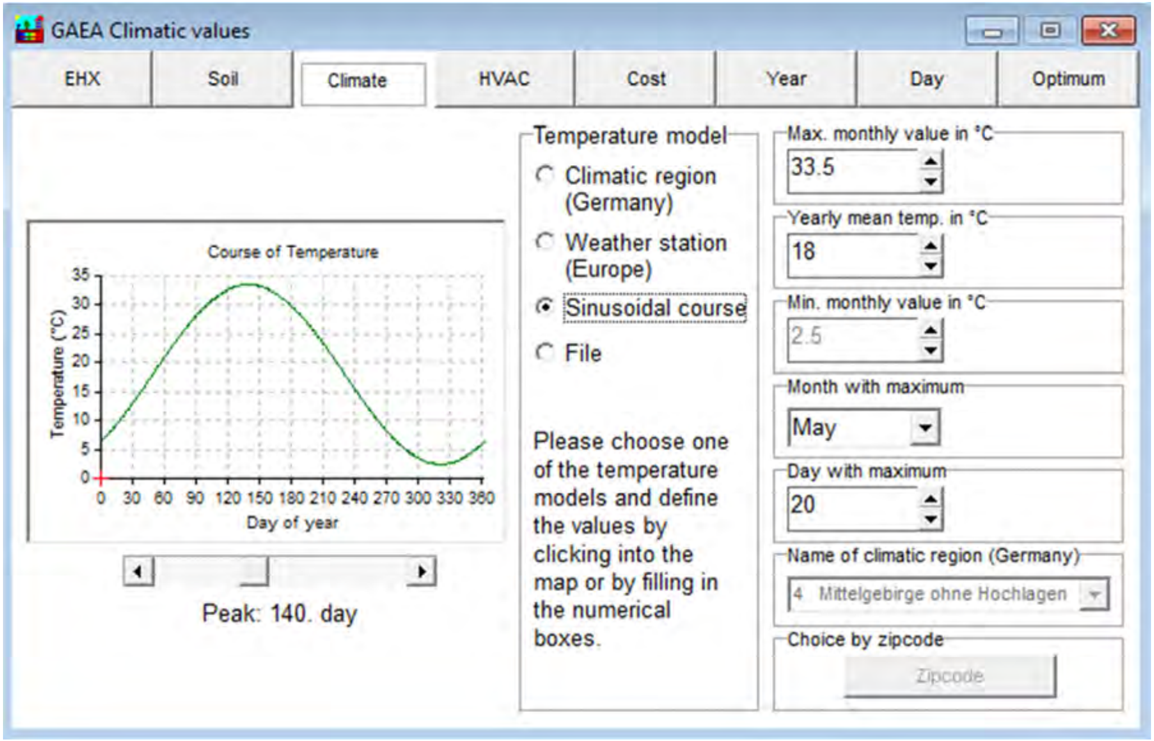
Density in kg/m³: 1520

Heat capacity in kJ/(kg K): 1.65

Thermal conductivity in W/(m K): 1.24

Ground water level in m: 20

c)



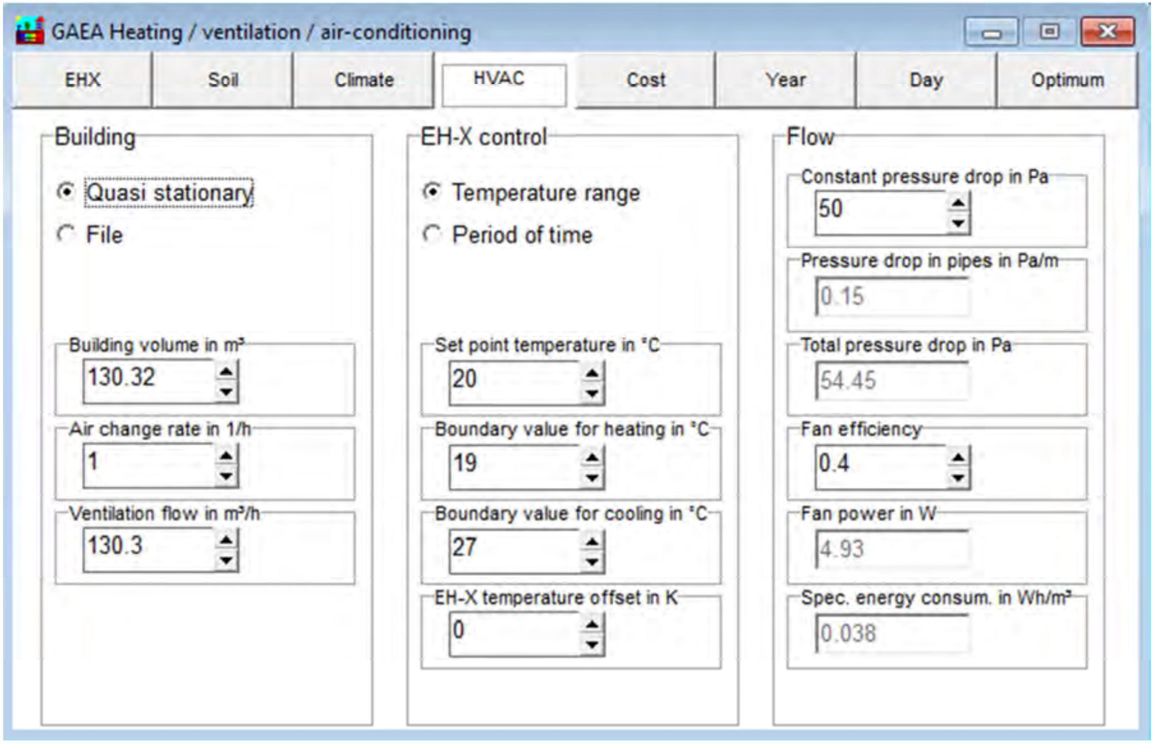
Peak: 140. day

Temperature model
○ Climatic region (Germany)
○ Weather station (Europe)
● Sinusoidal course
○ File

Please choose one of the temperature models and define the values by clicking into the map or by filling in the numerical boxes.

Max. monthly value in °C: 33.5
Yearly mean temp. in °C: 18
Min. monthly value in °C: 2.5
Month with maximum: May
Day with maximum: 20
Name of climatic region (Germany): 4 Mittelgebirge ohne Hochlagen
Choice by zipcode

d)



Building
● Quasi stationary
○ File

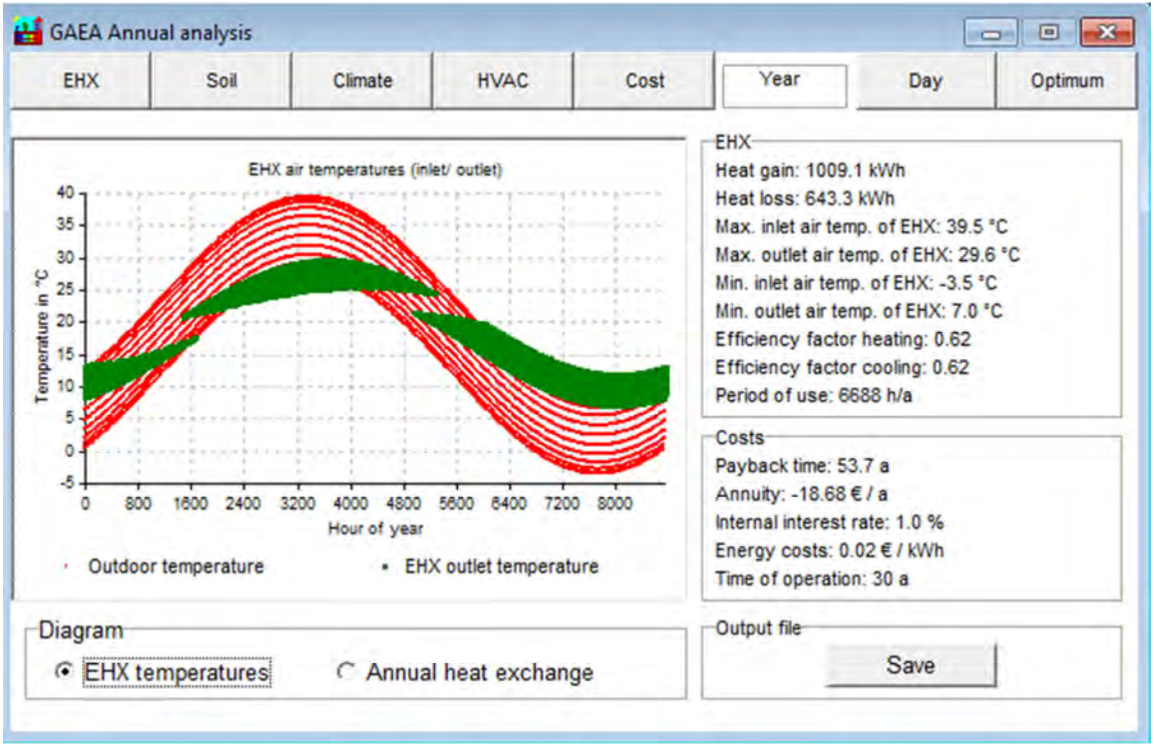
Building volume in m³: 130.32
Air change rate in 1/h: 1
Ventilation flow in m³/h: 130.3

EH-X control
● Temperature range
○ Period of time

Set point temperature in °C: 20
Boundary value for heating in °C: 19
Boundary value for cooling in °C: 27
EH-X temperature offset in K: 0

Flow
Constant pressure drop in Pa: 50
Pressure drop in pipes in Pa/m: 0.15
Total pressure drop in Pa: 54.45
Fan efficiency: 0.4
Fan power in W: 4.93
Spec. energy consum. in Wh/m³: 0.038

e)



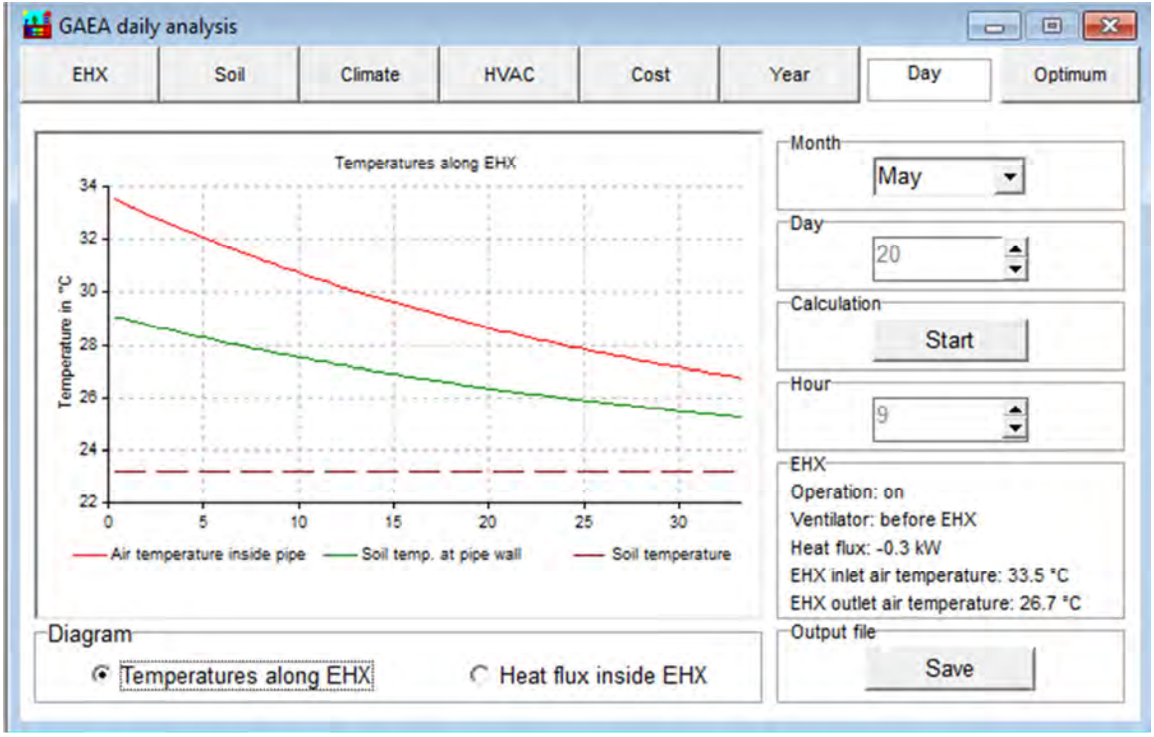
EHX
Heat gain: 1009.1 kWh
Heat loss: 643.3 kWh
Max. inlet air temp. of EHX: 39.5 °C
Max. outlet air temp. of EHX: 29.6 °C
Min. inlet air temp. of EHX: -3.5 °C
Min. outlet air temp. of EHX: 7.0 °C
Efficiency factor heating: 0.62
Efficiency factor cooling: 0.62
Period of use: 6688 h/a

Costs
Payback time: 53.7 a
Annuity: -18.68 € / a
Internal interest rate: 1.0 %
Energy costs: 0.02 € / kWh
Time of operation: 30 a

Diagram
● EHX temperatures ○ Annual heat exchange

Output file

f)



Month: May
Day: 20
Calculation
Hour: 9

EHX
Operation: on
Ventilator: before EHX
Heat flux: -0.3 kW
EHX inlet air temperature: 33.5 °C
EHX outlet air temperature: 26.7 °C

Diagram
● Temperatures along EHX ○ Heat flux inside EHX

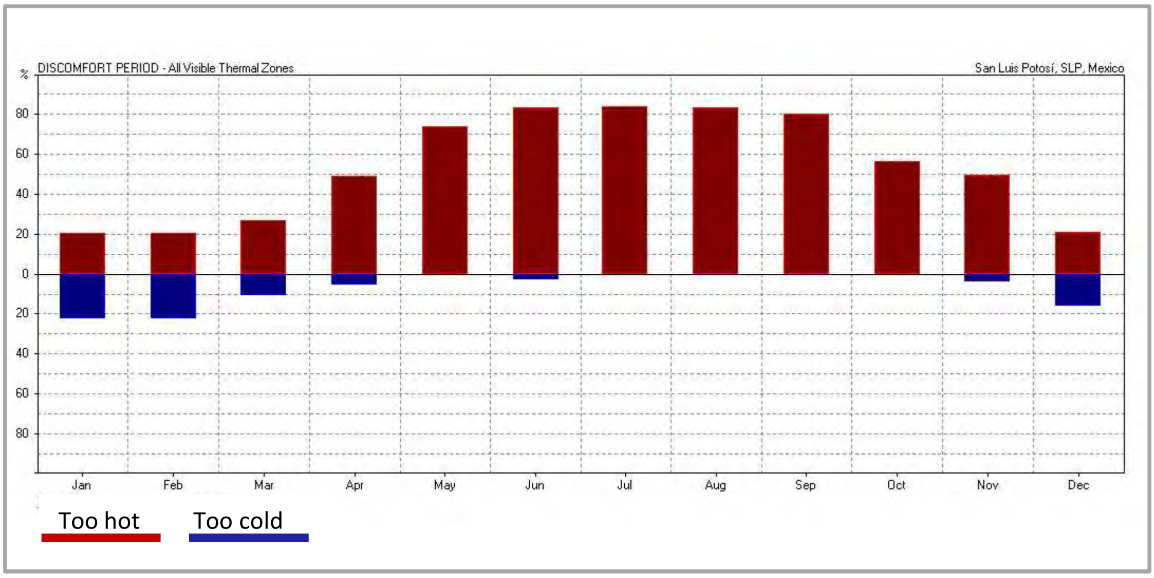
Output file

Source: Self-construction with GAEA 1.04.05 (2014)

Figure 46f shows the analysis of a determined day, May 20th which, according to the data of Meteonorm (2007), registers the highest average temperature of 33.5°C. The red line shows the air temperature inside the pipe along the 33.3m distance, while the green line represents the soil temperature at the pipe wall. As it can be seen, the analysis shows that, with the characteristics of the proposed EAHE, the inlet air temperature of 33.5°C descends as it travels through the pipe, to obtain an outlet air temperature of 26.7°C at the end of the system, which is more than 6°C of difference. This graphic shows that as the distance increases, the difference of temperature between the air inside the pipe and the pipe wall is smaller.

On the other hand, a thermal simulation was performed with the software Autodesk Ecotect, considering the common construction system of brick and plaster walls with a U-value of 2.3W/m2K, single glazing and aluminum frame windows of 5.73W/m2K, and concrete-plaster roof of 2.563W/m2K (McMullan, 1998). These characteristics along with the spatial configuration, orientation and windows location, showed that the analyzed housing unit has more discomfort regarding hot spaces along the year than it does for cold spaces. In summer time, and up to September, the house is too hot almost 80% of the time, while in winter, it is too cold 20% of the time (See Table 17).

Table 17. Percentage of time on discomfort



Source: Self-construction with Autodesk Ecotect (2014)

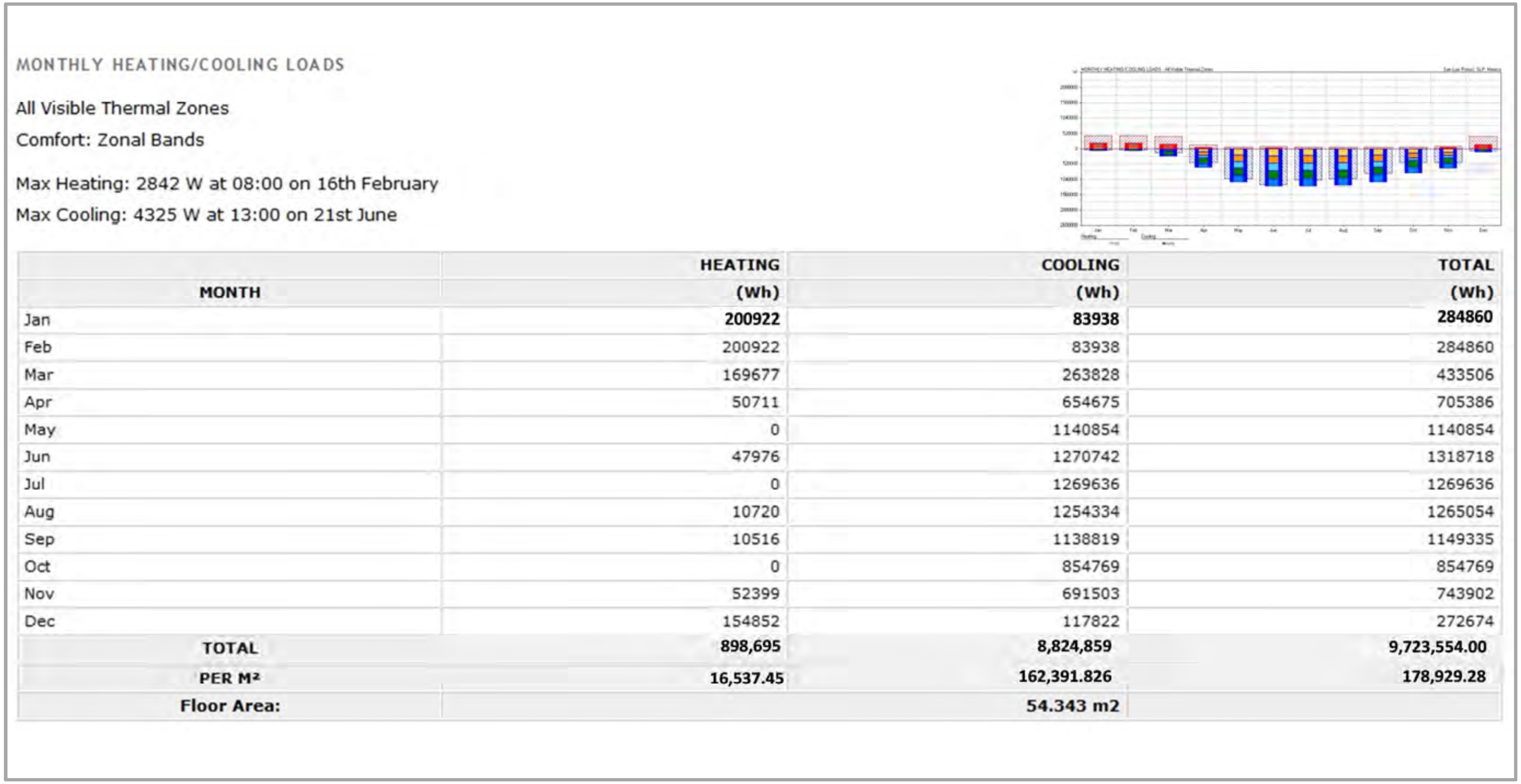
This software uses the weather file from Meteonorm (2007). Since it contains all the hourly values for the specified location, it is helpful to calculate the monthly heating and cooling loads, giving as a result the annual values and the values per square meter. Table 18 shows that, even if the degree days show that more heating is required over the year, the materials, layout and orientation of a row house can increase the cooling demand to 162kWh/m^2/year, while the heating demand is lowered to 16.53kWh/m^2/year.

The maximum heating load is registered for February 16th at 8:00 with 2.84kW, and the maximum cooling load for the summer solstice at 16:00 with 4.32 kW. The heating value for the same house with a detached configuration is 131.18 for cooling and 44.45kWh/m^2/year for heating. Figure 47 shows the comparison of both, detached and row configuration, displaying the consumption percentage of every analyzed zone.

These results show that the cooling of the house must be prioritized, especially from May to September. The usage of the EAHE combined with the solar chimney has a great potential to satisfy the cooling demand. The software Autodesk Revit and a plug-in of Flow Design were used to determine the effectivity of the solar chimney using the prevailing wind from the NE. Setting the wind direction and the speed of 4m/s (Aguillón Robles, 2007), Figure 48 shows the comparison between a house with and without the solar chimney. It can be seen that the airflow is conducted through the chimney at speeds of 4.7m/s, and reaching up to 6m/s above it.

Figure 49 shows more clearly the effect of the wind speed increment as it flows through its center, an effect that can help suck the interior air with help of the stack effect, as the ascending warm air has lower pressure, as well as the faster flowing air. Regarding the material of the chimney, it is important to use solid, rigid materials that can resist the elements and the wind speed. It is proposed to be made of OSB panels covered with fiberglass to resist rain, and painted black to absorb the solar radiation. It is important to mention that the solar chimney opening must be able to be regulated on the colder months to avoid the air suction and profit from the air heated by the radiation that emanates from its black surface.

Table 18. Monthly heating and cooling loads



MONTHLY HEATING/COOLING LOADS

All Visible Thermal Zones

Comfort: Zonal Bands

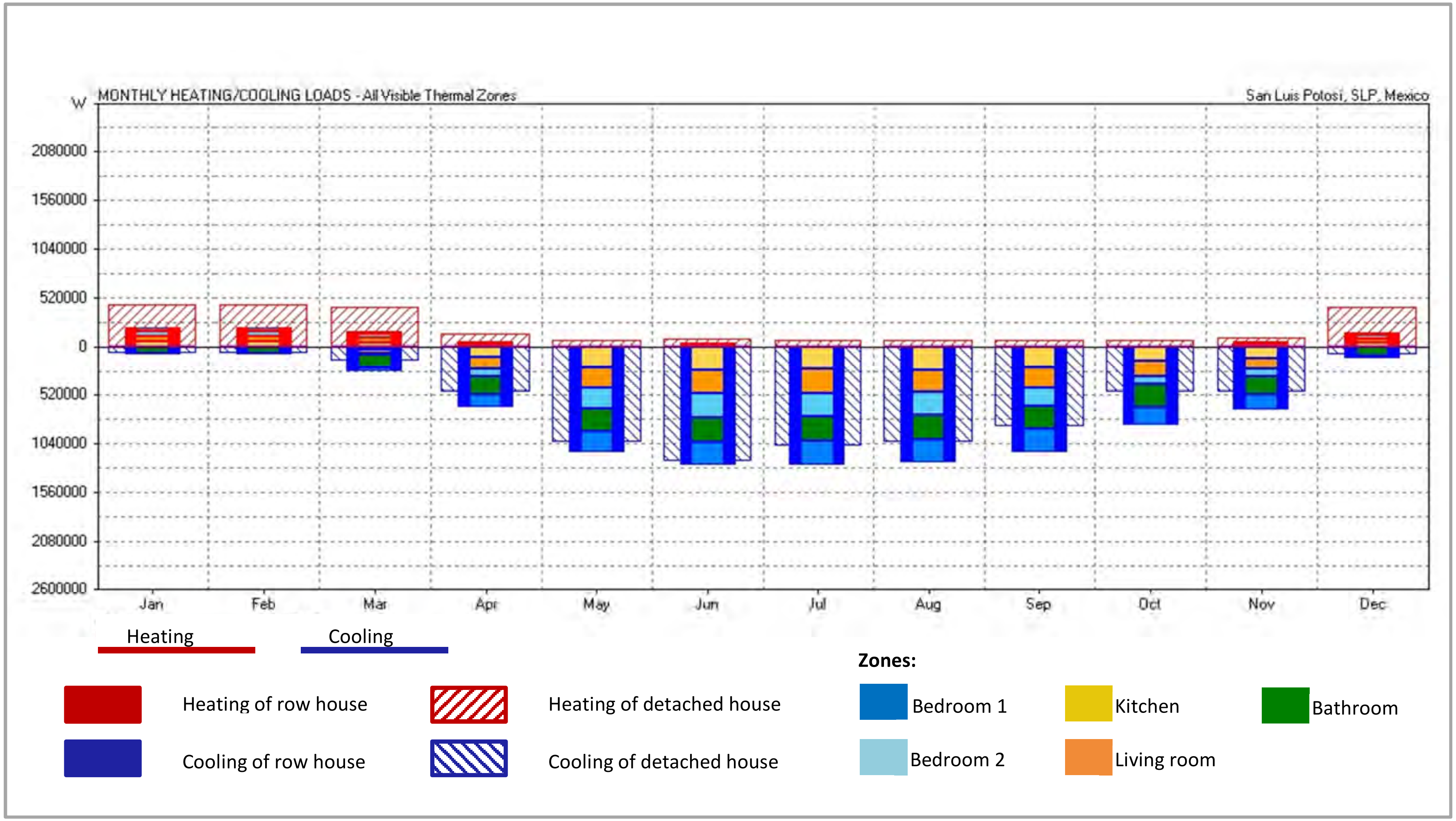
Max Heating: 2842 W at 08:00 on 16th February

Max Cooling: 4325 W at 13:00 on 21st June

MONTH	HEATING (Wh)	COOLING (Wh)	TOTAL (Wh)
Jan	**200922**	**83938**	**284860**
Feb	200922	83938	284860
Mar	169677	263828	433506
Apr	50711	654675	705386
May	0	1140854	1140854
Jun	47976	1270742	1318718
Jul	0	1269636	1269636
Aug	10720	1254334	1265054
Sep	10516	1138819	1149335
Oct	0	854769	854769
Nov	52399	691503	743902
Dec	154852	117822	272674
TOTAL	**898,695**	**8,824,859**	**9,723,554.00**
PER M²	**16,537.45**	**162,391.826**	**178,929.28**
Floor Area:		**54.343 m2**	

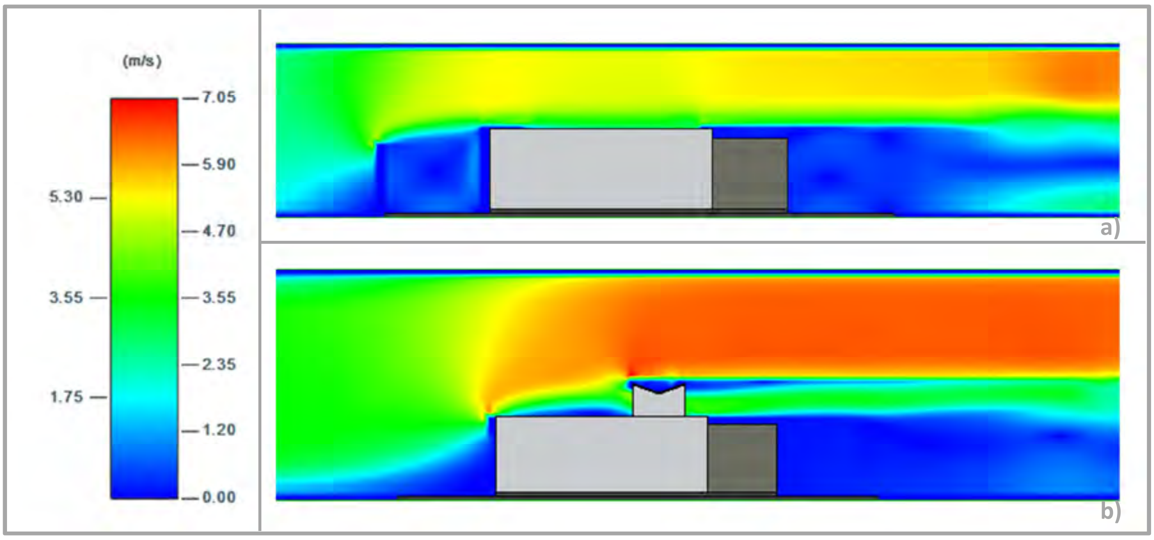
Source: Self-construction with Autodesk Ecotect (2014)

Figure 47. Monthly heating and cooling loads comparing detached and row house



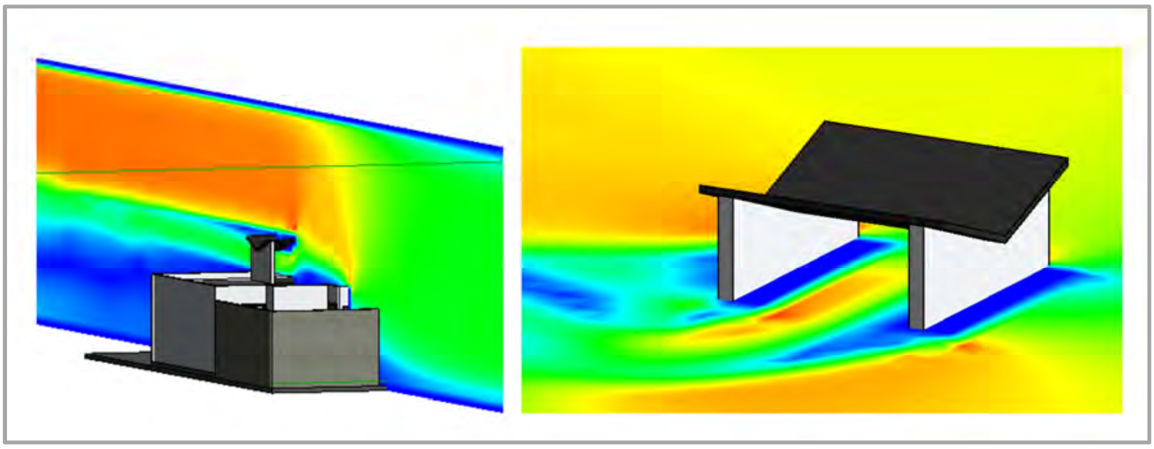
Source: Self-construction with Autodesk Ecotect (2014)

Figure 48. Wind speed comparison between a house with and without the solar chimney



Source: Self-construction with Autodesk Revit and Flow Design (2014)

Figure 49. Airflow through the wind chimney



Source: Self-construction with Autodesk Revit and Flow Design (2014)

6 Conclusions

Social housing in Mexico includes a wide range of actors that go from public sector to private financial institutions, secretariats, programs, housing developers and consumers. In a capitalist society, it is normal that construction companies seek to increase their revenue as much as possible. Therefore, it is common that housing developments are designed and built alien to their environment, with minimal dimensions and requirements, and often not considering the climate zones or the orientation of the prototype house that is repeated over and over in the site.

With a growing tendency on sustainable development over the world, Mexican government targeted sustainability goals since the National Development Plan of 2007-2012, which proposes a reduction of GHG emissions through –among others- more energy-efficient housing units through the implementation of the NAMA for sustainable housing and its three phases of EcoCasa I, EcoCasa II and EcoCasa Max.

Unlike developed countries, the funding programs for reaching sustainability approaches such as Green Mortgage have been beneficiating the lower income sector. It might be considered as a bottom-up strategy, but at the end the constructors are the ones who decide which eco-techniques they use in the projects to fulfill the program’s requirements. Besides, this sector of the population might not fully understand the concept of sustainability, and would need an operation manual for the eco-technologies applied in their new house to use them properly and to give them maintenance.

Usually, another big constraint of these kinds of programs is that a lack of agreement between the actors at federal and state levels can be found. Many times, every state and even every municipality has their own development plans, which also may change along the incoming governmental periods, making it really difficult to regulate the housing conditions in the three governmental scopes. Nevertheless, the NAMA is projected to be expanded other housing segments, and to impulse the implementation of the Sisevive-Ecocasa program as a regulation for building codes in a municipal level in a medium term.

In a long term, the NAMA framework seeks to include EcoCasa Max to the sustainable housing units, which intends to reach the Passive House Standards. This represents major challenge since -up to now- there are not prototypes of these kinds of dwellings, and the NAMA framework sets 2020 as a possible date to implement them. Besides, the Passive House standards are the most demanding standards regarding energy efficiency, focusing specially on the usage of thermal insulation. If we consider that the usage of insulation is relatively new for most of the actors involved in the construction sector, and that providers and installers are barely found in the country, the way to achieve this standards might rely on better architecture practices and passive acclimatization systems. The PHPP already considers systems such as the EAHE in Europe, so it might be complicated to implement it in Mexico, but it is possible since the DEEVi is in a stage where it is open to new proposals.

Therefore it is also important to be familiar with the passive acclimatization systems commonly used in the residential sector. As it was seen in Chapter 3, most of the systems require attached spaces, thick walls or specific orientations. Even if they are all important aspects, they are also limitations when considering the dimensions and characteristics of a social housing unit. EAHE systems are usually used in big terrains; nevertheless, it was demonstrated that a 30m long pipeline can be laid in the terrain of a social housing unit taking advantage of the excavation of the foundations, which also represents an economic saving for the constructors and, therefore, for the final users.

Even if the heating and cooling degree days for the city of San Luis Potosí show that more heating is needed in the houses than cooling, the simulation performed on Autodesk Ecotect revealed that the cooling load is more significant due to the configuration of the house and the distribution of its spaces, being a premise to prioritize cooling especially from May to September.

Literature about natural ventilation indicates that the cooling potential of the ambient air at speeds from 0.5 to 1.5m/s is enough to provide a cooling effect on the body of the users, and that only if its temperature is higher than that of the skin temperature (37°C) it requires a passive or active cooling. The average temperatures on the weather data of the city of San Luis Potosí don't reveal any temperatures above 29.3°C, and the data obtained from Meteonorm (2007) has registered a maximum of 33.5°C on May 20th at 13:00. This means that cooling the air is not essential in the city, and that the cooling demands can be covered with a good location of windows to profit from natural ventilation, materials with higher thermal mass, and adequate shading devices in the openings that require them, especially on the south.

Nevertheless, depending on natural ventilation is difficult, since the behavior of the wind cannot be predicted, changing along the year and even along the day. Therefore, an EAHE is a good option to ventilate a house, since it can be used with natural airflow, or with a fan to inject the air to the pipeline when there is not enough wind, making it independent from the wind direction and not limited to a specific orientation. The advantage of an EAHE over other passive acclimatization systems is that they provide cooling and heating, depending on the season of the year. It has other advantages such as air filtering and noise reduction, since the windows don't need to be opened to ventilate a room, which is really useful on dense urban areas.

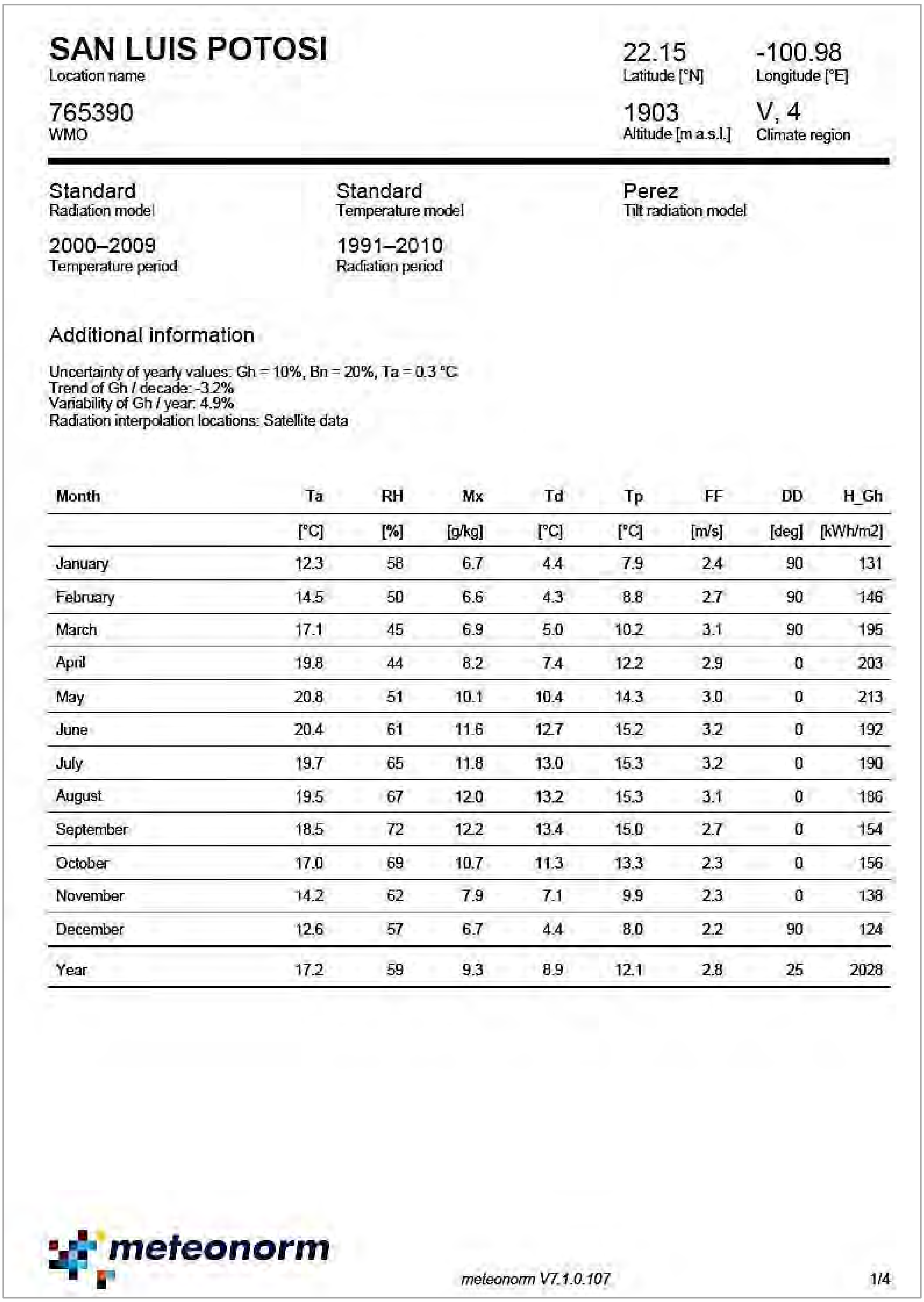
The simulation performed with the software GAEA showed that, even in a sandy soil, the EAHE can help cool or heat up to 6°C, which will reduce environmental impacts in the housing sector while decreasing the energy used to reach a comfort temperature inside a housing unit. A big constraint for the implementation of the EAHE system on the city of San Luis Potosí is that almost 80% of the soils in the state have physical limitations for use, including petro-calcic and rocky and gravel limitations most of the times at depths smaller than 1m, and only 13.5% are deep (greater than 1m) and without usage limitations, representing a restriction for horizontal and vertical configurations of the EAHE.

Further research

Future research is suggested to analyze the performance of the proposed EAHE system:

- Analyzing the thermal properties of the soils registered on the city of San Luis Potosí, as well as the depth limitations to determine where can it be applied and where not
- Experimentation on different configurations of the EAHE such as diameter, length, materials to determine the best solution for the specified climate
- Experimentation on different layouts of the EAHE, even try with a vertical layout
- Experimentation on different solutions for the solar chimney
- If the terrain is donated by the INVIES, the EAHE can be implemented with the best characteristics and combined with the solar chimney to prove the performance of the hybrid system
- Further studies regarding the implementation of the system in other climate regions of the country

Annex A. Weather Data from METEONORM (2007)



SAN LUIS POTOSI
Location name

765390
WMO

22.15
Latitude [°N]

-100.98
Longitude [°E]

1903
Altitude [m a.s.l.]

V, 4
Climate region

Standard
Radiation model

Standard
Temperature model

Perez
Tilt radiation model

2000–2009
Temperature period

1991–2010
Radiation period

Additional information

Uncertainty of yearly values: Gh = 10%, Bn = 20%, Ta = 0.3 °C
Trend of Gh / decade: -3.2%
Variability of Gh / year: 4.9%
Radiation interpolation locations: Satellite data

Month	Ta	RH	Mx	Td	Tp	FF	DD	H_Gh
	[°C]	[%]	[g/kg]	[°C]	[°C]	[m/s]	[deg]	[kWh/m2]
January	12.3	58	6.7	4.4	7.9	2.4	90	131
February	14.5	50	6.6	4.3	8.8	2.7	90	146
March	17.1	45	6.9	5.0	10.2	3.1	90	195
April	19.8	44	8.2	7.4	12.2	2.9	0	203
May	20.8	51	10.1	10.4	14.3	3.0	0	213
June	20.4	61	11.6	12.7	15.2	3.2	0	192
July	19.7	65	11.8	13.0	15.3	3.2	0	190
August	19.5	67	12.0	13.2	15.3	3.1	0	186
September	18.5	72	12.2	13.4	15.0	2.7	0	154
October	17.0	69	10.7	11.3	13.3	2.3	0	156
November	14.2	62	7.9	7.1	9.9	2.3	0	138
December	12.6	57	6.7	4.4	8.0	2.2	90	124
Year	17.2	59	9.3	8.9	12.1	2.8	25	2028

meteonorm

meteonorm V7.1.0.107

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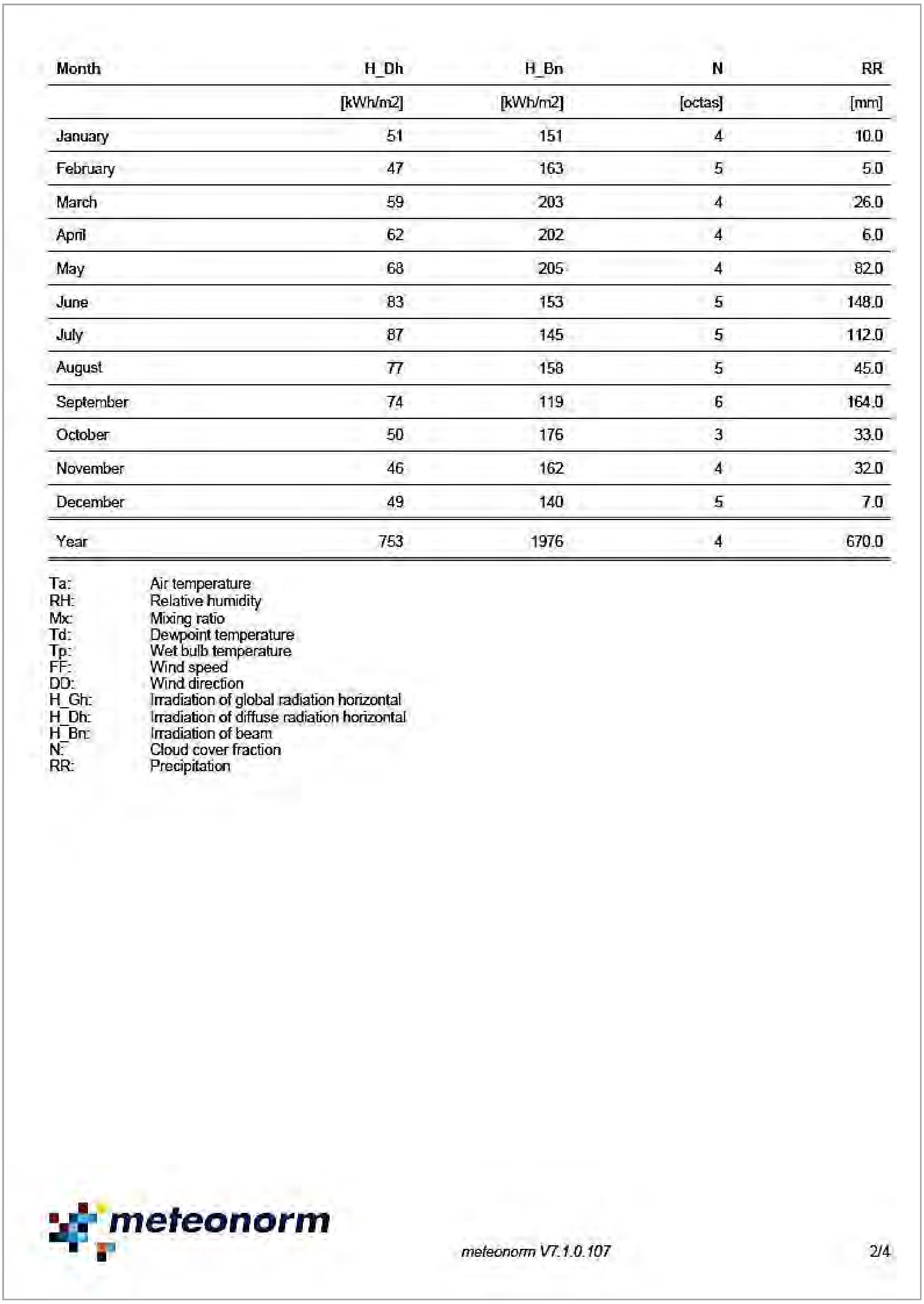


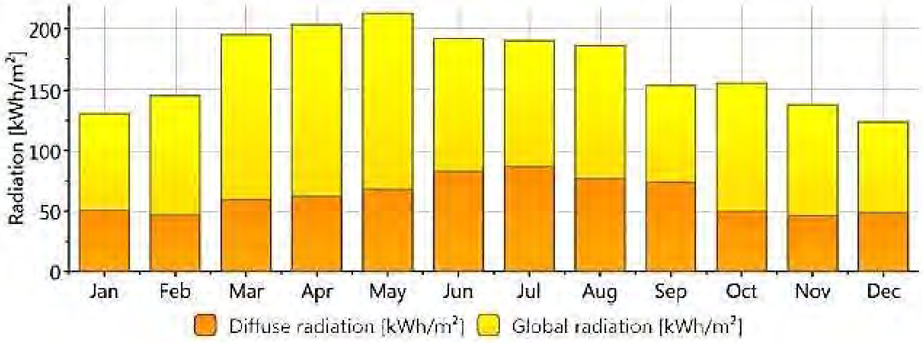
Month	H_Dh	H_Bn	N	RR
	[kWh/m2]	[kWh/m2]	[octas]	[mm]
January	51	151	4	10.0
February	47	163	5	5.0
March	59	203	4	26.0
April	62	202	4	6.0
May	68	205	4	82.0
June	83	153	5	148.0
July	87	145	5	112.0
August	77	158	5	45.0
September	74	119	6	164.0
October	50	176	3	33.0
November	46	162	4	32.0
December	49	140	5	7.0
Year	753	1976	4	670.0

Ta: Air temperature
RH: Relative humidity
Mx: Mixing ratio
Td: Dewpoint temperature
Tp: Wet bulb temperature
FF: Wind speed
DD: Wind direction
H_Gh: Irradiation of global radiation horizontal
H_Dh: Irradiation of diffuse radiation horizontal
H_Bn: Irradiation of beam
N: Cloud cover fraction
RR: Precipitation

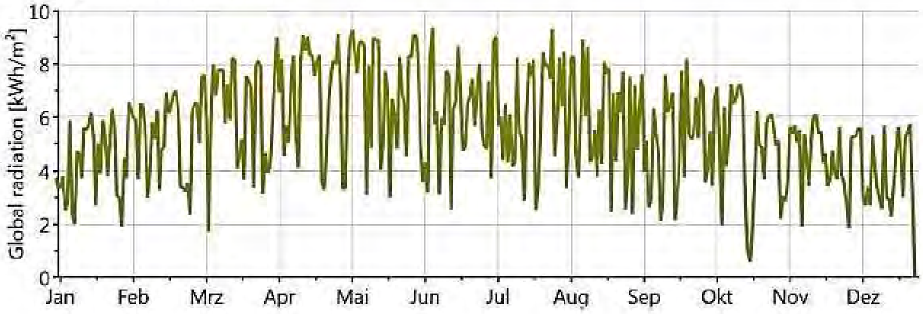
meteonorm

meteonorm V7.1.0.107 2/4

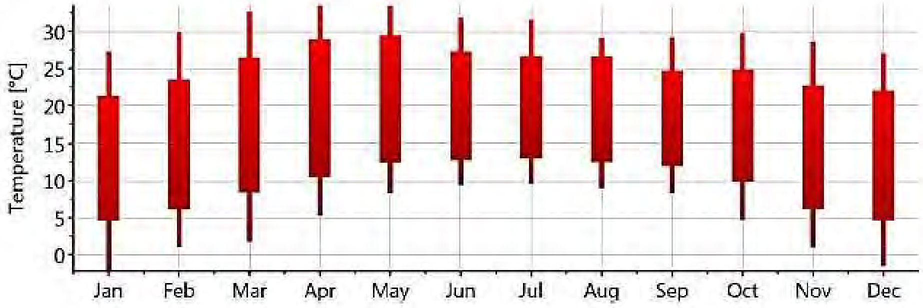
Monthly radiation



Daily global radiation



Monthly temperature



meteonorm V7.1.0.107

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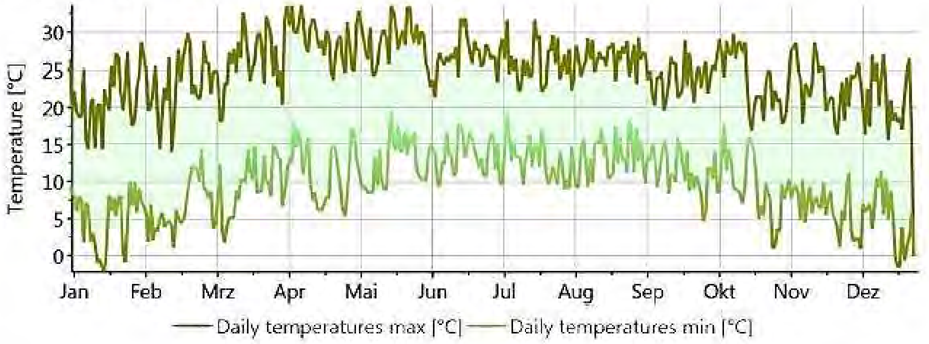
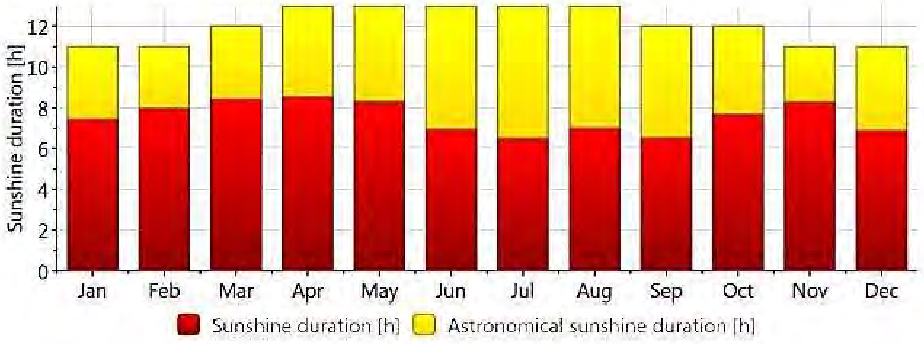
Daily temperature



Precipitation

Sunshine duration



meteonorm

meteonorm V7.1.0.107

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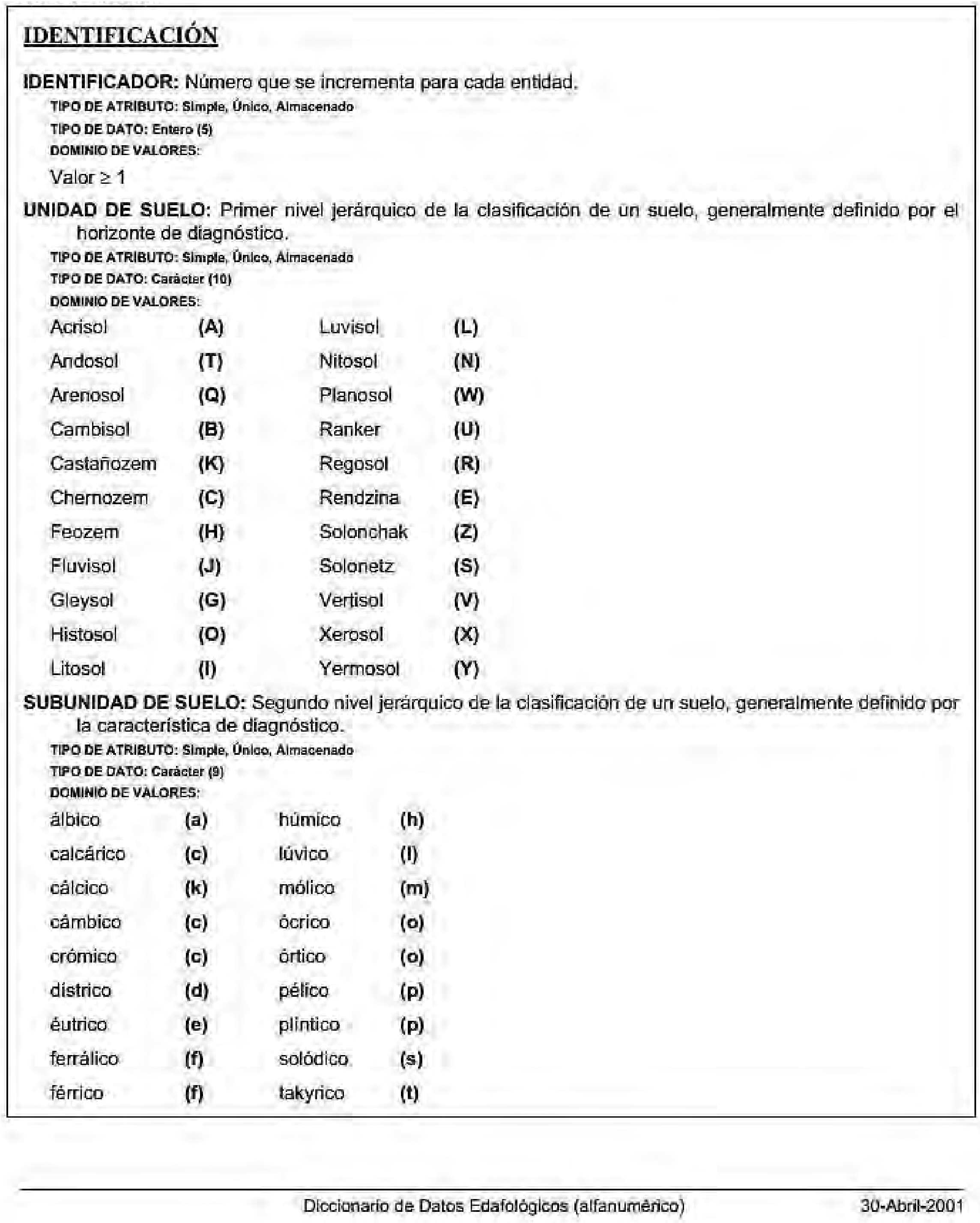
Annex B. Soil nomenclature (Edaphology).

Source: (INEGI, 2001)



IDENTIFICACIÓN

IDENTIFICADOR: Número que se incrementa para cada entidad.

TIPO DE ATRIBUTO: Simple, Único, Almacenado

TIPO DE DATO: Entero (5)

DOMINIO DE VALORES:

Valor ≥ 1

UNIDAD DE SUELO: Primer nivel jerárquico de la clasificación de un suelo, generalmente definido por el horizonte de diagnóstico.

TIPO DE ATRIBUTO: Simple, Único, Almacenado

TIPO DE DATO: Carácter (10)

DOMINIO DE VALORES:

Acrisol	**(A)**	Luvisol	**(L)**
Andosol	**(T)**	Nitosol	**(N)**
Arenosol	**(Q)**	Planosol	**(W)**
Cambisol	**(B)**	Ranker	**(U)**
Castañozem	**(K)**	Regosol	**(R)**
Chernozem	**(C)**	Rendzina	**(E)**
Feozem	**(H)**	Solonchak	**(Z)**
Fluvisol	**(J)**	Solonetz	**(S)**
Gleysol	**(G)**	Vertisol	**(V)**
Histosol	**(O)**	Xerosol	**(X)**
Litosol	**(I)**	Yermosol	**(Y)**

SUBUNIDAD DE SUELO: Segundo nivel jerárquico de la clasificación de un suelo, generalmente definido por la característica de diagnóstico.

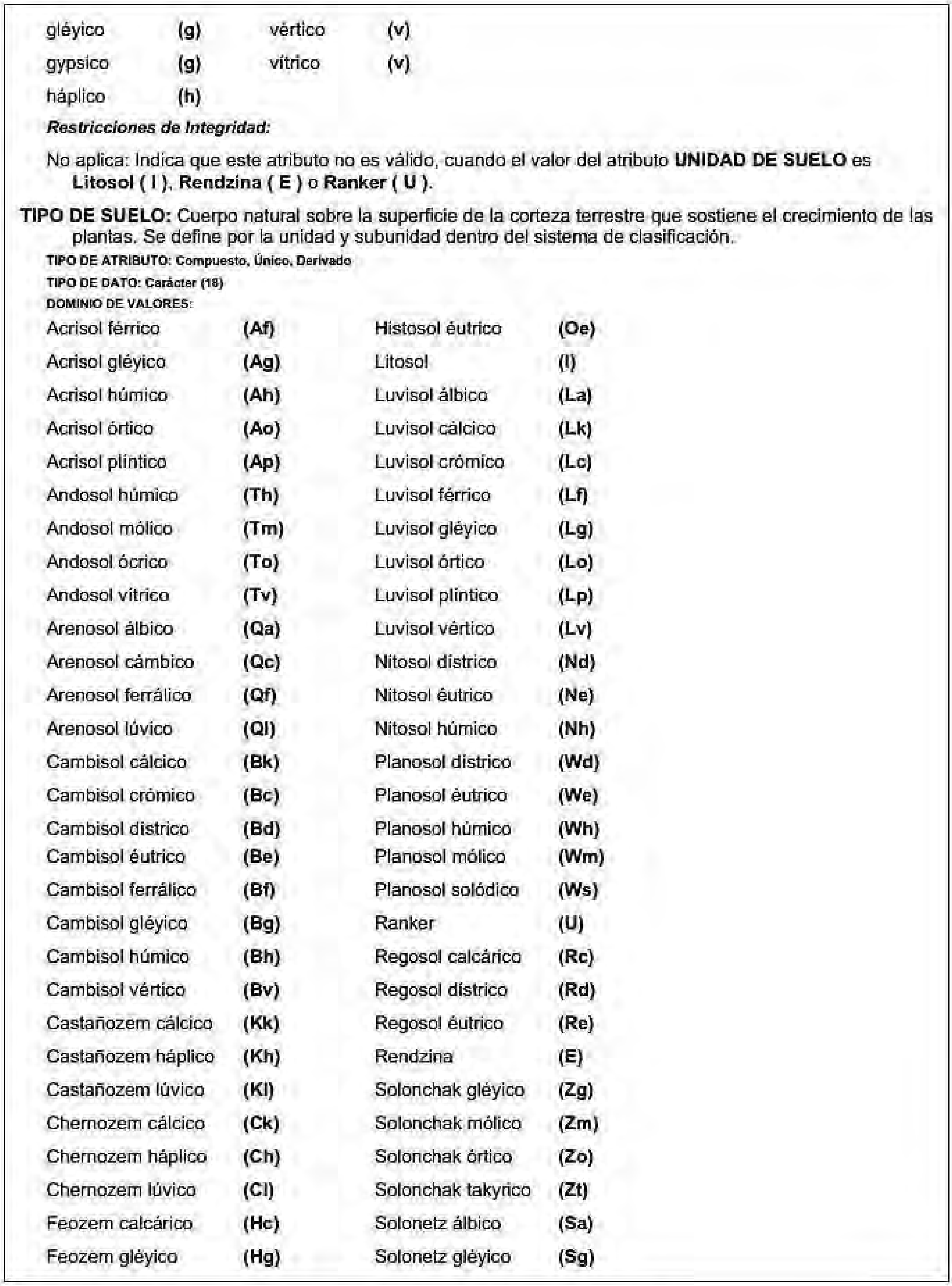
TIPO DE ATRIBUTO: Simple, Único, Almacenado

TIPO DE DATO: Carácter (9)

DOMINIO DE VALORES:

álbico	**(a)**	húmico	**(h)**
calcárico	**(c)**	lúvico	**(l)**
cálcico	**(k)**	mólico	**(m)**
cámbico	**(c)**	ócrico	**(o)**
crómico	**(c)**	órtico	**(o)**
dístrico	**(d)**	pélico	**(p)**
éutrico	**(e)**	plíntico	**(p)**
ferrálico	**(f)**	solódico	**(s)**
férrico	**(f)**	takyrico	**(t)**

Diccionario de Datos Edafológicos (alfanumérico) 30-Abril-2001



gléyico	**(g)**	vértico	**(v)**
gypsico	**(g)**	vítrico	**(v)**
háplico	**(h)**		

Restricciones de Integridad:

No aplica: Indica que este atributo no es válido, cuando el valor del atributo **UNIDAD DE SUELO** es **Litosol (I)**, **Rendzina (E)** o **Ranker (U)**.

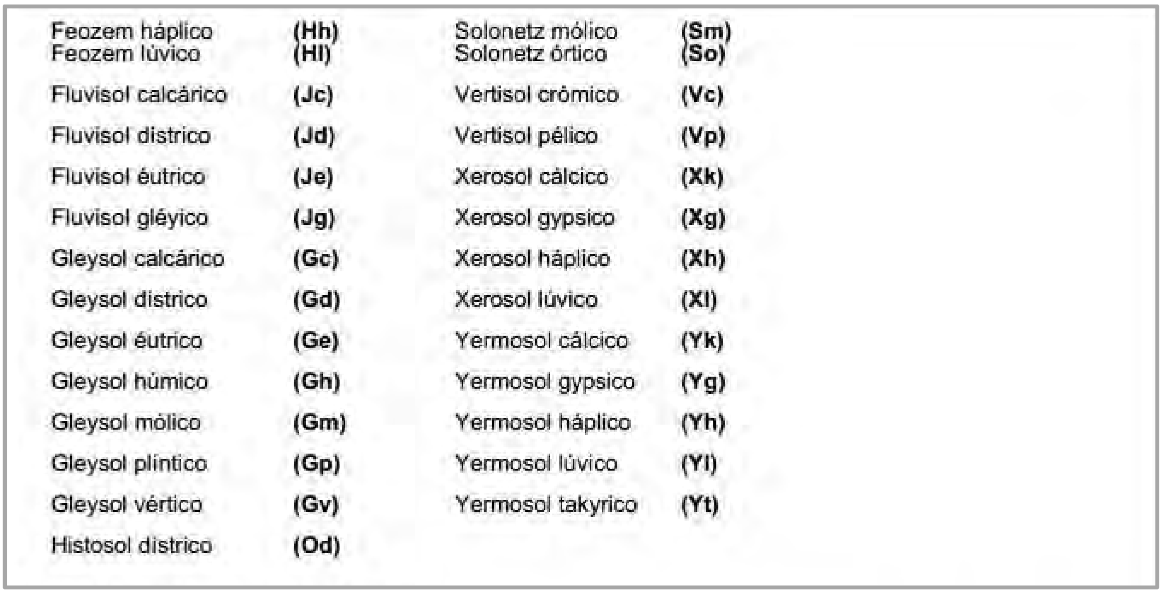
TIPO DE SUELO: Cuerpo natural sobre la superficie de la corteza terrestre que sostiene el crecimiento de las plantas. Se define por la unidad y subunidad dentro del sistema de clasificación.

TIPO DE ATRIBUTO: Compuesto, Único, Derivado

TIPO DE DATO: Carácter (18)

DOMINIO DE VALORES:

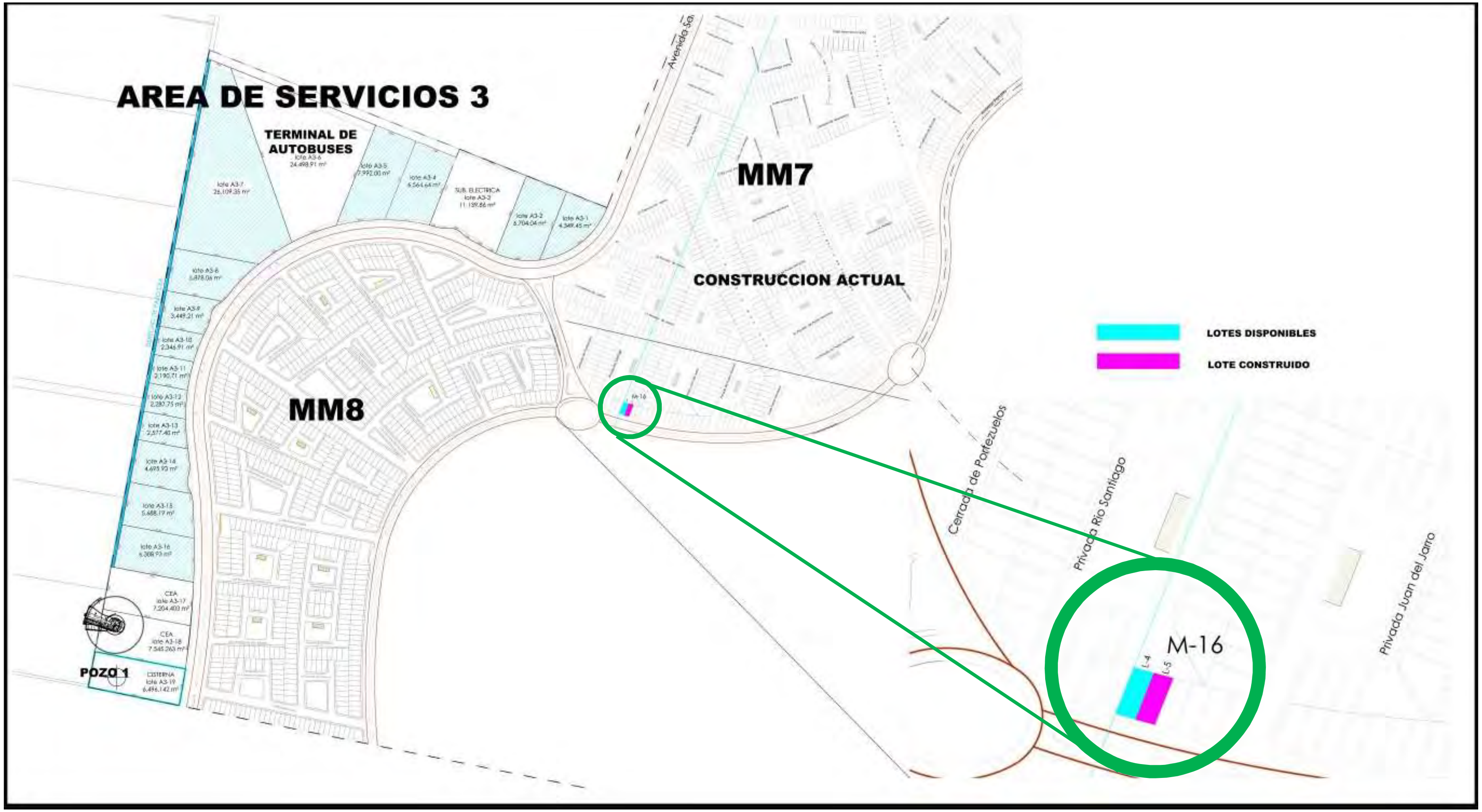
Acrisol férrico	**(Af)**	Histosol éutrico	**(Oe)**
Acrisol gléyico	**(Ag)**	Litosol	**(I)**
Acrisol húmico	**(Ah)**	Luvisol álbico	**(La)**
Acrisol órtico	**(Ao)**	Luvisol cálcico	**(Lk)**
Acrisol plíntico	**(Ap)**	Luvisol crómico	**(Lc)**
Andosol húmico	**(Th)**	Luvisol férrico	**(Lf)**
Andosol mólico	**(Tm)**	Luvisol gléyico	**(Lg)**
Andosol ócrico	**(To)**	Luvisol órtico	**(Lo)**
Andosol vítrico	**(Tv)**	Luvisol plíntico	**(Lp)**
Arenosol álbico	**(Qa)**	Luvisol vértico	**(Lv)**
Arenosol cámbico	**(Qc)**	Nitosol dístrico	**(Nd)**
Arenosol ferrálico	**(Qf)**	Nitosol éutrico	**(Ne)**
Arenosol lúvico	**(Ql)**	Nitosol húmico	**(Nh)**
Cambisol cálcico	**(Bk)**	Planosol dístrico	**(Wd)**
Cambisol crómico	**(Bc)**	Planosol éutrico	**(We)**
Cambisol dístrico	**(Bd)**	Planosol húmico	**(Wh)**
Cambisol éutrico	**(Be)**	Planosol mólico	**(Wm)**
Cambisol ferrálico	**(Bf)**	Planosol solódico	**(Ws)**
Cambisol gléyico	**(Bg)**	Ranker	**(U)**
Cambisol húmico	**(Bh)**	Regosol calcárico	**(Rc)**
Cambisol vértico	**(Bv)**	Regosol dístrico	**(Rd)**
Castañozem cálcico	**(Kk)**	Regosol éutrico	**(Re)**
Castañozem háplico	**(Kh)**	Rendzina	**(E)**
Castañozem lúvico	**(Kl)**	Solonchak gléyico	**(Zg)**
Chernozem cálcico	**(Ck)**	Solonchak mólico	**(Zm)**
Chernozem háplico	**(Ch)**	Solonchak órtico	**(Zo)**
Chernozem lúvico	**(Cl)**	Solonchak takyrico	**(Zt)**
Feozem calcárico	**(Hc)**	Solonetz álbico	**(Sa)**
Feozem gléyico	**(Hg)**	Solonetz gléyico	**(Sg)**



Feozem háplico	**(Hh)**
Feozem lúvico	**(Hl)**
Fluvisol calcárico	**(Jc)**
Fluvisol districo	**(Jd)**
Fluvisol éutrico	**(Je)**
Fluvisol gléyico	**(Jg)**
Gleysol calcárico	**(Gc)**
Gleysol districo	**(Gd)**
Gleysol éutrico	**(Ge)**
Gleysol húmico	**(Gh)**
Gleysol mólico	**(Gm)**
Gleysol plíntico	**(Gp)**
Gleysol vértico	**(Gv)**
Histosol districo	**(Od)**
Solonetz mólico	**(Sm)**
Solonetz órtico	**(So)**
Vertisol crómico	**(Vc)**
Vertisol pélico	**(Vp)**
Xerosol cálcico	**(Xk)**
Xerosol gypsico	**(Xg)**
Xerosol háplico	**(Xh)**
Xerosol lúvico	**(Xl)**
Yermosol cálcico	**(Yk)**
Yermosol gypsico	**(Yg)**
Yermosol háplico	**(Yh)**
Yermosol lúvico	**(Yl)**
Yermosol takyrico	**(Yt)**

Annex C. Urban development “Ciudad Satélite” and the proposed terrains

Source: (INVIES, 2014)



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