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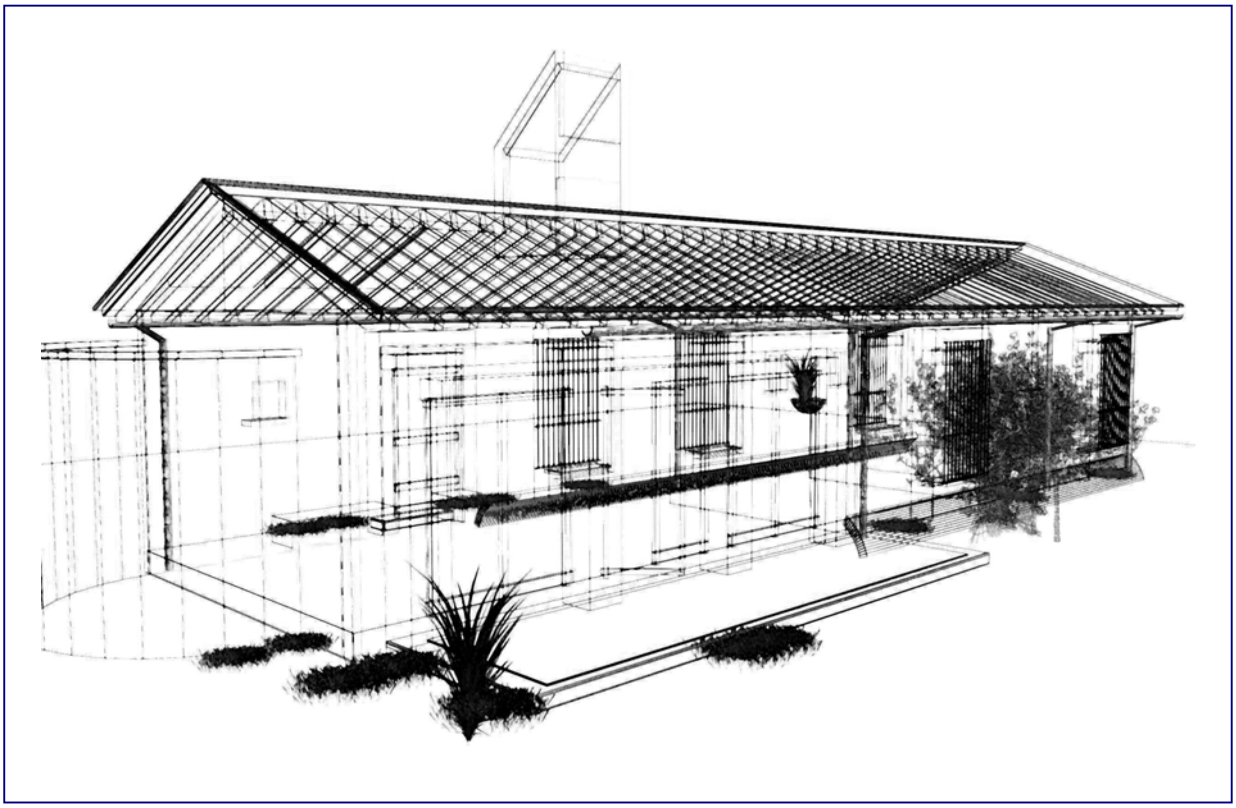

Energy Analysis and Optimization of a 100 m² Prototype Ecological House in Guanajuato, Mexico

Master's Thesis within the Sustainable Energy Systems' programme

ROLLUX PIERRE-EMILE

Department of Energy and Environment
Division of Building Services Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2010
Report No. E2010:01

MASTER'S THESIS

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Cover:
Original design of the prototype: basis support for analysis and optimization work.

Chalmers Reproservice
Göteborg, Sweden 2010
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Preface

The project of building a prototype ecological house in the State of Guanajuato, Mexico, started already several years ago. But the youth of ecological awareness in Mexico, the lack of fund and the uncertainty of any strong and money-demanding policies has definitely and naturally affected its development.

Such a project is new; ecology is not the priority in Mexico. Rare career opportunities that strongly include sustainability concept as a fundament are emerging here and there only now. Consequently the achievement of such a project takes a radically different form in Mexico than it would take in Europe.

As a result, working on this project as a Master's thesis does not carry a very deep theoretical content. Studies and analysis are roughly achieved, decisions have to be quickly and often intuitively made, financial support drives every single designing step… In that context, the report and the thesis work aims at constituting a pedagogical introduction to "eco-designing", a reliable data base for the further development of such a project and an orienting energy analysis to scientifically support big designing lines, more than at providing a very detailed and accurate knowledge on a specific point of the design. For this reason, many basic theoretical paragraphs and explanations are included in this paper that rather addresses future Mexican students working on the project, decision-making actors of the CIATEC Center of Investigation, than any student, engineer or architect specialized or clearly involved in ecological building design, technologies and processes.

This thesis represents the final part of the Master Programme in *Sustainable Energy System* at Chalmers University of Technology in Gothenburg, SWEDEN. It has been achieved in Leon, Guanajuato, MEXICO within the CIATEC[1] Center of Investigation and conducted from February to September 2009.

I would like to thank everyone that has made this thesis feasible, all the staff in CIATEC that always helped me out the different integration and administrative issues. And also:

- my parents that financed the main part of my journey and always supported me a lot in my decisions;
- Jan-Olof DALHENBACK, my supervisor at Chalmers for his great availability and the quality of his guidance and technical support.
- Dr Ricardo GUERRA for his great support in CIATEC and all the members of the environment department.

But I would also like to make a very special thank to Dr. Jose-Luis PALACIOS, my supervisor in Mexico to whom I owe everything about this incredible experience. He has always been guiding me, taking care of my stay, been available and helpful, taken me all across the country and, with his great family, made my stay much more than a enriching master thesis but a unique and unforgettable experience.

Pierre-Emile ROLLUX

[1] Further information available at http://www.ciatec.mx/

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Abstract

The report describes the energy analysis and optimization of a 100m² prototype ecological house in Mexico which carries an important educational function. It required detailed investigations. Since the availability of material data, budget, climate data and technical support is rather restricted, the need for establishing a background data-base was an important part of the work. The selection of appropriate energy software to support the analysis, according to well-defined objectives and requirements is also presented.

A definition of a base-case prototype and its energy analysis is performed (electricity demand, indoor climate energy requirements…) using BV² software. The chosen optimization strategy is a statistical analysis (ANOVA) of a 2^k factorial experiment, performed by Statgraphics software and supported by the BV² software. The results first confirm BV²'s consistency and lead to important conclusions: a rather good and uniform insulation of the building envelop is recommendable (double-glazed windows, basically insulated roof and walls), the usage of external shading is highly relevant and the investment in an advanced HVAC system might be avoided, according to budget restrictions and only if good attention is paid to natural ventilation schemes.

Analysis of the electricity demand needed the establishment of scenarios that depend on the global functioning of the prototype and a series of assumptions about users, activities, occupancy, domestic equipments energy efficiency, etc... On the basis of the reliable climate data base, documentation of design and purchase processes of a hybrid wind/solar energy system that covers more than 60% of the house demand is presented; it contributes to the educational function of the building.

Key words: ecological house - ecological design - energy analysis - hybrid wind/solar system

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Notations

Mexican official entities

SENER *Subsecretaria de Energia*, National Energy Office

SIE *Sistema de Informacion Energetica*, System of Energy-related Information

CRE *Comision Reguladora de Energia*, Energy Regulating Commission

SMN *Servicio Meteorologico Nacional*, National Climate Service

CFE *Comision Federal de Electricidad,* Federal Commission of Electricity

LFC *Luz y Fuerza del Centro,* Light and Power of the centre (Mexico City)

CONACYT *Consejo Nacional de Ciencia y Tecnologia,* National Council for Science and Technology

CONCYTEG *Consejo de Ciencia y Tecnologia del Estado de Guanajuato,* Council for Science and Technology of the State of Guanajuato

IMUVI *Insituto Municipal de Vivienda de Leon,* Leon Institute of Housing

SEDESOL *Secreteria de Desarrollo Social,* National Office for Social Development

CANADEVI *Camara Nacional De la Industria de Desarrollo y de la promocion de Vivienda,* National Chamber of Industrial Development and Housing Promotion

CMIC *Camara Mexicana de la Industria de la Construccion,* Mexican Chamber of the Building Industry

INFONAVIT *Instituo del Fondo Nacional de Vivienda para los Trabajadores,* National Funds Institute for Workers' Housing.

IVEG *Instituto de Vivienda del Estado de Guanajuato*, Housing Institute of the State of Guanajuato

Others

EIA Energy Information Agency (US)

CCPP Combined Cycle Power Plant (Gas fuelled)

NG Natural gas

IPP Independent Power Producer

THPP Thermal Power Plant

1 Introduction

1.1 The energy context of the project

1.1.1 National scale: the Country of Mexico

Mexico has maintained a very strong economic growth rate of around 6% since the end of World War II to the beginning of the 1980's. It therefore logically got its place in the so-called class of "developing countries". By the end 20th century, the national economy could not sustain such a high rate and the growth slowed down to a 2% level. To face this problem, Mexico has taken various measures, mainly based on opening global markets to foreign investment, as well as privatization of crucial sectors such as industry, energy, finance and telecommunications. This wave of privatization has definitely revitalized Mexico's economic growth (through higher competitiveness, for instance) which is now reaching a rather stable level of 4%. The SENER ("Secretaria de Energia", National Energy Office) has evaluated a 20% growth of national economical activity index from 2003 to today (Mexican Bank of economical information). However, those results did not slow down the dynamic launched by the government at the end of 20th century and sustained by current president Felipe Calderon who was elected in 2006. Mexico continues to open its borders to more and more capital, and to plan constitution reforms to soften legislation regarding the crucial sectors mentioned above (OECD, 2006) in order to better use and benefit from its national resources. This first part will consider and briefly discuss the current energy situation of Mexico, as well as describe the state of its natural resources' and power generation system.

<u>Mexico's natural resources</u>

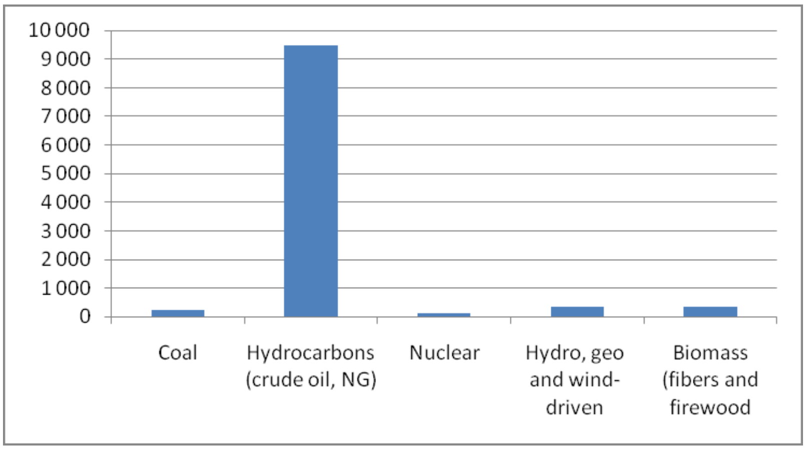

Figure 1-1: Annual production of primary energies in Mexico 2007, PJ (Sener, SIE)

It is important to notice that the graph refers to primary energy production and not to resources or reserves. This makes a significant difference since it gives a more complete idea of the government's strategy and choices regarding energy production than a simple presentation of energy reserves would do. As clearly shown by the graph above, Mexico's main primary energy production consists of hydrocarbons, i.e. crude oil and natural gas. Consequently this paragraph related to natural resources will mainly concern hydrocarbons. Nuclear and “Clean energies” will be briefly discussed in the next paragraph entitled “the power generation system”.

- *Crude Oil resource*

The country definitely relies on huge proven reserves of crude oil. Indeed its territory, both on and offshore, contains the 9th largest proven reserves in the world and the 3rd largest of the Americas behind Venezuela and the United States of America. Its production rate is however the 6th in the world ranking and 2nd in the Americas (behind the USA). According to the Political Constitution of the United Mexican States of 1917, oil production is a monopoly of the state and as such is, together with extraction and distribution operations, originally and exclusively controlled by the giant state-owned oil company PEMEX which was created in 1938. PEMEX generates 10% of total Mexican export earnings and one third of total government revenue (from EIA, US Energy Information Administration) via hydrocarbons production. EIA also calculated that PEMEX sent approximately 60% of its annual turnover to the federal government in 2005. This important dependency of the government goes together with a strong and constraining control of the Mexican Congress whose approval is required on PEMEX’s yearly budget (it is often achieved according to governmental economic interests and to how large governmental deficits are). The government’s financial dependency and overwhelming control result in a lack of funds and freedom when it comes to PEMEX’s decision-making processes regarding new exploration projects. However the sector is being gradually opened to private capital especially since the election of President Felipe Calderon (2006) who aims to promote, enhance and develop the oil business and by doing so, to level off growing gas imports.

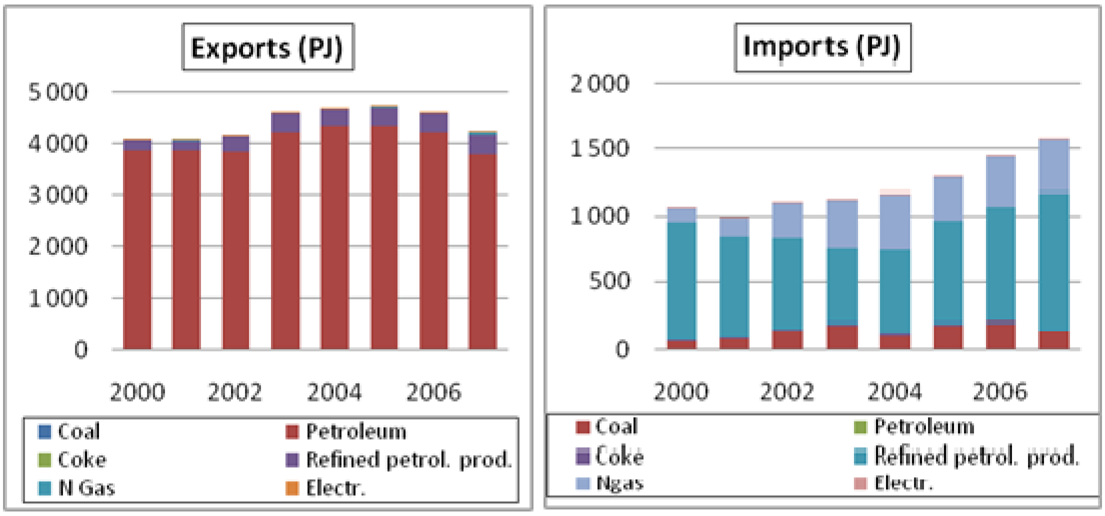

Figure 1-2: Evolution of energy exports and imports sorted by energy source from 2000 to 2007 (PJ)

The graphs above illustrate perfectly the huge proportion of the Mexican Oil market (mainly with the USA) within Mexican international trade of energy. Almost three fourths of Mexico’s crude oil reserves consist of heavy crude oil: the so-called “Magna”. Since relatively few oil refineries are currently in service in Mexico, most of this heavy “Magna” is sent to the USA to be refined and imported back as “refined petroleum products”. This clearly appears on the imports graph above. The “exports” graph shows the size of the oil exports, almost 90% goes to the USA and represents approximately one half of Mexican oil production.

Finally it is evaluated that the rather strong economic growth of Mexico leads to quick depletion of its oil reserves. Indeed the ratio "proven reserves"/"production rate" fell from 17 years in 2000 to 9 years in 2008. Mexico definitely needs to put some more efforts on energy conversion efficiencies and on exploration activities in order to convert those probable or possible reserves into proven ones.

- *Natural gas*

Natural gas resources are equally under large control of the state-owned company PEMEX, and exactly as it is occurring with the oil market, the gas market is getting more and more privatized. The privatization process first started on the down-stream portion of the entire natural gas production chain (i.e. transport, storage and distribution operations) in 1995 and later on extended up-stream (i.e. exploration, production and first hand sales contracts) in 2003 through the MSCs process (Multiple Service Contract). According to the Energy Committee and the Chamber of Deputies of Mexico, this wave of privatization would increase the growth rate of national demand to 6.8% until 2012 (it has remained quite stable from 2000 to 2004 at around 5.8%). The phenomenon especially affects the power sector which accounts for a significant part of the national demand as illustrated below. Indeed the privatization of the gas market results in increased investment in NG-based Combined Cycle Power Plants (CCPP). This will be further discussed in the paragraph related to power generation.

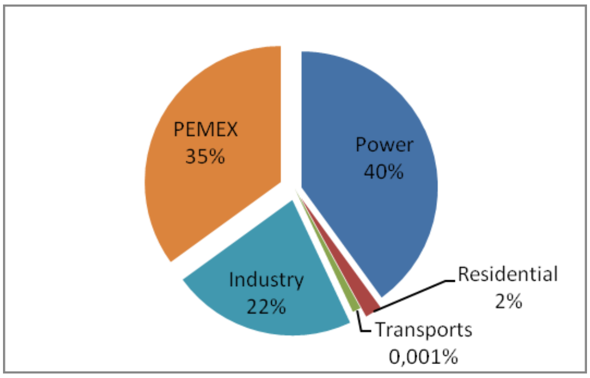

Figure 1-3: Predicted cumulative Natural Gas consumption sorted by sector between 2004 and 2012

To fulfill this growing demand PEMEX is obliged to import more and more expensive natural gas and cannot, for the same reason as mentioned above concerning oil, develop and extend its own production because of the lack of funds. Mexico remains consequently a net importer of NG.

Power generation system

- *Thermal power as a basis and on fundamental changing process*

Almost 97% of the Mexican population has access to electricity and consume annually around 175 TWh of electricity. This represents a quite low per capita consumption of 1.8 MWh/cap.year (in 2007) compared to the 31 MWh/cap.year consumed in Iceland (world 1st rank) and the 15 MWh/cap.year consumed by each Swedish citizen. Of course the impact of the cold climate plays an important role in those figures.

The electricity sector including production and distribution operations is controlled by the state-owned entity CFE (Federal Electricity Commission) over the whole country except in Mexico City where electricity distribution is managed by a specific sub-entity of the CFE called LFC(Light and Power of Mexico City).

Global electricity demand is largely dominated by the industry sector that accounts for more than half of the entire demand. Domestic demand represents one quarter of the total consumption and commercial, agricultural and services demands share the rest. The price of electricity has globally risen 50% since the year 2000 (mainly due to expensive gas imports), and today prices of domestic and industrial electricity are both equal (0.1 US$/kWh). By comparing this value to other countries it appears that the Mexican residential electricity price is one of the lowest in the world while the industrial price stands among the highest.

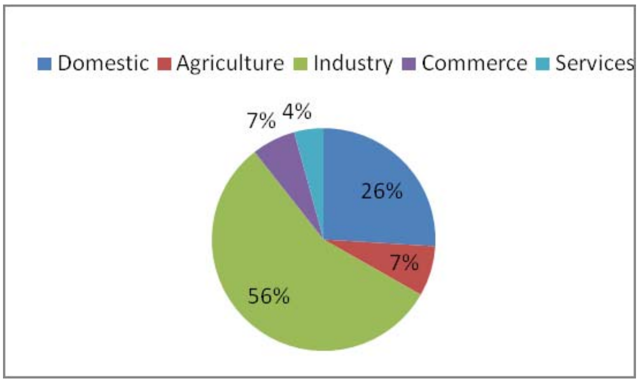

Figure 1-4: Electricity consumption by sector (2007)

To satisfy such a demand, Mexico has achieved significant improvements on the generation side and electricity is now produced in Mexico in a much more energy-efficient way. Indeed the global combustible consumption for electricity generation is decreasing year after year and has been shortened by one third from 2001 to 2008.

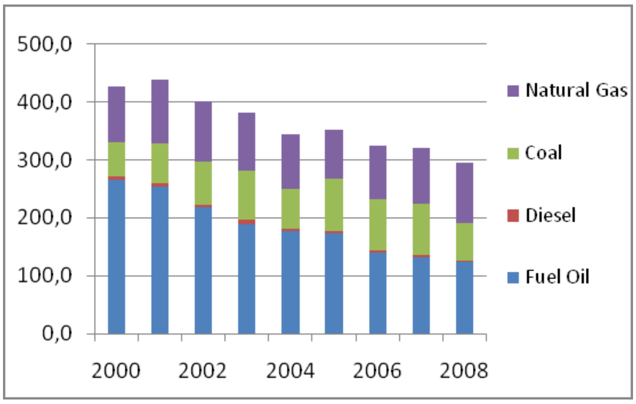

Figure 1-5: Combustible consumption for electricity generation on an energy content basis in TWh from 2000 to 2008

This significant decrease appears to be the result of two important factors: on the one hand oil burning for electricity generation seems to be gradually phased out and replaced by more efficient gas-based CCPPs, on the other hand the alternative energy proportion in the global generation mix grows progressively and especially hydroelectricity that now reaches 18% of global generation. A valuable switch is currently taking place in the power generation system of Mexico, heading toward better energy efficiency, better ecological performances and better security through increased diversity.

The phenomenon has been partly driven by the recent launch of the privatization policy. The following graph shows the evolution of the energy mix in Mexico and illustrates in a clear way the development of that privatization movement. In percentages, the proportion of electricity generated by Independent Power Producers (IPPs) in the global mix increased from 0.7% in 2000 to 32% by 2008 (it corresponds to 23% in terms of installed capacity). All of the electricity generated by the IPPs is exclusively sold to the CFE that deals with its distribution over the country. The Mexican government created the Energy Regulating Commission (CRE) as a monitoring entity, coordinating CFE, LFC and IPPs production but it is also in charge of delivering permits to new private energy projects.

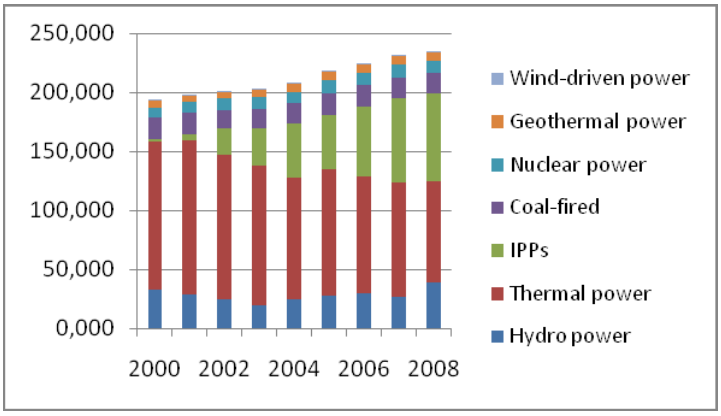

Figure 1-6: Evolution of power generation in Mexico in TWh from 2000 to 2008

In fact most of the private investments referred to as “IPPs” in the graph are related to NG-based electricity production using CCPP (Combined Cycle Power Plants) which are now state-of-the-art Thermal Power Plants (THPP); they are cleaner and more energy-efficient than any other fossil fuel-based THPP. Furthermore under the category referred to as “Thermal Power”, more than one half of the generated electricity (56%) comes from Combined Cycle technology.

The comparison of respective evolutions of combustibles consumption for power generation purposes (see Figure 1.5 p. 18) and electricity generation (above) emphasizes the energy-efficiency improvements of the Mexican power generation system. Indeed more power is produced while fewer combustibles are burned.

- *Renewable energies: few but promising facts*

Finally, it is important to have a look at the renewable energy portion of the generation mix. It accounted for 20% of the electricity generated in 2008 and 24% of the global installed capacity. Hydropower is definitely the most important of them and covers a significant part of the electrical base-load especially in the south of the country. Although approximately 12 GW of clean energy are installed in the country (91% hydro, 8% geo and 1% wind-driven), “clean energy” is still too expensive for the country. The government owns a large number of the Mexican hydro-dams and wind power facilities but does not invest more. In that field even more than in the hydrocarbons field, private capital is needed to reach a more diversified and more sustainable power system. As an example, the solar radiation potential of Mexico is tremendous at 2,2MWh/m².year (the potential in Sweden is 1MWh/m².year as well as that of Germany). Nevertheless no significant photovoltaic installation exists in Mexico while more than 2500MW[2] of photovoltaic power is already installed in Germany (almost one fifth of all clean energy capacity installed in Mexico according to 2009 figures by the SENER, "subsecretaria de Energia"). Concepts of sustainability or ecology are today far from Mexicans' day-to-day life and financial accessibility. Nevertheless in the country things are starting to grow in that sense and a large majority of Mexicans have at least heard about global warming. The CRE recently approved 3 wind farm projects representing an installed capacity 266 MW, tripling current national wind energy capacity. Principal ecological ideas and messages are gradually and definitely being sent around Mexico, eventually reaching minds but still hardly ever leading to concrete environmental-friendly actions, habits and policies.

1.1.2 Local scale: the state of Guanajuato, the city of Leon

Energy situation

Of the 48 municipalities of Guanajuato, the municipality of Leon is the most populated with almost 30% of the population and it consumed one fourth of the electricity generated in Guanajuato in 2004.

An efficient way to present the energy situation of an entity, be it a city, a region, a state or a whole country is to establish an energy balance of the entity commonly referred to as the Reference Energy System (RES). In that respect, at the end of 20th century the state government of Guanajuato initiated a state-focused energy analysis via the Council of Science and Technology of Guanajuato (CONCYTEG) and the National Council of Science and Technology (CONACYT). This analysis was meant to collect energy data, define energy sources and evaluate both transformation and distribution losses, in order to better support any future new energy and/or environmental state policy. Furthermore data campaigns to measure solar and wind energy potentials over the state have also been achieved to create a rather complete energy database referred to as SIEG[3].

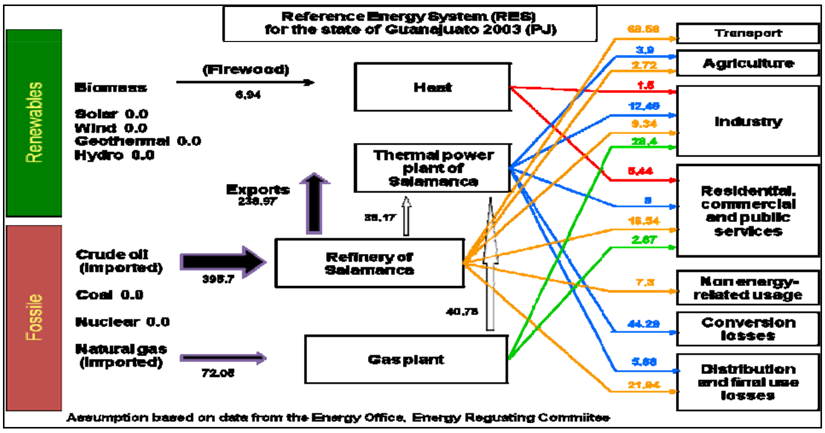

Figure 1-7: Rough Reference Energy System for the state of Guanajuato, 2003, PJ

[2] From the 2007 report on PV solar electricity: Solar generation IV by Greenpeace and EPIA (European Photovoltaic Industry Association) available at: http://www.epia.org.

[3] "Sistema de Informacion Energetica de Guanajuato", (Energy Information System of Guanajuato), established by the CONCYTEG, available at: http://www.concyteg.gob.mx.

Unfortunately, the whole set of data about energy fluxes in diagram is not complete so far and it has preferred not to mention numbers in the diagram and focus on the structure.

The consumption of Guanajuato reached 6.7 TWh/year in 2003 which represents 1.35 MWh/cap.year (1.8 MWh/cap.year in 2008 in the entire country). The pillar of electricity supply in Guanajuato is the state-owned Salamanca site that combines both a refinery and thermo power facility. As seen on the RES diagram above, around 98% of the primary energy supply consists of fossil fuels (82.9% crude oil and 15% natural gas) and transits through Salamanca to end up either as electricity (with a rather good energy efficiency of 42%) or as refined products such as gasoline, refined gas. The power supplied by Salamanca nearly covers the entire state demand; however a small amount of imported electricity is required to fulfill the peak load.

The only significant source of renewable energy registered in Guanajuato is biomass which is mainly burned for thermal use. It accounted for less than 2% of the primary energy supply in 2005 for Guanajuato.

A few words about the environmental situation in Guanajuato

The state of Guanajuato has been evaluated by the Mexican Institute of Competitiveness to stand in 16th place out of 32 states on the global competitiveness ranking but falls to 21st place when it comes to environmental competitiveness. It definitely suffers from strong environmental burdens:

- a growing part of the state is affected by a high degree of soil erosion , reaching 85% by 2004 (from SEDESOL);
- a significant lack of water resources and a rapid depletion rate of groundwater due to inappropriate and overwhelming urbanization schemes, lack of concrete measures for water reuse or rainwater collection, intensive use for agricultural purposes to cope with very warm temperatures and low precipitation rates (88% of total water demand)…
- low number of water treatment plants;
- significant water and soil contamination due to intensive and inappropriate industrial activities;
- …

Most of these facts can be related to the constraining and difficult climatic conditions but, also some of them obviously result from the lack of environmentally-aware policies, measures and actions usually due to the lack of funds and knowledge.

1.2 The project initiation: the fifteen-year long process of an idea

1.2.1 The early stages: historical overview

At the end of the 1990's, the critical environmental situation in Leon regarding water resources, contamination and erosion levels joined the growing technological movement launched a little earlier and both resulted in ecological ideas or initiatives that arose here and there in the State: this included in particular ideas about sustainable ways of life, sustainable housing…

In Leon, there is no place where people could see what an ecological house looks like, how it is possible to enjoy sun, water or wind energy, how one can treat sewage water to reuse it for watering… Based on the fact that education constitutes a primary foundation to any sustainable future, a group of people decided to address the ecology and preservation of the environment in the area of Leon. In 1996, Doctor Jose Luis Palacios first tried to propose the construction of a prototype ecological house to the Cultural Center of Sciences, also called Explora (Leon, GTO). The idea was a prototype that could be seen by thousands of students and people of all ages and allow them to discover new house-related green technologies, note the potential energy and financial savings, learn how to build a house with fewer ecological impacts.... This pioneer project would enhance the development of ecological consciousness, support and orientate new investment but also on a decision-making level to face financial constraints, it would require participation of many institutions and create for the first time a promising collaboration network with ecological perspectives. Associations of private entrepreneurs such as the CMIC (Mexican Construction Industry Chamber) or the CANADEVI (House Companies Chamber) and other construction corporation leaders would form the network. Moreover they could be supported by some public institutions such as the INFONAVIT (National Fund Institute for Workers' Housing) or the IMUVI (Municipal Institute of Housing), the IVEG (Housing Institute of the State of Guanajuato) and the CONCYTEG (State Council of Science and Technology). Furthermore Dr. Palacios imagined involving educational institutions such as universities, architecture colleges and schools, mechanical and electrical engineering schools, biology faculties that would help in the project and enhance new ecological careers by creating new ecological vocations and interests… Unfortunately the project was never accepted mainly for financial reasons. Another way, another place and another financial support had to be found…

In 2006, some people from Leon highly motivated and conscious of the lack of environment-caring institutions decided to create the first non-profit organization of Leon involved in environment protection activities, environmental consulting and ecological education with a non-lucrative vision. This definitely brought on something new in comparison to the exiting private consulting companies. Don Jorge Arena Torres Landa, a powerful and influential land owner, president of a society of rural production in Sierra de Lobos next to Leon (northward) and leader of a huge reforestation project in the same Sierra, along with Dr. Palacios founded *"Sistemas Ambientales Agua y Bosque, AC"* (Environmental systems, Water and Forest, NPO). The principal objective of the organization was to create, in the Sierra, a cultural center where it would be possible to learn about reforestation processes as erosion remedies, water collection and storage technologies as agricultural necessities, but also about sustainable houses and ways of living; an example of how to cope with local environmental constraints.

"Agua y Bosque" decided to design a prototype ecological house that could show the financial and energy benefits of using different new technologies, materials and concepts such as "auto sufficiency", "domotics (house automatization with energy savings purposes)","passive energy"…

1.2.2 Currently acquired items: start point of the thesis work

Thanks to Don Jorge Arena, Dr. Palacios, Architects René Ortega (Bioclimatic design), José Luis Arizti and other engineers and students that joined the association, “Agua y Bosque” now owns 3,750m² of land in the Sierra, with access infrastructures, a small lake for rainwater collection and storage and a flat and secured place to build the first Ecological Education Center of Guanajuato. A first design of the house has also been achieved and today the project is seeking more financial resources to start the construction of the house.

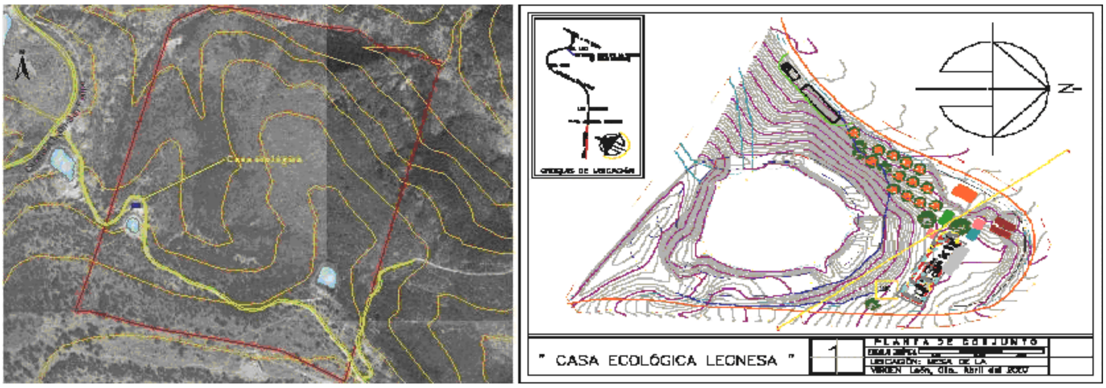

Figure 1-8: Topographical maps of the piece of land (left side) and of the construction site (right side)

Furthermore some basic studies have already been performed by students. They concern:

- Domotics (see appendix 1: What is “domotics”?)
- Qualitative materials considerations
- Water treatment system design.

The results of these works are not presented as part of the report.

1.3 Thesis work: objectives and limitations

1.3.1 Energy analysis and optimization of the house: global methodology

The project consists in the design and construction of a 100m² prototype ecological house. The prototype is meant to be designed with respect of ecological principles; this basically consists in taking care of the three ecological cycles that are water, nutrients and energy.

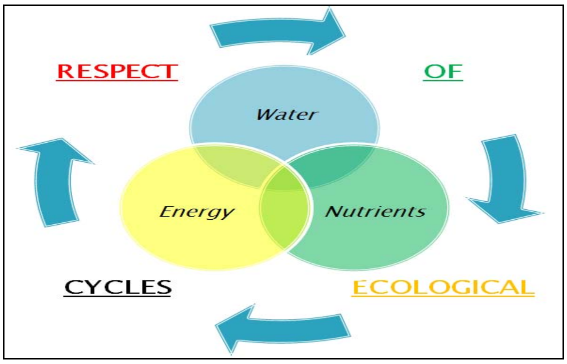

Figure 1-9: Basis of ecological design

This thesis work specifically aims at an energy analysis and optimization of the design. It basically consists in studying energy related issues of the design that might be classified in 2 major categories:

- *Energy related to indoor climate:* Thermal analysis, optimization of the building and harmonization with outdoor climate. An energy software has been investigated and used as main tool for this analysis, it is called BV² (see paragraph 2.2.2 p.32)
- *Electrical demand and supply:* Consumption scenarios analysis and optimization, design and purchase of hybrid system for renewable electricity consumption.

The work outline follows different steps that logically constitute the different part of this paper:

1. Investigation and establishment of a background database (climate data, material data, software selection...)
2. Thermal analysis of a base-case building with base-case data (consumption scenario based on number of person and activity scenario, common domestic equipments, commonly used materials...)
3. Building optimization with proposition of alternatives
4. Design and purchase processes of the energy supply system: electricity and heat.

This paper aims at reporting main investigation and optimization results to constitute a solid and trustful basis for the future development of the project: this objective is referred to as the knowledge transfer. It is also meant to perform an educational function about ecological design for students of architecture or any engineering careers; this latter function is referred as the educational function and explains why some theoretical and basic design details are provided in this report.

1.3.2 Support analyses previously made within the project framework

Since various investigations have already been performed for the project, the following points are not or partially approached:

- "Evaluation of materials performances for an ecological house", by student Elena Salazar[4]. This work led to various qualitative conclusions on different material options. More quantitative data is required (see paragraph 2.4 p.39
- "Water treatment for ecological house", unknown student[5]. This document rather complete and no further investigations or calculations are required
- "Bioclimatism applied to the first ecological house of the state of Guanajuato", by student Clara Torres[6]. This paper presents basic principles of the design of an ecological house, without specific details. Nevertheless it presents a Solar Diagram that analysis the optimum orientation of the building; the value is used for this thesis and not further questioned.
- Base-case architectural plans by Arc. René Ortega Macias. Various plans are given in Appendix 2: Architectural plans.

1.3.3 Financial, time and legal limitations

Financial support: main limitation

In such a project, money drives everything since no proper funds are available. Most of the financial support has to come from government, the State of Guanajuato and Municipality of Leon. But in a developing country such as Mexico, health situation, struggle against drugs' market, education, energy issues come first and ecology and sustainability are not major priorities. However, Mexican government and population ecological awareness is definitely growing and good initiatives emerge here and there with increasing frequency and ecological value. In order to grant significant financial support to such a non-lucrative project, government requirements of accuracy on planning, construction, definition of objective and other aspect are drastic and unfortunately difficult to fulfill without knowing the exact budget. A sort of vicious cycle affects the budget: without exact budget value, difficult to build a clear and well-defined design, which is in turn required to get financial support. This vicious cycle has affected the construction and clear definition of the project and resulted in a sort of undefined trajectory whose vagueness definitely brakes and affects its evolution.

Many detailed budget plans have been imagined, changed, reviewed considering financial offers from the state of Guanajuato via the CONCYTEG (Council of Science and Technology of the State of Guanajuato), the municipality of Leon via the IMUVI (Municipal Institute of housing) and donation promises from private parties (tiles, roof structure…). However details about financial management of the project are not presented as part of the report.

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[4] "Evaluacion del desempeño de materiales en un conjunto ecológico", Salazar Granados Irma Elena, Instituto Technologico Superior de Irapuato.

[5] "Humedales, tratamiento de agua secundario", unknown student

[6] "Diseno y construcción del primer conjunto ecológico autosuficiente de Guanajuato", Torres Uicab Clara Sugeydy, Instituto Technologico de Chetumal

So far only 75,000.00 pesos (approximately 4,000.00 euros) from the CONCYTEG are considered to be safe and dedicated to energy systems purchase. Out of those, 20,000.00 pesos have been set aside for Domotics development (see Appendix 1: What is “domotics”?) and the left 55.000,00 for actual passive systems. This budget constraint is crucial in the design process of a hybrid system for electrical production (see paragraph 5.2 p.80).

Time: a curious constraint

Lack of funds, in such a project, leads to a number of constraints of various types. First it highly affects project planning process, definition of objectives and work organization. The impact on those areas of project management results in upsetting the time management of the project. It also requires a high flexibility in designing process because when sudden financial constraints appear, affecting the budget, it in turn impacts the design perspective.

When it comes to alternative energy systems analysis and purchasing process, financial constraints fundamentally affect any decision, but it also happens to add time constraints. Indeed, basically the already granted budget (55,000.00 pesos) had to be quickly spent in equipments or cancelled due to legal/administrative requirements,. Consequently, electrical consumption analysis, power dimensioning, evaluation of natural potential resources had to be completed with hurry and before knowing the exact design of the house. But this makes little sense. Usually when architectural plans are carefully analyzed and definitely accepted, natural lighting and HVAC systems electrical demand can then be evaluated, optimized and quantified, and finally the rest of electrical demand and alternative energy system can be considered and efficiently dimensioned.

It is also important to mention that a general time constraint related to the thesis usual duration (approximately 6 months) definitely influenced some design and analysis decision.

One legal requirement specific to Mexico

According to the law, every public investment in equipments requires a comparison analysis of at least 3 different suppliers. Therefore 3 companies have been consulted and 3 different quotes have been studied and compared. All results are presented in Appendix 3: Quotes comparison for the hybrid system. This legal requirement makes the analysis a bit more laborious but definitely results being of really great consistency. A commercial negotiating process on prices is also made possible and eventually leads to more cost-efficient investments.

2 Background data

2.1 General ecological principles of an ecological house in Leon, Mexico

In order to achieve the design of an ecological main principles have to be kept in mind. The basis lays in the respect of the 3 natural fundamental cycles which are Water, Nutrients and Energy (see Figure 1-9 p.24). Since eco-construction is definitely recent and new in Mexico, no specific requirements are set, no building code sets legal requirements and, as a result, no real eco-objective are defined (this is definitely inconvenient and makes design and planning difficult. Consequently the ecological optimization is basically made according to budget and personal judgments, knowledge and experience (Dr Palacios has built several ecological houses since years and has then acquired a consistent know-how in this field). Since this thesis work deals precisely with the energy-related design, only very main principles about water and nutrients considerations are presented in this report

2.1.1 Water and nutrients cycles

Water-related design

The water cycle is major preoccupation in the region of Leon (see paragraph 1.1.2 p.20). Some basic and cheap actions can make a big difference in the sense of water savings.

- *Rain water collection*

Efficient water collection system are already commercialized and of limited investment. Furthermore natural active carbon filters can be implemented for better quality water used for domestic usage such as bathing, cleaning… This appears as a basic improvement but shows crucial advantages especially in the very dry region where the project is being developed. The system has already been evaluated in the reference book[7] and is not described in this report.

- *Consumption savings*

Apart from the way of life and the ecological awareness of the house users that is of primary importance, some water-saving devices are commercialized and of significant efficiency. Depending on the budget, a short investment can be made and is considered in this project.

- *Water treatment*

A previous study has been achieved about the design and dimensioning of the water treatment system. As main principles, one can mention:

  - Black (sanitary) and grey (chemical containing) waters separation
  - First physical separation in decantation tank

[7] "La casa ecológica, ¿cómo construirla?", Dr Palacios, printed by Nexo Grafico, edition of July 2007.

- Further biological/chemical treatment
- Water treatment wetlands where plants are taking out left nutrients for biological needs

All of this aim at either being able to recycle the water and further enhance the saving process or let the water infiltrate in the soil as it usually does within the natural water cycle.

Nutrients

When it comes to nutrient cycle, the main principles to take care of are:

- Waste management
- Construction material selection

Domestic waste management is primordial and covers various ecological advantages. The main one is the recycling opportunities: glass, metals, papers, plastics and organic wastes. In Mexico, recycling is still rare and undeveloped but efforts are gradually being put in this direction. However on the small scale and within the project, a "biodigestor" has been considered to recycle organic wastes and potentially residues from sanitary water and produce biogas for cooking applications. This represents a really efficient system that can be built by hand, requiring relatively small investment. It is described in the reference book[8].

2.1.2 Energy-related ecological principles and technical requirements

In Europe many eco-labels about building are emerging here and there (Minergie[9] in Swtitzerland, Passivhaus in Germany, Effinergie...) and establish energy requirements to get the "eco"designation. The requirements are drastic and imply high investments and advanced designs. They also correspond to European climate that differs to large extents with Mexican climate. That is why it is inappropriate and makes little sense to try to apply those requirements to this prototype. Since there is no building code here in Mexico, no building efficiency requirements and even less "eco"-requirements, the design and the energy performances of the prototype are optimized as much as possible , according the budget and without well-defined energy efficiency objectives. This lack of defined objectives definitely appears as an inconvenient.

However, some principles have to be followed when it comes to "eco energy design".

Indoor climate: comfort definition

In Mexico, climate conditions require dealing in priority with cooling during a large part of the year (see paragraph 2.3 p.32). However air-conditioning systems that usually represent high investments and high variable costs (energy consumption and maintenance) are not commonly used in residential buildings and most frequently cooling loads are covered by natural ventilation and windows-airing. For this prototype the attention is placed on good insulation with heavy material to reach sufficient thermal inertial delay and maintain acceptable temperature during daytime.

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[8] "La casa ecológica, ¿cómo construirla?", Dr Palacios, printed by Nexo Grafico, edition of July 2007.

[9] At http://www.minergie.ch

Doing so, eventual heating demand during nights (and especially in winter time when nights can be very cold in the Sierra, including negative temperatures) will partially be covered by the delayed transmission of heat, stored during the day in heavy thermal mass. Attention on good schemes of natural ventilation is supposed to help refreshing (potential solar chimney). Extra heat load will be covered by wood or biomass combustion.

Indoor comfort temperature range is set relatively large for the analysis: between 20°C and 25°C. This expresses a rather large level of tolerance level that is part of an ecological way of life because it naturally results in lowering energy consumption. Humidity ratio control will not be considered since humidity control devices (mainly humidifiers since outdoor humidity ratio is rather low, 45%, see paragraph 2.3.2 p. 34, compared with common range of comfort, 60-80%) are out of budget. Usage of materials that naturally control ambient air relative humidity such as wood, adobe or compacted earth consequently appears recommendable in that respect.

The comfort definition is further explained as part of the statistical analysis and the definition of the "objective functions" (see paragraph 4.1.3 p.55).

Electrical demand/supply

- *Demand: first stage energy savings*

First a significant effort is expected from the prototype's users to convert usual habits into ecologically aware life style. However, a selection of energy-efficient domestic equipments of a certain energy-class will hopefully be considered when purchasing the equipments; they obviously imply higher investments but are of crucial importance when it comes to electricity savings. Recommendations are presented in the base-case model through the correction of roughly established consumption scenario (see paragraph 3.3 p.44). Significant savings are achieved through better equipment selection.

- *Electricity supply: efficient technologies, clean energies and diversification*

Since budget is limited, a total electrical auto sufficient house may not be feasible. A connexion to the grid appears unavoidable (but does not imply tremendous investment since the grid is already rather close to the construction site). However investments in renewable electricity systems appear more than necessary and appropriated. First tremendous solar and significant wind potentials for electricity generation definitely call for that type of investments. Second, energy diversification is one fundamental principle of any sustainable future and it appears crucial to respect it in the design of such an exhibition prototype. Third, according to the latter educational function of the prototype that is meant to be an ecological education centre, showing different ecological technologies off also seem logical as a main part of the design. Such a system is then dimensioned, designed and purchased as part of the thesis work (see part 5 p.73)

Heat demand for hot water and cooking purposes

- *Solar water-heater system*

The solar potential of the site can be used for electricity production (Photovoltaic cells) but also for water heating needs. Consequently, a solar water-heater system will be purchased to cover hot water demand for 4 to 6 persons depending on the budget.

- *Biodigestor: gas for cooking application and huge electricity savings*

As it will be described when establishing the electrical consumption scenario (see paragraph 3.3.2 p.46), the usage of electrical hot plates for cooking applications represents a tremendous consumption of electricity (up to half of total house electrical demand). According to what has been mentioned about nutrient cycle, the biodigestor option can, if well dimensioned, and according to personal experience of such design, provide enough biogas for all cooking needs. The biodigestor definitely shows both very pertinent advantages: nutrient recycling and huge electricity savings. It also fits with the educational function of this ecological prototype. The biodigestor design and dimensioning have been previously achieved in another study and is not presented as part of this report.

2.2 Energy calculation software

2.2.1 Why and what? Definition of specific technical requirements

Residential energy demand for heating, cooling and domestic appliances represents a significant part of the global energy demand in the world. It varies significantly depending on the country but amounts to 36% of electricity consumption in the US, which is higher than the industry sector[10]. It reaches 26% in Mexico (from SENER) and according to the EIA (Energy Information Agency), it represents around one fifth of the world energy consumption. It is now well-known that tremendous energy savings can be made from energy efficiency improvements in buildings, concerning for instance:

- Insulation of building envelope (materials, design…)
- Use of natural light
- Structural design and architectural plans (to avoid thermal losses via infiltration, thermal bridges…)
- HVAC (Heating, Ventilation and Air Conditioning) systems
- Domestic equipment
- …

All those variables combined with many others parameters such as climate data, orientation, occupancy schemes and activities make energy requirement hand-calculations laborious and often inaccurate. As a result hundreds of software programs related to energy calculations of buildings have been created to analyze and further optimize energy requirements and performances. Logically, it has therefore been

[10] From Clean Energy Website , at http://www.clean-energy.us/facts/electricity.htm

decided to use one of those programs to improve the accuracy and reliability of the presented results and conclusions.

A long and precise investigation has been carried out to determine what program to use for the project. The table in Appendix 4 ("Pieces of software for energy analysis and simulation") presents a list of the most relevant and appropriate pieces of software that have been chosen first. Basically the selection considered various aspects:

- *Purchase price:* definitely a determining parameter in such a project.
- *Languages:* a Spanish version to allow efficient knowledge transfer to coming Mexicans working on the project. However English also remained important to facilitate the evaluation of this thesis work.
- *Energy approach:* since the thesis work is rather short in time (around 6 months long), a wide and global approach has been preferred. It appeared that very specific and detailed applications implying laborious and accurate time-dependent simulation processes were not necessary and could be left out.
- *Acquisition of handling knowledge:* for the same time constraint as mentioned above, a rather short learning period has been required.
- *Material database:* since on-site (or rather close-to-site) materials are of primary interest as part of an ecological design (adobe, local stones, compacted earth …) and since those materials are definitely not of common use in industrialized countries where such programs are developed, either a very wide material database or the ability to feed the program with material properties (mainly thermal) instead of material designation was required.
- *Climate data base:* although important efforts are currently on-going Mexico and the state of Guanajuato lacks of climate database and measurement infrastructures. As a result, as well as for the material database, Mexican climate files or an ability to implement some self-made ones, were definitely recommended. Nevertheless some climate similarities could have been established between Mexican and American climates in order to perform the calculations (like the HEED program, see appendix 1, which uses 16 California climate files).
- *Type of building*: the analysis of a simple 100m² house does not require all commercial or office building design and calculation features. Advanced and complicated programs have consequently been abandoned favoring simple residential building application.

A first selection has been made (see Appendix 4) and basically according to the decision-making factors listed above, BV² software (see 2.2.2 p.32) has been chosen to be the supporting program for the project.

2.2.2 BV2 software: overall presentation[11]

BV² is a program that was developed within Chalmers University and specifically in CIT Energy Management AB. The original Swedish version of the program definitely showed good technical and educational features for energy requirement calculations of buildings. An English version has consequently been gradually developed and is still updated on a regular basis in order to further widen the field of potential users.

BV² is not a simulation program in the sense of time-dependant step-by-step calculations and discretization of variable domains. It uses a calculation method based on a specific way of expressing the building's thermal balance. This expression relies on the so-called "duration curve" that basically represents the external temperature's evolution through the year. The curve represents specifically the site's climate and is the basis of all BV² calculations. Every term of the thermal balance carries specific design parameters and is graphically combined with the temperature duration curve. Then using different scaling factors, heat and cooling requirements are calculated from specific areas on the diagram while separating day and night times. A brief illustration of these principles is shown in Appendix 5: BV² software presentation and explanations. For more information a manual is available on the internet (see note n°1 above).

This software contains different toolboxes that help with:

- Climate data through site selection (mainly over Scandinavia but more locations can be further implemented, Torreon Mexico for example)
- Material properties and U-Value calculations for walls, windows, roof and ground slab
- Domestic hot water system design
- Electricity consumption (from definition of internal heat production schemes)
- Price analysis
- Results analysis

BV² is rather easy to use and was already basically known when starting the work; it then matched most of the requirements mentioned earlier (see paragraph 2.1 p.27). Furthermore the ability to consult easily and rapidly with the design team[12] and free access to a BV² license would further explain why it has been chosen as the main computational tool for the work.

2.3 Climate data investigation: importance, difficulties and results

The construction site is located in a remote place in the sierra "Sierra de Lobos". Accurate and specific climate data was therefore difficult to find although it is of fundamental importance for the analysis value. First, as a guide to the investigation

[11] At http://www.bv2.se/default_e.htm, presentation, details, demo, manual…

[12] Basically Tommy Sundström

process, general requirements are listed in paragraph 2.3.1 p.33. Then investigation features are briefly described and paragraph 2.3.3 p.38 summarizes and discusses the final investigation results.

2.3.1 Climate data requirements

<u>Thermal balance of the house</u>

Since it has been decided to use the BV² software to calculate energy requirements related to the thermal balance of the house, the climate data requirements are those of BV² and are mainly related to outdoor temperature. Table 1 below presents the main climate data requirements as they are displayed in BV² (see paragraph 2.3.3 p. 38 for values)

Table 1: Climate data BV²'s requirements

<table>
<tr><td colspan="2" rowspan="2">Power dimensioning
(Temperature exceeds Tref during α% of the year)</td><td colspan="3">Energy calculations</td></tr>
<tr><td rowspan="3"><u>Mean annual outdoor temperatures</u></td><td>>Highest annual mean (°C)</td><td>×</td></tr>
<tr><td>α</td><td>T_{ref} (°C)</td><td>>Normal (°C)</td><td>×</td></tr>
<tr><td rowspan="3">0% (maximal temperature), 0.4%, 1%, 2%, mean temperature, 99%, 99.6% and 100% (minimal temperature)</td><td rowspan="3">×</td><td>>Lowest annual mean (°C)</td><td>×</td></tr>
<tr><td rowspan="2"><u>(Extreme temperatures)</u></td><td>>Maximal outdoor temperature over the last 30-year period (°C)</td><td>(×)</td></tr>
<tr><td>>Minimal outdoor temperature over the last 30-year period (°C)</td><td>(×)</td></tr>
</table>

This climate data basically appears on the "duration curve" (See appendix 5: BV² software presentation and explanations). Based on the duration curve and indoor temperature targets for comfort, the heating and cooling "degree-days" and "degree hours" are instantaneously calculated for both days and nights.

Extreme temperatures are also called "design temperatures" and as such, also support the power dimensioning process. However, they are not always available, do not appear on the duration graph and BV² can be run without them.

It is important to mention that solar radiation (beam and diffuse) is also taken into account and approximated from site specific geographic coordinates (latitude, longitude and altitude). This enables heat transfer via radiation processes to be included.

<u>Resources of renewable energies</u>

An ecological building is meant to consider as much as possible the 3 basic ecological cycles: water, nutrients and energy. When it comes to energy, diminishing energy losses on one hand (highest potential of savings) and the benefit of renewable energies on the other hand are the most fundamental points to take into account when ecologically designing. As such, investigations about wind, solar and hydro potentials appear in the foreground of a preliminary study.

- *<u>Solar radiation</u>*

Climate data about average solar radiation (beam radiation and diffuse radiation) is first used for thermal balance calculations (see above, "Thermal balance of the house") in the BV^2 program. However, they are not accessible as such for users since radiation calculations are internally completed from previously input geographic coordinates. It is therefore important to search for specific data because on the second hand, this data is used to evaluate both thermal and photovoltaic solar potentials. Data is usually given as the average solar energy flux per square meter or as the average daily (or annual) number of hours of sun. Therefore, one needs to establish what can be considered as a standard hour of sun (morning hour radiation is not equal to afternoon hour radiation). Consequently a standard hour of sun is set to be equivalent to 1 kWh of solar energy or counted as such as an average radiation power of 1 kW for one hour.

- *Wind energy*

Wind energy is very difficult to cope with due to its high degree of variability and the difficulty to foresee and establish reliable models. It indeed depends so much on site-specific data such as relief, obstacles, sun effects and earth surface temperatures that existing global models are not of significant reliability. However, it is important to quantify the approximate wind potential of the site in order to have an idea of how much to invest in wind technologies and how to size the energy systems. Annual average wind velocity is usually used to predict how much electricity can be generated from a given turbine. Similarly to the consideration of extreme design temperatures for HVAC system power dimensioning, maximum wind gust velocities are crucial factors for turbine sizing which basically determines turbine longevity and maintenance requirements (storm brake, blade size, rotor size, maximum power production peak, batteries…)

- *Hydro-energy*

In a few cases of river or waterfall proximity hydro-energy might be considered, especially since micro hydro-energy recently emerged in the hydro-energy market as a reasonable option. Although this is not the case for this project, a quick analysis has nevertheless been carried out to evaluate the feasibility of implementing a small water turbine between the small lake slightly above the house and the house itself. The lake is meant to act as rainwater storage for domestic water usage of the house. The gravitational potential energy could eventually be utilized via a small water turbine. In collaboration with Dr. Raul Olalde Font of the University of Santa-Clara, a Cuban specialist in micro hydro-energy, a brief topographical analysis was started but remains unachieved (see Appendix 3: Topographical description for the potential hydro energy from the lake). Actually it has been determined that the site's topographical configuration does not present any real energy efficient possibility but, nevertheless, due to the demonstrative function of the prototype, a small hydro-turbine could reasonably be installed.

2.3.2 Investigations and sources

BV^2 temperature file: Torreon (climate file) vs Leon (project site)

Initially, the BV^2 climate data base concerns exclusively Scandinavia (Sweden, Norway, Finland and one site in East Russia). All climate data comes from a international climate database for engineers called Meteonorm[13] (over several versions depending on up-dating frequency). A specific climate file has been established only for the project's usage. For practical reasons and lack of climate data, the climate file refers to the city of Torreon, located 500km north of Leon, the project's site. However, as shown on Figure 2-1 below, Torreon and Leon belong to the same climate zone, called the Tropical or Torrid Zone.

Figure 2-1: Geographical situation of Torreon (climate file) and Leon (project's site). Both belong to the same climate zone.

In order to further validate the usage of Torreon's climate file or at least to figure out to what extents it may differ from Leon's climate file and what to keep in mind when interpreting the results, a temperature comparison is presented on Table 2 p.35. The data comes from 30-year measurements of monthly or annual averages and is provided by the National Meteorological Service of Mexico. First of all, Torreon's temperatures show larger variability. Furthermore, it is important to mention that, the collected data corresponds to a climate station called "La Calzada" that appears to be one of the warmest place in Leon[14]. The construction site is located in the Sierra de Lobos (see paragraph 1.2 p.21), where average temperatures would be assumed lower than in the city due to higher wind exposure and lower air pollution levels. Those factors will have to remain in consideration when analysing the BV² simulation results (see Appendix 7: Climate file of Torreon).

Table 2: Temperature comparison between Torreon (climate file) and Leon (project's site)[15]

	TORREON	LEON (La Calzada)
Mensual mean maximum temperature over past 30 years (°C)	38,5	33,8
Annual mean temperature over past 30 years (°C)	21,9	19,6
Mensual mean minimum temperature over past 30 years (°C)	2	4,9

Other climate data of Leon

The 2000 report on the physical characteristics of the Leon municipality[1] gives various details about climate data of Leon, but exclusively refers to meteorological stations located in the urban area. Therefore, it is difficult to extrapolate the data, or

[13] Available at http://www.meteonorm.com
[14] "El estudio fisico natural 2000 del IMPLAN", Municipal Planning Institute of Leon
[15] From Servicio Meteorologico Nacional (SMN), at http://smn.cna.gob.mx/

even use it, because it differs significantly from the site-specific climate data. Most of climate data reported come from the SMN (see note 2 at the bottom).

- *Precipitation and evaporation rate:*

The annual rate is equal to 654 mm/year for the climate station of “la Calzada”. The annual average evaporation rate amounts to 2201.3 mm/year. The difference explains the high level of water resource depletion. However, this data should not differ significantly from site-specific data.

- *Humidity ratio:*

The annual average relative humidity is equal to 45%, which is rather low when compared to 77.8% in Sweden[16].

- *Wind velocities:*

Table 3: Wind velocities data from Leon Airport

Periods	Directions of major winds	Frequency	Mean Velocity
Jan-Feb-Mar	from W-WSW	26%	27.7 km/hr
Apr-May-Jun	from W	14.5 %	14.8 km/hr
Jul-Aug-Sept	from ENE-E	16%	14.8 km/hr
	from S	5%	
Oct-Nov-Dec	from WSE-W	10%	14.8 km/hr
	from ENE-NE	7%	38.8 km/hr

Apparently, the wind blows mainly north-eastward which is important to notice since the house will be built on the north-facing side of the mountain; therefore it will only be slightly exposed to wind.

Other data provided by wind turbine suppliers and a wind energy consulting company is summarized in Table 4: Climate data summary, p.38.

- *Solar radiation:*

The solar radiation is crucial climate data to determine when building a house, especially an ecological house (see paragraph 2.3.1 p.33). It is used for the thermal balance analysis of the house but also for solar energy potentials for electricity and heating applications. BV² contains its own radiation database and uses it for calculations of thermal balance. A previous study, performed by a former student about bioclimatic design and natural lighting, determined an optimum building orientation of -30°.

But furthermore a French program called Heliodon[17] designed by Benoit Beckers and Luc Masset, for sun radiation analysis on buildings has been basically used to calculate how much solar radiation can be expected to hit solar panels located on the roof (3m high). A variable angle of inclination has been set for optimization purposes.

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[16] From http://www.climatetemp.info
[17] Available demo at http://www.heliodon.net/heliodon/software.html

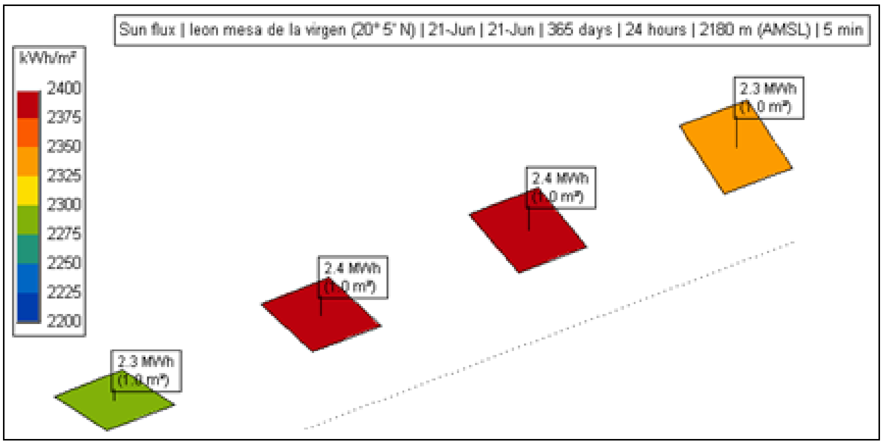

Figure 2-2: Solar radiation on roof mounted panels depending on inclination angle (0°, 11°, 21°, 31°)

The different positions correspond to optimal angles for summer season (11°), winter season (31°), global annual optimum (21°=site latitude) and to the case of a flat roof (0°). Theoretically the average per square meter annual solar radiation flux is calculated to be 2,4MWh/m².year or in daily terms 6,4kWh/m².day. It also appears that a 10° inclination creates a difference of 100kWh/m².year, which is definitely significant enough to be considered. Given that point, the angle of the roof will have to be close to that inclination for optimum performance.

However this does not take into account the climate effects of cloud reflection. In order to account for it, a very simple weighting calculation has been made from both the cloud cover frequency (from the meteorological data provided by the SNM [18]) and the influence of cloud cover on surface solar radiation. First three levels of cloud cover (no clouds, half sunny/half cloudy, fully cloudy) are defined. They basically correspond respectively to 100%, 70% and 20% of solar radiation[19] received by the solar panel (diffuse radiation is not negligible and even possibly enhanced depending on cloud type). Considerations about wavelength variations through scattering or reflection and their influence on photovoltaic effect have been disregarded and a cloud type with a medium level of absorption (between cirrus and cumulonimbus) has been used. Then a brief statistical analysis of Leon annual cloud cover data establishes that the cumulative annual proportion of full cloud cover, half cloud cover and no cloud cover are one month, 4 months and 7 months respectively. The evaluations of frequency levels and absorption power levels are not very precise and therefore one needs to use the approximation carefully. The final weighted coefficient representing the decrease of annual solar radiation due to cloud cover has been evaluated to be 0.83. Therefore, the actual potential of solar energy is reduced to 2 MWh/m².year. More advanced methods to perform this calculation could definitely have been employed but time restrictions required a simple and quick evaluation;

[18] Servicio Meteorologico Nacional (SMN), at http://smn.cna.gob.mx/

[19] Ocean Dynamics review, The influence of clouds on solar radiation at Sea, Guy A. Francescini, 1968

2.3.3 Summary and discussions

Table 4: Climate data summary

	Investigations results	Chosen value	Comments	Sources
Temperature	*see BV2 climate file*			
Humidity				
Precipitation rate(mm/year)	654 mm/year		Low precipitaion rate (rain season lasts 4 months). Strong negative balance that explains high lack of water	*SMN (National meteorological service)* [1]
Evaporation rate (mm/year)	2204 mm/year			
Relative humidity (%)	45%		Rather low rate (Sweden 78%)	
Wind				
Main direction	Mainly north-eastward			*Leon Airport*
Average annual velocities (m/s)	5,5	5,5	Approximations for wind velocities have to be taken with good care	*Inovatek and E2energias providers* [2]
	4,4-6,5			[3]
Sun				
Average radiation (kWh/m².day),***	6,4*0,83=5,31	5,42		*From Heliodon software* [4]
	5,79			*Inovatek and E2Aenergias*
	6,56*0,83=5,44			*CONCYTEG*
	5,87-7,14 (mean=6,5) 6,5*0,83=5,4		Site specific range of data	[3]
	6,2*0,83=5,15		Extrapolated values from SMN data	*CIATEC estimations*

Notes

[1] *http://smn.cna.gob.mx/*

[2] *Unknown source. Both providers give same values.*

[3] *Fisrtlook data base recomended by Mexion wind consulting company . At http://firstlook.3tier.com*

[4] *Heliodon software's demo version is available at http://www.heliodon.net/heliodon/software.html*

Comments:

** A 0,83 factor is applied to take meteorological influence into account*

*** Inclination angle optimization is neglected. It almost doesn't affect energy fluxes on a daily basis*

Concerning temperature, the entire set of data used is a climate file in BV². The climate file also contains other sets of data such as solar radiation schemes that are not directly accessible. One should remember that the climate file refers to the city of Torreon, located 500km northward from the project's construction site. Some temperature differences are notable and as presented in paragraph 2.3.2 p.34, have to be kept in mind. For a more complete analysis, a climate file dedicated to Leon would be preferable.

As an ideal case, a meteorological station has been purchased that can measure all climate data types with reliable accuracy but due to time constraints of this project long term data was not available. However in the future, a site-specific set of climate data will be available and will therefore give even more reliability to the calculations and analyses presented in this report.

Climate data investigation is definitely a difficult and laborious task whose results must always be carefully considered. Indeed, the approximation level is usually high, different sources give different values… However, average values can reasonably be considered when it comes to energy flux calculations. But one should keep in mind that in the case of power dimensioning, average value will typically lead to an undersized system, which in turn results in money and efficiency losses. To conclude the quality of such a design project where climate is a fundamental factor remains strongly dependent on the quality of data and the data collection and discussion has anyway to be performed rigorously and carefully.

2.4 Material data

Material selection is of primary importance in the design of an ecological building. A consistent life-cycle consideration has ideally to be performed to evaluate the ecological quality of a specific material. Where is it provided from? How much energy is consumed in manufacturing and transport processes? How contaminant is it for the environment? To what extent can it be recycled, left on the site, deposited in the nature? This is not achieved as part of the report and it is hoped that such considerations have at least been thought about. A previous qualitative selection is reported in the next paragraph and a further quantitative investigation has been achieved on this basis.

2.4.1 Qualitative considerations

Some previous studies have been performed about construction materials and ended with qualitative considerations such as:

- Fire behavior;
- Acoustic properties;
- Mechanical properties;
- Thermal properties;
- On-site or close-to-site availability;
- Price considerations.

Those analyses have not been reviewed as part of this thesis work; however, the main results are presented in Appendix 8: Material data, qualitative data.

As a conclusion to those preliminary qualitative studies a selection of materials has been made. Those which have been qualitatively selected for further quantitative investigations are:

- Adobe
- Masonry natural stones (site-collected, investigated as being basaltic rocks)
- Compacted earth (with a specific process that Dr Palacios knows well from having scientifically studied it for several years)
- Brickwork
- Concrete and light concrete

- Clay roof tiles
- Polyurethane or mineral wool insulation
- Basic single and double glazing windows (Non metal frame)

2.4.2 Quantitative considerations

Thermal properties are definitely required in this study. Indeed all calculations performed with BV² are performed on the thermal balance basis of the building. As a result, thermal conductivity (measured by the λ-value in W/m.K or, when including thickness value, the U-value in W/m².K) and heat capacity (given in J/kg.K) have been investigated. All of the results are shown in Appendix 9: Material data, quantitative data.

Such an investigation task is definitely very laborious because most of the materials are not listed in common databases. Indeed for financial reasons most of them are natural, site specific, hand-made and are no longer used in developed countries where common databases are constructed. Therefore a significant variability affects the precision of the results and sometimes weighting methods have been performed to account for a source's reliability.

3 Base-case description and energy scenario

3.1 Building envelop

3.1.1 Main dimensions of the original design

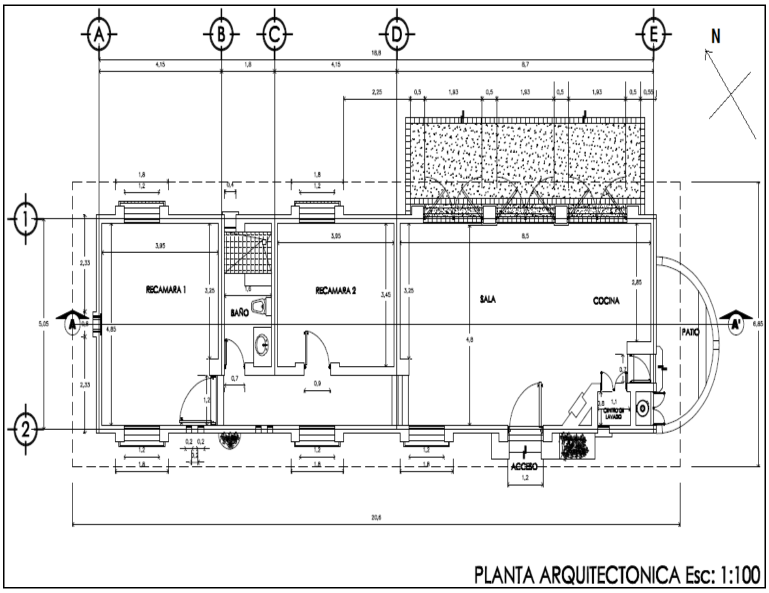

Figure 3-1: Architectural plan of the prototype (Recamara=Bedroom, Bano=Bathroom, Sala=Living room, Cocina=Kitchen, Acceso=Entrance, ESC= scale)

Table 5: Basic architectural dimensions (as used by BV² software)

	Walls area (m²)	**Window area (m²**	**Window share of the facade %**
North facing	54,9	18,607	33,9
South facing	54,9	7,3	13,3
East facing	17,8	0	0
West facing	17,8	0	0
Wall height (m)	2,92[1]	*[1] North and South facing walls*	
Peak height (m)	4,14[2]	*[2] East and West facing walls*	
** The type of roof is called "sloping roof" or "gabled roof". The gable is the triangular portion of east and west walls.*			
Roof inclination (°)	26[3]	*[3] In figure , optimal inclination for PV solar radiation is approximetaly 30°.*	
Surface (m²)	94,94	*General comment*	
Perimeter (m)	47,7	*All the values presented in this table are required and used as such by the BV² program*	
Volume (m³)	329,4		

A first architectural design has been achieved by Arq. René Ortega and will the basis of the analysis. It is 94,94m² single floor house, with 2 bedrooms, 1 corridor, 1 living room and 1 kitchen. Large windows are located on the north facing façade in order to enjoy the nice view on the Sierra De Lobos from the living room and will have a significant impact on the thermal analysis the building.

3.1.2 Design parameters: commonly used structures and materials

Since no specific data has been designed by the architect, common Mexican structures and materials are used for the base case analysis. The overall description of building is presented below and the thermal balance results of BV² software are presented in paragraph 3.4.4 p.50.

Walls

For the base case, the walls are made of brick work (see Appendix 9: Material data, quantitative data.), 14cm thick (common blocks size) U value = 2.47 W/m².K. This structure is very common here in Mexico. It is definitely set as a high thermal mass building.

Roof: 2 configurations

- *The real base case model*

It consists of a "sloping roof of 2 two slopes" or "gabled-roof" (the gable is the triangular portion of a wall between the edges of a sloping roof). Inclination is given is given in Table 5 p.41. Usually it is made of clay roof tiles that are mounted on a wood or steel carpentry. A 5cm air gap and a 5 cm insulating layer (cheap mineral wool or polyurethane) constitute a basic roof insulation that is not so common in Mexico (usually no insulating layer) but a reasonable base-case configuration for a new advanced house.

- *Another common case, provided as an example*

The first configuration consists of a flat single roof that presents the following structure. It is included as a base case model but actually will serve more as a reference case to be compared with.

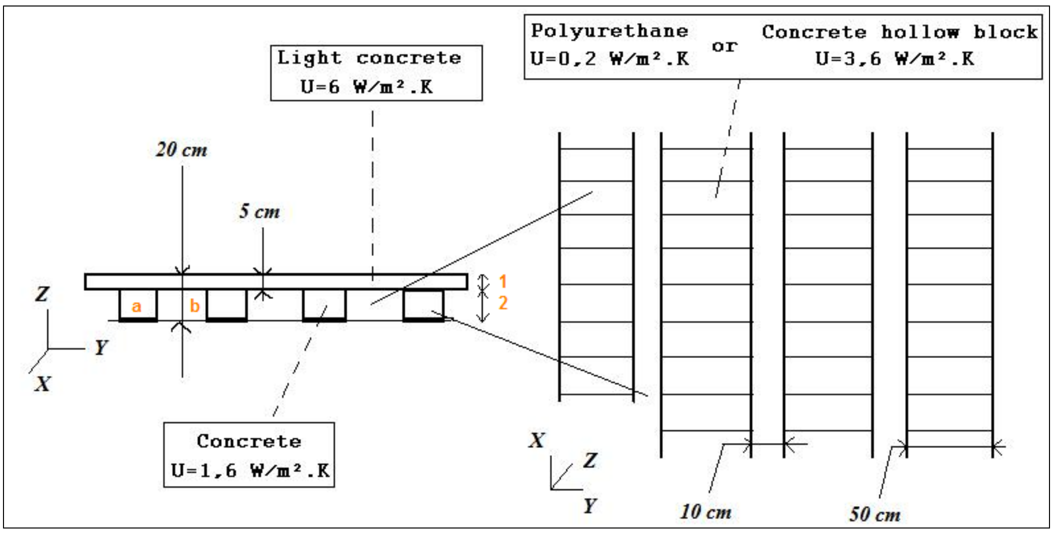

Figure 3-2: Base case roof model, configurations 1 and 2(as a reminder, the U-value already account for the thickness e, and λ-value of thermal conductivity, U=λ/e)

To calculate the U-value equivalent to the entire roof, basic thermal equations are used (just see red notes on Figure 3-2 above):

$$U_1 = \frac{\lambda_1}{e_1}$$

$$U_2 = s_a \times U_a + s_b \times U_b$$

$$U_{eq} = 1 \Big/ \left(\frac{1}{U_1} + \frac{1}{U_2} + R_{indoor} + R_{outdoor} \right)$$

With λ, thermal conductivity of the material, W/m.K;e, thicknessof the portion of material, m; s, the surface proportion of a and b (s_a +s_b=1); R_{indoor} , $R_{outdoor}$, the surface thermal resistances (commonly set to 0,13 and 0,04 m².K/W respectively)

Respective U-values for the different configurations are listed in Table 11 p.50.

Windows

Basic single glaze windows with a non-metal frame have been chosen as base case windows because they are commonly in Mexico. Material investigations came up with a really high U-value of 5.3W/m².K. This type of window is definitely a huge disadvantage in the thermal balance of a building. This will be illustrated in part 4 p.53.

Ground slab

Using BV² calculation tool for ground slab U-values, a basic ground slab as described in the following table has been considered.

Table 6: Thermal description of the base case ground slab

	Value	Comments
Internal heat resistance (m².K/W)	0,13	*Common surface effect via convection*
External heat resistance(m².K/W)	0	*No surface effect since no free surface*
Heat resistance of ground slab exclusive heat resistance of ground (m².K/W)	0,12	*Basic non insulated 20cm concrete slab, very common in Mexico*
λ value of underlying ground (W/m.K)	2,3	*Intermediate value between: -clay, drained sand or gravel (1,4) -rubble stone (3,0)*
Global U-Value (W/m².K)	1,098	*Calculated by BV²*

HVAC system

As already mentioned (see paragraph 2.1.2 p.28), in Mexico, advanced HVAC systems are really rare because of high investment and variable cost (energy consumption and maintenance). Natural ventilation and windows-airing has consequently been chosen as the base case HVAC option. When setting this type of HVAC system, air leakages in the building have to be set. One value is set when indoor/outdoor temperature difference is equal to zero; it represents overall heat transfer through infiltration, set to 0.2 ACH (air changes per hour). A second rate has to be set when infiltration is driven by a significant temperature difference of 20°C; it is set to 0.4 ACH. These values are commonly used for that type of building and envelop quality. However, in the sloping roof case, the tile layer naturally let high infiltration rate and the insulating layer only slightly reduces the leakages. As a consequence, both air leakage rates are set 0.4 and 0.8 ACH respectively to take into account this low air proof roof structure

As required by BV² when dealing with this basic type of system, a minimal acceptable temperature has been set to 20°C so that BV² can calculate the annual heat demand of the house. However, since the cooling demand depend very much on the cooling system, maximum temperature has been set and no cooling demand is calculated. This demand has then to be evaluated by using other factors. It is presented in paragraph 3.4.1 p.50.

A basic windows-airing scheme has been fed to BV². It consists in defining the window opening degree as a linear function of indoor temperature. The opening degree is set to vary from 0 (closed) when indoor temperature is equal to 23°C to 1 (completely open) when indoor temperature is equal to 27°C.

3.2 Prototype's global functioning scenario

3.2.1 Occupancy

It is very difficult to deal with this point since nothing is built yet. In order to get a basis for the calculations, it is assumed that the house is occupied all over the year, i.e. 365 days per year.

3.2.2 Activities

It is assumed that the house is occupied as a rather common house is occupied during the week-end. It means that, since nobody will leave in the house (i.e. going to work during the week and rest during weekends), only week-end and vacation life styles are considered for all 365 days per year. It implies, wake up around 8 in the morning, relaxing activities, together lunch at 13h, relaxing and outdoor activities during afternoon, together dinner at 20h, TV/movie after dinner both in bed rooms and living room... This type of life style is expressed through the definition of the internal heat generation (via persons, lighting and domestic equipments) in paragraph 3.4.2 p.49.

3.2.3 Persons

The prototype is meant to be an educational center about ecology, an exhibition site where people can see, experiment and discover ecological principles and ecology. It is very likely that the house will be rented to families, a group of persons for few days, with certainly a sort of preliminary lecture about the prototype, the systems, the maintenance … It is then supposed that an average of 4 persons occupy the house.

3.3 Electricity considerations

In the reference book written by Dr Palacios and called "La casa ecológica, como construirla?"[20], which means in English "The ecological house, how to build it?", everything about the basic construction principles of an ecological house is reported and a chapter is exclusively dedicated to the first designing steps of this prototype.

[20] "La casa ecológica, ¿cómo construirla?", Dr Palacios, printed by Nexo Grafico, edition of July 2007.

Three scenarios of electrical consumption are reported in the book: one low, one high and one medium. On that basis, one single scenario, more accurate and documented, has been established to be able to evaluate both annual electricity consumption and determine the power supply peak (dimensioning load).

3.3.1 Demand for lighting

Light bulbs are chosen low-energy consuming (fluorescent, 15W) and the required number, previously calculated, is supposed to result from a correlation with natural lighting potential.

On the graph below, the time schedule for lighting is presented according to different time slots on the X axis.

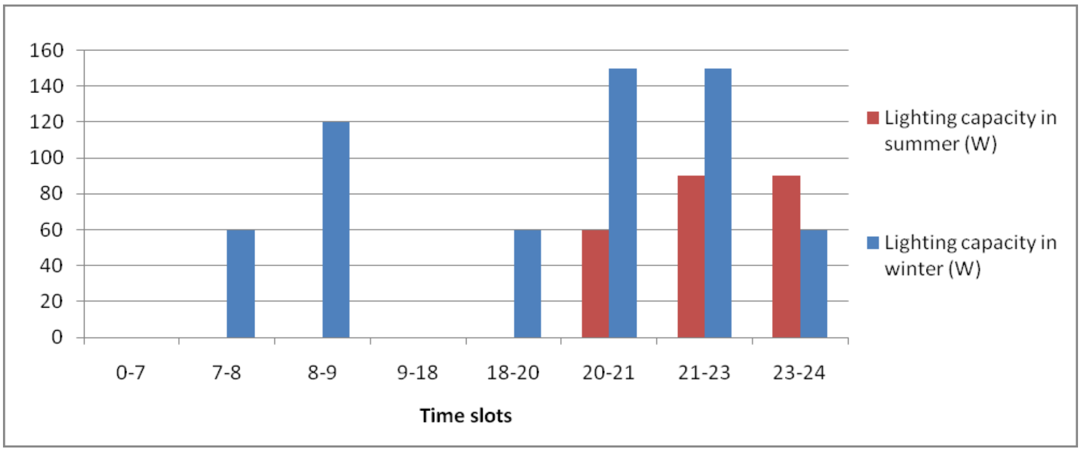

Figure 3-3: Operating time schedules and required capacity for lighting (BV² scenario)

On this basis, a global study of electricity demand for lighting has been achieved and the results are listed below in Table 7 p.46. Since those schedules refer either to summer (3.6 months of the year according the BV² standards) or winter (2.4 months), an intermediate consumption scenario has been established for the left 6 months (spring and autumn). The daily consumption for lighting during these 6 months is taken as the average daily consumption between winter and summer consumptions. When it comes to annual electricity consumption, the result is calculated as weighted average whose weights are time proportion of the year. It finally has to be mentioned that, since the house is not supposed to be commonly occupied by a family but either occasionally rented (in the beginning) or used a educational center; scenario is therefore made for week-end days and assumed to be valid all along the year. It therefore results in a rather high consumption scenario.

Table 7: Summarized electricity results for lighting

Total final (lighting)	**Summer**	**Winter**	**Others**	**TOTAL:**
Time period (months)	3,60	2,40	6,00	
Installed capacity (W)	90,00	150,00	120,00	150,00
Electricty demand (Wh/day)	330,00	810,00	570,00	546,00
Electricity demand (kWh/year)	36,83	60,26	106,02	203,11
Electricity demand (kWh/m².year)	0,39	0,64	1,13	2,16
Comments:				
All days are considered as if they w ere w eek-ends' days.				
Summer is defined as the 30% w armest days (3,6months), w inter as 20% (2,4 months) and value for the left 6 months are average (BV2, standards)				

Table 7 shows that electricity demand for lighting remains rather low. For the sake of comparison, the famous Swiss eco-label called Minergy[21] recommends 10.5 kWh/m².year for an office building, which is around 5 times higher than this prototype demand. First an office building naturally requires higher level of lighting and also days are on average longer in Mexico than in Switzerland. However this underlines the efficiency of the architectural design that definitely takes maximum benefits from natural lighting. The Minergy label does not account for life mode while in this calculation, an ecologically-aware life style is assumed and implies a careful electrical usage; this can further explain the difference. The calculation of numbers of bulbs is taken for granted in this analysis and not questioned, it might also be underestimated.

3.3.2 Demand for domestic equipments

The approximate reference scenario presented in the reference book[22] used for all calculation has been reviewed and corrected as a result of a more consistent investigation. Basically the corrections refer to more realistic capacity features of the equipments. Actually the better documented investigations result in correcting the original capacity usually lowering them by selecting equipments of A or A+ class of energy efficiency (the scale goes theoretically goes from class G to A++, although all new equipments belongs for the less energy-efficient one at least to B). Choosing a bit more carefully the equipments, without buying very state-of-the-art equipments in terms of energy, leads to significant energy savings. The corrections are also related to a more careful usage of the equipments (less time usage). The prototype is supposed to be converted in an ecological education center, it is normal to assume that the selection of equipments pays a strong attention to the energy efficiency. Thus energy consumption depends on both time and capacity since energy consumption is calculated as:

$$E = P \times t, \quad (in\ kWh)$$

With E, energy consumption; P, capacity of the equipment, kW; t, usage duration, hours

On Figure 3-4 p.47, corrected annual consumptions are summarized and one can see that most of them are corrected to lower value (lower usage duration or lower capacity or both).

[21] At http://www.minergie.ch/

[22] "La casa ecológica, ¿cómo construirla?", Dr Palacios, printed by Nexo Grafico, edition of July 2007.

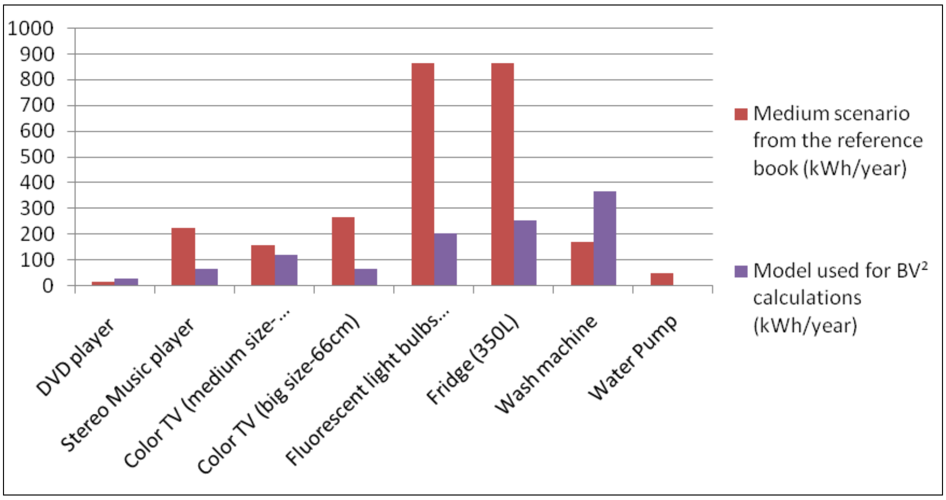

Figure 3-4: Consumption corrections from medium scenario presented in the book and final scenario used in BV²

The consumption results for domestic are summarized in the table below.

Table 8: Summarized electricity consumption results for domestic equipments

Total for domestic equipments	Without electrical hot plate	With electrical hot plate (1000W)
Installed capacity (W)	700,00	1555,00
Peak time slot (hrs)	11-12	12-13
Daily electricty demand (kWh/day)	2,46	5,46
Annual electricity demand (kWh/year)	897,90	1992,90
Annual electricity demand (kWh/m².year)	9,55	21,20

Definitely the consumption of an electrical plate is tremendous and consumes as much as all other equipment put together. It is necessary to find a substitute to it. Three options have been considered:

- *A solar cooker:* completely in accordance with the main educational objective of the prototype but definitely too expensive;
- *Traditional gas plates:* this would be the most feasible option since gas remains very cheap in Mexico;
- *Biogas plates:* a biodigestor is projected to be built on site to collect compost and sewages water (blackwaters only) to produce biogas (mainly methane and CO_2). This option would be very interesting because a biodigestor can be simply constructed and does not require huge investment, and it would produce free gas for cooking applications. Digested material can be used as fertilizers for plants in total respect of the ecological nutrient cycle (see paragraph 2.1.1 p.27). The biodigestor design process is not included in this report but appears in the reference book[23].

[23] "La casa ecológica, ¿cómo construirla?", Dr Palacios, printed by Nexo Grafico, edition of July 2007.

3.3.3 Global electricity consumption: summary

Table 9: Summarized global electricity results

Global electricity demand	Without electrical hot plate	With electrical hot plate (1000W)
Surface (m²)	94,00	
Required installed capacity (W)	720,00	1555
Daily electricity demand (kWh/day)	3,01	6,01
Annual electricty demand (MWh/year)	1,10	2,19
Annual electricty demand (kWh/m².year)	11,67	23,32

Total electricity demand amounts for 11.67 kWh/m².year and the consumption doubles when including an electrical hot plate (by the way, BV² software evaluates electricity demand to 21kWh/m².year including the hot-plate). Required capacity is evaluated to be 720 W (1.5 kW with the hot plate), those values will serve in the dimensioning process of electricity supply system. An analysis of potential resources will find out how large proportion of the demand can be covered by free and renewable energies. However, it already appears that the high required capacity will require the extra connection to the power grid.

3.4 HVAC considerations: mainly heat demand analysis

Since no electricity-consuming HVAC system is envisaged in the base-case definition mainly for budget restrictions, it is possible to decouple the considerations for electricity demand scenario from HVAC considerations. However analyzing HVAC requirements needs the previous definition of electricity scenario since the latter represents a significant part of the internal heat generation (see paragraph 3.4.2 p.49).

3.4.1 "Objectives functions"[24] and comfort definition: the main parameters to control

When designing a house envelop the obvious goal is to try to minimize both heating and cooling load. It is therefore important to be able to quantify both demands. BV² usually enables to calculate both heating and cooling demands from a set comfort temperature range. As explained in paragraph 2.1.2 p.28, the temperature comfort range has been first set rather large according to an assumed high level of tolerance; the life style represents the major application field in reducing both heating and cooling demands, before taking care of improving technological efficiency of energy systems.

The definitions made in this paragraph constitute the basis for the base case results but also for the further variance analysis (supported by BV²) achieved and presented as the optimization part of the work (see part 4 p.53)

<u>Heating demand</u>

The comfort level is set to be above 20°C; this enables BV² to calculate a proper annual heating load (in kWh/m².year).

[24] This is a standard naming when it comes to statistical optimization field. See paragraph 4.1.3 p.55.

Cooling demand

Since base case cooling system is set to be natural ventilation with windows airing (see paragraph 3.1.2 p.42), BV² cannot calculate a proper cooling demand that depends pretty much on the cooling system type. Therefore one has to find other indicators to be able to quantify the cooling demand. These indicators are listed below; they enable to virtually set a high comfort threshold to 25°C:

- Maximum indoor temperature during day time (8:00-18:00)
- Maximum indoor temperature during night time
- Numbers of hours above 25°C during day time
- Numbers of hours above 25°C during night time

3.4.2 Internal heat generation

When analyzing the thermal behavior of a building, an important point has to be presented because it has a significant impact on the overall heating demand (and cooling demand): the internally generated heat (lighting, persons and equipments), see Appendix 5 about BV². This has to be carefully studied and feed into the BV² software under the form of time schedules of heat generation. They are calculated for different types of room, for different seasons (only for lighting). The heat generated has to be expressed in W/m², therefore the size of the room where they are located has to be taken into account. The generated heat is basically expressed thanks to a heat conversion factor (see Table 10 p.49) that varies with the type of equipments. For instance, a light bulb or a hot plate have high heat conversion factors, and wash-machine a very low one since almost all the heat is removed in flue water. Most of the heat conversion factors come from the lecture "design, needs, requirements and loads" of the HVAC course of Chalmers University.

Table 10: Generated heat by diferent heat sources[25]

Equipment	Capacity (W)	Heat conversion factor	Heat generated (W)
Fridge	150	0,4	60
TV big size	120	1	120
Hot plate	1000	0,95	950
DVD	25	1	25
Music player	150	0,7	105
Wash machine[1]	400	-	0
Bulbs	15	0,9	13,5
Persons	-	-	100[2]
Comments:			
[1] *Almost all the generated is removed in flue water*			
[2] *It is the average heat generation for an adult standing with light activity. Sleeping persons are neglected.*			

[25] From the lecture "design, needs, requirements and loads" of the HVAC course of Chalmers University

The main results about internal heat generation are summarized on the graphs below.

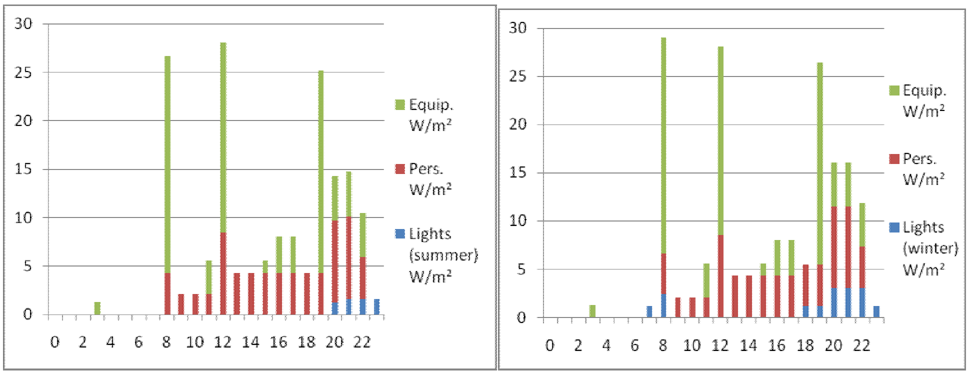

Figure 3-5: Internal heat generation in summer and winter

One can notice the high heat generation during dinners, when cooking usually generates a lot of heat as well as the reunion of all persons. Some intermediate values about the total number of person (that is assumed to be 4) represent the fact that for example during breakfast time (between 8 and 9) people are usually moving frequently from one room to another. The graphs model the addition of both types of rooms (kitchen/living room and bedrooms that have same surface).

3.4.3 Heat for hot water supply

This part has not been studied in details since the purchase of solar water-heater for 4 persons is supposed to provide sufficient hot-water. No further analyses have been performed.

3.4.4 Global base-case thermal characteristics and performances

The results are presented in the following table.

Table 11: Base case results for thermal behavior

		Heating demand (kWh/m².year)	Indicators of cooling demand			
Roof type	Uvalue equivalent (W/m².K)		Maximum indoor temperature day time (°C)	Maximum indoor temperature night time (°C)	Number of hours above 25°C during day time (°C)	Number of hours above 25°C during night time (°C)
Flat roof with concrete hollow blocks	1,87	105	25,7	25,7	107	254
Flat roof with polyurethane blocks	1,3	88	28	28,2	509	1153
Gabled roof with tiles+air gap+plyurethane insulating layer [1]	0,78	82	27,2	27	188	674
Comments:						
[1] *For this configuration , air leakges rates are doubled in comparison with the others in order to take into account the high infiltration rate through this type of roof structure*						

The heating demand does not include the heat for domestic hot water.

<u>Comments</u>

A full statistical analysis is achieved and presented in part 4 in order to see what optimizations can be made in priority. However from these first base-case results one can draw some important conclusions.

A better roof insulation definitely decreases the required heat supply to meet minimum indoor comfort temperature. However, it somehow seems to increase the cooling demand. Indeed, maximum indoor temperature goes up and time above 25°C is pretty much extended. Insulation first appears controversial, a good understanding of its effects combined with a good definition of the objectives is necessary to make the right decision.

A higher ventilation rate (higher air leakages) as set for the gabled-roof levels off these effects since improving roof insulation, i.e. decreasing U-value by almost half (1.3 to 0.78), does not reduce significantly the heat demand for thermal comfort but clearly decreases maximum indoor temperatures.

Conclusions

The real base case (gabled roof) presents quite low heat demand in comparison with the “reference cases” (common in Mexico). But apparently the high thermal mass has a positive effect on delaying heat transmission (night and day maximum indoor temperatures are almost equal, this means that the indoor peak temperature must be around 18h).

From this base case, one can assume that high thermal mass, good insulation and good ventilation schemes can be recommended to both lower heating and cooling demand. See more refined analysis in part 4.

4 Analysis and optimization process

4.1 Statistical analysis

4.1.1 Introduction to statistical analysis

In order to get an overall idea of what parameters influence the most the thermal balance of the house, and to what extent, a basic statistical analysis is performed via the construction of a full 2^k factorial experiment. The results are roughly treated to get first idea of best design alternatives.

Basically one has to see the experiment as a way to better know a function (in our case called the "objective function", see paragraph 4.1.3 p.55). For instance the heat demand of the prototype depends on many parameters, here called "factors", which influence on the function via their "principal effects" (independently from other factors) and their "interaction effects" (when coupled with others factors), see paragraph 4.1.2 p.54. The statistical analysis aims at better knowing the effects of the parameters (or "factors") on the objective functions. An experiment then consists in choosing a numbers of these factors and, through various "simulations" (or "experiments" or "measurements") of different combinations of the values of those parameters, building a consistent model of the objective function. The numerical model relies then on the evaluation of the principal and interaction effects of the chosen factors. Once the effects are evaluated i.e. the model can be built, a statistical comparison between the own properties of the established model (variability, significance of the parameters…) and the observed results (in this case, BV² software's outputs) gives information about model's consistency. This comparison is performed thanks to the ANOVA[26] analysis. This actually expresses the experiment design goodness and consistency (selection of the parameters, selection of their different levels, design of the different combinations...), and therefore the reliability of the resulting conclusions.

The analysis aims at better knowing the thermal behaviour of the prototype through 3 different objectives:

- Confirm consistency of BV² results. The Statgraphics software[27] will perform an analysis of variance and give indicators of the validity of the way the whole statistical experiment has been built and to what extent it is reliable;
- Analyse and confirm the principal effects of 6 major parameters on the objectives functions defined and their potential significant interactions;
- Obtain a model-based optimal combination thanks to a "multiple response optimization".

[26] Analysis of Variance, see paragraph 4.1.5 p.57

[27] At www.statgraphics.com

4.1.2 Introduction to full factorial experiment at 2 levels

A "full factorial experiment" is one basic type of experiment design, usually interesting when measurements are cheap and not time-consuming (here the measurement are performed by the BV² software). In this type of experiment, all factors can be set at only 2 levels (one referred to as "low" or "level -1" and the other as "high" or "level +1"). They can be quantitative (such as a concentration, a temperature... see factors X1, X2, X4, X5 in Table 12 p.56) or qualitative (such as a type of technology, the presence or not of a chemical substance, see factors X3 and X6 in Table 12 p.56). The calculated effect of a factor on the objective function expresses what the impact of changing the factor value from the low level to the high level on the objective function is.

The word "full" expresses the fact that all combinations between both levels of each factor are tested. The number of combinations measured in such an experiment is calculated as follows:

$$N = n \times N_c = n \times 2^k$$

With N, number of measurements; n, number of number of measurements to achieve for each combination; N_c, number of combinations; k, number of factors to be tested

Some more advanced calculations allow achieving a preliminary selection to reduce the number of combinations whose measurements or calculations might be time and/or money consuming. In this report the full experiment has been chosen for being easily achieved since all combinations are only fed into BV² program that calculates the responses (objective functions values) and easily treated. The only issue with this design is the number of combinations to test (adding another factor doubles the number of combinations). As a consequence only 6 factors will be evaluated in this work; it represents 2^6=64 combinations (results are reported in Appendix 10: Results of the full factorial experiment).

The effect of a factor is calculated as the difference between the average value of the results of all combinations having the factor at high level (in this case 32 combinations) and the average value of the results of all combinations having the factor at low level (the 32 combinations left).

$$E_A = \overline{y_{A+}} - \overline{y_{A-}} = \frac{2}{N_c} \times \sum_{i \in A_+} y_i - \frac{2}{N_c} \times \sum_{j \in A_-} y_j$$

With E_A, effect of changing factor A from low to high level, i.e. "principal effect of factor A"; $\overline{y_{A+/-}}$, average value of results of all combinations having A at high/low level; N_c, number of combinations; $y_{i/j}$, result of combination i/j; $A_{\pm}$, set of combinations having factor A at high/low level.

Note: 2/Nc represents the cardinality of sets A+ and A-

Interactions between two factors can also be estimated although it is only slightly considered in this report. Indeed, the level of one factor can influence on the principal effect of another factor. For instance, the effect of changing factor A from level -1 to level +1 when factor B is set at level -1 (B→-1) is not the same as effect of factor A when factor B is set at level +1 (B→+1). One has to be careful; this interaction concept is different from factors dependency, which represents the fact that setting a factor at level might affect the level of another factor. An interaction is analysed at the end of paragraph 4.1.6 p.59 as an example of significant interaction. Interaction effect of factor AB is calculated as follow:

$$E_{A(B\to-1)} = \overline{y_{A+(B\to-1)}} - \overline{y_{A-(B\to-1)}}$$
$$E_{A(B\to+1)} = \overline{y_{A+(B\to+1)}} - \overline{y_{A-(B\to+1)}}$$
$$E_{AB} = E_{BA} = E_{A(B\to+1)} - E_{A(B\to-1)}$$

With $E_{A(B\to+1/-1)}$, effect of factor A when B is set at level +1/-1; $\overline{y_{A+/-(B\to+1/-1)}}$, average value of results of all combinations having factor A at level +/- and factor B at level +1/-1; E_{AB}, effect of interaction AB.

4.1.3 Comfort definition and "objective functions"

Introduction: comfort definition

Designing how to create a comfortable indoor climate is very complex. How to define what comfort is when this is completely? Many studies are ongoing on the understanding of the concept of comfort creating and calculating new indicators such as the Predicted Mean Vote (PMV) or Predicted Percentage Dissatisfied (PDD) that aim at scaling comfort perception and predict it[28]. Many factors such as air quality, sound and light levels are influencing comfort perception but, as part of this report, the focus is put on the thermal comfort. It depends on a large number of physical variables listed below:

- Ambient air temperature
- Mean radiant temperature of surrounding surfaces
- Relative air velocity
- Water vapor pressure in ambient

They all affect different type of heat transfers: convection, conduction, radiation (sensible heat transfers), latent heat exchange (condensation, evaporation…). Furthermore thermal comfort result as well of human factors such as clothing, metabolism, activity, etc... It is possible to analyze every single heat transfer and see to what extent each factor influence comfort perception but this cannot be performed as part of this work for time restrictions but also because financial budget cannot support the advanced results of such a level of investigations.

In this work things are really simplified and the focus is put on how to lower energy consumption more than on how to fully meet the ideal comfort requirements (as explained in paragraph 2.1.2 p.28, a high tolerance level is assumed as part of an ecologically aware lifestyle that naturally reduces energy consumption via heating and cooling demand reduction). Consequently the objective consists in minimizing both heating and cooling load with respect to a rather large temperature range of comfort. It is therefore important to be able to quantify both demands. BV² enables to calculate both heating and cooling demands from a set comfort temperature range (see paragraph 2.2.2 p.32 and Appendix 5 about BV²).

[28] See authors such as Bedfort, Fanger (about comfort perception measurement), Berglund, Wyon, Pepler, Johansson, Federspiel (about productivity loss)...

<u>Objective function 1: heating demand</u>

The comfort level is set to be above 20°C; this enables BV² to calculate a proper annual heating load (in kWh/m².year).

<u>Objective function 2, 3, 4 and 5: cooling demand</u>

Since base-case cooling system is set to be “natural ventilation” with windows airing (see paragraph 3.1.2 p.42), BV² cannot calculate a proper cooling demand that depends pretty much on the cooling system type. One has to find other indicators to be able to quantify the cooling demand. A high comfort temperature threshold of 25°C is virtually set and the following indicators will give information about cooling demand:

- Maximum indoor temperature during day time (8:00-18:00)
- Maximum indoor temperature during night time
- Numbers of hours above 25°C during day time
- Numbers of hours above 25°C during night time

It is important to remind that the climate file used by BV² refers to Torreon, located 50 km north of Leon. Temperatures in Leon are on average 2°C lower than in Torreon (see Table 2: Temperature comparison between Torreon (climate file) and Leon (project’s site) p.35). As a result, one should somehow pay a bit more attention on lowering heating load, which will be naturally higher in Leon, than on lowering cooling demand which is naturally lower in Leon.

4.1.4 Definition of factors and levels

Table 12: Definition of factors and levels of the factorial experiment

Factors		Low value (-1)	High value (+1)	Comparative example	Unit	Comments
Window type	X1	*Single glazed, basic non metal frame U= 5,3*	*Double glazed, basic non metal frame U=3*	*State-of-the-art windows, triple glazed U ≈1*	W/m².K	*See materials tables in Appendice, Minergie requirement U≤1,0*
Window size	X2	*Actual size -15%*	*Actual size + 15%*			*See base-case dimensions in part 2*
Shading	X3	*External shading*	*No external shading*			*BV2 enables to define a relation between shading degree and outdoor temperature*
Wall Uvalues	X4	*U=2*	*U=0,7*	*Low insulation with a 14cm thick brick wall, U=2,7*	W/m².K	
Roof	X5	*Non insulated, wood carpentry and roof tiles U_{roof}=5*	*Insulated with 5 cm polyurethane or 10 cm mineral wool U_{roof}=0,5*	*Eco-label Minergie, minimum roof insulation U ≤0,15*	W/m².K	*Minergie is valid and employed in France and Swiss climate conditions*
Hvac system	X6	*Natural ventilation (rather low airchanges, between 0,2 and 0,4)*	*Exhaust air system (hygienic airchanges between 0,4 and 0,8)*	*Common value in Swedish code for residential building 0,5*	ACH (air changes per hour)	*ASHRAE standards* requires a natural infiltration rate lower than 0,35 ACH*
<u>Note:</u> *Standards 62-89 from ASHRAE (American Society of Heating, Refrigerating and Air Conditionning Engineers)*						

In order to build the full 2^6 factorial experiments, factors and levels have to be chosen and defined. Choices and definitions are presented in the table above. They definitely present large variations in order to better see the impact, some values are somehow exaggerated but will be further refined afterwards.

Concerning wall U-values, for the sake of comparison, the high level i.e. high insulation (0.7 W/m².K) represents a level of insulation slightly lower than the worst insulation configuration in Sweden (U=0.5 W/m².K). The low level (2W/m².K) refers to very basic common and cheap wall configuration used in Mexico; low insulation quality.

Roof values are exaggerated and especially the low value (5 W/m².K). In Mexico, it is common to see such tiles "sloping roof" non-insulated at all. The levels are chosen to put the light on the benefits of insulating the roof even with cheap mineral wool layer.

About HVAC systems, the most likely option in the natural ventilation. Exhaust air system consists of adding a fan that sucks the air to the outside increasing infiltration rates. The original function of it is related to air quality more than energy efficiency.

4.1.5 ANOVA[29] analysis: consistency of the experiment and results

The resulting values of the 5 objectives functions for the 64 combinations of the full 2^6 factorial experiments are displayed in Appendix 10: Results of the full factorial experiment. When statistically analyzing results one should first check the consistency of the experiment and see how reliable it is. This can be made thanks to the analysis of the variance (ANOVA). This analysis has to be performed independently for each of the 5 objective functions. In this paragraph, only important results on consistency and factors significance are presented. Since the ANOVA theory is rather complex (actually entire books are written to explain it) only very general theoretical points are explained only to give an idea of the factors signification: no equation is presented[30].

Table 13: Main results of ANOVA

Objective Functions	R^2 (%)	R^2adj (%)	Significant factors by decreasing order of significancy [1]	Most significant interactions [2]
Heat load	99,9988	99,9832	X5, X4, X6, X1, X2, X3	45, 25, 24
Max daily indoor temperature	98,62	97,92	X3, X5, X2, X4, X6, X1	35, 32, 34
Max night indoor temperature	98,2549	97,3823	X3, X2, X5, X6, X4, X1	35, 34, 32
Hours above 25°C during the day	95,978	93,967	X3, X5, X2, X4, X6	35, 45, 23
Hours above 25°C during the night	96,0297	94,0446	X3, X5, X2, X4	35, 34
Comments:				
[1] *The order is based on the values of the 6 principal effects and whether a factor is siginficant or not is based on the "p-value" test (with a significance level of 5%, considering the "null-hypothesis")*				
[2] *If declared significant by the "p-value" test , only the 3 most significant interactions are reported by decreasing order of significancy*				

[29] Analysis Of Variance, with the Statgraphics software (see note [27] page **Fel! Bokmärket är inte definierat.**)

[30] See "Análisis y diseño de experimentos" by Humberto Gutiérrez Pulido and Roman de la Vara Salazar, Edition McGraw Hill, 2nd edition, January 2008.

R^2 and R^2_{adj}: consistency indicators

Respectively called “Coefficient of determination” and “Adjusted coefficient of determination” they basically represent the same information.

A regression model for the objective functions can be established from principal and interaction effects of the factors by a regression algorithm. The idea behind the R^2 is to evaluate to what extent the variability of the model (due to the only effects of the chosen factors) can explain the total variability of the results. In this case, Table 13 shows that the combined effects of the only 6 studied factors (X1 to X6) can explain at least 95% of the variability of each objective function (the different variability are quantified by the so-called “sum of squares”).

It is commonly approved that the R^2 of an experiment should not be below 70%, that above 80% the experiment is rather acceptable and consistent and that above 90% the experiment is completely reliable and well-designed.

In order to give a good explication of what they mean, one can express what a low R^2 would signify (below 70%):

- The effects of chosen factors cannot explain by themselves more than 70% of the total variability of the experiment results; some other very influencing factors have certainly been forgotten.
- The chosen levels of the factors are too closed to each other and consequently the effect of changing factors from low to high level cannot be seen correctly.
- Other factors than the studied ones did not remain stable enough and resulted in increasing the total variability.
- Experimental errors and measurements are really significant.

Points 3 and 4 do not make real sense in this case since experiments and measurements are fully simulated by the BV^2 software. Very high R^2-value confirm that the way factors and respective levels have been chosen is definitely consistent, that BV^2 software is very reliable and provides consistent results (i.e. the calculations performed by BV^2 are consistent).

Note: The Adjusted-R^2 takes into account the sample size and the phenomenon of “statistical shrinkage”; the values are displayed mainly to the attention of experimented and careful readers. However in this report a basic use of R^2 is considered as meaningful enough to draw relevant conclusions on consistency.

4.1.6 Results and physical interpretation

Table 14: Main estimated effects summary

		Window type	Window size	Shading	Wall Uvalues	Roof insulation	HVAC system	
		X1	X2	X3	X4	X5	X6	
Low value		Single glazed non metal frame (Uvalue= 5,3)	actual size - 15%	no Exterior shading	2	non insulated (U_{roof}=5)	Natural ventilation	
high value		Basic non metal frame Double glazed (Uvalue=3)	actual size + 15%	Exterior Shading	0,7	Insulated with 5 cm polyurethane or 10 cm mineral wool (U_{roof}=0,5)	Exhaust air system	
	Unit	**Effects of changing factor from level -1 to level +1**						**Most significant interaction**
Heat demand	kWh/m².yr	-16,9063	-12,2188	2,71875	**-43,7188**	**-140,344**	20,8438	3,71875
Indoor max temp. Day	°C	0,240625	0,665625	**-2,71562**	0,534375	**1,16563**	0,446875	-1,10937
Indoor max temp. Night	°C	0,196875	1,15938	**-2,87813**	0,384375	**1,07188**	0,559375	-1,13437
Hours above 25°C Day	hrs	**31,7813**	103,594	**-335,594**	83,2813	**194,906**	44,6563	-167,406
Hours above 25°C Night	hrs	**39,0313**	201,344	**-693,344**	165,969	**361,719**	**-5,28125**	-332,094
Legend:								
Legend:	*Most significant interaction*							
Legend:	*Declared unsignificant by first "p-value" test (more refined "p-value test" might remove other factors but original test in regarded)*							

With 6 factors, 6 principal effects and 15 interaction effects can be analyzed. As presented on Table 13 p.57, not all of them are however significant enough to be specifically considered; the so-called “p-value” test enables to evaluate the significance of an effect. With a 5% confidence level (common standard value) some effects are statistically considered as insignificant and are therefore left aside. Furthermore, although the significant interactions are ideally important to consider and interpret, it has been decided that only the most significant one will be considered and taken into account in this analysis since it is only supposed to roughly “orientate” the design trajectory. All the effects are listed in the following table.

<u>Comments and results from the observations of the objective functions</u>

On the 3 so-called “Pareto” charts below effects of changing level from -1 to 1 of the 6 factors for every objective functions are compared. It is then possible to clearly determine which factors influence the most and to what extents. Afterwards some interpretation comments are given and ordered by focusing on each factor.

- *Heat demand*

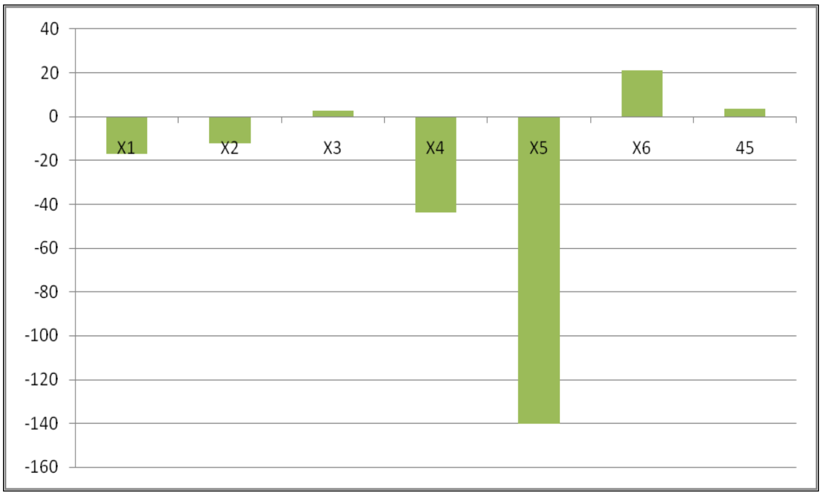

Figure 4-1: Pareto chart for heat demand (kWh/m².yr)

X1,window type - X2, window size – X3, external shading – X4, wall insulation – X5, roof insulation – X6, HVAC system - (more details in Table 12p. 56 and Table 13 p. 57)

Heat demand is drastically reduced by insulating the roof and one can see the significant thermal benefit of simply adding an insulating layer. The wall insulation also appears to be of significant interest in decreasing the heat demand. Increasing window size (+35% from low to high level) reduces somehow the heat demand, this can be further enhanced if window enlargement is made on the south façade and since the interaction 12 (X1 and X2) is rather low (but still considered significant, see Table 13 p.57) the result remains valid for both window glazing types.

It is interesting to notice that installing an exhaust air system with higher air change rate than natural ventilation (infiltration and windows airing) significantly increases the heat demand. Of course the rate can eventually be monitored depending on the indoor/outdoor temperature relation over the year but it requires higher financial investments.

- *Cooling demand*

Both Figure 4-2 p.61 and Figure 4-3 p.61 are related to what is called “cooling demand” (divided into 4 objective functions defined in paragraph 4.1.3 p.55). From the point of view of the thermal wave theory and as a response to thermal variations (with a 24 hours frequency), they give interesting information about thermal behaviour of the building envelop; respectively about temperature magnitude response and time-related temperature response (time-delay).

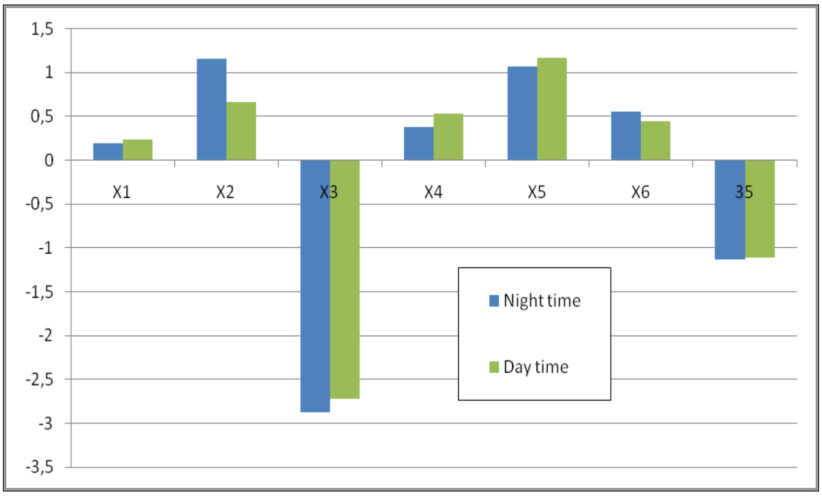

Figure 4-2: Pareto chart for maximum indoor temperature (day and night time, °C)

X1,window type - X2, window size – X3, external shading – X4, wall insulation – X5, roof insulation – X6, HVAC system - (more details in Table 12p. 56 and Table 13 p. 57)

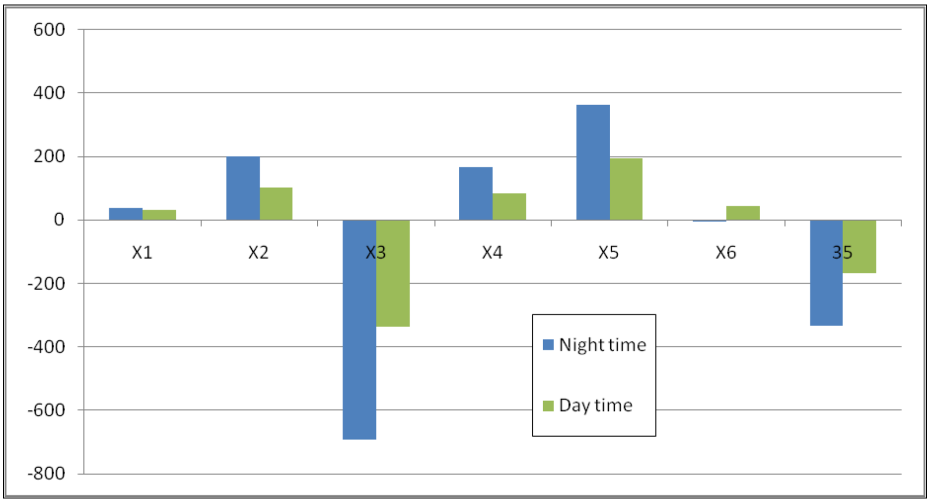

Figure 4-3: Pareto chart for number of hours with indoor temperature above 25°C (day and night time, hours)

When it comes to cooling demand, exterior shading appears to be determining and globally reduces indoor maximum temperatures of more than 2,5°C (during both day and night times). Most of the other factors that have the ability to reduce heat demand (see Figure 4-1 p.60) simultaneously increase the maximum indoor temperature and the numbers of hours of over comfort threshold temperatures i.e. the potential cooling demand. One might therefore look for a balance to both minimize heat demand and minimize cooling demand; external shading definitely works in that sense.

- *Inertial thermal effect*

Comparing Figure 4-2 p.61 and Figure 4-3 p.61 might enable to visualize the effect of thermal inertia. Those effects are commonly designated as "damping effect" and are due to the high thermal mass of building envelop. According to the thermal wave theory, outdoor temperature variations can be considered as thermal excitement of the building envelop with a 24-hours frequency approximately (even if this changes with the seasons). This excitement creates thermal wave that goes through the walls and finally results in heat transmission flux variations and, as a result, in indoor temperature variations.

Thermal wave theory is complex and this paper does not aim at explaining the theory but giving certain general ideas. Damping phenomenon induced by the ability of a wall to store heat (heat capacity) presents two aspects: it levels off the magnitude of the thermal wave while crossing the building envelop inwards (thermal losses at the top and bottom of the wall) and introduces a time delay between outdoor and indoor variations on the other hand. Magnitude and delay can be analytically related to our objective functions: maximum indoor temperature (day and night) and periods with indoor temperature above 25°C (day and night) respectively. They are further underlined thanks to the set decoupling day and night times. Effect during day time correspond to the thermal wave's peak at the external side of the wall (maximum outdoor temperature and inward heat fluxes) and effect during night time to its valley (low temperature and heat fluxes); being able to decouple day and night time will help drawing conclusions about time delay and magnitude enfeeblement. One also should remind that, since internal heat generation fluxes is much lower than solar radiation fluxes (respectively 30W/m² as peak value as calculated in paragraph 3.4.2 p.49 against approximately 1000 W/m² during day time) and over a long period of time in a year, indoor temperature variations can be almost exclusively allocated to solar heat gain.

It can be seen that the decoupling (difference between the effects during day and night time) is much clearer when it comes to time considerations (numbers of hours above 25°C) than it is regarding thermal magnitude variations (maximum indoor temperatures). This definitely emphasizes the characteristics of inertial effects. One can first notice that indoor peak temperature is very similar for day and night time (the average values for the 64 combinations are 28.13°C and 28.3°C for day and night time respectively). This means that indoor peak temperature takes place around 18h or 18h30 (time threshold between day and night time), which is much later than the actual outdoor peak temperature (around 13h): damping delay is equals to 5 to 6 hours. Furthermore when it comes to the time periods of indoor temperature higher than 25°C (Figure 4-3 p.61), the decoupling is much clearer; periods are much longer during night time than day time. This definitely expresses the consequences of magnitude damping and time delaying effect of high thermal mass in the walls. More quantitative conclusions would require more specific measurements.

Comments and analysis by "factor":

After having analyzed the results and drawn conclusions about the objectives functions; it appears interesting to take look at those results factor by factor.

- *Window type X1: not energy significant factor*

Although levels are set really far from each other (U-Values of 5.3W/m².K and 3 W/m².K for low and high levels respectively), windows type effect is generally rather low compared to the others and, according to Table 13 p.57, is not involved in any significant interactions. An investment for double-glazed windows (rather significant) doesn't seem to be justified at first sight.

- *Window size X2: the actual design seems rather consistent*

The enlargement of global window surfaces results in significant heating savings but simultaneously in higher maximum indoor temperatures and longer periods above 25°C. An intermediate value such as the originally designed one seems to be fair enough.

However it will be seen that, if minimizing heating demand is set as being slightly more important than minimizing cooling demand (due to the fact that project's site average temperature is lower than the climate file site), the multiple response optimum recommends the low level i.e. small windows (see paragraph 0 p. 67).

Heat transmission through a wall or a window is a sum of different heat transfer modes: conduction, convection and radiation. For equivalent U-values (equivalent conduction rate), the "radiation" coordinate of global heat transmission rate is definitely higher for windows than for walls, other coordinates remains more or less equal. It is why larger windows allow reducing heat demand but it also explains the significant interaction between external shading and windows size. If solar shading already reduces drastically solar radiation, window size no longer has a large impact on heat transmission and the difference between a wall and a window is no longer significant.

Thus it appears that windows size is not a prior parameter to think of and especially if external shading is used. However one should keep it mind that windows size can lead to significant impacts on construction expenditures.

- *External shading X3: very cost-efficient investment*

This factor appears to be one of the most energy efficient that can be made (this is not a surprise). Indeed, one can see that while most of favorable factors for heating demand are unfavorable for cooling demand or vice-versa, external shading rather slightly affects heat load but tremendously decreases maximum indoor temperature (-2,5°C on average) and durations of periods with indoor temperature above 25°C (-500 hours on average). Off course one could think that using external shading on the north face windows would be a shame since it affects the really nice view on the Sierra but shading has been differently set on north face (where view is of interest) and on south face (where complete shading is important). The settings refer to a "partial" shading of the "awning type" on the north face (mainly blocks beam radiation but does not affect the view) and vertical shading on south face (blocks both diffuse and beam radiation).

Furthermore, shading is involved in rather significant interactions on cooling demand. Interaction n°35 with factor X5 i.e. roof thermal insulation is the most significant one; as such its analysis is performed p. 65 and may also exemplify the definition of the effect of an interaction and why some of them are important to be carefully considered.

As conclusion about factor X3, the use of solar external shading is definitely recommended since it shows very significant energy advantages and does not represent a big investment.

- *Wall U-value X4: a better insulation has a mitigated effects in Mexican climate conditions*

As a reminder, low and high levels of this factor are respectively set to 2W/m².K (low insulation corresponding to a common value for Mexican building) and 0,7W/m².K (better insulation but slightly worst than an energy inefficient building in Sweden).

A better insulation clearly reduces the heat demand as supported by Figure 4-1 p.60; changing wall U-value from low to high level reduces approximately the heat demand of 43 kWh/m².year, a significant value if compared with average heat load of all 64 permutations that amounts for 116 kWh/m².year; it helps keeping heat inside the building (and especially during winter time). However a good insulation (i.e. a low U-value), during summer high temperatures, also limits the heat losses through the building envelop and this results in a relative increasing of the cooling demand; it is well illustrated on both Figure 4-2 p.61 and Figure 4-3 p.61. This effect is even enhanced when the temperature difference between the indoor and outdoor is relatively low (which corresponds to a quite large period of time in Mexico); a low U-value and low driving force logically leads to very low heat transfer through the walls. Then the inside temperature goes up, "fed" by internally produced heat. Such a design is very suitable in cold climate since it tends to retain in the inside every single internal heat gain; from both internal generation (fireplace, kitchen...) and solar radiation through windows for example. Consequently it appears that a low U-value doesn't fit very well to this case because of warm climate conditions where cooling is more often required than heating. On the other hand, a too bad insulation (i.e. high U-value) would require a high and expensive heat production during cold winter time, especially nights when temperature often fall under 0°C and a constant natural ventilation during summer even with a high thermal mass that delays the inward heat diffusion.

From Table 13 p.57, one can notice that the interaction with external shading (n°34) is rather significant when it comes to the 4 indicators of cooling demand. It will be discussed below.

- *Roof U-value X5: great energy of even a basic and cheap insulating layer*

Basic insulation of the roof with a thin layer of insulating material as mineral wool underneath the tiles tremendously reduces the heat demand by approximately 140 kWh/m².year (43 kWh/m².year for wall insulation). It however increases the cooling demand (maximum indoor temperatures are lifted up of approximately 1°C and the periods of indoor temperature above 25°C are also extended, especially during night time; almost 400 hundred hours i.e. more than 2 weeks). Such a structure of the roof with roof tiles, air gap and insulating layer presents good performances because it enables better ventilation rate than a layer of concrete and tiles.

See also the interpretation of the interaction 35 p.65 that further informs on effects of roof insulation

- *HVAC system X6: no need for expensive exhaust air system*

The main difference between the natural ventilation system and the exhaust air system is that infiltration rate is naturally driven in one case and controlled/forced in the other one. The latter system maintains indeed a minimum rate called "hygienic rate" at a higher level than the naturally driven flow rate (leakages, infiltrations, natural ventilation).

As it appears on Figure 4-2 p.61Figure 4-3 p.61, the exhaust air system leads to increasing both heating and cooling demands. Due to this maintained air mixing, indoor temperature tends to more closely follow outdoor variations and happens to even deviate from the comfort margin. This becomes an evident energy issue during winter and summer time, when outdoor temperature gets out the 20°C to 25°C range. Of course a monitored fan would be much more appropriate and indoor air quality would get improved but such a performing exhaust air system requires rather large investments costs (as well as variable costs such as maintenance, energy supply…) that apparently do not seem crucial in this context. Furthermore such a monitored system principally stands as counteracting effect for the usage of the thermal masses in the walls (acceleration of heat storing and releasing processes by greater convection), this usage has anyway been previously accepted and declared appropriate.

According to the "Weatherization"[31] article of ASHRAE Standards [32], an exhaust air system remains recommendable if infiltration rate is below 0,35 ACH (air changes per hour), for air quality reasons. This supports the fact that, if the investment related to an exhaust air system is not considered worth enough, a careful attention will have to be put on natural ventilation and air-change rate for comfort interests.

- *Interaction 35: the performance and pertinence of external shading*

It concerns external shading and roof U-value. Likewise the interaction between external shading and wall U-value seems also important. One can suppose that the involved physical mechanisms are rather similar for both interactions. Therefore one may extrapolate the interpretation of the interaction plot below to a sort of global interaction between external shading and the insulation level of the whole building envelop (see Figure 4-5 p.66).

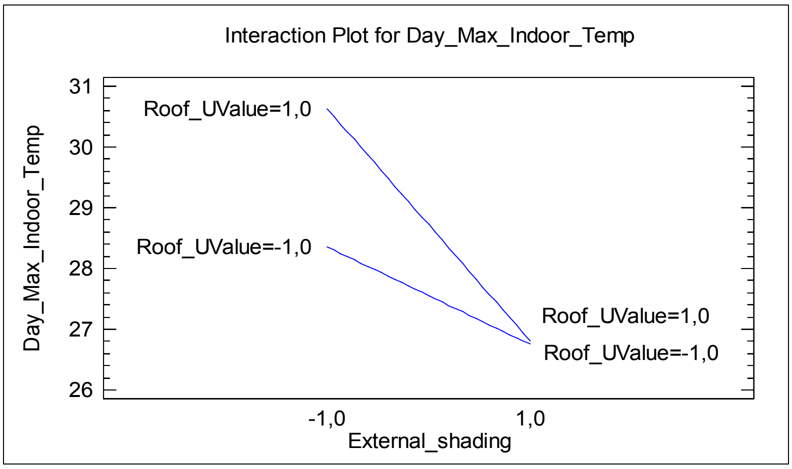

Figure 4-4: Interaction plot for day maximum temperature (°C): external shading and roof insulation

[31] Weatherization: practice of protecting a building and its interior particularly, from sunlight, rain and wind.

[32] ASHRAE (American Society of Heating, Refrigerating, Air Conditionning Engineers) Standards, available for purchase as downloadable Digital Publications (PDFs), hard copy, or CD-ROMs in ASHRAE Online Bookstore at http://www.ashrae.org/publications/page/1285.

The effects of this interaction on all the 4 cooling demand indicating variables present the same form. As an example, the effect of interaction 35 on day maximum temperature is illustrated below.

As shown on the graph, the effect of insulating the roof (from low to high level of “roof U-value”) is much more significant without external shading (level -1) than with (level 1). Another way to say it is that, if external shading is used, the roof U-value is not of great influence and changing its level does not affect very much the cooling demand. Extrapolating this to global insulation of the house (Figure 4-5 p. 66 shows that interactions between external shading and both roof and walls U-values present the same shape) enables drawing crucial conclusions.

It has been seen when looking at results by factor that decreasing building envelop U-value, i.e. increasing insulation level, i.e. changing factors 3 and 4 (wall and roof U-values) from low to high level, leads to decreasing significantly the heat demand but unfortunately also increases the cooling demand (indoor maximum temperatures and periods indoor temperature above 25°C). As a result and if one only consider principal effects, the decision about whether to well insulate or not was not easy to make (keeping the implied high investment in mind). However, in the light of this interaction analysis, it can be concluded that external shading, that already shows very interesting principal effects on cooling demand, presents the other advantage of drastically attenuating the undesired effects of insulation on cooling demand without preventing it from reducing heating demand.

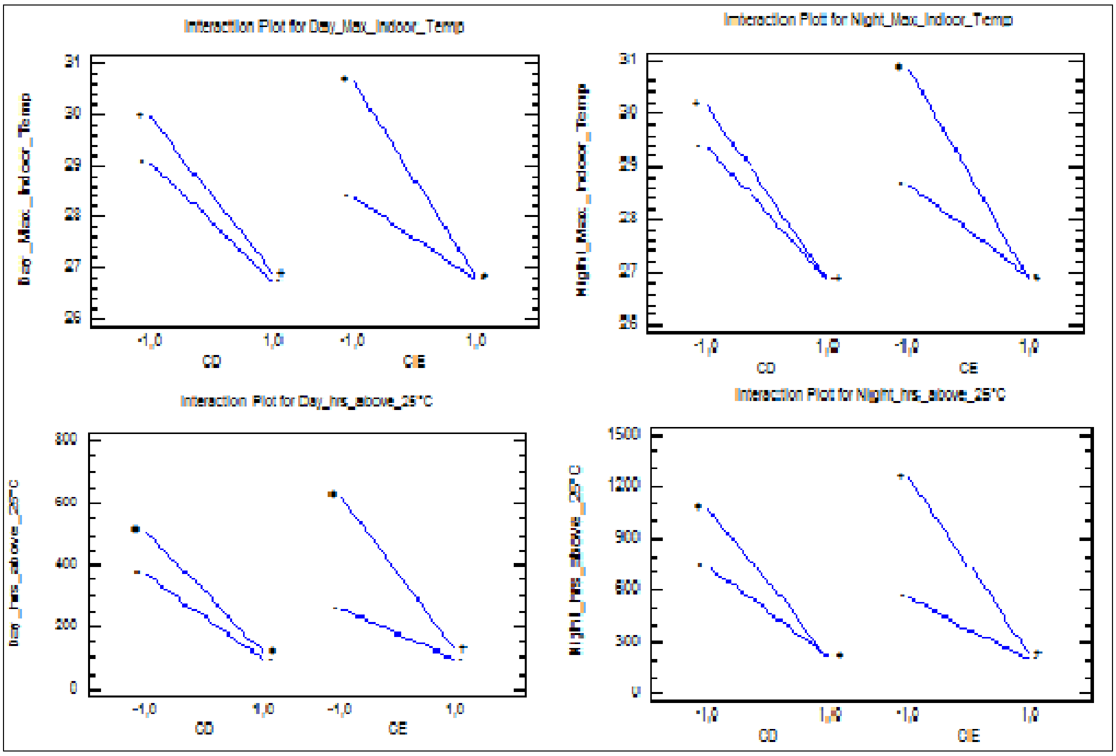

Figure 4-5: Shape of interactions between external shading (factor C) and envelop insulation (Wall U-value: D and Roof U-value: E)

This interaction analysis example points out the importance of taking a look at interactions and trying to understand them; it may lead to new important significant conclusions

4.1.7 Multiple response optimization

Introduction

The multiple response optimization is a theory that has been continuously developing for the last 40 years. Various approaches exist but today the most widely used is the "desirability approach" and this is the one used by Statgraphics' software. The optimization is based on the maximization of a desirability function. First the optimization is made for each objective functions separately, the desirability function, that goes from 0 to 1, represents how desirable is the response of a given combination of factors. In our case, every objective function is to be minimized since the objective is to reduce both heating and cooling demand (but an objective function can either be minimized or maximized or maintain at a set value). In this case, the desirability function is defined as follows:

$$d = \begin{cases} 0 & , y > high\ value \\ \left(\dfrac{y - high}{low - high} \right)^s & , low\ value \le y \le high\ value \\ 1 & , y < low\ value \end{cases}$$

With d, the desirability function; low/high values ,limit values that the response can take; y, response value; s, factor that affect the shape of the desirability function traducing the importance of getting close to the objective or not.

If s=1, the function d(y) decreases linearly from 1 to 0. If s>1, the function increases very fast at first when response values are high (close to high, not desired values) and then levels off when response comes closer to the low value. If s<1, the desirability increases very slowly when values are high and then speeds up when response get closer to the objective low value. It is therefore possible to decide whether it is very important to be close to the objective, then a large s-value is set or not.

Once each objective function has been optimized, a global desirability is calculated; it represents a geometric average of each desirability value and it is possible to set some impacts (sort of "weights") to take into account that some objective functions, i.e. some responses might be more important than the others. The global desirability is calculated as follows:

$$D = \left(d_1^{I_1} \times d_2^{I_2} \ldots d_N^{I_N} \right)^{1 / \left(\sum_{i=1}^{N} I_i \right)}$$

With D, global desirability function; d_i, desirability of response i; I_i, impact of response i; N, number of responses.

Optimal combination, optimum, impacts and performances

In this paragraph, the optimization process is performed step by step evaluating different cases. All the results about performances and combinations are presented at the end of the paragraph, Table 15 p.69.

- *Case n°1: what permutation out of the 64 tested is the most desirable?*

In this first case, all 5 objective functions are set to have equal importance. It has been first intuitively suspected and further confirmed thanks to Statgraphics that combination n°29 is the most desirable. It consists of simple glazed windows of small size, insulated walls and roof, using external shading and with natural ventilation.

In Table 15 p.69 one can notice that the established regression model give rather satisfying predictions. However, for both models, "day and night numbers of hours with indoor temperature above 25°C", predicted results are rather far from the experimental ones. This goes in accordance with the consistency results (R^2 given in Table 13 p.57). Indeed the coefficient of determination for these two objective functions happen to be the lowest ones, they somehow explain the large error of the models.

- *Case n°2: "weighted responses" and "ideal optimum"*

The definition of the objective functions (see paragraph 4.1.3 p.55), originally consists in minimizing both heating and cooling demand. Heating demand can be expressed and quantified as such by BV² software but cooling demand had to be evaluated by the mean of 4 indicators, the other 4 objective functions. It is consequently logical to allocate different "weights" to the functions; for instance, ½ for heating demand and 1/8 for each of the four others, in order to put the same importance on heating and cooling demand. The idea of weights is expressed through the concept of "impacts" when it comes to multiple response optimization (see above the introduction of multiple response optimization). Impact value can go from 1 to 5, therefore putting the same importance on heating and cooling would be result in impact values of 4 for heating demand and 1 for the 4 cooling demand responses.

Nevertheless, it has already been mentioned that a bit more importance should be put on how to minimize heating demand than cooling demand since the average temperature of the actual site is a bit lower than the average temperature of the climate file's site used by BV² (see paragraph 2.3 p.32). Finally an impact of 5 is allocated to heating demand and impacts of 1 for all other functions.

Looking at the table below, one can be surprised that although optimized value of a factor can take any values between level -1 and level 1 in order to ideally optimize, one can see that the optimum combination only takes limit values and correspond to an existing combination: combination n°30. Combination n°30 is the same as n°29 but with the better insulated window (double glazed). It makes complete sense since it is an optimum that traduces higher interest in minimizing heat demand, i.e. lowering heat losses, improving insulation. This combination corresponds to insulated envelop (windows, walls, roof), with external shading, and natural ventilation system.

Table 15: Results of Multiple response optimization (from Statgraphics)

Responses		*Case n°1*			*Case n°2*		
	Unit	*Impacts*	*Observed*	*Predicted*	*Impacts*	*Observed*	*Predicted*
Day_hrs_above_25°C	hours	1	53	85,1563	1	53	138,594
Day_Max_Indoor_Temp	°C	1	26	26,3094	1	26,5	26,6656
Heat_demand	kWh/m².year	1	26	26,5938	5	15	14,9688
Night_hrs_above_25°C	hours	1	80	138,844	1	80	152,719
Night_Max_Indoor_Temp	°C	1	25,5	25,8531	1	25,5	25,9531
Desirabitily observed	-	0,984049			0,97476		
Desirability predicted	-	0,952739			0,951566		
Factors	**Window type**	**Window size**	**External Shading**	**Wall Uvalue**	**Roof insulation**		**HVAC system**
	X1	X2	X3	X4	X5		X6
Low value	Single glazed non metal frame (Uvalue= 5,3)	actual size -15%	no Exterior shading	2	Non insulated (U_{roof}=5)		Natural ventilation
High value	Basic non metal frame Double glazed (Uvalue=3)	actual size +15%	Exterior Shading	0,7	Insulated with 5 cm polyurethane or 10 cm mineral wool (U_{roof}=0,5)		Exhaust air system
Combinations	X1	X2	X3	X4	X5	X6	N°
Case n°1	-1	-1	1	1	1	-1	29
Case n°2	1	-1	1	1	1	-1	30

See case n°1 and n°2 above for more details.

One should notice that in both cases, desirability function (whose maximization is the base of the multiple response optimization algorithms) takes really high value above 95%. Desirability is a bit higher for observed results than for model-based ones (predicted ones). This is rather positive since the energy results of BV² take all other parameters into account and are therefore closer to reality than the predicted results based on the statistical regression model established by Statgraphics and restricted to the only 6 chosen factors.

4.1.8 Statistical analysis conclusions

Consistency of the experiment design

The full factorial 2^6 design completely fulfilled its original objectives. The ANOVA analysis confirmed that the choice of factors and levels is relevant and successfully gives a basic idea of the thermal behaviour of a building; it also confirms the reliability of BV² software that provided consistent results. Of course a much more experimented and refined use of Statgraphics could have been achieved for further details and discussions.

Principal effects and interactions

The analysis of main interactions traducing the effect of external shading on wall and roof U-value resulted in modifying the conclusions related to their effect as single factors. The interaction analysis showed that insulated walls and roof U-values are recommendable.

This shows how important it is to take into consideration the significant interactions when analyzing an experiment design.

Multiple response optimization

As a result of the multiple response optimization performed by Statgraphics, the optimum combination regarding the different objective functions and the way they have been weighted is an already tested combination (i.e. one of the 64 tested as part of the full factorial design): combination n°30, presented under case n°2 in the table above and in the beginning of paragraph 0 p.67.

4.2 "Physical" conclusions

4.2.1 High thermal masses and inertial effect

In these specific climate conditions, where day temperature can be very high and night temperature very cold, the usage of high thermal mass makes full sense and this is logically supported by BV^2 that clearly shows the drastic increase of both heating and cooling demand when lowering the mass of the building.

Furthermore this important conclusion fits perfectly with the fact that thermal heavy building material can be purchased or extracted directly on site (stones, compacted earth, adobe or brick work). A good environmental aspect is pointed out.

4.2.2 Investing in insulation

The multiple response optimization recommends to invest in double-glazed windows and rather well insulated walls and roof. Of course the double-glazing didn't appear very significant at first but this conclusion fits with a common rule of thumb, well widely accepted that consists in trying to give a certain uniformity in the insulation of the whole building envelop. For example, investing in very well-insulated triple-glazed windows doesn't make any sense if the roof is very badly insulated; interactions play again an important role.

It is important to mention that such U-Values can be reached easily by adding cheap insulating layer such mineral wool or polyurethane; 30 cm natural stones insulated with 7 cm of mineral wool leads to a U-Value of 0,7 $W/m^2.K$. However, according to BV^2, further improving insulation gives rise to heat demand decrease but also important increase of cooling necessity, unless a better and more expensive ventilation system is purchased. The values for roof, walls and windows appear reasonable in that sense.

4.2.3 External shading

External is definitely a great way reduce the cooling demand during warm summer temperature and sun radiations through windows. If well-used it can be removed so that solar heat gains through windows help heating the indoor during winter time. Its cost efficiency is definitely justified in this case since it doesn't represent a high investment. Appropriate shading types have to be implemented to respect the esthetic value of a large north facing windows and also fulfill its thermal function ("awning" type on the north facade to enable enjoying the nice view and vertical type on south facade to efficiently shade the strong summer solar radiation.

4.2.4 Small windows

In order to practically validate the usage of rather small windows, a refined analysis seems necessary including financial aspects. It depends also pretty much on the way the shading is monitored (as illustrated by the analysis of interaction 35, p.65). This constitutes a very interesting point to be analyzed from the "domotics" point of view (see Appendix 1: What is "domotics").

4.2.5 HVAC system

Even without taking the financial aspect of investing in an exhaust air system, the results show that a rather good comfort can be obtained with the only natural ventilation, infiltration. Off course a good attention has to be paid to the infiltration rate that should be high enough without being an obvious source of heat losses, to the level of Weatherization (see note [1] p.65). A bad harmonization of it can lead to undesired air quality and indoor comfort or to the need of better HVAC system.

4.3 Limits and recommendations for the continuation of the project

4.3.1 The interest for "domotics" field

A further investigation, refining can be performed to better know the opportunities offered by domotics systems (see Appendix 1: What is "domotics"). Indeed, monitoring of windows airing, natural ventilation, external shading might have a very interesting influence on thermal behavior of the house as well as carrying an important educative value for the knowledge transfer and the promotion of ecological concepts.

4.3.2 A further physical refining of other design parameters

Only 6 parameters have been roughly evaluated and analyzed. Off course taking a look at the effect and influence of other parameters would enable to further energy-optimize the design.

4.3.3 Investigation and inclusion of financial data

All the results and previously drawn conclusions still have to validated and supported by the main restriction of such a project: the financial restriction. To do so, an exhaustive and time-consuming investigation about prices, costs, suppliers, financial sponsoring has to be achieved. This appears as the most important part to carry out before deciding on the final design of the prototype.

5 Electricity supply system

5.1 Generalities

From the evaluation of potential natural resources and according the limited budget available to buy and design the renewable power supply system, it has appeared since early stages that the potential hydro energy delivered by the water reservoir just above the house (see paragraph 2.3.1 p.33) was not worth according to energy and financial aspects. The system will be hybrid solar and wind power.

The combination of solar and wind energy in such an hybrid system presents the main advantage of reaching an acceptable level of reliability and energy security that only solar or only wind definitely cannot reach when used alone. Indeed the climate data of the region shows that wind velocities are higher during winter time when solar radiation is lower and somehow lower when solar radiation. Same phenomenon occurs as well in single day time: wind usually blows more during night when earth surface cools down than during day, when the sun shines. Since peak wind velocities and solar radiation generally occur at different times, both energies can compensate each other and consequently the hybrid solar/wind system can balance out major critics made about wind and solar power taken separately and produce energy on a rather constant basis.

5.1.1 Description of an hybrid system and general notions

The use of such a rather small-sized system, is usually made in very remote places where no connection to the power grid is possible (one can find bigger systems closer to the grid since extra energy is sold to the grid and make the investment more cost-efficient). A common scheme of such a system is presented below.

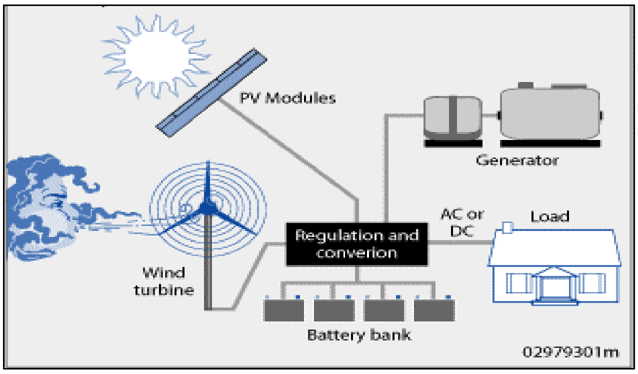

Figure 5-1: Scheme of a hybrid solar/wind power system in a remote place

In the project case, the back-up role is not played by a generator but the grid itself since a connection is assumed feasible and unavoidable.

Solar panels

The solar panels are made of photovoltaic cells that convert solar radiation (photons energy) into electricity (electrons motion), direct current. The panels can be connected either in series or in parallel. The first option enables a higher voltage out of the solar module (voltages) but is more exposed to power drop due to radiation variations.

Indeed, the voltage of one panel does not vary significantly with the radiation but current intensity does as shown on the figure below.

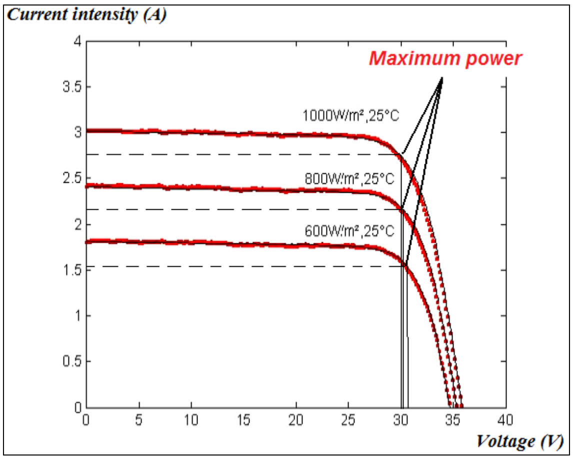

Figure 5-2: Current/voltage characteristic of a solar module for various solar radiation levels

For 3 different solar radiation levels, it appears that nominal voltage (which corresponds to nominal power for a certain radiation level) remains rather constant, the intensity varies a lot. As a result, if a temporary shadow affects the radiation on one panel, its current intensity drops down and decreases intensity of the entire module. This phenomenon does not affect panels mounted in parallel. In this configuration, the module produces a higher current intensity but at a lower voltage. Electrical characteristic depends very much on connection configuration of the panels, PV cells type...

Wind turbine

The electricity production of a wind turbine is very difficult to predict and varies significantly. Therefore the dimensioning process of the whole hybrid system considers wind energy only as an extra capacity. It is used to recharge bank of batteries when needed and is often automatically disconnected when not needed.

Wind generated electricity is under alternative form (AC) while batteries are charged and discharged with direct current (DC). This usually requires a specific regulator/convertor for wind generator. It is commonly implemented between the turbine and the bank of batteries.

The figure below represents the usual base curve to very roughly predict how much electricity can be produced by a wind turbine in certain climatic conditions.

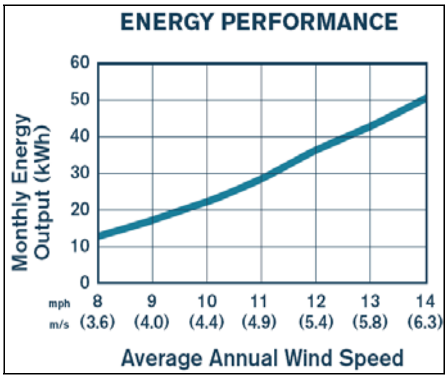

Figure 5-3: Wind velocity/electricity production characteristics for a specific wind turbine[33]

Such a characteristic is provided by the supplier and depends very much on the turbine size, type... Since it is based on rough approximation, it also has to be carefully considered.

Regulator (or charge controller)

This device is essential to monitor charge and discharge cycle of the bank of batteries and contributes to its longer life time and efficiency. Often one regulator is required for each current type (AC for wind and DC for solar). However, some hybrid regulators exist and achieve wind and solar current regulation, wind-generated current conversion and charge/discharge of batteries according to supply/demand constant comparison. A display function enables checking instantaneously batteries state of charge, electricity production rate, electricity demand... This function, which is not always available, is very interesting and fits perfectly with the initial educational objectives. It is also part of the development of “domotics” concept (see Appendix 1: What is “domotics”).

Batteries

They also can be connected either in series or in parallel. The series version allows higher voltage to the convertor but lower energy capacity. The parallel connection allows better uniformity in the use of every battery and usually higher capacity, i.e. longer autonomy for the system. It however delivers a lower voltage.

Batteries accept and deliver direct current DC. The different types of electrolytes and electrodes mainly influence longevity performances and maintenance requirements; in the case of a small-sized system as the one presented, longevity goes from 3-4 years for basic acid-plumb ion batteries to 10 years for more advanced one.

Various and advanced considerations about voltage and current evolution with charge state are of relevant importance but will not described in this report.

Batteries have to be considered as a way to level off energy production since wind and solar electricity production are very variable, they present peak and low production rates that neither coincide with each other nor with electricity demand peak and low periods. They both level off wind and solar production side and also enable harmonization with demand side.

[33] See technical fiche of hybrid system components in Appendix

Convertor (or inverter)

The convertor converts direct current from the bank of batteries into alternative current usually used for domestic equipments. The alternative current delivered by the convertor can be of different wave forms: square, semi-sinusoidal, almost sinusoidal or pure sinusoidal. Usually convertors of small application deliver semi-sinusoidal wave forms. Its size will determine how many pieces of equipment can be connected to the hybrid-system simultaneously. Some convertor can also monitor the grid connection but usually of much higher investment cost, higher capacity and would require a much larger solar installation to be cost-efficient.

5.1.2 Theoretical dimensioning calculations, applied to the thesis case

Preliminary comments

Several reports and studies have been achieved about how to optimize the design of a hybrid system. Some of them are very advanced and were complete PhD thesis. This means that optimizing and dimensioning a hybrid system is not a simple task. It ideally involves various parameters and requires multidisciplinary analyses:

- accurate energy models for solar and wind generation;
- accurate electrical analysis for losses and electrical components harmonization;
- accurate statistical approach for wind velocity and solar radiation previsions;
- financial optimizing algorithm;
- …

Such an accurate analysis is not performed in this project due to time constraints and wider objectives. However, since the design of the hybrid system is part of this work, very basic principles and results are presented in order to give a general idea of how to roughly dimension such a system. Project specific conditions are assumed for the dimensioning process.

Two types of approach are possible to roughly dimension a system: budget limiting dimensioning or PV-surface limiting dimensioning. In the case of this project, important financial restrictions highly affect the system design. Basic calculations enable to roughly evaluate what size of panel is required, what battery capacity is necessary to reach autonomy objectives... Main principles, equations and results are explained in the next paragraph.

Since the prototype is designed with a strong ecological educational perspective whose main idea is to exhibit several ecological technologies, it has been decided that both wind and solar energy will anyway be implemented. This avoids a certain number of questions to solve during analysis and design processes. However basic linear programming calculations with parameters such as potential resources data, investment costs, maintenance costs, expectable life times, financial budget, discount rate, economic growth rate can be performed to maximize energy production and determine the optimal energy mix. Since already strong factors such as the decision of having a hybrid system anyway, a limited range of options of wind turbine size (see paragraph 5.2 p.80) and uncertainties about climate data already affect the project, it has been decided not to perform these calculations; the results would certainly not be of relevant interest.

As previously mentioned and also illustrated in paragraph 5.2 p.80 very limited range of option concerning wind turbine sizing was available since 2 out of the 3 companies recommend the same wind turbine. Consequently only the solar part of the system has to be dimensioned, since wind turbine size and production rate was somehow imposed.

Basis parameters

To perform those dimensioning calculations a certain number of parameters about electricity demand, natural resource potentials, system specificity and objectives are required. They are presented/reminded in the following table.

Table 16: Preliminary parameters for basic dimensioning calculations for solar part of the system

Designation	Preliminary parameters	Values
D *(demand)*	*House consumption (kWh/year)*	1100
R *(radiation)*	*Solar radiation (kWh/m².year)* [1]	1978,3
α	*Solar conversion factor* [2]	0,13
P (price)	*Price of m² solar panel (pesos/m²)* [3]	9600
l *(losses)*	*Losses factor (storage, transmission, conversion)* [4]	0,6
A *(autonomy)*	*Autonomy objective (days)*	5
B *(budget)*	*Budget (pesos)* [5]	25000
Comments:		
[1] *See climate data apendix. Extrapolated value from daily radiation 5,42kWh/m².year*		
[2] *Common efficiency of good quality PV-cells. Suppliers data gives a factor between 12,5% and 12,9%*		
[3] *Rough average price from suppliers quotes*		
[4] *The losses are assumed rather high because the factor somehow includes a security range*		
[5] *Roughly estimated budget allocated to solar energy, out of global 55,000 pesos. Wind turbine and all other equipments expenditures are assummed to approximately account for 30,000 pesos*		

PV-surface-limiting dimensioning

The theoretical required surface of PV panel is calculated as follows:

$$S_{required} = \frac{D}{R \times l \times \alpha} = \frac{1100}{1978{,}3 \times 0{,}6 \times 0{,}13} = 7{,}13 m^2$$

This represents the following cost:

$$Cost = S_{required} \times P = 7{,}13 \times 9600 = 68{,}448.00\, pesos$$

It largely exceeds the budget P, and confirms the necessity of a budget limiting dimensioning approach.

Budget-limiting panel dimensioning

The calculation results very obvious. With the budget available, how large surface of PV cells is affordable and how much electricity would it produce?

$$S_{affordable} = \frac{B}{P} = \frac{25000}{9600} = 2,6m^2$$
$$E_{produced} = S_{affordable} \times R \times l \times \alpha = 2,6 \times 1978,3 \times 0,6 \times 0,13 = 401,2kWh/year$$

This would consequently cover 36.5% of the electrical demand (the hot plate consumption is disregarded)

Battery dimensioning

First the bank of battery has to provide sufficient power to the converter to be able the cover the instantaneous required capacity (it off course depends on what and how many pieces of equipment are connected to the hybrid system). It also has to be able to store enough energy to be able to cover electricity demand during cloudy days. The autonomy is set to 5 days (this is not questioned and comes from preliminary objectives decided by the project leader, Dr Palacios). The figures refer to the case where the hot plate is not connected to the hybrid system.

Battery capacity is roughly estimated as follows:

$$C = A \times D_{daily} \times \frac{1}{V_{battery} \times d_{discharge} \times \eta_{convertor}} = 5 \times \frac{1100.10^3}{365} \times \frac{1}{12 \times 0,8 \times 0,9} = 1744Ah$$

With D_{daily}, daily electrical demand in Wh; $\eta_{convertor}$, conversion efficiency (common value); $V_{battery}$, the battery voltage in Volts; $d_{discharge}$, the discharge depth that helps prolonging batteries life time, (usually between 70 and 80% depending on battery type). See Table 16 p.77 for other designation details.

A capacity of 1744Ah basically means that, with a 12V voltage, it is possible to obtain a current of 1744A for an hour or 17,44A for 100 hours .Actually the capacity of battery to some extents depends on the intensity of the discharge current due to electrochemical losses, the Peukert equation accounts for this phenomena[34]. This explains why a battery capacity specification (in Ah) comes with an hour rating specification. As an example, a 100 Ah battery (at 20 hours rating) means than the battery can deliver of 5A current for 20 hours. This battery is described as "100 AH battery C20". The common opinion would assume that the same battery could deliver a 10 A current for 10 hours; it is not the case and last actually less. The Peukert equation gives:

Peukert's original equation: $T = \frac{C_P}{I^n}$

With T, discharge time (hours);C_p, Peukert's capacity (be very carefull, see below, Ah);I, discharge current (A);n, Peukert's coefficient (depending on battery type and age).

The Peukert's capacity corresponds to the battery capacity at a 1A discharge current. It is very rarely given (almost 1% of batteries) and this equation no longer works when used without the specified Peukert's capacity. In the chosen example, "100 AH battery C20", $T=100/5^{1.3}=12.3$ hours and not 20 hours (1,3 is a typical Peukert's coefficient for deep cycle wet batteries usually used in such hybrid system). To take it into account this issue, and be able to use the equation with usually specified capacity, the equation is a little adapted.

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[34] A very detailed article tells about this effect at http://www.smartgauge.co.uk/peukert2.html, Peukert is the one that first quantified this effect, discovered by Shroder.

Peukert's adapted equation: $T = \frac{C_p'}{I^n} = \frac{R \times (C_S / R)^n}{I^n}$

With Cs, specified capacity (at a specific hour rate, Ah); R, battery hour rating (hours).

With that formula applied to the chosen example, T=20x(100/20)$^{1.3}$/(5^{1,3})=20 hours as specified. It can be seen that doubling the discharge current (10A) does not decrease the discharge time by half (10 hours) but a bit more: T=20x(100/20)$^{1.3}$/(10$^{1.3}$)=8,1hours. Another way to see the phenomenon consists in saying that a higher discharge current than specified, results in lower capacity (Ah) than specified; a 100Ah battery C20 (20 hours rating, i.e. 5A discharge current) actually delivers 80Ah when delivering 10A discharge current.

Coming back to the theoretical capacity of the battery bank 1744 Ah, it is basically calculated to deliver for 5 days (Autonomy requirement, i.e. 120hours) a current of 1744/120=14,5A. Taking into account Peukert's effect as shown in the calculation below, this capacity requirement actually corresponds to a 1172 Ah battery C20 (most of commercial technical specifications refers to C20 hours rating).

$$C_p' = \frac{R \times C_s^{\,n}}{R^n} = \frac{120 \times 1744^{1.3}}{120^{1,3}} = 3974Ah$$

$$I^n = C_p'/T \Rightarrow I = \exp\left(\frac{\ln\left(C_p'/T\right)}{n}\right) = \exp\left(\frac{\ln\left(3974/20\right)}{1,3}\right) = 58,6A$$

$$C_{20} = I \times T = 58,6 \times 20 = 1172Ah$$

Such a battery bank can deliver a 58.6A current for 20 hours. At a 12V voltage, it means a power of 58.6x12=703W, which in turn amounts for an energy of 14.06kWh. As a comparison the house daily consumption is expected to be 3.01 kWh/day and its peak demand requires a 820W capacity.

This storage capacity is definitely enormous and would make sense for an isolated site, without back up option and where electrical supply of crucial importance (specific type of activities, research centers with laboratories...). However, for this project since a connection to the grid is possible and represents a comfortable "back-up" plan and since money is strongly limiting, such a long autonomy is not necessary and one day is enough, which decreases required capacity to 334.6Ah C20 (repeating same calculations with new autonomy objective of 24 hours). Furthermore it has been mentioned that, due to limit of converter power (due to financial reason) and to prolong battery life time by avoiding drawing too high currents, some pieces of equipment such as the refrigerator and the wash-machine should not be connected to system. For example those apparatus daily consume together 1.7 kWh (0.7kWh and 1kWh respectively). Considering this point, the required batteries capacity goes down to 145Ah C20 (repeating again the same calculations with a daily demand of 1.3kWh instead of 3.01kWh). This capacity would be theoretically enough, but in order to cope with peak power supply considerations, temperature variations, battery time decline, a security factor is applied and is approximately set to 2. A total storage capacity of 290Ah is then recommended. It can be covered by 2 batteries of 12V or more, connected in parallel to cope with the voltage requirement. A parallel connection requires identical batteries of same age, diodes to avoid any discharge of one battery in another and capacities should also be added.

Considerations about electrical wires and regulator dimensioning are not of significant interest and are not presented in this report.

5.2 The specific project's hybrid wind/solar system

5.2.1 Basic description

The specific hybrid system designed for the prototype is presented on the scheme below and is further described in next paragraph and Table 18 p.83.

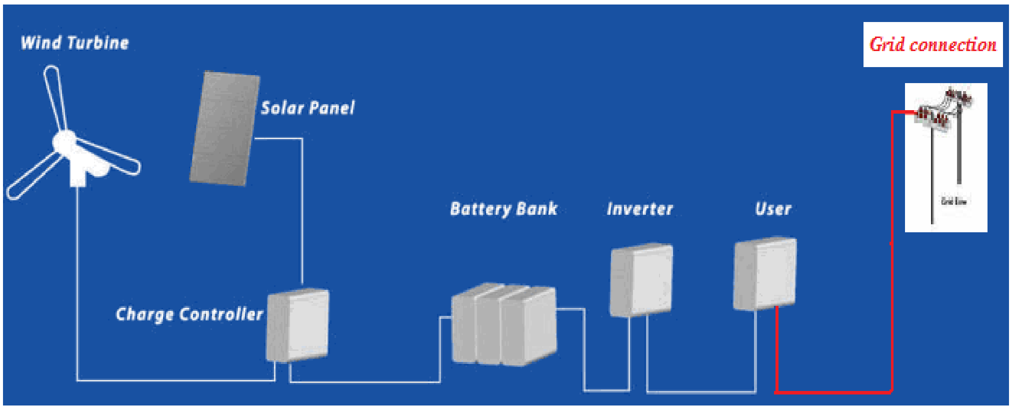

Figure 5-4: Specific structure of the project's hybrid solar/wind energy system

Since it is feasible (proximity) and since the budget does not allow designing and purchasing a completely sufficient system, a connection to the grid is considered and will aliment back-up situations and high capacity equipments.

5.2.2 Quotations analysis and comparison

In accordance to the law (see paragraph 1.3.3 p.25), 3 companies have been consulted: E2 energias[35], Inovatek[36] and Saecsa[37]. All 3 companies proposed 3 quotes that have been studied, reviewed, discussed and, once separately optimized, compared. However, this first process before comparison mainly aimed at better understanding of harmonization and electrical connexions considerations, price negotiations and optimization in respect with budget and necessities. But it also served to better evaluate professional quality of the engineers and company in general. Saecsa company appeared not to be reliable and competent enough (it confirmed an existing opinion) and was rapidly disregarded. Furthermore good discount prices have been obtained playing on commercial competition. Related results are presented in this report.

The engineers of Inovatek and E2 energias are specialized and supposed to provide well-harmonized systems. The specific motivations and scientific principles used for

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[35] At www.e2energias.com, *contact:* Ing. Guillermo Corona, gcorona@e2energias.com
[36] At www.inovatek-er.com, *contact:* Ing. Felix Arroyo Wessner, ventas@inovatek-er.com
[37] At www.saecsa.com, *contact:* Ing. Fernando Guzman Flores, gomufer@hotmail.com

such harmonization process are consequently not further detailed although they have been generally discussed.

All technical details of all components of every quote are summarized in Appendix 3: Quotes comparison for the hybrid wind/solar system. Only main comparison results are presented in the following table.

Table 17: Main results of the comparison of hybrid system quotations

Prices (pesos)			
	E2	**Inov.**	**Sae.**
Solar panels	13595	12378	-
Wind turbine	10752	10814	-
Batteries	7754	5428	-
Regulator	2550	1429	-
Convertor	1366	940	-
Additional equipment	791	742	-
Solar water-heater system (without VAT)[1]	6956		
Installation expenditures	1700	3752	-
Support structures	1000	3202	-
Subtotal	39507	38685	42057
Total (with 15% VAT)	**45433**	**44488**	**48365**

Energy results			
	E2	**Inov.**	**Sae.**
Annual total electricity production (kWh/year)	672,82	621,75	858,1
Daily total electricity production (Wh/dia)	1843	1703	2 351,0
Solar electricity (Wh/dia)	791	651	271,0
Wind electricity (Wh/dia)	1052	1052	2 080,0
Solar panel efficiency (%)	12,90	12,50	-
Solar panel surface (m²)	1,51	1,20	-
Batteries capacity (Ah) C/20 [2]	272	317	
Investment prices (pesos/W)	**127**	**127**	***8,0***

Comments:

[1] No included in the total for fair comparison

[2] See paragraph 5.3.2 about battery dimensionning and Peukert's effect

5.2.3 Discussions and conclusions

As previously mentioned, Saecsa quotation has been preliminarily abandoned due to obvious lack of professionalism. This also explains why data are not available for components quoted by Saecsa.

Energy performance considerations

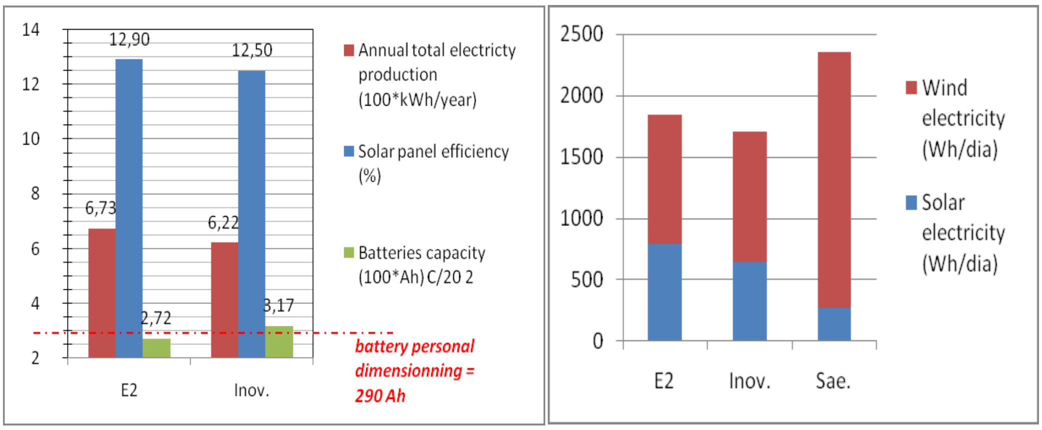

Figure 5-5: Energy mix and performances comparison of E2 Energias and Inovatek quotes (Saecsa is included as example)

From the only energy efficiency point of view, Figure 5-5 p.81 and Table 17 p. 81 seem to favor E2 quote. Indeed it theoretically shows higher annual production (the values account for global system efficiency, i.e. the electricity production refers to electricity potentially delivered by the inverter). The solar panel efficiency is also calculated to be slightly higher (both are relatively satisfying efficiencies). One can also mention that the battery dimensioning resulted in consistent number even if such a dimensioning anyway contains uncertainties. Apparently E2 quoted bank of batteries could be slightly limiting but one has to remind that dimensioning result of 290Ah (C/20) already includes a large security factor of 2.

When it comes to production mix, E2energias and Inovatek quoted exactly the same wind turbine, very roughly estimated average daily wind energy production would respectively account for 57% and 62% of total daily production. The example of Saecsa shows that the quoted hybrid system would rely on approximately 89% of wind energy. This is very risky according very high uncertainty level of wind production estimation. Even if total production is calculated to be significantly higher, such an energy mix should not be recommended.

Price considerations

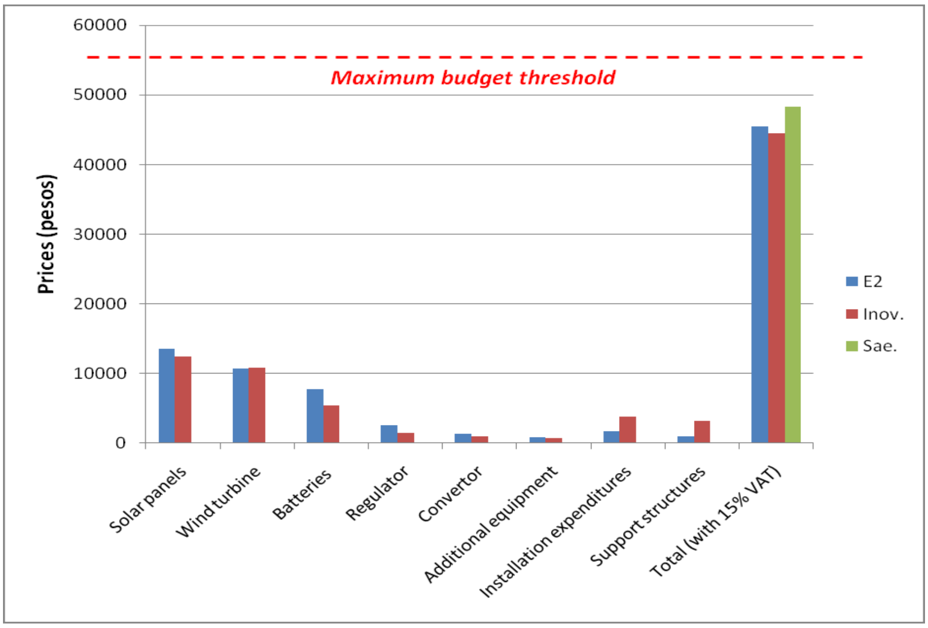

Figure 5-6: Investments comparison of 3 quotes.

The presented results do not include the solar water-heater system (SWHS). According to the fixed budget threshold one can see that Saecsa is the most expensive and the few left money is probably not enough for the SWHS purchase. Global prices of E2's and Inovatek's quotes are roughly equal (1000 pesos higher for E2) but when analyzing further the prices, it appears that all E2 equipments are more expensive than Inovatek ones (they are actually of better quality) but all services appear to be cheaper. For equal total prices, investment with E2 is then rather based on better equipments than on services and additional expenditures; this is definitely a good point, favoring E2energias, given that the installation of such a system is rather simple and does not require very advanced expertise.

Conclusion

The comparison of 3 quotations from 3 different companies happened to be very helpful in the final design and purchase of the project's hybrid system of electricity generation. Energy and price analysis (see above) slightly favor the quote of E2Energias Company.

Furthermore other practical arguments have been taken into consideration and led to the final selection of E2Energias hybrid system:

- E2Energias is the only company that also proposes a Solar Water-Heater Module and furthermore offers an attracting discount on the entire package; it has been assumed that purchasing all equipments to the same company is a crucial advantage mainly because the potential for satisfactory customer services after purchase is made greater.
- E2Energias proposes as well, in complete accordance with the educational and knowledge transfer aim of the project, a free formation for us to be able to both install the hybrid system and the solar water-heater system and also get a great understanding of how these systems work and what are the maintenance processes. This appeared to be very interesting.

Table 18: Hybrid system technical details, main energy and price results

			Unit price		Total price	
Qty	Model	Description	US$	pesos	US $	pesos
3	PF65	65 WP photovoltaic panel/17,6 VDC/ power 65W ±5%/750x670x36mm/Weight 5,96kg/Cells number 36	338,18	4532	1014,54	13595
1	INV600	Inverter 600WP/12 VDC to 115 VAC/250W	101,94	1366	101,94	1366
1	PR2020	Solar regulator 20Amp/ 12 or 24 VDC/with display screen	190,31	2550	190,31	2550
2	T12-136	Acid deep wet cycle battery/12VDC/136Ah C20h/Free of maintenance	289,31	3877	578,62	7754
1	AB200	Wind turbine package/200WP/12VDC	802,39	10752	802,39	10752
1	KIT	Connecting wires and apparatus	59	791	59	791
1	CS188	Solar water-heater system/188l capacity/with:wtaer storage, support structure and pipes	519,4	6960	519,4	6960
1	CAP	Formation and manuals for systems installations (electrical and termico)	0	0	0	0
	*	Additional equipments for fixation, connections, wind turbine support…. Estimated to cost 1000 pesos		1000		1000
	Main figures					
		Total price (US$)	3755,83			
		Total price (pesos)	50328,12			
		Annual electricty production (kWh/year)	673			
		Wind electricity (kWh/year)	384			
		Solar electricity (kWh/year)	288,7			
		Solar panels efficiency (%)	12,9			
		Electricty storage capacity (Ah, C/20h)	272			
		Per installed w att investment cost (US$/W)	9,51			
		Per installed w att investment cost (pesos/W)	127,41			
		Hot w ater supply (Liters - persons)	188	4		

The hybrid will cover approximately 61.2% of annual electricity demand. It will be connected to all equipments of the house except the fridge and the wash-machine. Doing that way, high discharge currents of batteries are avoided, back-up energy will almost always be available (for an extra lap-top, or the recharge of a cell phone…). However it is recommended to design the house connection network so that the users can manually connect equipments either to the hybrid system or to the grid, according to batteries' state of charge, instantaneous energy production rates of PV/wind generators and current domestic consumption on the regulator display screen. Off course this can be basically monitored using "Domotics" systems but, nevertheless the manual switching would lead to a better consciousness and understanding of how to manage consumption and resource in a sustainable way; this fits perfectly with the original goal of the prototype.

Some calculations about Net Present Value (NPV) or Payback Period have been performed to have a clue about the consistency of such investment. They happen to result in very surprising values. Indeed, with a discount rate of 7%, an estimated life time of 20 years, the domestic electricity price of 0.1 US$/kWh and disregarding the changing of batteries every 5 or 7 years, the NPV (*=Discounted benefits-Investments*) is clearly negative (-35210 pesos) and the payback results unachievable. This can have various explanations:

- The first function of the prototype is the exhibition function. A certain budget has been granted to buy alternative energy equipments so that people can see how they work. This first function is performed, but financial consistency of the investment remains questionable.
- Such a small hybrid system would be pertinent in a remote place, with such a low demand that the hybrid system covers it all and avoid heavy investments in grid connection.
- Since investment prices do not increase proportionally with system capacity, it is reasonable to assume that a larger investment would definitely be more consistent (and especially if it can avoid the grid connection).
- It has been seen in the first part of this report that Mexico domestic electricity price is one of the lowest in the world. This makes still expensive small-scaled renewable electricity investments less pertinent than in other countries (NPV=-21000 pesos with Italia's residential electricity price of 0,23US$/kWh, the comparison makes sense if it considers a very sunny site in the south of Italy). One might conclude that, financially speaking, Mexico is still not a very appropriate country for small-sized hybrid system investments (too high investment cost for standard Mexican revenue and too low electricity prices).

6 Conclusions and discussion

Building a prototype ecological house in order to promote and develop ecological awareness in Leon Guanajuato, Mexico started more than a decade ago. It can be considered as a pioneer ecological project, especially in that part of the country. As such many difficulties from lack of experience, lack of data and technology and, above all, lack of fund has been faced. The thesis work represents only a step in the realization of that project, it has also been affected but these lacks, but it constitutes a rather complete fundament for its future development. It covers:

- The establishment of a reliable database including: climate data, material data, software documentations and selection;
- A serious energy analysis and optimization of a base-case design that result in important recommendations and guidelines for an energy efficient building. It mainly promotes a rather uniformed insulation of the whole building envelop even basic, the great efficiency of external shading and the non-necessity of an high-tech HVAC system if good attention is paid on natural ventilation schemes.
- The establishment of documented and justified electricity consumption scenarios for the house taking into account: domestic appliances, occupancy schemes, electrical usage schedules;
- The design and purchase documentation of a hybrid wind/solar system for renewable electricity supply that fits in budget restrictions and covers 65% of house demand.

Furthermore, since the project carries, as its essence, an educational and pedagogical function to show off green technologies and teach ecological concepts, this report had to fit completely with that part. It consequently fulfills its function of “knowledge transfer” by presenting:

- The major points and a global methodology of “eco-designing”, what aspects it includes, what to think about when designing an ecological building;
- A specific and further detailed energy approach of “eco-designing;
- Different pieces of energy software for buildings energy analysis and how to consider them;
- A basic and theoretical methodology for dimensioning and hybrid wind/solar hybrid system for renewable electricity supply.

As a conclusion this thesis work and report constitutes a solid and reliable basis for the future development of the project. This was definitely needed.

Under the light of this work, a couple of refining and optimization actions may be recommended. Indeed, more specific and accurate climate data might be provided by the purchase of a small climate station located on site and would refine and optimize the results. A better and more refined analysis has to be performed including financial data about materials, technological items, etc… As suggested many times in the report, the field of “Domotics” (see Appendix 1: What is “domotics”?) might bring up new improvement opportunities on monitored shading, windows airing, energy consumption and availability… It also fits perfectly with the demonstrative function of the building. It should be further studied.

The only achievement of a project, regardless of its technical perfection is already a great success for all the institutions, entities and persons it involved, be them private investors, public councils or chambers, universities, centers of investigation… The development of ecological awareness starts from education and grows with “technico-institutionnal complexes” (UNRUH, 2000 and 2002). Especially in developing countries whose demography is exploding, the fight of Dr Jose Luis Palacios is more than extraordinarily worth, it is crucial.

References

Most of the references used for data collection are mentioned in the different data summarizing tables in Appendices.

Books:

Palacios Blanco J.L, (2007), *La casa ecologica, ¿Cómo construirla?*, 1st edition, Nexo Grafico

Gutierrez Pulido H., de la Vara Salazar R., (2008), *Análisis y diseño de experimentos*, 2nd edition, McGraw Hill.

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Reports :

Georges Nely, (1989), *Les Séries à évaporites en exploration pétrolière: Méthodes géophysiques*, Chambre syndicale de la recherche et de la production de Pétrole et du Gaz naturel, commission exploration, Edition Technip

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Articles:

Torcellini P.,Pless S., Long N., Judkoff R., (2004), *Zion National Park Visitor Center: Performance of a Low-Energy Building in a Hot, Dry Climate* , Conference paper presented at the World renewable Energy Congress VII, Denver, Colorado., available at: http://www.nrel.gov/buildings/pdfs/36272.pdf

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Web sites :

- Energy :

SENER, www.sener.gob.mx/

EIA, www.eia.doe.gov/

Standards from ASHRAE (American Society of Heating, Refrigerating and Air Conditionning Engineers), www.ashrae.org

- Climate data

CONACYT, www.conacyt.mx/

SNM, smn.cna.gob.mx/

First look for wind and solar potential, http://firstlook.3tier.com

- Materials:

Solitec, www.soliftec.com

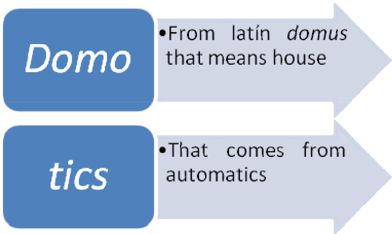
Atomer, www.atomer.fr

Matweb, www.matweb.com

Engneering tools, www.engineeringtools.com

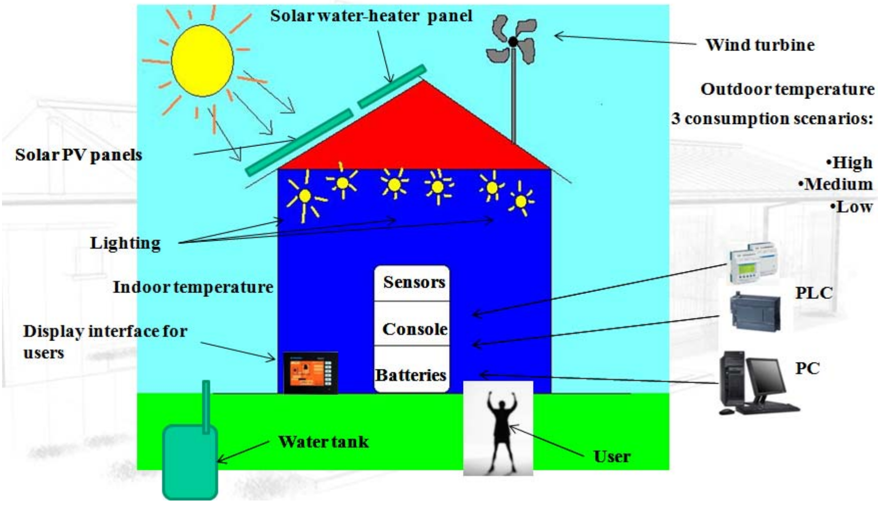
APPENDICES

Appendix 1: What is "domotics"?



Definition: Domotics comes from a French word « Domotique » that Larousse Encyclopedia defined in 1988 as: the house concept that includes all automatics related to security, comfort, energy control of energy consumption, communications… It led to the concept of "***intelligent house***".

Brief overview of domotics concept from a study achieved by Eng. Dante Migoni (Monterrey Institute of Technology and Higher Education of León)



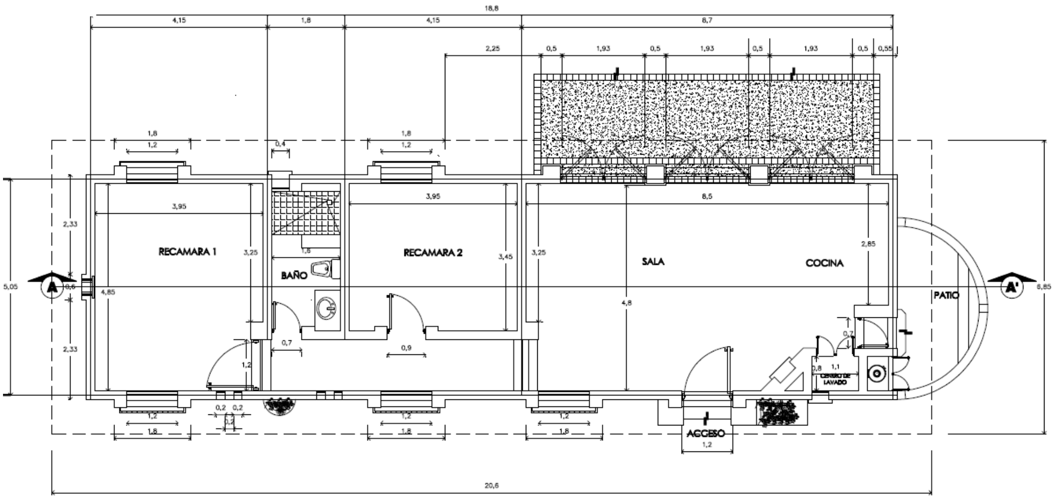
Inputs

I1- Presence Sensor Rec. 1
I2- Presence Sensor Rec. 2
I3- Presence Sensor *Bathroom*
I4- Presence Sensor *Corridor*
I5- Presence Sensor *Window*
I6- Contact Switch *Open Window*
I8- Contact Switch *Closed Window*
I9- Off Switcher *Bedroom 1*
IA- Off Switcher *Bedroom 2*
IB- Temperature Sensor
IC- Wind Sensor
ID- Luminosity Sensor
IE- Precipitation Sensor
IF- Off Switcher *Bathroom*
IG- Off Switcher *Corridor*
IH- Regulator Dimmer1
IJ- Regulator Dimmer2

Outputs

Q1- Bulb Bedroom 1
Q2- Bulb Bedroom 2
Q3- Buld Bathroom
Q4- Bulb Corridor
Q5- Command: open window
Q6- Command: close window
Q7- Garden watering
Q8- Alarm
QB- Dimmer1
QC- Dimmer2

<u>*Appendix 2: Architectural plans*</u>

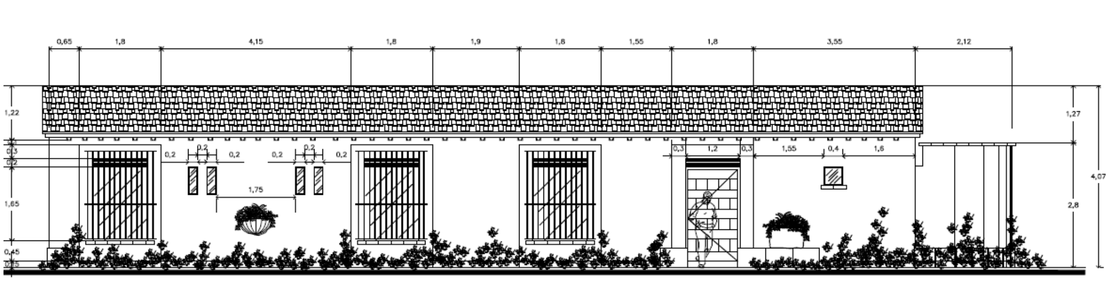


PLANTA ARQUITECTÓNICA Esc: 1:50

First plant

FACHADA POSTERIOR Esc: 1:100

North-facing façade



FACHADA PRINCIPAL Esc: 1:100

South-facing facade

Appendix 3:

Quotes comparison for the hybrid wind/solar system

Main data assumption:

DATOS:		***Unidades***	***Commentarios***
Sol	6,5	kwh/m².dia	*Promedio Heliodon con panel horizontal*
	6,56	kwh/m².dia	*Promedio segun CONCYTEG*
	7,39	kwh/m².dia	*Factor 1/0,88 debido a una orientacion optimal del panel (30°)*
	5,69	kwh/m².dia	*Impacto de la meteo (0,77)*
	5,79	horas/dia	*Segun inovatek y E2a*
Viento	5,5	m/s	*Segun first look, promedio al ano*
	40	kWh/mez	*Segun la curva (Output vs average wind speed) del constructor*
	480	kWh/ano	
	0,8		*Factor de planta*
Tiempo de vida	20	anos	*Aerogenerador*
	20	anos	*Paneles Fotovoltaicos*
Cambio	13,4	pesos /US$	

Details of the results:

	E2a	***Inovatek***	***Saecsa***
Paneles solares (US$)	***1014,54***	***923,7***	
Paneles solares (pesos)	***13594,84***	***12377,58***	
Modelo	PF65	Conergy Q 50 PI	SAE-FE-400-50
Tamano (un modulo) m²	0,50	0,40	
rendimiento (%)	12,90	12,50	
Numero de entidades	3,00	3,00	1,00
Voltage MPP(V)	17,00	16,50	
Potencia nominal STC por panel (Wc)	65,00	50,00	50,00
Potencia nominal por m² STC (Wc/m²)	129,22	125,00	
Potencia global STC (Wc)	195,00	150,00	50,00
Produccion de energia al dia (salida del inversor) Wh/dia	830,35	639,84	289,50
Production de energia al ano (salida del inversor) kwh/an	303,08	233,54	105,67
Precio unitario US$	338,18	307,90	
Precio global US$	1014,54	923,70	
Precio unitario (pesos)	4531,61	4125,86	
Precio global (pesos)	13594,84	12377,58	
Precio del kWc (pesos/Wc)	69,72	82,52	
Garantia		5,00	20,00
	E2a	***Inovatek***	***Saecsa***
Aerogenerador (US$)	***802,39***	***807***	
Aerogenerador (pesos)	***10752,03***	***10813,80***	
Modelo	Airbreeze	Airbreeze	
Altura (m)	6,00	6,40	6,00
Voltage(V)	12 o 24	12 o 24	12 o 24

Potencia max (W)	200,00	200,00	400,00
Velocidad minima de arranque	2,68	2,68	
Velocidad optimal (m/s)	12,50	12,50	
Velocidad max	49,20	49,20	
Production de energia al ano (kWh)	384,00	384,00	759,20
Production de energia diaria (Wh)	1,05	1,05	2,08
Precio (US$)	802,39	807,00	
Precio (pesos)	10752,03	10813,80	
Precio del kW (pesos/W)	53,76	54,07	
Precio del kWh (pesos/kWh)			
Garantia	3,00	3,00	
	E2a	***Inovatek***	***Saecsa***
Bateria (US$)	***578,62***	***405,08***	
Bateria (pesos)	***7753,51***	***5428,07***	
Modelo	T12 236M	Cale solar	electrosolar S1
Numero de entidades	2,00	4,00	4,00
Voltage	12,00	12,00	
Capacidad (Ah)	136 - C/20	115 - C/100	
Precio unitario (US$)	289,31	101,27	
Precio global (US$)	578,62	405,08	
Precio unitario (pesos)	3876,75	1357,02	
Precio global (pesos)	7753,51	5428,07	
Garantia	7,00		
Tiempo de vida	10,00		
	E2a	***Inovatek***	***Saecsa***
Controlador de carga (US$)	***190,31***	***106,67***	
Controlador de carga (pesos)	***2550,15***	***1429,38***	
Modelo	PR 2021	PWM Vision 20	
pantalla	si	si	
Salida USB para conectar a la compu	?	si	
Voltaje	12,00	12 o 24	12,00
Corriente max de salida del consumidor (A)	20,00	20,00	10,00
Proteccion contra descarga profundida	<30% (11,1V)		
Precio US$	190,31	106,67	
Precio pesos	2550,15	1429,38	
	E2a	***Inovatek***	***Saecsa***
Inversor (US$)	***101,94***	***70,18***	
Inversor (pesos)	***1366,00***	***940,41***	
Modelo	IC12120-600	HP 600	CD-CA SAE-1/50
Potencia Max de salida (Watt RMS)	250,00		
Potencia Max de salida (Watt OMP)	600,00	600,00	

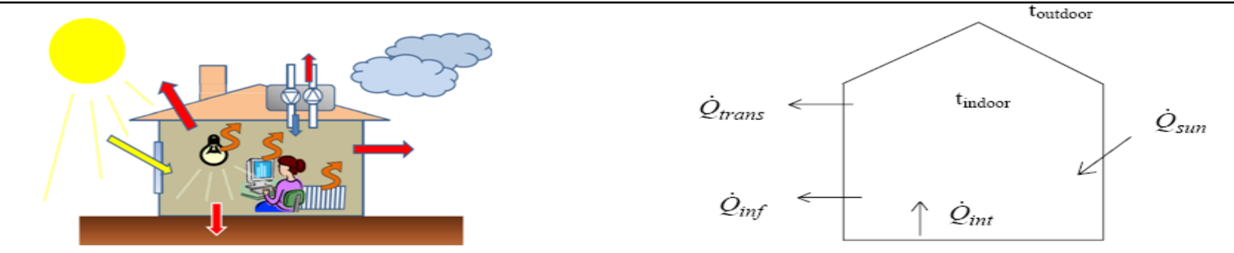
Salida maxima (A)	2,08		
Voltage salida	120-60hz	120-60hz	
Voltaje entrada	13 o 24	entre 10 y 15V	
Forma de onda	semi-senoidal	Senoidal modificada	
Precio US$	101,94	70,18	
Precio pesos	1366,00	940,41	
	E2a	**Inovatek**	**Saecsa**
Equipo adicional (US$)	***59***	***55,35***	
Equipo adicional (pesos)	***790,60***	***741,69***	
Estante metalico para las baterias		x	
Cableado y conectores	x	x	
	E2a	**Inovatek**	**Saecsa**
Estructura de soporte US$	***74,63***	***238,95***	
Estructura de soporte pesos	***1000,00***	***3201,93***	
Mastil (US$)	59,70	117,82	
Mastil (pesos)	800,00	1578,79	
Juego de herrajes (US$)	14,93	24,80	
Juego de herrajes (pesos)	200,00	332,32	
Bastidor de almuninio para los paneles (US$)	regalado	96,33	X
Bastidor de almuninio para los paneles (pesos)	regalado	1290,82	X
Calentador solar (US$) +IVA	***519,14***		
Calentador solar (pesos)	***6956,48***		
Capacidad (Litros)	188,00		
Sitema de circulacion de agua	gravedad		
	E2a	**Inovatek**	**Saecsa**
Instalacion (US$)	***126,86***	***280***	
Instalacion (pesos)	***1700,00***	***3752,00***	
** E2a: son nuestros viaticos de ir para los componentes*			
	E2a	**Inovatek**	**Saecsa**
Sub total (US$)	***3265,94***	***2886,93***	***3138,55***
Subtotal (pesos)	***43763,60***	***38684,86***	***42056,62***
TOTAL (con IVA) (US$)	***3755,83***	***3319,97***	***3609,34***
TOTAL (con IVA) (pesos)	***50328,14***	***44487,59***	***48365,11***
Produccion total (kwh/ano)	***687,08***	***617,54***	***864,87***
Produccion total (Wh/dia)	***1882,41***	***1691,90***	***2369,5***
Precio precio por W instalados (pesos/W)	***9,508***	***9,486***	***8,021***

Appendix 4: Pieces of software for Energy Analysis and Simulation

Software name	Main application	Language	Climate database	Free or not	Comments	Why not retained?	Link
Codyba	Dynamic simulations of overall energy performances of Buildings + Indoor temperature and humidity evolution calculation	French and English	France	Simple version free , complete version not (999€)	A very sophisticated and powerful software for general approach	Expensive and requires time consuming learning phase	*http://www.jnlog.com/codyba1.htm*
DOE2	Overall energy performances, design, retrofit for residential or commercial buildings	English	US	NO	Very famous one and very sophisticated	Expensive and requires time consuming learning phase	*http://simulationresearch.lbl.gov*
TRNSYS 16	Overall energy performances, design, retrofit for residential or commercial buildings + energy load + renewable energy + powerful graphical interface	English	US	NO	Very performing one	Expensive and requires time consuming learning phase	*http://sel.me.wisc.edu/trnsys*
APACHE	Huge platform with several specific purpose oriented subprograms + thermal dynamic approach	English	US	NO (usually not, except small subprograms)	Very complete one with many different oriented applications	Expensive and too scattered entities	*http://www.iesve.com/*
HOT 2000	Energy loads, fuel consumption calculation, HVAC dimensioning+ performing graphical interface	English	US	YES	Very , very interesting	Was a major candidate	*http://www.buildingsgroup.nrcan.gc.ca/software/hot2000_e.html*
Green Building Studio	Energy loads, fuel consumption calculation, HVAC dimensioning+ performing graphical interface +carbon footprint + energy potential for wind and solar energy	English		YES	Very interesting	Was a major candidate	*http://www.autodesk.com/greenbuildingstudio*
Enercad	Heat balances and energy calculations + solar toolbox based on European norms	English, French, German and more	Europe	Student version 60€ Professional version 700€	Very interesting simplified calculation models	A bit expensive	*http://www.enercad.ch*
Heed	Energy simulations + cost analysis + CO2 calculations+ based on ASHRAE standards + basic HVAC systems	English and Spanish	California	YES	Very interesting	Was a major candidate	*http://www.aud.ucla.edu/energy-design-tools*
BV2	Energy loads based on duration curve calculation + cost calculations	Swedish, English	Sweden + Torreon (Mex)	NO	Already known, direct contact with designers		*http://www.bv2.se*

Appendix 5:
BV² software, presentation and explanations

a) *Thermal balance*



Thermal balance $\dot{Q}_{sol} + \dot{Q}_{int} + \dot{Q} - \dot{Q}_{trans} - \dot{Q}_{inf} = 0$

$\dot{Q}_{sol}$ = Heat gained by solar radiation *[W]*

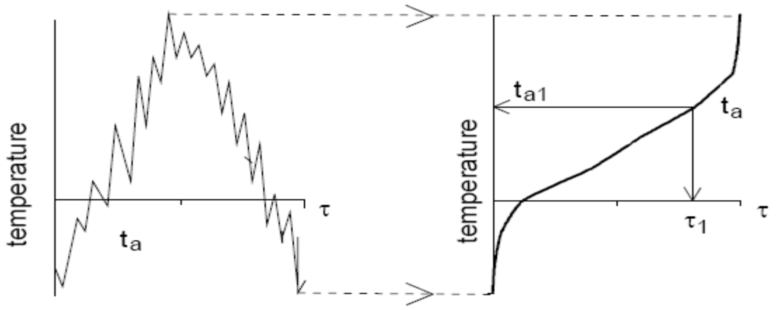
$\dot{Q}_{trans}$ = Heat transmission through the building envelope *[W]*

$\dot{Q}_{int}$ = Internally generated heat *[W]*

$\dot{Q}_{inf}$ = Air infiltration or air leakage *[W]*

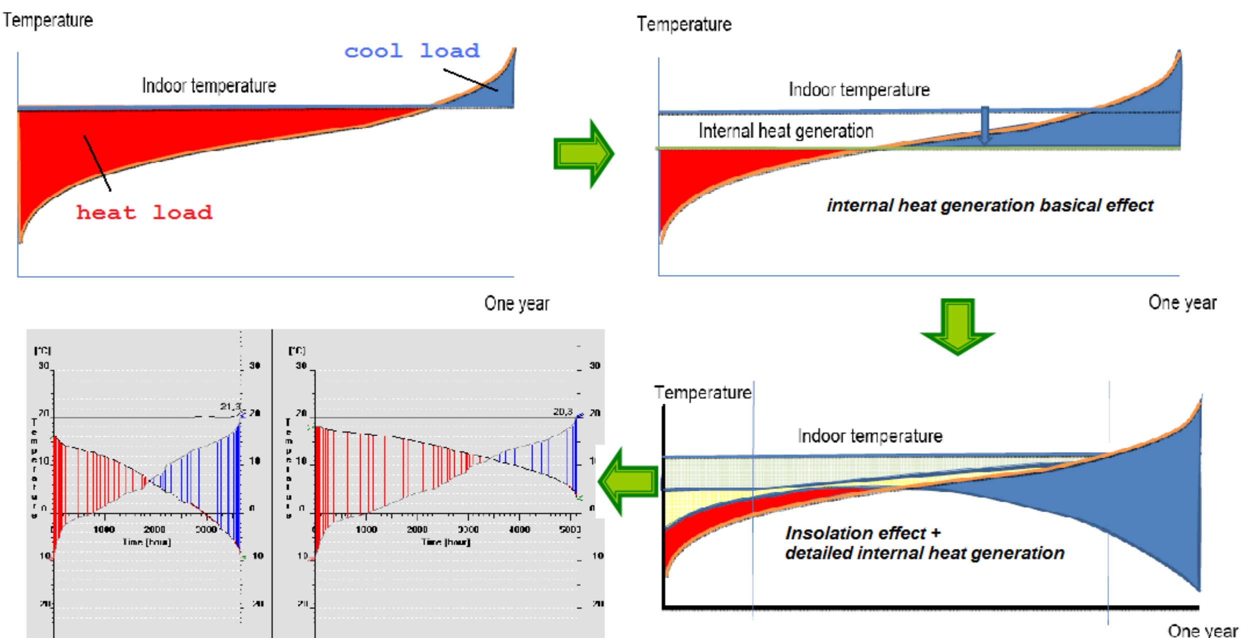
$\dot{Q}$ = The amount of heat that must be removed or added to the room to maintain the given room temperature *[W]*

b) Duration curve



The outdoor air temperature t_a, is related to the time period τ, means that the time period when outdoor air temperature has been equal or less than t_{a1} is τ_1.

c) Graphical representation of thermal balance and duration curve



From those areas energy and power requirements are calculated using various scaling factors. Only the basis of BV² software is described here. Further information at http://www.bv2.se/)

INPUTS

$$\dot{Q}_{sun} + \dot{Q}_{int} - \dot{Q}_{trans} - \dot{Q}_{inf} = \pm \dot{Q}$$

OUTPUTS

Thermal balance variables

Climate data

- Mean annual outdoor temperature: normal, highest and lowest
- Extreme temperatures: maximal and minimal outdoor over past 30 years

Qsun (sun radiation):

- Orientation
- Shading schemes
- Solar factors for windows
- Geographic coordinates (latitude, longitude , altitude)

Qint (internal heat):

- Occupancy and activity scenarios
- Lighting and equipments thermal details and using schemes

Qtrans (heat transmission through envelop)

- Envelop UValues (material properties…)

Qinf (infiltration and ventilation)

- HVAC systems
- Air changing rates
- Windows airing ...

Extra variables

Architectural main features and dimensions
Domestic hot water systems
Prices values for fuels and electricity

→

Thermal balance model / Duration curve

Subcalculations (materials, flows…)

Results conversion into energy requirements

(scaling factors)

Price calculations

Fuel consumption calculations

→

Thermal balance-related

Energy loads in $kWh/m^2.year$

- Heat in $kWh/m^2.year$
- Electricity for HVAC systems (heat and cool producing)
- Electricity for lighting
- Electricity for equipments

Power dimensioning values in W/m^2

- Same entities as energy ones

Indoor temperatures

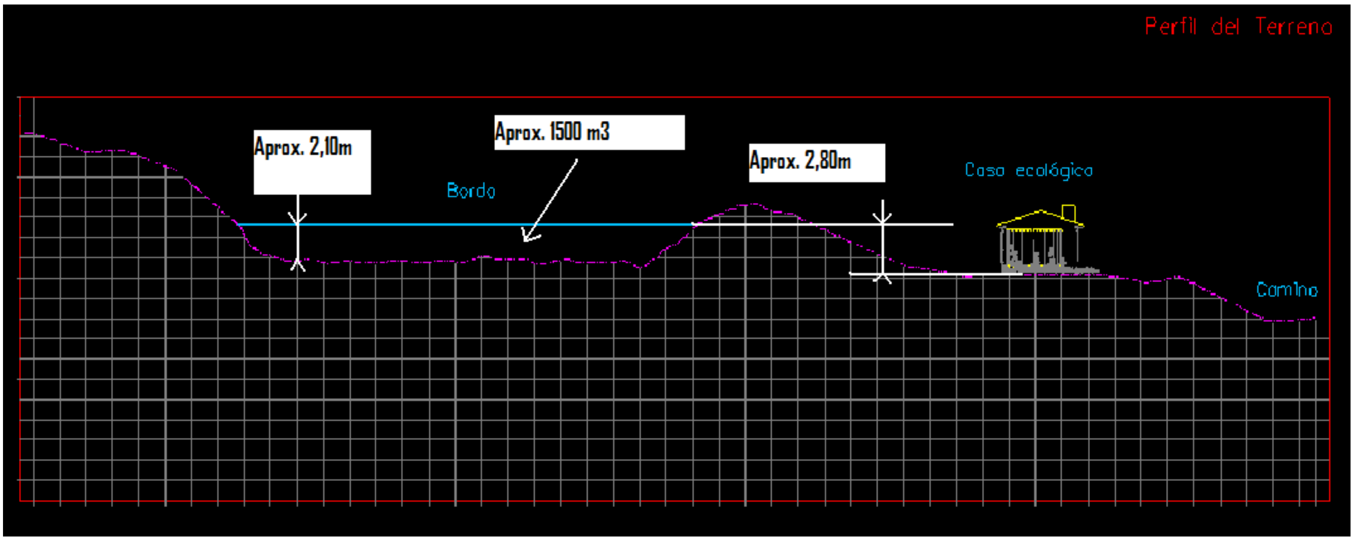
- Annual max and min
- Duration values

Fuels consumption for heat production

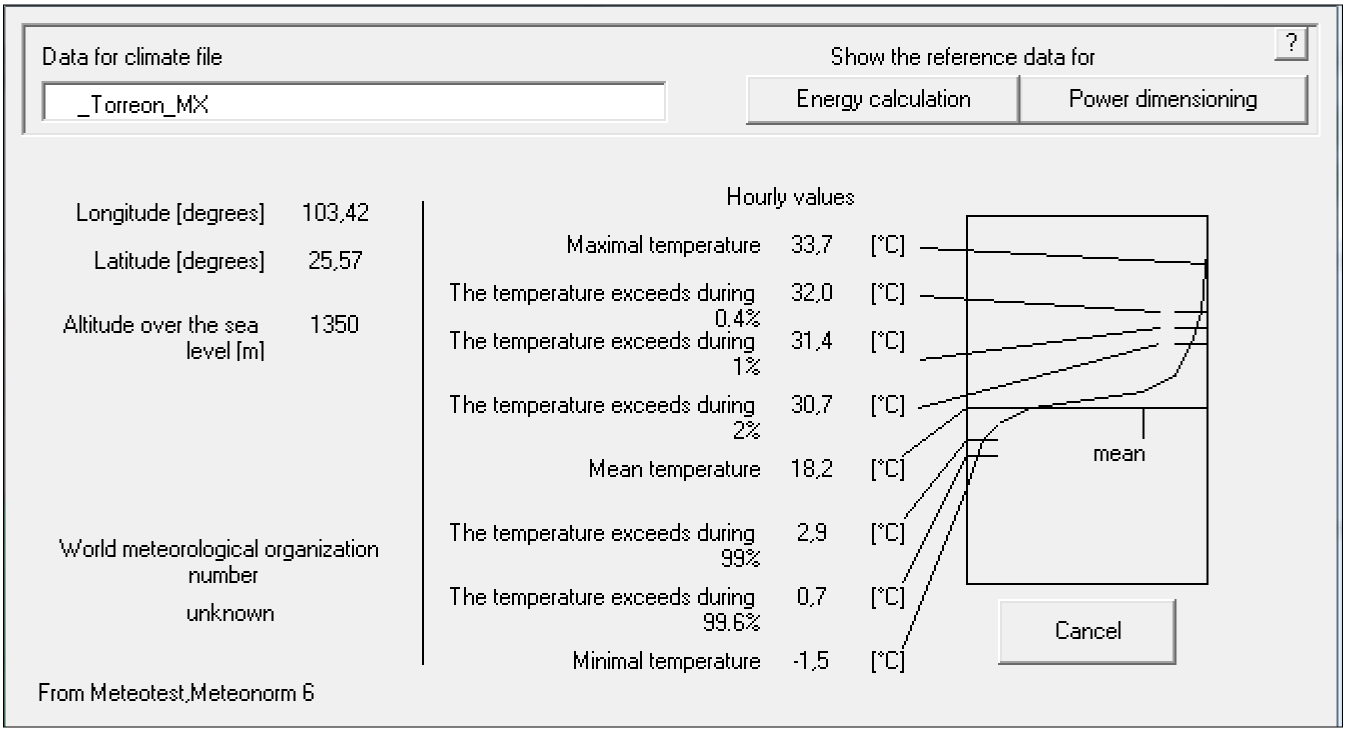
Extra results

Results of price analysis
Comparison of different designs

Appendix 6: Topographical description for the potential hydro energy from the rainwater reservoir



Appendix 7: BV² climate file of Torreon, Mexico



Appendix 8: Material data, quantitative data

	Found λ values (W/m.K)	Used λ (W/m.K)	Heat capacity (kJ/kg.K)*	Comments	Sources
Walls					
Natural stones	3	2,3	0,84	Average λ value calculated with site stones: basalte, concrete joints (20% wall surface)	BV² data base
	2,5-3,5				www.soliftec.com
	2,38-2,92 (basalte)				[1]
Adobe	0,274-0,315	0,26	0,92	Average value of all 4 values	[2] (measurements made in Argentina)
	0,20-0,25				[3]
Brick block, heavy clay	0,6	0,68	0,95	Average value of all 5 values	BV² data base
	0,65				www.soliftec.com
	0,36-0,53				[2] (measurements made in Argentina)
	0,84				www.atomer.fr
	0,87				[3]
Compacted earth	0,8	0,92	1,26 (dry earth, higher with moisture)	Average value. 1st value refers to specific type of earth and 2nd to compacted earth block	CratTerre, 2006
	1,05				www.labrivert58.fr
Roof					
Concrete (reinforced concrete)	1,6	1,6	0,75	very good unanimity	www.atomer.fr
	1,6				www.matweb.com
	1,63				[3]
	1,63				[4]
Light concrete	0,3	0,3	-		BV² data base and www.matweb.com
	0,51	0,55	-	Average value	BV² data base
	0,6				[2] (measurements made in Argentina)
Polurethane	0,029	0,03	-	Very good unanimity	www.atomer.fr
	0,03				www.soliftec.com
Tiles (clay, ceramic slurry)	0,68	0,68		see Brick block	see Brick block
	U values (W/m².K)	**Used U (W/m².K)**			
Windows					
Single glazing	5	5,3	-	Basic and Non metal frame	www.soliftec.com
	5,7			Basic 1-glass 6mm	BV² data base
Double glazing	3	3	-	Basic double glazed	www.soliftec.com and BV² data base

Notes:

* *www.engineeringtoolbox.com*

[1] *Les Séries à évaporites en exploration pétrolière: Méthodes géophysiques, Chambre syndicale de la recherche et de la production de Pétrole et du Gaz naturel, commission exploration,Goerges Nely, Edition Technip, 1989*

[2] *Comportamiento termico de muros de Tierra en Tucuman, Argentina, Lucia Arias, StellaLatina, CRIATiC-FAU-UNT, Centro Regional de Investigaciones de Arquitectura en Tierra Cruda, May 2007*

[3] *El comportamiento termico y la inercia termica de las fabricas con bloques de termoarcilla, Dr. Arq. F. Javier Neila Gonzalez , Dr. Arq. César Bedoya Frutos*

Comments:

In the summation of Uvalues , indoor and outdoor surface coefficient convection (+ radiation) coefficient have to included (as R_{indoor}=0,13m².K/W and $R_{outdoor}$=0,04m².K/W)

Appendix 9: Results of full factorial experiments

Factors		Low value (-1)	High value (+1)	Comparative example	Unit	Comments
Window type	X1	*Single glazed, basic non metal frame U= 5,3*	*Double glazed, basic non metal frame U=3*	*State-of-the-art windows, triple glazed U≈1*	W/m².K	*See materials tables in Appendice, Minergie requirement U≤1,0*
Window size	X2	*Actual size -15%*	*Actual size + 15%*			*See base-case dimensions in part 2*
Shading	X3	*External shading*	*No external shading*			*BV2 enables to define a relation between shading degree and outdoor temperature*
Wall Uvalues	X4	*U=2*	*U=0,7*	*Low insulation with a 14cm thick brick wall U=2,7*	W/m².K	
Roof	X5	*Non insulated, wood carpentry and roof tiles* U_{roof}*=5*	*Insulated with 5 cm polyurethane or 10 cm mineral wool* U_{roof}*=0,5*	*Eco-label Minergie, minimum roof insulation U≤0,15*	W/m².K	*Minergie is valid and employed in France and Swiss climate conditions*
Hvac system	X6	*Natural ventilation (rather low airchanges, between 0,2 and 0,4)*	*Exhaust air system (hygienic airchanges between 0,4 and 0,8)*	*Common value in Swedish code for residential building 0,5*	ACH (air changes per hour)	*ASHRAE standards* requires a natural inflitration rate lower than 0,35 ACH*

Note: *Standards 62-89 from ASHRAE (American Society of Heating, Refrigerating and Air Conditionning Engineers)*

Experiments	X1	X2	X3	X4	X5	X6	Heat load (kWh/m². yr)	Max daily indoor temperature (°C)	Max night indoor temperature (°C)	Hours above 25°C during the day	Hours above 25°C during the night
1	-1	-1	-1	-1	-1	-1	215	27,5	27,5	158	337
2	1	-1	-1	-1	-1	-1	199	27,5	27,5	158	337
3	-1	1	-1	-1	-1	-1	200	28,7	29	347	522
4	1	1	-1	-1	-1	-1	179	28,5	29,2	347	522
5	-1	-1	1	-1	-1	-1	218	26,5	26,5	53	141
6	1	-1	1	-1	-1	-1	202	26,5	26,5	53	141
7	-1	1	1	-1	-1	-1	203	26,5	27,2	91	244
8	1	1	1	-1	-1	-1	181	26,5	27,2	91	244
9	-1	-1	-1	1	-1	-1	166	27,5	27,5	158	513
10	1	-1	-1	1	-1	-1	150	28	28	158	513
11	-1	1	-1	1	-1	-1	155	28,7	29,2	250	702
12	1	1	-1	1	-1	-1	135	29,2	29,7	347	702
13	-1	-1	1	1	-1	-1	168	26,5	26	53	141
14	1	-1	1	1	-1	-1	152	26,5	26	53	141
15	-1	1	1	1	-1	-1	157	26,5	27,2	91	244
16	1	1	1	1	-1	-1	136	26,5	27,2	91	244
17	-1	-1	-1	-1	1	-1	69	29	29	349	876
18	1	-1	-1	-1	1	-1	55	29,5	29,5	349	876
19	-1	1	-1	-1	1	-1	59	30,2	30,5	462	1372
20	1	1	-1	-1	1	-1	41	30,5	31	593	1372
21	-1	-1	1	-1	1	-1	70	26	26	53	141
22	1	-1	1	-1	1	-1	55	26	26,2	53	141

23	-1	1	1	-1	1	-1	60	26,5	26,5	53	150
24	1	1	1	-1	1	-1	41	26,5	26,7	91	244
25	-1	-1	-1	1	1	-1	25	30	30,2	597	1314
26	1	-1	-1	1	1	-1	13	30,5	30,5	775	1545
27	-1	1	-1	1	1	-1	21	31,5	31,5	770	1571
28	1	1	-1	1	1	-1	8	32,7	32,7	1043	1968
29	-1	-1	1	1	1	-1	26	26	25,5	53	80
30	1	-1	1	1	1	-1	15	26,5	25,5	53	80
31	-1	1	1	1	1	-1	23	27,2	27,2	91	244
32	1	1	1	1	1	-1	9	27	27	91	150
33	-1	-1	-1	-1	-1	1	237	27,5	28	158	337
34	1	-1	-1	-1	-1	1	221	27,5	28	158	513
35	-1	1	-1	-1	-1	1	222	28,7	29,2	347	522
36	1	1	-1	-1	-1	1	200	29,2	29,5	347	522
37	-1	-1	1	-1	-1	1	241	27	26,5	92	141
38	1	-1	1	-1	-1	1	224	27	26,5	92	141
39	-1	1	1	-1	-1	1	226	27	27,2	157	244
40	1	1	1	-1	-1	1	204	27	27,2	157	244
41	-1	-1	-1	1	-1	1	187	28,5	28,5	252	513
42	1	-1	-1	1	-1	1	171	28,5	28,5	252	513
43	-1	1	-1	1	-1	1	176	29	29,5	347	896
44	1	1	-1	1	-1	1	155	29,2	29,5	347	896
45	-1	-1	1	1	-1	1	191	27	27	92	141
46	1	-1	1	1	-1	1	175	27	27	92	141
47	-1	1	1	1	-1	1	180	27	27,7	91	244
48	1	1	1	1	-1	1	159	27	27,5	91	244
49	-1	-1	-1	-1	1	1	90	29,5	29,5	465	693
50	1	-1	-1	-1	1	1	75	30	30	465	876
51	-1	1	-1	-1	1	1	79	30,5	31	593	876
52	1	1	-1	-1	1	1	59	30,5	31,5	593	1141
53	-1	-1	1	-1	1	1	92	27	27,2	92	337
54	1	-1	1	-1	1	1	77	27	27	92	235
55	-1	1	1	-1	1	1	82	27	27,7	91	346
56	1	1	1	-1	1	1	63	27	27,7	157	244
57	-1	-1	-1	1	1	1	44	30,5	30,5	597	1069
58	1	-1	-1	1	1	1	30	31	31	597	1069
59	-1	1	-1	1	1	1	38	31,5	32	770	1571
60	1	1	-1	1	1	1	22	32,7	33,2	910	1772
61	-1	-1	1	1	1	1	47	27	27,2	158	235
62	1	-1	1	1	1	1	35	27,7	27	252	235
63	-1	1	1	1	1	1	43	27	27,5	250	346
64	1	1	1	1	1	1	28	27,5	27,5	250	346

Appendix 10: Climate data, summary

	Investigations results	Chosen value	Comments	Sources
Temperature	*see BV2 climate file*			
Humidity				
Precipitation rate(mm/year)	654 mm/year		Low precipitaion rate (rain season lasts 4 months). Strong negative balance that explains high lack of water	*SMN (National meteorological service)*[1]
Evaporation rate (mm/year)	2204 mm/year			
Relative humidity (%)	45%		Rather low rate (Sweden 78%)	
Wind				
Main direction	Mainly north-eastward			*Leon Airport*
Average annual velocities (m/s)	5,5	5,5	Approximations for wind velocities have to be taken with good care	*Inovatek and E2energias providers*[2]
	4,4-6,5			[3]
Sun				
Average radiation (kWh/m².day),***	6,4*0,83=5,31	5,42		*From Heliodon software*[4]
	5,79			*Inovatek and E2Aenergias providers*[2]
	6,56*0,83=5,44			*CONCYTEG*
	5,87-7,14 (mean=6,5) 6,5*0,83=5,4		Site specific range of data	[3]
	6,2*0,83=5,15		Extrapolated values from SMN data	*CIATEC estimations*

Notes

[1] *http://smn.cna.gob.mx/*

[2] *Unknown source. Both providers give same values.*

[3] *Fisrtlook data base recomended by Mexion wind consulting company . At http://firstlook.3tier.com*

[4] *Heliodon software's demo version is available at http://www.heliodon.net/heliodon/software.html*

Comments:

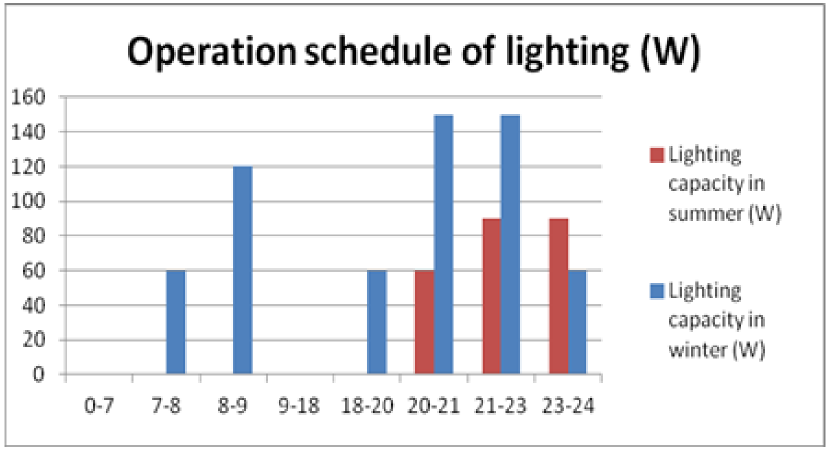
** A 0,83 factor is applied to take meteorological influence into account*

*** Inclination angle optimization is neglected. It almost doesn't affect energy fluxes on a daily basis*

Appendix 11: Electricity consumption scenario

Summer	time slots									Total
	0	7	8	9	18	20	21	23	24	
	0-7	7-8	8-9	9-18	18-20	20-21	21-23	23-24		
Number of bulbs						4	6	6		
Lighting capacity in summer (W)						60	90	90		90
Numbers of hours per time slot (hours)	7	1	1	9	2	1	2	1		
Electricity demand (Wh/day)	0	0	0	0	0	60	180	90		330

Winter	time slots									Total
	0	7	8	9	18	20	21	23	24	
	0-7	7-8	8-9	9-18	18-20	20-21	21-23	23-24		
Number of bulbs		4	8		4	10	10	4		
Lighting capacity in winter (W)		60	120		60	150	150	60		150
Numbers of hours per time slot (hours)	7	1	1	9	2	1	2	1		
Electricity demand (Wh/day)	0	60	120	0	120	150	300	60		810



TOTAL for Lighting	**Summer**	**Winter**	**Others**	**TOTAL**
Time period (months)	3,60	2,40	6,00	**12,00**
Electricity demand (Wh/day)	330,00	810,00	570,00	**546,00**
Electricity demand (kWh/year)	36,83	60,26	106,02	**203,11**
Electricity demand (kWh/m².year)	0,39	0,64	1,13	**2,16**

<u>Comments:</u>

All days are considered as if they were week-ends' days.

Summer is defined as the 30% warmest days (3,6months), winter as 20% (2,4 months) and value for the left 6 moths are average (BV2, standards)

The electricity demand for lighting equals 2,2 kWh/m².year which is way less than the Minergy label (swiss) that recommend 13,89 kWh/m².year; the lighting might not be sufficient

		time slots																	TOTAL	
		0	3	4	8	9	11	12	13	14	15	16	18	19	20	22	23	24		
Equipment	**Capacity (W)**	**0-3**	**3-4**	**4-8**	**8-9**	**9-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-18**	**18-19**	**19-20**	**20-22**	**22-23**	**23-24**		**Annual consumption (kWh/year)**	**Daily operation time (hrs/day)**
Fridge	140		140		140		140				140			140					255,5	5
TV big size	55				55			55						55	120	120			60,225	3
hot plate (double burner)	1000				1000			1000						1000					1095	3
DVD	25														25	25			27,375	3
Music player	60						60					60							65,7	3
Wash-machine	400						400	400											292	2
TV small size	30				30							30			30	30			65,7	6
TOTAL																				
Installed Capacity With HP (W)		0	140	0	1225	0	600	1455	0	0	140	90	0	1195	175	175	0		1455	
Installed Capacity Without HP (W)		0	140	0	225	0	600	455	0	0	140	90	0	195	175	175	0		600	
Number of hours per time slot (hours)		3	1	4	1	2	1	1	1	1	1	2	1	1	2	1	1			
Energy consumption With HP (kWh/day)		0	0,14	0	1,225	0	0,6	1,455	0	0	0,14	0,18	0	1,195	0,35	0,175	0		5,46	
Energy consumption Without HP (kWh/day)		0	0,14	0	0,225	0	0,6	0,455	0	0	0,14	0,18	0	0,195	0,35	0,175	0		2,46	

Global consumption (lighting + equipments)	
Surface (m^2)	94,00
Required installed production capacity (kW)	720,00
Electricity consumption (kWh/day)	3,01
Annual electricity consumption (MWh/year)	1,10
Annual electricity consumption ($kWh/m^2.year$)	11,67