INTERNATIONAL
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Towards Net Zero Energy Buildings

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

OCTOBER 2012
THESSALONIKI – GREECE

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Abstract

This dissertation was written as part of the International Hellenic University MSc in Energy systems. In it, the evolution of energy and environmental policies which are the main drivers for the wide adaptation of Net Zero Energy Buildings are presented. Moreover extensive review of many pioneering passive and hybrid systems responsible for space conditioning and DHW are described and assessed in an attempt to evaluate under which conditions each system is considered appropriate and operates efficiently. These system reviews are followed by the description of some demonstration NZEB projects which incorporate some of the aforementioned systems in appropriate combinations in order to achieve zero energy balance. Finally a residential building constructed by C. BAKALAS S.A. Construction Company in Athens, Greece which incorporates advanced HVAC systems and insulation and achieves near NZEB performance is extensively reviewed as a commercial example of all the aforementioned systems and methods. Moreover a scenario under which this becomes a truly NZEB is included in this review.

Finally, I would like to thank Dr. Dimitrio Anastaselo for his support, assistance and guidance during this endeavor from the beginning until the completion of this dissertation on such an interesting and appealing subject.

Dimitrios Konstantinidis

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Contents

1. Introduction

In the last decades, events such as the oil crisis, the depletion of natural resources and large scale catastrophes attributed to the environmental change for which pollution is responsible have caused considerations among the developed and developing countries which led to a new era of policies focused on sustainability and the preservation of the environment. These policies are focused on the production of energy from renewable and clean sources and the reduction of energy consumption through increased efficiency and increased environmental awareness of the population.

Since in developed countries the building sector is responsible for the 40% of global energy consumption and at the same time 30% of direct and indirect green house gas emissions [IEA Energy Technology Perspectives: Scenarios and Strategies to 2050], it was clear that the entire philosophy under building construction should be altered. This change led to concepts such as net zero energy buildings (NZEB) and green buildings.

According to the EU Directive 2010/31; a net zero energy building is a building with extremely high energy efficiency which is determined by the efficiency of the appliances, heating cooling and ventilation systems, lighting etc. and the characteristics of the insulation used. This highly efficient building’s energy consumption should be a small fraction of the energy consumption of a conventional building and an amount of energy equal to the one consumed by the building throughout the year must be produced locally from clean and renewably energy sources; thus reducing the overall energy consumption to zero.

Green buildings differ from NZEB since they focus on environmentally responsible methods and resource efficient materials throughout the buildings life from construction to demolition. Although green building design is concerned with reducing water consumption and the efficient use of energy, it is the NZEB that takes into account all these variables that are affected by daily life, appliance and HVAC system operation etc. that provide more detailed data on energy consumption and ways to reduce that.

This dissertation focuses on the design and systems that can be incorporated in a NZEB and is not concerned with construction methods or the environmental impact of the materials used.

More precisely in chapter two is presented an overview of the legislation and policies that promote NZEB in developed and developing countries. The European Union states and U.S.A. for example with their high standard of living have the potential to considerably reduce energy consumption in the building sector through highly efficient appliances which can easily replace older energy intensive ones and through building renovation further reduce the energy needed for space conditioning without compromising the comfort of the residents. China on the other hand which has at the moment a rapidly developing building sector aims to incorporate energy saving measures during the construction of new buildings and avoid the need of renovation in the near future. The policies of other countries which present innovative solutions regarding NZEBs such as Japan and Canada are also presented.

In the following chapter an extensive review of many experimental or pioneering passive systems for space conditioning are described. Passive systems take advantage of the environmental conditions such as wind or insolation in order to provide a desirable effect into the conditioned space which otherwise would be provided by an energy consuming system. The principals under which each system operates is described in the beginning which is followed by the implementation of the system in a demonstration project and the assessment of its effect on energy consumption under various parameters including weather conditions, seasons, location etc.

Chapter four is used to describe hybrid systems that can be integrated in NZEB. Hybrid systems combine passive and active systems to provide space conditioning. They usually consist of highly efficient active (energy consuming) systems which are complemented by passive ones and can achieve high degree of utilization when cleverly designed. Energy consumed by the active systems is replenished by locally produced clean and renewable energy. Chapter four has the same structure with chapter three, meaning system description followed by assessment through the integration on a demonstration project.

In chapter five some demonstration projects of NZEB are being reviewed. In each occasion, studies suggest appropriate combinations of passive and hybrid systems described in the previous chapters along with specific orientation, design and interior layout which further enhance the building efficiency when chosen appropriately.

In chapter six a near NZEB constructed in Athens, Greece is presented. Describing a materialized commercial implementation of a near NZEB results in increased validity of the systems and design methods used in the rest demonstration projects since it takes into account many factors such as increased cost of construction and of HVAC systems, urban regulations and everyday life specificities. Such project can reveal over time any misconceptions adopted by the design and construction methods, resulting in their improvement. Moreover energy consumption data are presented and a scenario under which the building can become a NZEB is discussed.

Finally in the last chapter the most important conclusions extracted from the system and NZEB presentation and analysis are explained.

2. Legislative Framework Review

The energy policy of most countries before the first oil crisis of 1973 had the single target to satisfy energy demand, without any provisions for the environmental impact of the steadily growing consumption or the energy security of each individual country. After the oil crisis though, energy policies turned to the diversification of energy sources and energy demand reduction mostly through increased energy efficiency. In most developed or developing countries, the building sector consumes up to 40% of the country's total energy demand and as a result it became apparent early on that it had to be thoroughly regulated in order for energy policy targets to be achieved. Below we reference the legislation frameworks focusing on energy efficient and zero energy buildings of the European Union and other countries that possess a leading role in energy conservation in the building sector.

2.1 European Union

European Union's general direction in its environmental policy is expressed by the "Climate Change and Energy Package" or "20-20-20", adopted in 2008. It states that until 2020 each member state must reduce its ghg emissions by 20% below 1990 levels, increase energy efficiency by 20% compared to projected levels and achieve 20% penetration of renewable energy sources [1]. In the European Union, buildings are accountable for 40% of total energy consumption [2]; as a result any improvements in the building sector with regard to energy consumption would be a significant step towards the aforementioned goals.

The first significant step was made with Directive 2002/91/EC on the Energy Performance of Buildings. Its purpose is to improve the energy performance of buildings within the EU and this is achieved by the issuance of "Energy performance certificates", showing that specific performance requirements are met. Moreover regular inspection for boilers and air-conditioning systems became mandatory in order to ensure their good operating condition which translates in higher efficiencies and reduced ghg emissions compared to insufficiently maintained ones [3].

Directive 2002/91/EC has been amended by Directive 2010/31/EU which specifies up to a degree the methodology for calculating the energy performance of buildings; sets minimum performance requirements for new and existing buildings and, having in mind the move towards smart electricity grids, encourages the installation of intelligent energy monitoring systems. Furthermore it sets a target for all new privately owned buildings to be nearly zero-energy consuming until 2020 and those serving public purposes should comply by the end of 2018. In order to provide a smooth transition from existing buildings to high performance and in the future zero-energy ones, the directive takes provisions by setting intermediate targets for the performance of building by 2015 and by adopting financial incentives for the improvement of existing ones [4].

Two more directives supporting the promotion of zero-energy buildings are Eco-Design Directive 2009/125/EC and Energy End-Use Efficiency and Energy Services Directive 2006/32/EC. The purpose of Eco-Design Directive is to contribute to sustainable development by establishing a framework that sets mandatory requirements for the production of highly efficient appliances and other non energy consuming products such as windows that contribute in the performance of a building by providing air tightness and improved insulation. While the directive primarily aims to reduce energy consumption it also has a wider goal to reduce the environmental impact by setting rules for material use; water use; waste issues etc. Furthermore by setting the same standards across Europe it ensures the free movement of such products within the EU market [5]. Directive 2006/32/EC aims to eliminate hurdles that deter the efficient use of energy by setting indicative measures, as well as economic and legislative frameworks. It creates appropriate conditions for the promotion of an energy service oriented market, so that ultimately energy saving programs as well as measures related to the improvement of energy efficiency can be applied [6].

2.2 United States of America

In the U.S., although the energy and environmental policy is determined by federal legislation, each state is allowed to have specific programs and incentives in order to achieve the goals stated by the federal government.

Energy Policy Act of 2005 is a legislative framework aiming to combat increased energy consumption and environmental impact. Among its many provisions, it provides fiscal incentives to those making energy conservation improvements to their houses and for energy efficient commercial buildings [7].

This is followed by the Energy Independence and security Act of 2007 which addresses subjects such as energy independence and security and customer protection. Its purpose among others is to achieve increased renewable energy production and increased efficiency of energy consuming products and buildings. For energy consuming devices, it sets efficiency standards for many energy intensive appliances; demands 25% greater efficiency for light bulbs by 2014 and 200% by 2020 and bans the manufacturing of low efficiency incandescent light bulbs. Additionally, great reference is given to the building sector, since industrial and commercial buildings are accounted for half of United States energy consumption [8]. For the promotion of energy efficient buildings, an Office of Commercial High Performance Buildings has been created and aggressive targets have been set. These targets require that all commercial buildings must be net zero energy buildings by 2050. Moreover, by 2020 federal buildings must reduce fossil fuel use 80% compared to 2003 levels and all new federal buildings must be carbon neutral by 2030. Finally subsidies are created for the construction of energy efficient educational and other public institutions [9].

Although not yet signed by the United States President, the Energy Savings and Industrial Competitiveness Act of 2011 will likely by the next legislation framework upon which United State’s energy policy will be based. According to it, the buildings sector is responsible for 40% of the countries’ primary energy, thus it describes investments in building efficiency as one of the most cost-effective energy saving measures possible. It is targeted to achieve net zero energy buildings by 2030 and it is estimated that if successful $90 billion would be saved each year because of the reduced energy consumption [10]. Furthermore, appliance and HVAC standards are provided with the consent of manufacturers and plans are made for worker training in energy efficient building design and operation. Additionally, fiscal incentives are provided to those who are willing to make energy-efficiency improvements to their homes or businesses or other existing buildings [11].

2.3 Canada

In Canada, like in the U.S. each state is responsible for defining a specific legislative framework related to energy efficiency in the building sector; however there exists the Energy Efficiency Act of 1992 (amended in 2009) along with its accompanying Energy Efficiency Regulations and their regular amendments that express Canada’s energy and environmental policy. In Canada the trade of a range of energy-using products that do not comply with the energy efficiency standards is prohibited [12]. With recent amendments the range of these products became wider and new minimum energy performance standards were introduced [13]. Moreover, Canada with programs such as the Eco-Energy Retrofit Program which offers financial incentives for reducing the energy needs of houses [14]; energy efficiency standards for buildings such as the R-2000 standard [15] and energy efficiency rating programs for houses [16], promotes the reduction of energy consumption in the building sector. With its policy Canada aims to achieve a 20% absolute reduction of its ghg emissions by 2020 [17].

2.4 Japan

Japan, concerned by the oil crises of 1970 passed the first Energy Conservation Law in 1979 which was later amended multiple times. Although the initial purpose of the law was strictly energy conservation and energy security; in 1993 because of increasing environmental issues and concerns it was revised from "in consideration of Japan’s energy situation in which there is no choice but to depend on imports from abroad for fuel resources" to "to meet the economic and social environment of energy at home and abroad" [18], introducing new goals such as climate change mitigation.

Initially, the law focused in the energy conservation of the industrial sector. In the building sector, obligations apply only to constructors building more than 150 buildings per year. For the rest it was limited in providing guidelines and advice for achieving greater energy efficiency. The same approach was followed for energy intensive equipment and appliances. Additionally for these, labels informing about their efficiency were made mandatory. This loose approach had as a result a significant increase of 44% in energy consumption in the building sector between 1979 and 2007, as opposed to the industrial sector where consumption fluctuated slightly.

To remedy the increased energy consumption, Japan initiated “Top-Runner” program in 1999 (reinforced in 2006) which set energy efficiency standards for appliances [19]. Moreover, in the building sector, the 2008 amendment of the Energy Conservation Law required that before the construction or renovation of a building, a notification of energy-saving measures should be submitted to the relevant authorities. These authorities have the ability to intervene and impose further improvements if the original energy saving measures proves to be insufficient.

In order to achieve further reduction of energy consumption the Japanese government has resorted to informative campaigns in an attempt to educate the public regarding energy consumption and has established organizations such as the “New Energy and Industrial Technology Development Organization” (NEDO) which focuses on energy efficiency through improved equipment installation; “Japan Electro-Heat Centre which is occupied with the efficiency of HVAC systems and “Conference of LP Gas Associated Organizations” promoting the installation of highly efficient water heating systems [20].

2.5 China

In China, the residential building sector account for approximately 30% of its final energy consumption and it is estimated that it will rise for 1.1% every year due to continuous urbanization [21]. Moreover, of great importance are the facts that residential buildings in china consume between 50 to 100% more energy to cover their heating needs compared to buildings in the same climatic zone in Europe and North America [22] and that the life-cycle of buildings in china is much shorter in relation to buildings in industrialized countries [23]. All the above, along with the prediction that by 2025 half of the global building construction will take place in china [24], underline the importance of the promotion of energy efficient buildings since they provide many advantages such as greater security of supply through reduced energy consumption, health and comfort by improved building designs, social welfare because of lower energy bills and finally, energy efficient buildings can be an important factor to economic growth.

Fortunately, in China, there is an ambitious strategy that promotes improved energy efficiency in the building sector, expressed by legislation frameworks, policies and incentives. Initially in 1998 came in effect The Energy Conservation Law of the People’s Republic of China. It states that “Building designs and construction shall (…) employ energy-saving types of construction strictures, materials, facilities and products, improve heat insulation properties and reduce energy consumption for space heating, cooling and lighting” [25]. In the amendment of 2007, non-compliance with energy efficiency standards became punishable and in order to urge local government officials to enforce the corresponding legislation, it is explicitly stated that the fulfillment of energy conservation targets plays important role in the evaluation of the local government [26].

The Renewable Energy Law of the People’s Republic of China entered into effect in 2006 and its subject among others is to promote the integration of renewable energy sources in public buildings. The Ministry of Housing and Urban-Rural Development was obliged to develop technical standards for the integration of renewable energy sources into buildings and financial incentives were given to house owners in order to facilitate the installation of renewable energy appliances [27] or for the retrofitting of existing energy intensive buildings.

Currently, increased uncertainty in the energy sector and high oil prices encourage roughly all developed and developing countries to adopt similar legislation frameworks and energy policies that promote increase energy efficiency and clean and renewable energy production.

3. Passive Solar HVAC systems

Solar passive systems combine collection and storage in one system, offering simple and inexpensive means of space conditioning. They can prove to be very reliable since they rarely involve the use of mechanical and electrical devices and if such a system takes fool advantage of the local climate in can be very efficient. There are various principals that allow the use of solar energy to effectively heat or cool a space. Briefly, some of the most common principals used for heating are:

- Sun-tempering. Most houses are sun tempered to some degree. In the north hemisphere, all south facing facades receive solar radiation which translates to heat gains for buildings. Appropriate design of the south facing building elements and larger windows can increase this effect and as a result reduce heating needs during winter months.
- Passive capturing of solar thermal energy and convection of that energy into a building through a heat transfer medium (air or water).
- Direct capture of solar thermal energy in the heated space and storage of this energy in a thermal mass integrated in the internal walls or the floor.
- Trombe wall or thermal storage wall. Solar energy is captured and stored in an appropriate thermal mass such as a water tank behind glass or a concrete wall [28].

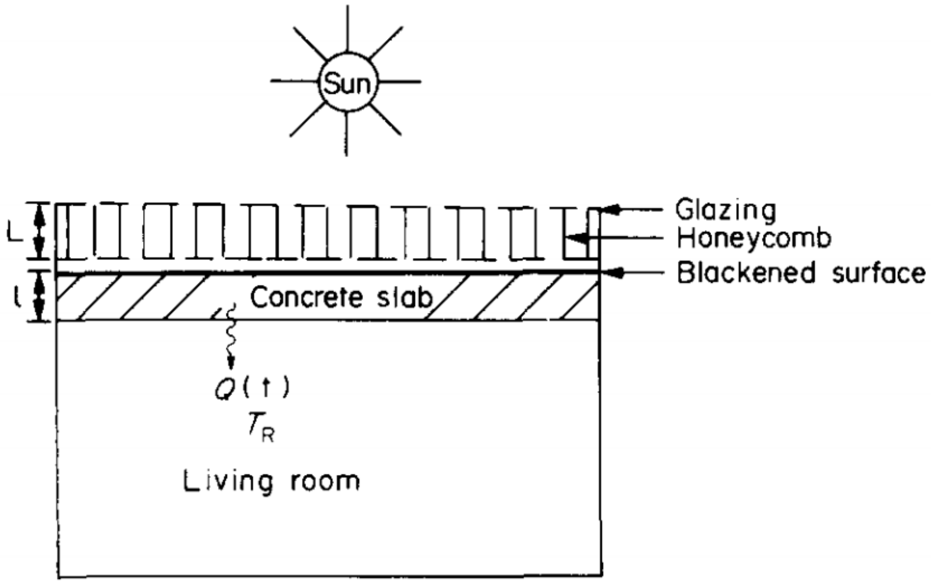
By using one or a combination of the above principals we can achieve through appropriate systems or more advanced hybrid systems sufficient space conditioning in residential and commercial buildings and thus reducing one of the most energy intensive needs a building has.

3.1 Honeycomb Roof Cover

Although direct gain passive heating methods offer good collection efficiencies, they present the disadvantage of glare and material degradation due to direct solar radiation in the living space, thus indirect passive solar heating is more preferable. The simplest configuration is a concrete roof slab with black coating on the surface. It is attributed with high thermal capacity and good insulation properties, however, large heat losses through the surface prevent it from heaving high solar collection efficiency. An alternative solution, remedying to a degree the aforementioned shortcomings is the honeycomb roof cover.

3.1.1 System Description

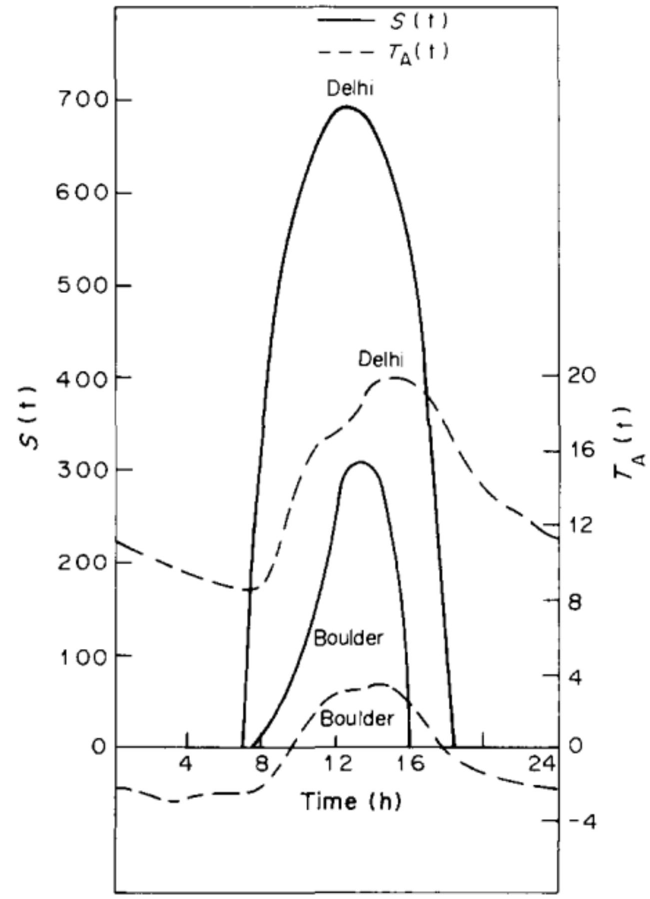
This system consists of a honeycomb like structure, placed above a concrete roof or heavy-duty galvanized iron sheets (Picture 1). On top of the honeycomb, exposed to external air from the top side, there is glazing which partially reflects and absorbs the incident solar radiation. Insolation that goes through the glazing is trapped inside the air filled honeycombs where it is further absorbed by the honeycomb surfaces and the blackened absorber plate. Because of the relatively large surface area created by the honeycomb and the entrapment of the infrared solar radiation by the glazing, the absorption is much greater and heat losses are considerably lower compared to a simple black coated concrete roof. Furthermore the small concealed spaces created by the honeycomb structure minimize convection losses. The concrete roof is considered as part of the system and provides heat storage as well as load leveling of the heat flux. The galvanized iron sheets will not provide any kind of thermal storage but the heating effect of the conditioned space will be much faster, as a result this is more appropriate for spaces occupied only during the day.



Picture 1: Honeycomb roof schematic

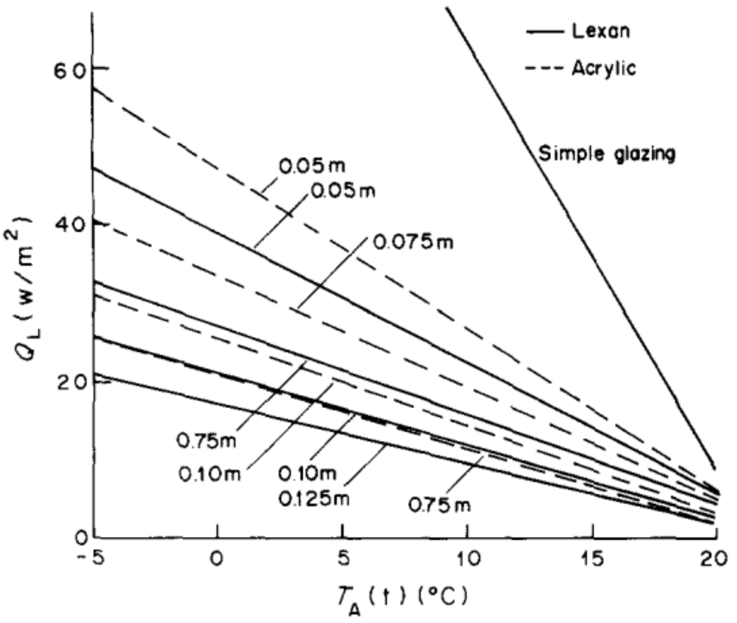
3.1.2 System Assessment

The system has been demonstrated in New Delhi (28^{O}N) and in Boulder (40^{O}N). In picture 2 the air temperature “T_A(t)” and the insolation “S(t)” during a typical winter day in New Delhi and during a cold winter day in Boulder are depicted.



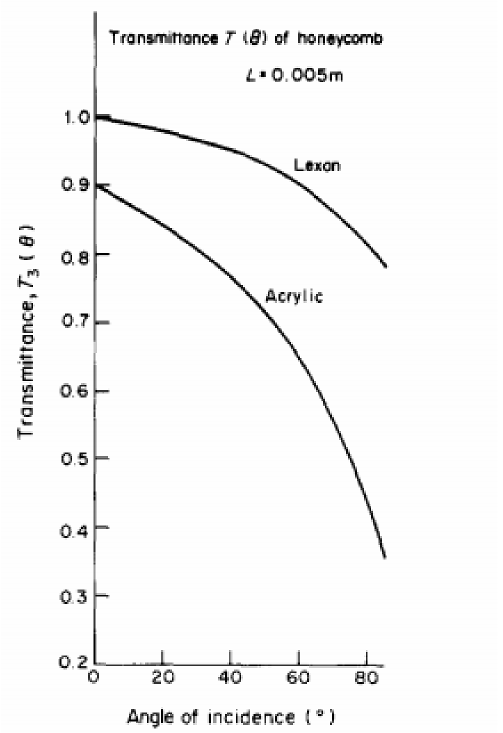
Picture 2: Variation of solar intensity and ambient air temperature in Boulder and New Delhi

For this demonstration square cell honeycombs, with 1.25 cm sides and variable height, which are constructed of thin lexan film or acrylic sheet have been used. Picture 3 depicts the thermal losses “Q_L” through the cover system for various ambient temperatures and different honeycomb depths. Heat losses for simple glazing refer to zero depth, thus no honeycomb structure is present between the glazing and the absorber. The conditioned space temperature “T_R” is assumed to be 20^{O}C. From this picture it is apparent that a 12.5 cm high honeycomb structure made out of lexan is the most efficient solution.



Picture 3: Variation of thermal losses with ambient temperature and different honeycomb depths

Furthermore it is observed that the higher the angle of incidence in a location is, the lower the solar transmittance is (picture 4).



Picture 4: Variation of solar transmittance of honeycomb (L=5cm) with angle of incidence

In table 1 the solar collection efficiencies during sunlight hours are presented for both test locations. Although the collection efficiencies at New Delhi are higher in all cases compared to Boulder, the honeycomb structure can be considered more advantageous in Boulder than in New Delhi. This can be explained because the reduced solar transmittance in Boulder due to its high latitude is compensated by the reduction in heat losses which in return result to longer periods of heat retention during night hours. Therefore high latitude may not be considered as a disadvantage for this system. The collector efficiency is provided by the function

$$\eta(t) = (\alpha\tau)_{eff}\,(t) - \frac{Q_L(t)}{S(t)}$$

Where $(\alpha\tau)_{eff}$ is the effective absorptivity - transmittivity product of the honeycomb cover.

Table 1: Solar collection efficiencies in New Delhi and Boulder

	Boulder			**New Delhi**		
Parameters	**Glazing**	**Acrylic**	**Lexan**	**Glazing**	**Acrylic**	**Lexan**
Q_L(W/m^2)	107.9	43.2	35.6	29	12.9	11
Q_L(W/m^2) night	131.3	50.4	41.5	48.6	22.8	19.1
$(\alpha\tau)_{eff}$	0.705	0.42	0.675	0.719	0.478	0.705
S(t)	178	178	178	560	560	560
H	0.1	0.177	0.475	0.667	0.455	0.685

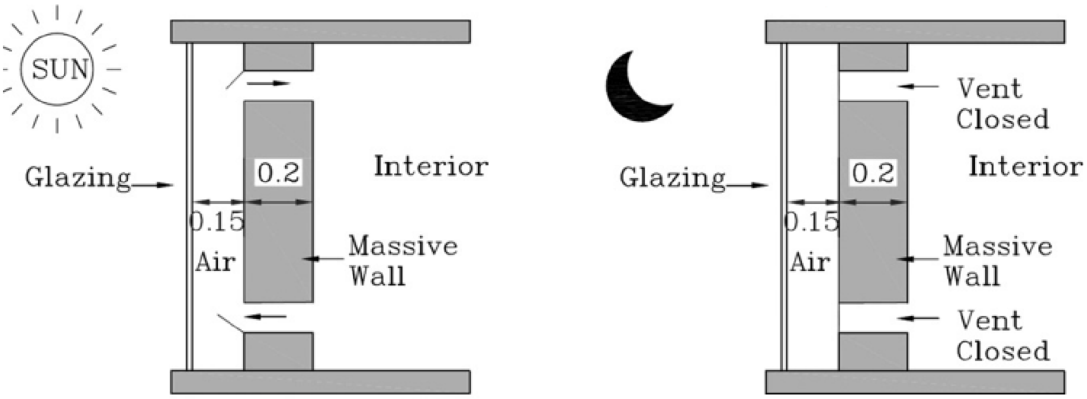
From the above we can assume that the honeycomb roof cover is an attractive solution for cold climates when it comes to passive solar heating [29].

3.2 Trombe Wall

Trombe wall is a popular system that incorporates a simple principal for capturing solar energy and using it for space heating that can be integrated into walls.

3.2.1 System Description

In the north hemisphere, Trombe wall is a south facing wall usually coated with a material that highly absorbs heat, with glazing separating the wall from ambient air. The glass is distanced from the wall so that air can flow in between and vents are placed at the bottom and top of the wall allowing the air flowing between the wall and the glazing to move to the conditioned space. Glazing with high ultraviolent transmittance from the outside and high reflectivity of the visible and infrared spectrum from the inside is desired for better performance. The system works as follows. Solar radiations pass through the glass heating the Trombe wall. The wall, having an increased temperature, emits back in the infrared spectrum but because of the high reflective properties of the glass in this spectrum, radiation is trapped between the glass and the wall minimizing thermal loses. Meanwhile, cold air enters from the lower vents and as it comes in conduct with the wall it is heated by convection, becoming less dense and rising until it exits from the upper vents into the conditioned space (picture 5). The air flow is controlled through opening and closing the vents, thus having the ability to control the temperature, block the air flow when space heating is not desirable or preventing heat losses from the vents during night hours. If a wall with sufficient thermal mass is used and there is adequate solar irradiance through the day, this system allows for heating during night hours taking advantage the heat stored in the wall during the day.



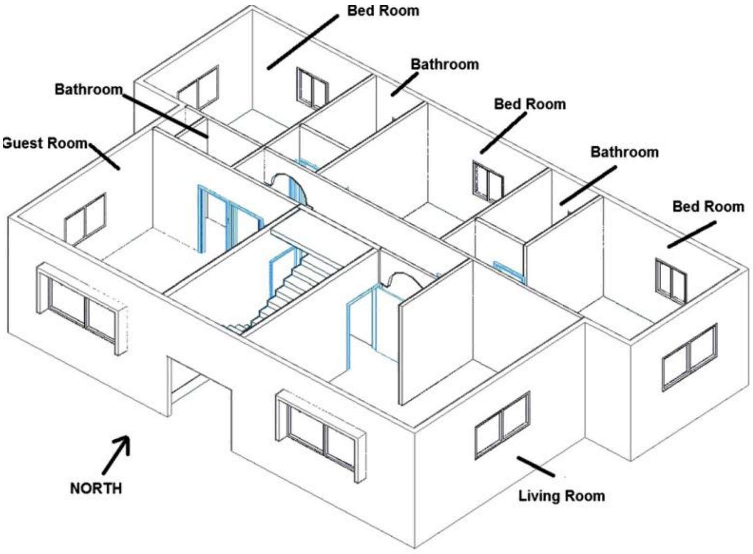
Picture 5: Trombe wall operating during the day (left) and with closed vents during the night (right)

While it is used primarily for space heating, an improved design of the Trombe wall with install dampers on the glazing allow for partial passive cooling during summer as well. Two adjustable dampers, one at the height of the lower vent and one at the height of the upper vent are installed at the glazing. During the summer, the lower dumper and upper vent are closed, while upper dumper and lower vent are left open. The buoyancy of the heated air between the glazing and the wall draws air from the conditioned space through the lower vent and upper damper out of the building, thus providing increased ventilation inside the room during the summer period [30].

Trombe walls may be used in conjunction with semitransparent photovoltaic panels to create a hybrid system that at the same time provides electricity and useful heat for conditioned spaces. In this case the glazing is replaced by a PV panel creating an integrated photovoltaic thermal system (BIPV/T).

3.2.2 System Assessment

The Trombe wall system is tested in type of building called “Dar” in Amman, Jordan (picture 6). This type of buildings represents the 72% of the total residential buildings in Jordan [DOS, 2004]. The floor area is 154 m^2, the ceiling is 3 m high and in the south side of the building where the Trombe wall will be installed, windows consume 30% of the area. During winter, desired conditions are 20^{O}C for temperature and 30% relative humidity.



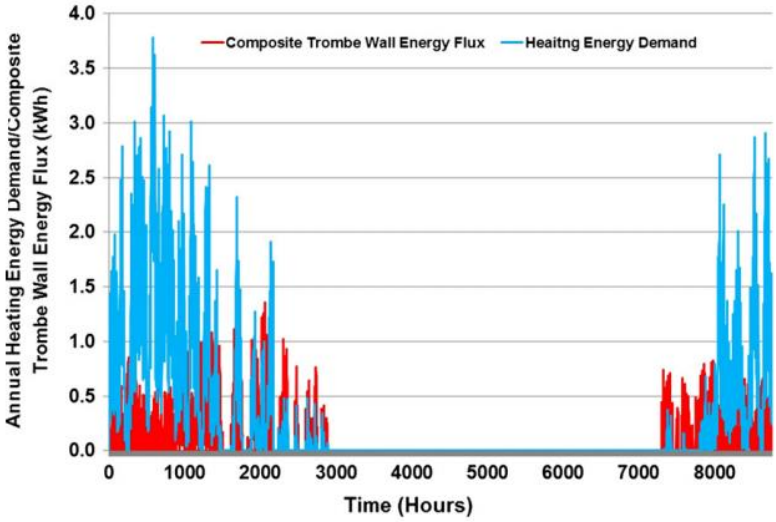
Picture 6: Building prototype

In this implementation, the Trombe wall is 20 cm thick covered with dark heat absorbing coating, in front of which a single layer glass is placed at a distance of 15 cm. It is assumed that when the building temperature is billow the desired set point, heat stored in the wall is extracted through air flow to cover the heating needs of the house. On the other hand when the building temperature is above the desired one, the excess energy is "damped" by installing insulation curtains in the gap between the glass and the wall. The detailed parameters of the Trombe wall are listed in the following table.

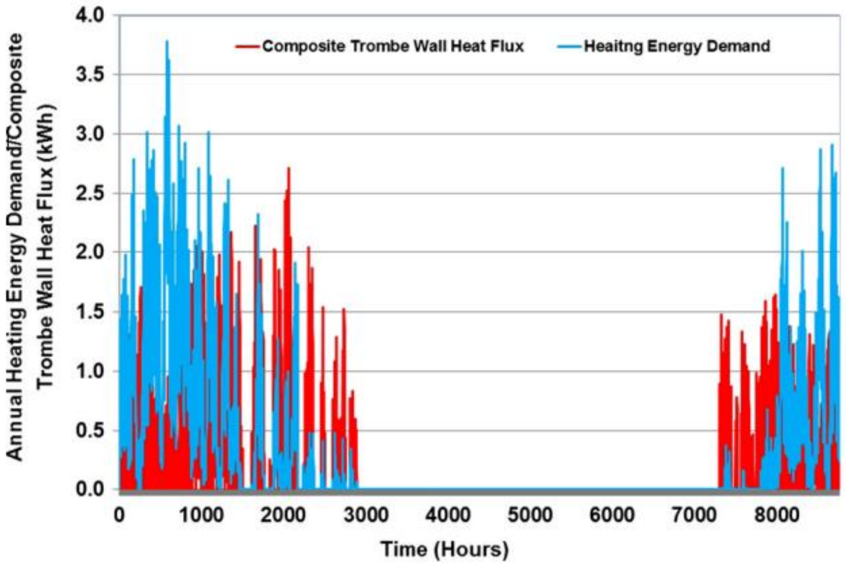
Table 2: Trombe wall parameters

Orientation	South
Wall height (m)	3
Wall thickness (m)	0.2
Wall thermal conductivity (W/m ^{O}C)	1.75
Wall specific heat x density (kJ/m ^{O}C)	1932
Wall solar absorbance	0.9
Glazing emittance	0.9
Space between wall and glazing 9m0	0.15
Number of glazing	1

Below are listed the results of this demonstration case. In pictures 7 and 8, heating energy demand and Trombe wall energy flux throughout a year are depicted in the case where the system is installed in two bedrooms or the bedrooms, guestroom and living room respectively and in table 3 the summary of the thermal analysis.



Picture 7: Trombe wall integrated to two bedrooms. Trombe wall ratio, 18%



Picture 8: Trombe wall integrated to two bedrooms, guestroom and living room. Trombe wall ratio, 37%

Table 3: Summary of thermal analysis

Trombe wall area ration (%)	0	18	37
Annual heating load (kWh)	2352	1892	1596
Max heating load (kW)	3.78	3.78	3.78
Specific energy (kWh/m^2)	15.27	12.09	10.36
Energy saving (%)	-	20.9	32.1
CO$_2$ reduction (kg)	-	289	455

Before adding the Trombe wall the annual consumption for space heating was 2352 kWh. In the first case where the system is implemented only in the two bedrooms (Trombe wall area ratio =18%) we observe that it is able to cover 20.9% of the total annual heating load, which is reduce to 1892 kWh. In the second case, the system is integrated to two bedrooms the guestroom and the living room (Trombe wall area ratio =37%) and its ability increases since the annual energy needed for space heating is reduced by 32.1% to 1596 kWh. It can be observed that the maximum heating load does not change with the implementation of the Trombe wall. Apparently during long cold period with minimum insolation, the wall is not heated and thus is unable to provide any aid in space conditioning. In such period all the heating needs must be covered with conventional means such as oil boilers [31]

Although Trombe wall has significant advantages such as simple configuration, zero running cost and high efficiency, it is not widely used because the walls visible black matt surface which is used for achieving better thermal absorption is found to be visually displeasing. Furthermore overheating of the spaces adjacent to Trombe walls may be caused during summer [32].

3.3 Passive Cooling by Evapo-reflective Roof

This model combines various existing systems used for passive cooling such as roof ponds, low emissivity surfaces and rocks with high thermal capacity in an attempt to provide higher efficiency and effectiveness compared to the rest of the systems alone. Initially the primary systems will be briefly described.

3.3.1 Subsystem Description

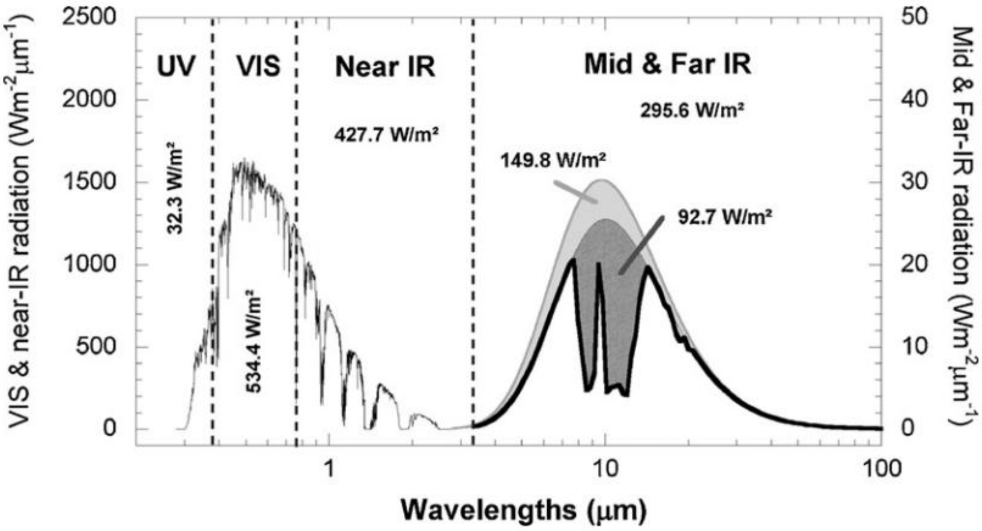
3.3.1.1 Roof Pond

Roof pond is an effective way to provide passive cooling by avoiding or delaying the effects of direct insolation in hot climates. In its simplest form it consists of a tank containing water on top of a roof. It is recommended that the water should be at least 30 cm deep. The water is heated by direct solar radiation or due to convection by the warm, because of its exposure to direct insolation, bottom of the pond. Simultaneously the water on the surface of the pond absorbs heat through evaporation until thermal equilibrium is reached. At the point of thermal equilibrium the heat gained by direct insolation and from the bottom of the pond is equal to the heat lost because of evaporation. Typically water temperature fluctuation is around 5^{O}C [33]. It is observed that an open roof pond 5 cm deep can reduce the temperature of a roof from 65.6^{O}C to 42.2^{O}C [34].

3.3.1.2 Low Emissivity Surfaces

The classic approach for reducing heat transfer through an opaque building element is by applying insulation on the internal surface of the wall or roof, thus providing resistance to heat transfer. A more innovative way is by applying materials on top of the surfaces with low emissivity properties in an attempt to achieve thermal equilibrium on these surfaces at low temperatures. An ideal material for this purpose should provide maximum reflectance of the entire solar spectrum reaching the Earth’s surface (Ultraviolent, Visible and Infrared), thus absorbing the smallest amount of solar energy possible and maximum infrared emissivity in order to reject any radiation absorbed in the form of heat.

For example, picture 9 depicts the spectrum of solar radiation reaching the Earth’s surface. The intensity of this radiation is 1290 W/m^2 for an ambient temperature of 15^{O}C. During the day, the spectrum can be separated in two components. The first consisting of UV, visible and near-IR comprises the 77.1% of total radiation and the second, for which earths background radiation and ambient air radiation are responsible, consisting of mid and far IR comprises the remaining 22.9% which corresponds to 295.6 W/m^2. It is observed that for a wavelength around 10μm there is a deficit of emissivity. During the night the second component is the only one present and it corresponds to 100% of received energy. The emitted spectrum of a black body at ambient temperature T_a=15^{O}C has its highest intensity for a wavelength of 10μm and corresponds to 388.3 W/m^2, as a result a material at the temperature of 15^{O}C can reject energy by radiating to the cold source which is the atmosphere. With appropriate sky conditions a surface can emit around 93 W/m^2 through IR radiation, thus radiative passive cooling is achieved.

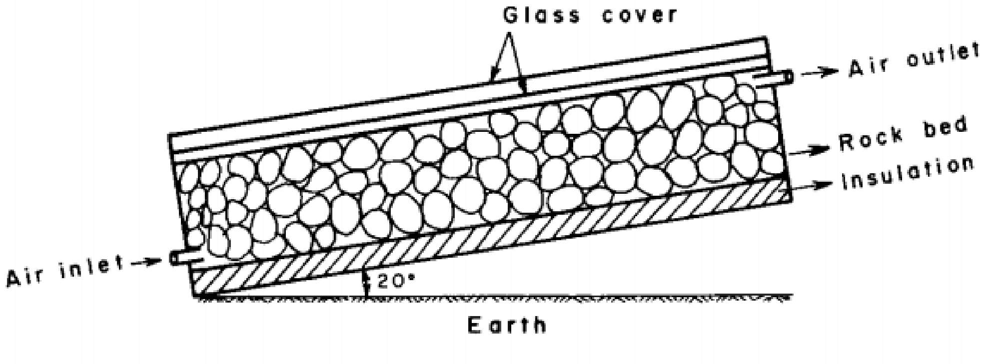


Picture 9: Solar spectrum. IR spectrum received to the Earth’s surface (thick line). Spectrum of a black body at 15^{O}C (dark gray). Spectrum of a black body at 30^{O}C (light gray)

The latest materials in this sector incorporate radiative mineral components in polymer matrix for film substrate or in liquid paint basis for easier application on roofs. To prevent the negative effects of photo degradation in thermoplastic films, the radiative materials are combined with anti-UV additives such as “hindered Amine Stabilizers” [35].

3.3.1.3 Rock Bed

Rock bed is exclusively used for sensible heat storage purposes. This can either be used in cold climates for storing thermal energy which can be then used to heat a space, or for storing undesired thermal energy and delaying excessive heat entering a conditioned space in hot climates. An example of a solar collector using a rock bed for storage device can be seen in picture 10. On top there is a solar collector and directly beneath it in an iron box 20 cm deep, rocks of around 5cm in diameter are stacked together. To minimize heat losses, the box is insulated from all sides except the top one which is the collector. The collector consists of glass which is placed 3cm above the top of the rock bed and to maximize the solar radiation absorption the top of the rock bed is sprayed black. Solar radiation is stored in the rocks as heat and when it is required, it is extracted from air whose circulation is aided by a motor. Cold air enters at the bottom of the collector and hot air exits at the top which can be later used for space heating.



Picture 10: Rock Bed Solar Collector

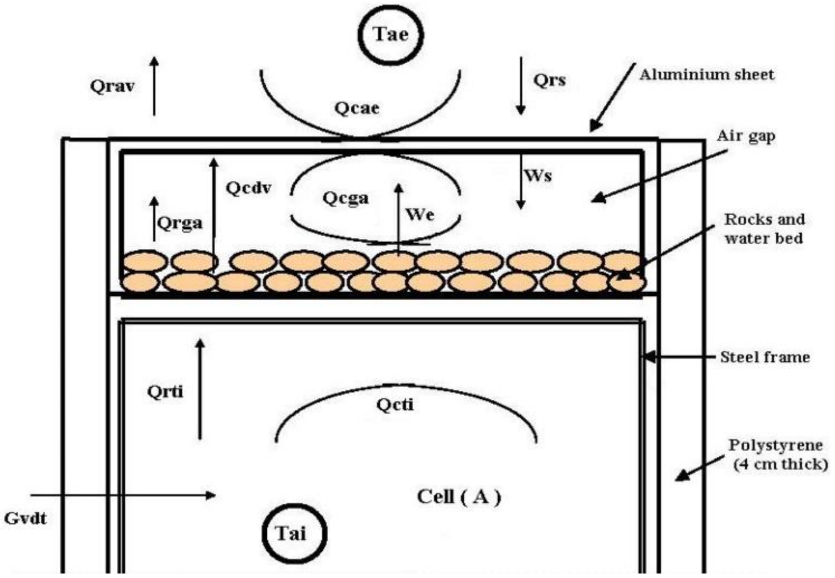
Although water has at least three times higher specific heat capacity than rock does, it poses disadvantages such as the need for properly insulated tanks, corrosion, leakage and freezing with the danger of destroying plumbing because of volume expansion. The only disadvantage of rocks is that for the same heating capacity they require more space. Moreover rocks are abundant and cheap thus they are preferable for system using solar heated air [36].

3.3.2 Evapo-Reflective Roof Description

This system can be considered as a passive cooling hybrid system that intergrades’ the aforementioned passive systems into one, aiming to provide increased cooling effect during the day into buildings in hot and dry climates.

3.3.2.1 System Description

The system is implemented above a flat concrete roof which consists’ the bottom layer. Above the concrete roof there is a layer of water (roof pond) mixed with high thermal capacity rocks (rock bed) followed by an aluminum sheet. Between the water layer and the aluminum sheet there is a layer of air. The system is tightly closed to prevent evaporated water escaping outside. The purpose of the aluminum roof is to prevent vapor escaping as already mentioned and to reflect part of the solar radiation away. The water and rock are both characterized by high thermal capacity and have the objective to store heat which otherwise would enter directly the conditioned space. An implementation of the Evapo-reflective roof is depicted in pictures 11 and 12 [37].



Picture 12: Evapo-reflective roof (all parameters are explained below)

- Tae: Outside air temperature
- Tai: Inside air temperature
- Qrav: Heat exchange through radiation between the roof and the sky
- Qcae: Heat exchange through convection between the roof and the outside air
- Qrs: Heat gain from solar radiation
- Ws: Heat change by condensation
- We: Heat change by evaporation
- Qrga: Heat exchange through radiation between the roof and the rock-water upper surface
- Qcdv Heat exchange by conduction between rocks
- Qcga: Heat exchange through convection between the air and rock-water upper surface
- Qrti: Heat exchange through radiation between the inside wall surfaces and the roof
- Qcti: Heat exchange through convection between the inside air and the roof
- Gvdt: Heat exchange between the inside and the outside through the walls and natural ventilation

Picture 12: Photo of the Evapo-reflective roof without the aluminum cover

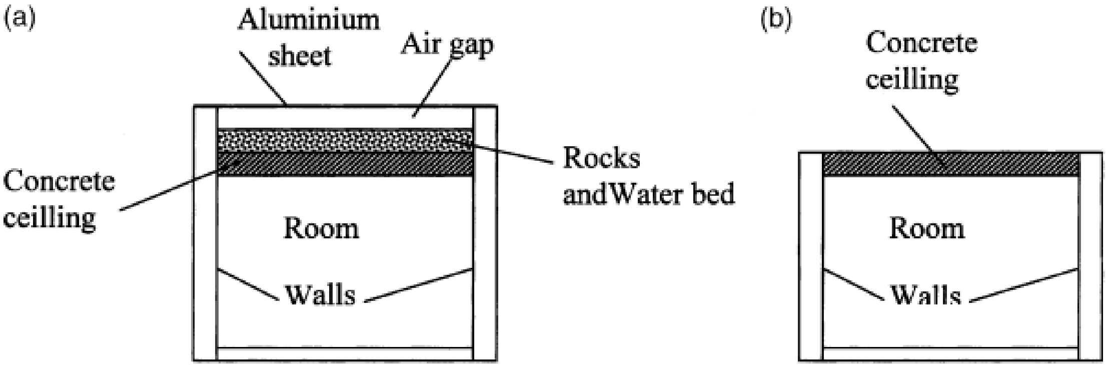
Since in hot and dry climates there is significant temperature fluctuation between day and night, this systems' purpose is to delay the effect of temperature change affecting the conditioned space by storing the solar radiation emitted on the roof in the form of heat during the day, thus preventing it from entering the conditioned space and causing thermal discomfort. During night hours, the stored heat is emitted back into the cold atmosphere in the form of infrared radiation, convection and evaporation. Again until all stored heat is rejected by the system the conditioned space remains relatively worm which might be a welcome feeling during the night. Overall, a building with this passive system installed should present much less temperature fluctuation compared to a conventional one.

3.3.2.2 System Assessment

In order to study the effectiveness of the Evapo-reflective roof system, a cubic room, assumed to be located in Laghouat, Algeria (latitude 33.46^{O} N) with 3 m sides was chosen. The openings consist of a window in the south wall and a door in the north wall. The simulated days were the 26th and 27th of July which are considered among the highest temperature summer days in this region. The specific characteristics of the materials used are listed in table 4 and their installation is depicted in picture 13.

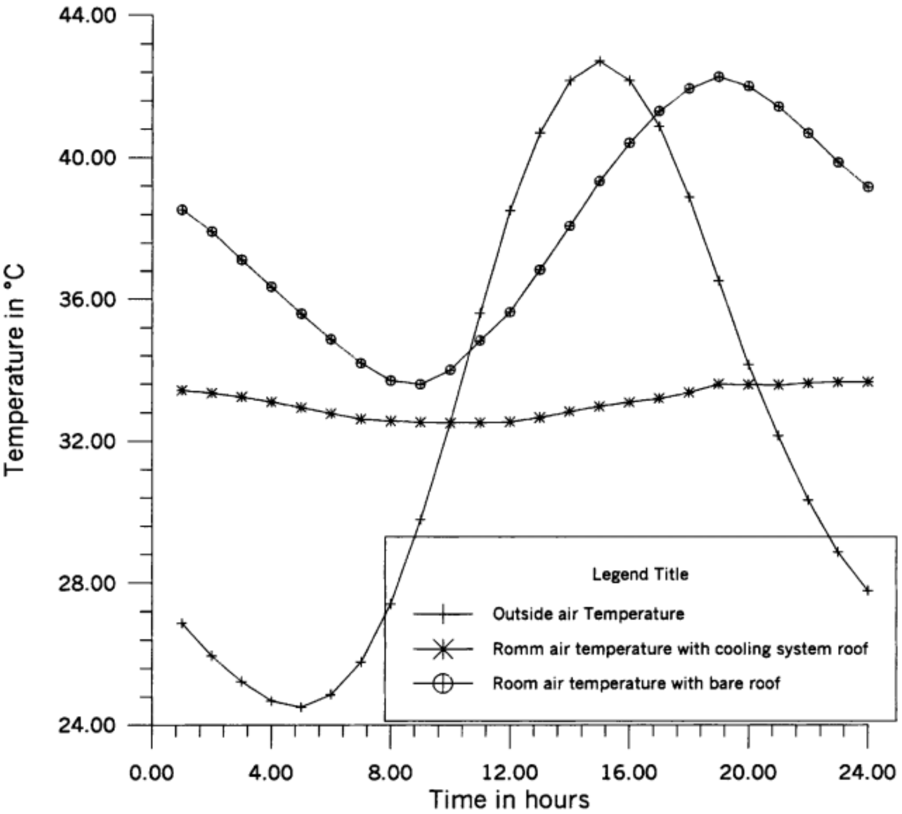
Table 4: Material properties

Element	Material	Thickness (m)	Density (kg/m^3)	Specific heat (j/kg K)	Conductivity (W/m K)
Roof	Concrete slab	0.1	2400	1080	1.8
	Rocks	0.1	2600	800	2.3
	Water	0.07	1000	4175	0.613
	Aluminum	0.005	2750	936	204
Walls	Concrete slub	0.2	2400	1080	1.8

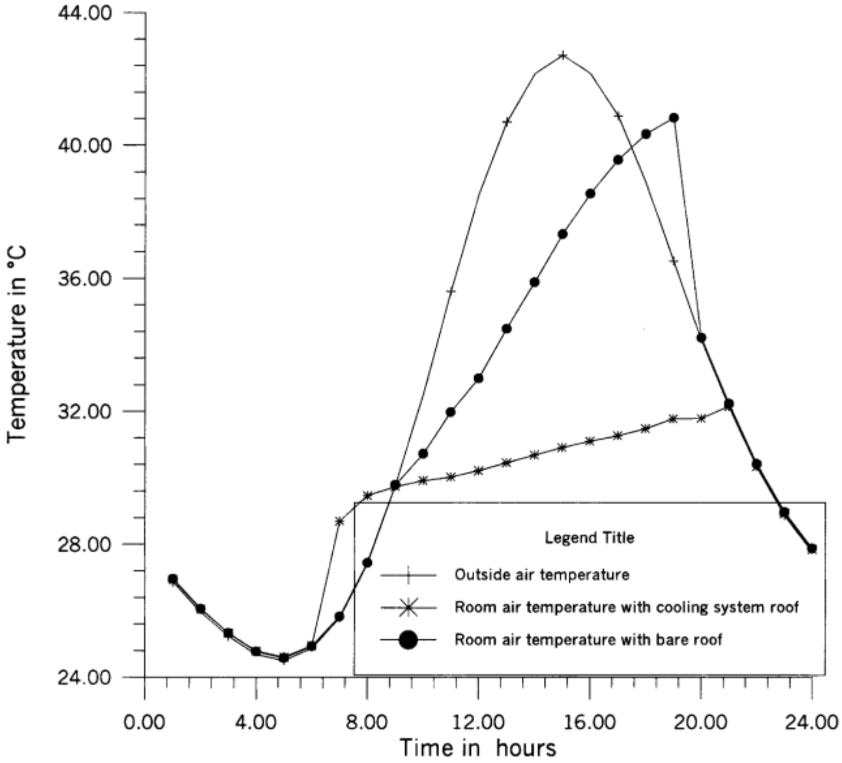


Picture 13: Test model with evapo-reflective roof (a) and test model without cooling system

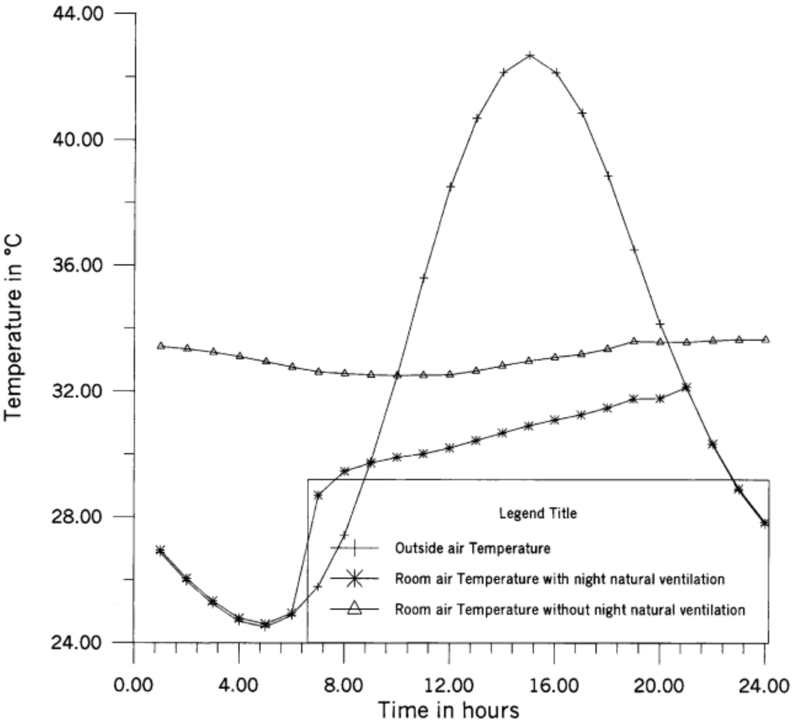
A comparison of the internal temperature between the room with the integrated system and the conventional room is made for a 24 hour period. Two scenarios were considered; one where the rooms are ventilated and one with no ventilation. The results of the study are depicted in the diagrams below.



Picture 14: Comparison of room air temperatures with cooling roof system and with bare roof for non-ventilated rooms



Picture 15: Comparison of room air temperatures with cooling roof system and with bare roof for ventilated rooms



Picture 16: Comparison of room air temperatures with cooling roof system for ventilated and non-ventilated room scenarios

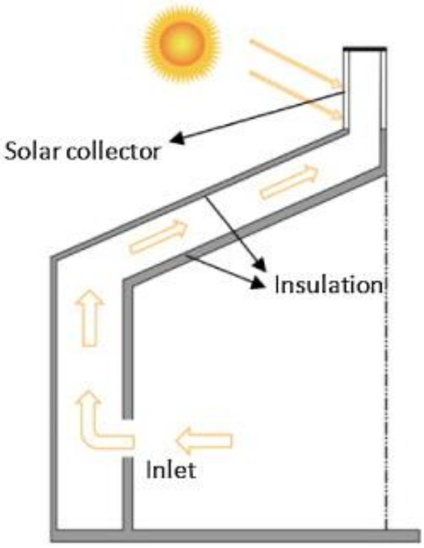
It can be seen that inside the room with the Evapo-reflective roof the temperature is up to $8^{O}C$ lower compared to that of the conventional room for the non-ventilation scenario and again for the ventilation scenario the temperature stays well below the temperature of the conventional room during the period of intense heat. From picture 16 we derive the conclusion that ventilation during night hours improves the condition of the living space since the temperature in the room with the Evapo-reflective roof is constantly lower and to more desirable levels throughout the day. Based on the above findings, the system can be characterized as considerably effective [38].

3.4 Solar Chimney and Roof Sprinkler

In this study a combination of a solar chimney and a roof sprinkler system is used to determine their effects in a conditioned space. Solar chimneys mail purpose is ventilation while the roof sprinkler aims to provide a cooling effect in the interior of the building.

3.4.1 Solar Chimney

A solar chimney uses the same principal with the Trombe wall. It usually consists of a black painted surface exposed to the sun with air ducts underneath it. The ducts have openings in their lower point facing the interior of the building (inlet) and in their upper point facing the environment (outlet). During the day, solar energy heats the chimney and as a result the air in the ducts beneath it. The buoyancy because of the heated air creates an updraft and as a result suction of air from the lower opening; which has as a result ventilation of the conditioned space. A typical solar chimney is depicted in picture 17.



Picture 17: Solar chimney

3.4.2 Roof Sprinkler

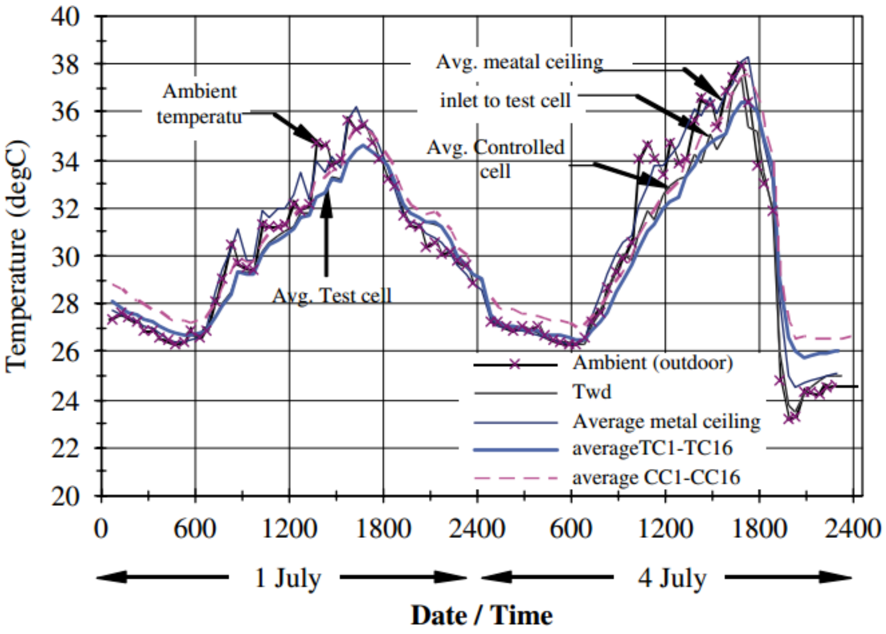
Roof sprinkler systems are intended for hot climates and they provide cooling by spraying water on the roof. After sprayed, the water evaporates absorbing from the roof latent heat during this phase change and consequently providing a cooling effect. Although this system does not consume any energy, it uses large amounts of water which is scarce in some areas, so this must be taken into consideration before installing one.

3.4.3 Assessment of the Solar Chimney and the Combination of the Solar Chimney with Roof Sprinkler

In this study, two identical rooms with pitch roof with a tilt angle of 45^{O} are used as test subjects. Their dimensions are 3.8m x 2.8m x 2.4 m; their frame is made out of wood and the walls are also made of a combination of wood and insulation which is coated with asbestos-cement from the outside. The side of the roof facing south is composed of terracotta roof tiles from the outside, a 15 cm air gap and gypsum board from the inside. The solar chimney studied is attached to the south side of the roof (also known as solar collector) and not to the façade of the building. The outdoor air can flow through fixed shutters which are placed under the south roof, in order to reduce hot air storage in the gap. The side of the roof facing north consists of an outer layer made of a metallic sheet arranged in an adjustable shutter style and an inner one which is made of a flat metallic sheet with a water pipe mounted on the upper part, which means that the roof sprinkler is mounted on this side (Picture 18). In the one room none of the two systems operate (controlled cell), while on the other at least one of the two systems operate (test cell). Both cells were placed on top of a building in Thammasat, Thailand and during tests all windows and openings are closed in both cells.

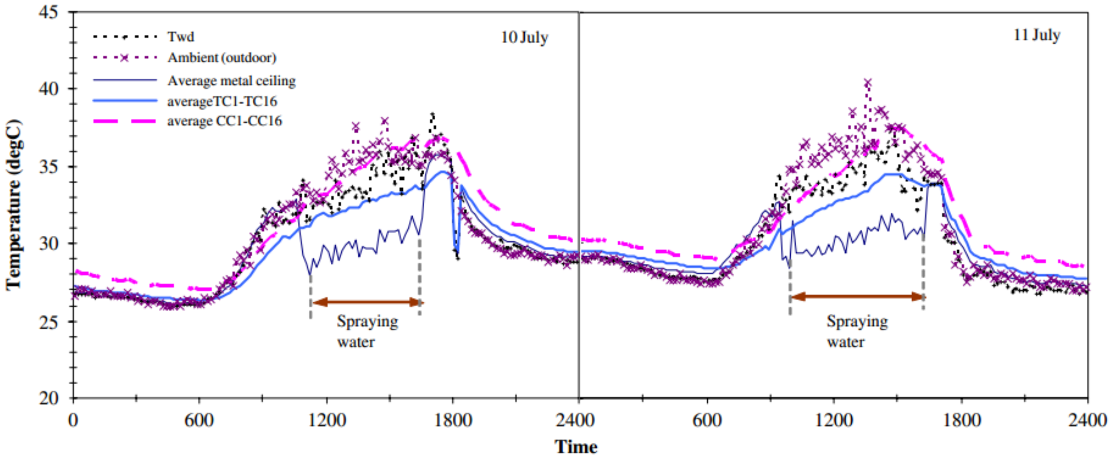
Picture 18: North facing side (a) and south facing side (b) of the test room

In this study the temperatures of the two cells under the same environmental conditions will be compared. In the first experiment, whose results are depicted in picture 19, only the solar chimney is utilized in the test cell. Each living space has sixteen temperature sensors and the average temperature of all of them is listed in the results. During the period with the most intense heat which is between 12:00 and 16:00 the test cell has an average temperature of $1.0\text{-}1.3^{O}$C compared to the controlled cell; therefore the cooling effect by natural ventilation through the solar chimney can be considered negligible.



Picture 19: Temperature results of the two cells when the solar chimney is utilized in the test cell. Twd is the window temperature and “average TC1-TC16” and “average CC1-CC16” is the average temperature of the sixteen sensors in the test cell and controlled cell accordingly

During the second experiment both the solar chimney in the south side and the roof sprinkler in the north side are utilized in the test cell. The sprinkler is utilized just for a few hours during the hottest period of the day. Moreover all windows and openings of both cells are closed to prevent the high ambient temperature from affecting the measurements. The results are depicted in picture 20.



Picture 20: Temperature results of the two cells when both the solar chimney and water sprinkler are utilized in the test cell

In this case a difference in the room temperature of 1.4-3.0^{O}C between the two cells is achieved with the test cell being the cooler one. Also the temperature difference between the test cell and the environment is 2.0-6.2^{O}C.

When ventilation is concerned, a value between 1.13-2.26 air changes per hour (ACH) was achieved during the period of June and September; while in a previous study of Khedari et al. [39,40] ACH values of 4-15 were observed. This significant difference is because in this study the effect of wind which enhances the air draft in the solar chimney was excluded.

According to the results even with no wind present, adequate natural ventilation can be provided by the solar chimney. Moreover some cooling effect is observed when high ambient temperature and high solar intensity are present. However the combination of a solar chimney and a roof sprinkler can increase the cooling effect since they provide reduced temperatures of up 3.0 ^{O}C compared to the controlled cell and up to 6.2^{O}C compared to the environment. A second advantage from this combination is that the reduced inside temperature results in an increased airflow through the solar chimney since the difference between the internal and external temperatures is higher.

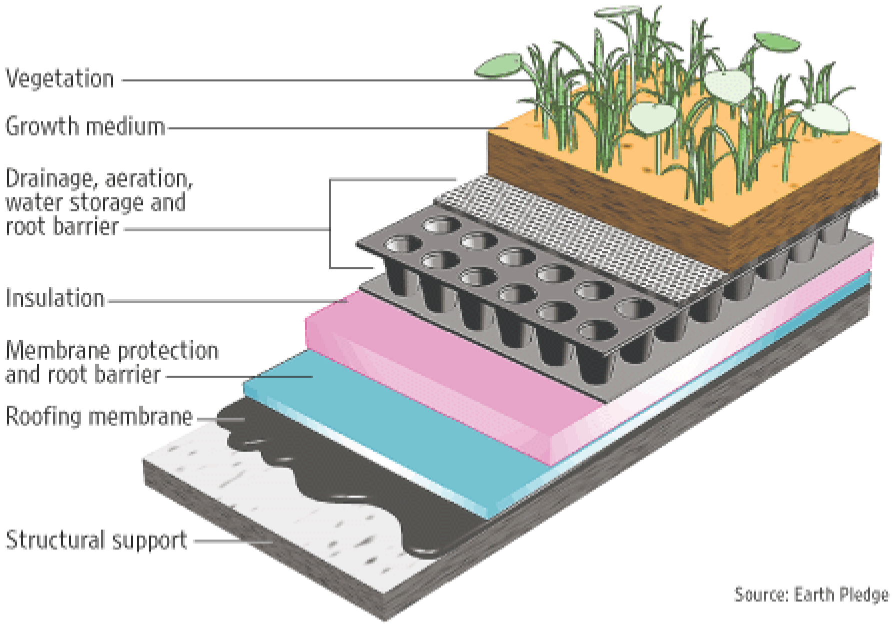
3.5 Green Roofs

Green roofs are considered an attractive way to improve the thermal efficiency of a building by providing additional insulation and increased thermal mass which have as a result reduced amount of heat transferred through the roof and smaller fluctuation of the roofs temperature.

3.5.1 System Description

A green roof is a roof of a building covered with flora. An implementation of a green roof comprises of a root barrier layer which prevents vegetation from wearing out the upper roof layer, a waterproofing membrane, a drainage layer which provides escape routes to excessive water that might have been accumulated thus preventing the entire installation from becoming overweight, growing medium and on top the vegetation.

Moreover in dry climates irrigation might be necessary. The section of a green roof is depicted in picture 21.



Picture 21: The various layers of a green roof

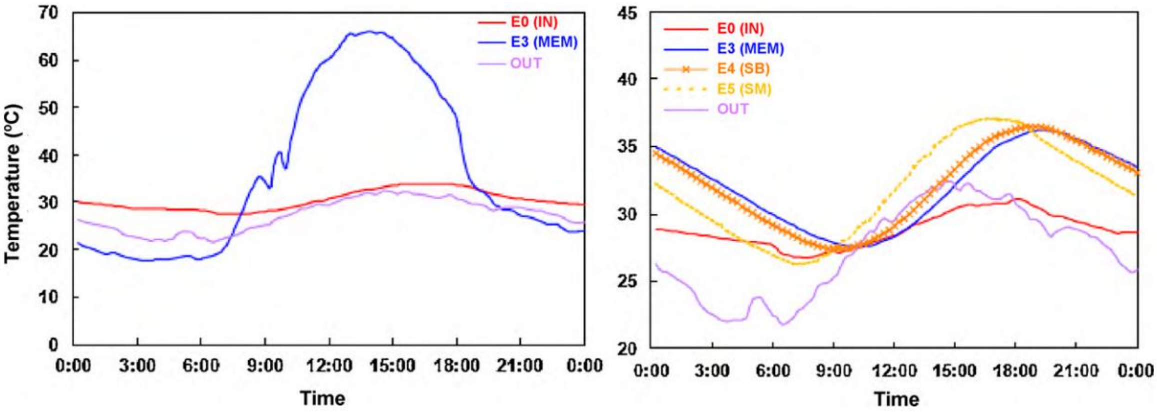
Green roofs have as a main purpose to provide passive cooling during the summer period. This is achieved by reducing the amount of solar radiation that reaches the roof structure, while also providing additional insulation. In this direction aid the shading provided by the foliage and the fact that green roofs provide improved reflectivity. It has been suggested that green roofs cool as efficiently as the brightest possible white roofs [42]. Additionally a cooling effect is provided through latent heat loss as the moisture on the plants and in the substrate evaporates. As a result, during summer an exposed black roof can reach 80^{O}C while a green roofs temperature can drop to 27^{O}C [43]. Although moisture in the soil provides a desirable cooling effect, it has the negative characteristic of reducing soils insulating properties, which means that dry growing medium offers better thermal insulation.

There are two types of green roofs; extensive and intensive. Extensive green roofs are characterized by a thin growing medium layer with low level vegetation such as sedum or lawn. This type is ideal for retrofitting the roofs of old buildings since there isn’t much extra weight added per unit area; hence the need for increased support of the roofs infrastructure is rare. Moreover this type of green roof can be considered relatively maintenance free and has no problem surviving in European climates [44]. For example, sedum is a popular choice for extensive green roofs, because it is a succulent plant and as a result it is extremely resilient under drought periods. Moreover, they offer good coverage and roof membrane protection since they grow across the ground rather than upwards and also they are easy to install. Intensive green roofs have a deeper growing medium layer and are able to accommodate plants with deeper roots such as shrubs or even trees.

If used in large scale in an urban environment, green roofs can present many advantages such as better storm weather management [45,46], improved urban air quality by converting CO_2 in oxygen [47], extended roof life [48], mitigation of the urban heat island effect [49] and increased biodiversity [50].

3.5.2 System Assessment

In an experiment performed by Lui and Minor in Toronto, Canada, a green roof with 75-100 mm of growing medium is compared with an identical bare roof. Both roofs consist of thermal insulation on top of a steel deck. The results are depicted in the following picture.



Picture 22: Summer temperature profiles for the reference roof (left) and the green roof (right). E_0 is the inside temperature, E_3 the temperature under the waterproof membrane, E_4 the temperature under the growing medium, E_5 the temperature in the middle of the growing medium and OUT the ambient temperature.

It is observed that the internal temperature of the green roof building is slightly lower compared to the reference building. The small difference between the two cases is due to the already installed insulation. Because of it, although there is a large reduction in heat flowing through the roof, only a fragment of this reduction is translated to temperature reduction. Moreover, the fluctuation of the temperature is a bit delayed in the green roof building. This is because of the thermal mass of the growing medium and plants that is added in the roof. This thermal mass besides the delay effect, also prevent extremely cold or hot temperatures, allowing for more stable temperatures throughout the year. Finally during the day the reference roof presented a slightly higher heat loss by 1-2 W/m^2 which means that green roofs can also prove beneficial during cold periods by retaining more heat inside the living space [51].

The cooling effect of green roofs on buildings with different roof insulation can be accessed from the work of Nichaou et al. This study takes place in Athens. The internal temperatures of two buildings with similar insulation properties were recorded for a period of three days in July. It was found that in the green roof building the temperature of the conditioned space climbed above 30^{O}C for 15% of the three day period, while in the reference building the same occurred for 68% of the three day period. Also the green roof building presented reduced daily mean temperature by 2^{O}C, 3^{O}C lower max temperature and 1^{O}C lower min temperature.

Additionally in the same study the annual energy requirement of an office building in Athens with varying insulation values are calculated with the use of TRNSYS software. The results are listed in table 5.

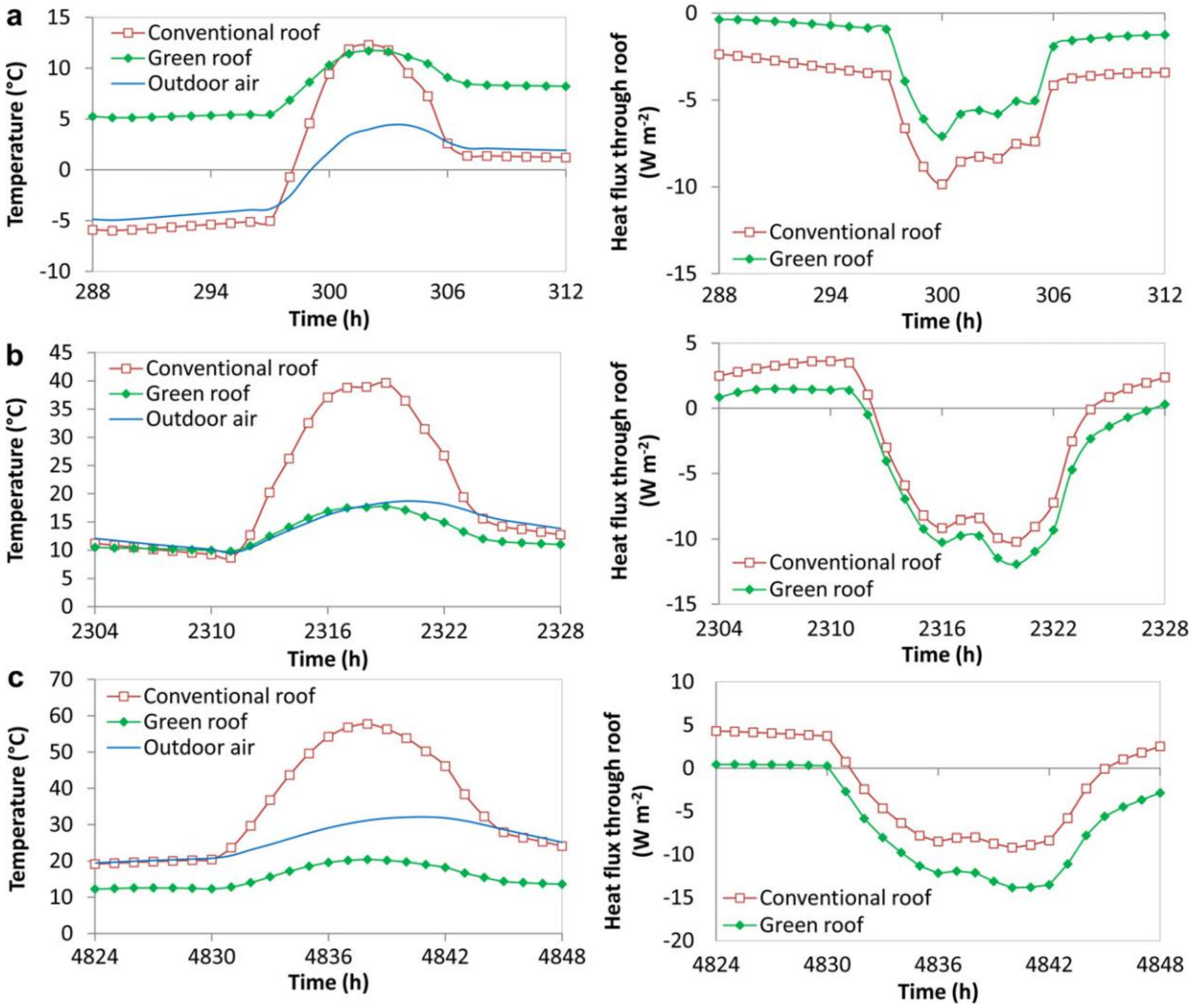
Table 5: Results

Roof Construction	**U-Value without green roof (W/m^2 K)**	**U-Value with green roof (W/m^2 K)**	**Annual energy saving for heating (%)**	**Annual energy saving for cooling (%)**	**Total annual energy saving**
Well insulated	0.26-0.4	0.24-0.34	8-9	0	2
Moderately ins.	0.74-0.8	0.55-0.59	13	0-4	3-7
Non insulated	7.76-18.18	1.73-1.99	45-46	22-45	31-44

From the results, becomes apparent the potential of green roofs in non insulated or moderately insulated roofs. It is interesting to notice that although green roofs are intended for passive summer cooling they provide more energy savings during the winter with their additional insulation [52].

In the final study presented, the heat flux between a green roof house and a conventional house is examined. The major heat fluxes in a green roof are the solar radiation absorbed by the foliage, the infrared radiation emitted by the foliage to the sky and to the soil, the heat convection among the foliage and the air in the canopy and the latent heat because of humidity evaporation in the foliage. For the experiment a house located in La Rochelle, France with an area of $96m^2$ and a window to wall ration of 0.18 is used. La Rochelle’s climate is described as temperate oceanic. The energy performance of an intensive green roof where sedum is grown and a reference roof is compared in this case. Three cases are studied. Two in the winter period during the day with the minimum yearly temperature and the day with the maximum solar irradiance and one in the summer period during the day with the maximum yearly temperature. The temperature and het flux results are presented in picture 23.

It is apparent that during the winter the soil temperature is well above the outside temperature. The reason for this is the presence of the foliage which prevents heat flux from the warm conditioned space to the colder environment. On the other hand during the sunny winter day the combination of increased evaporation and shading by the foliage keep the soil temperature $2.9^{O}C$ below that of the environment. For the same reasons the same cooling effect is present during the hot summer day. Moreover this study comes in agreement with the previous two to the fact that green roofs present much less temperature fluctuations through the day compared to conventional roofs. Finally the heat flux results appear to be a bit controversial. The green roof’s heat losses are lower in the cold winter day but higher in the sunny winter day. As already mentioned this is because of the shading provided by the foliage and the increased cooling effect through evaporation which are undesirable during winter because in increases the heating load. This comes in agreement with the temperatures recorded that day. The green roof’s temperature doesn’t go above 18 degrees. In the contrary the conventional roof reaches 40 degrees during the noon. This constant low temperature of the green roof has as a result increased heat flux from the worm interior to the roof. The passive cooling effect of the green roof, although not desirable during the winter, it provides increased heat flux from inside the worm conditioned space to the roof during the summer which helps keeping the cooling load low [53].



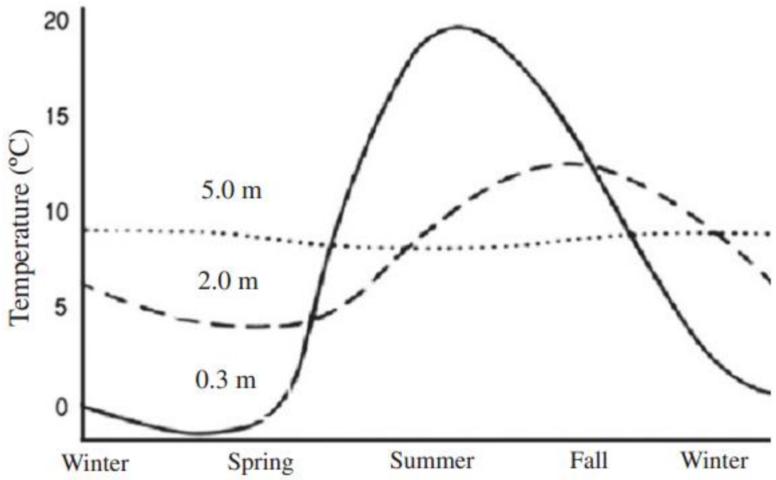
Picture 23: Temperature on the exterior surface of the roof (left) and heat flux through the roof (right) during cold winter (a), sunny winter (b) and hot summer (c)

4. Hybrid Systems

In this chapter various hybrid HVAC systems will be presented. Hybrids are called systems that combine both passive and active components in order to achieve their objective. The advantage of hybrid systems is that they usually combine renewable intermittent energy sources with conventional ones, which are always available on demand, allowing them to fully satisfy any needs for space conditioning with reduced energy consumption and environmental impact at the same time. Sometimes however the installation appears to be complex and the initial cost high which deter their broad use but the fact that a lot of research takes place in the sector of hybrid HVAC systems allows the belief that they will be accessible by the public in the near future.

4.1 Geothermal Heat Pumps

It is common knowledge that the majority of space heating and cooling are fulfilled directly or indirectly by the combustion of fossil fuels which are finite and polluting energy sources. In the shallow layers of the earth, meaning from the surface up to a few hundred meters depth, the soil temperature is usually around 14^{O}C [54]and its fluctuations are negligible and independent of the climate (picture 24). As a result, underground soil layers can be considered as inexhaustible thermal reservoirs which can be used for space heating and cooling, reducing considerably the thermal and cooling loads which otherwise would be covered by fossil fuels. Geothermal energy is described as clean and sustainable since there are no pollutants related to it and the heat extraction in negligible compared to Earth’s heat content [55].



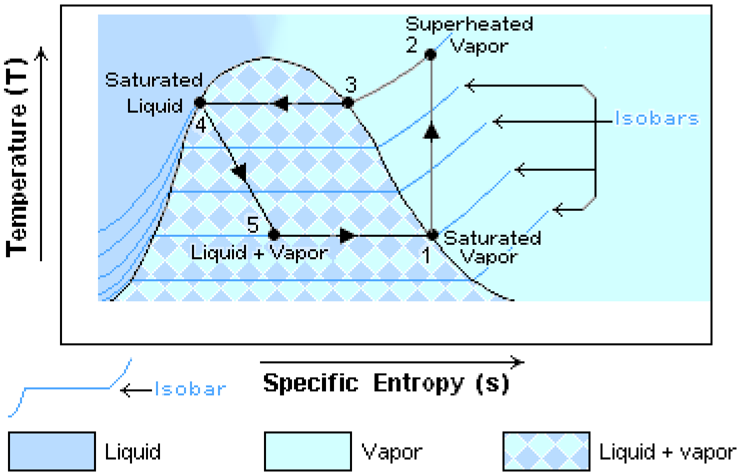
Picture 24: Annual ground temperature range for different depths for Ottawa, Canada

4.1.1 System Description

Geothermal energy for space conditioning can be used through the use of geothermal heat pumps (GHPs) which consist of three main systems; the geothermal heat pump, Earth connection and interior distribution system.

4.1.1.1 Geothermal Heat Pump

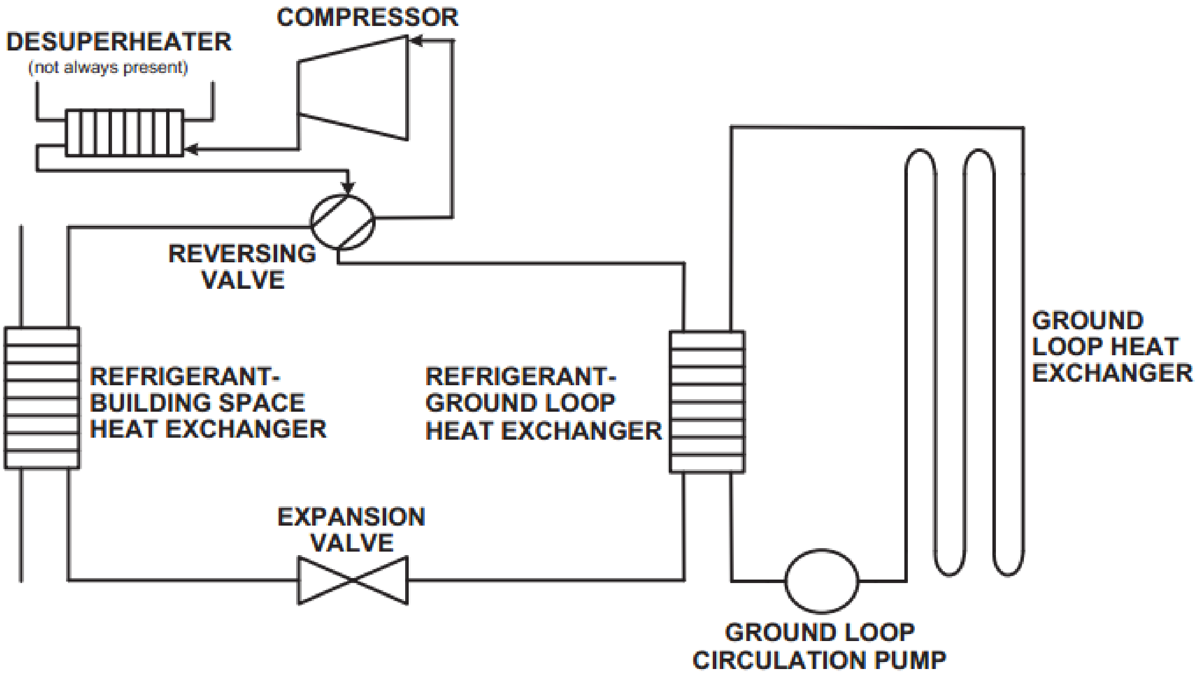
A heat pump is a mechanism that absorbs thermal energy from a reservoir with low temperature and rejects it to a reservoir with temperature higher than that of the first one. This flow of thermal energy is the opposite of the one that occurs spontaneously, so energy is required for this process. It is possible to reverse the way the heat pump operates by incorporating a four-way valve in the system thus allowing it to transfer heat from the hot to the cold reservoir. This allows for the utilization of the heat pump for space conditioning during both cooling and heating periods. In order to achieve their purpose, heat pumps use a refrigeration cycle. The most common one is the vapor compression refrigeration cycle (picture 25) which is used by refrigerators and air conditioners and its ideal version is described below.



Picture 25: Refrigeration cycle

Initially the refrigerant, in a state of saturated vapor (point 1), enters the compressor where it is isentropically compressed until it exits as a superheated vapor (point 2). Afterwards heat is rejected from the refrigerant through the condenser. While heat is rejected the superheated vapor initially cools and afterwards it changes phase until it becomes a saturated liquid (point 4). Then the refrigerant passes through the expansion valve where it is subjected to low temperature and pressure. During that stage the refrigerant evaporates absorbing latent heat from the environment until it becomes again a saturated vapor at point one.

A geothermal heat pump is depicted in picture 26. When it is used to heat a space, the ground loop heat exchanger plays the role of the evaporator (thermal energy is absorbed from the ground by the refrigerant during its evaporation stage) and the building space heat exchanger the role of the compressor (thermal energy is rejected inside the conditioned space during the refrigerants condensation stage). On the other hand when it is used for space heating, the ground loop heat exchanger and building space heat exchanger reverse their roles. The desuperheater depicted in picture 26 is an additional, optional heat exchanger located at the compressor exit. It acts as a condenser, rejecting the thermal energy of the superheated vapor to a water tank thus satisfying the domestic hot water requirements [59].



Picture 26: Basic layout of double loop geothermal heat pump system including desuperheater

4.1.1.2 Interior distribution system

The interior distribution system is basically the heat exchanger between the GHP and the conditioned space. There are water to air and water to water (hydronic) interior distribution systems. In the water to air system a heat exchanger transfers thermal energy between a close water loop in the ground and air which is used for space conditioning through air ducts. In the water to water system, water is also used for space conditioning through radiators or in floor radiant heaters that are used for heat exchange between the water and conditioned space air.

4.1.1.3 Earth Connections

Earth connections, also known as ground loop heat exchangers are a collection of underground pipes that allow to the fluid that circulates, with the aid of a circulation pump inside them to exchange heat energy with the ground. Earth connections are separated in double loop and single loop configurations. In double loop configuration, one working medium flows independently inside the earth connection loop and it exchanges thermal energy with a second working medium in a separate heat pump loop through a heat exchanger. Single loop systems are simpler and use only one working medium that flows through both the heat pump and the Earth connection loops thus eliminating the need for an exchanger in between. By using a slightly larger compressor in a single loop system it is possible to avoid the circulation pump which increases the COP of the system [60, 61].

4.1.2 System Assessment

Before any comparisons the definition of coefficient of performance is given.

4.1.2.1 Coefficient of Performance (COP)

In order to measure the efficiency of a heat pump the term coefficient of performance (COP) is used and it is defined as the ratio of desirable thermal energy product to energy input. To be more precise, during heating, COP is the amount of heat delivered to the hot reservoir (Q_{hot}) over the difference between the heat delivered to the hot reservoir (Q_{hot}) and the heat absorbed by the cold reservoir (Q_{cold}), while during cooling COP is the amount of heat extracted by the cold reservoir which is the conditioned space (Q_{cold}) over the difference between the heat delivered to the hot reservoir (Q_{hot}) and the heat absorbed by the cold reservoir (Q_{cold}). Theoretically it can be shown that $\frac{Q_{hot}}{T_{hot}} = \frac{Q_{cold}}{T_{cold}}$ when a heat pump operates at its maximum efficiency which allows COP to take the form in the right in each case in the following equations.

$$COP = \frac{thermal\ energy\ product}{energy\ input}$$

$$COP_{heating} = \frac{Q_{hot}}{Q_{hot} - Q_{cold}} \leq \frac{T_{hot}}{T_{hot} - T_{cold}}$$

$$COP_{cooling} = \frac{Q_{cold}}{Q_{hot} - Q_{cold}} \leq \frac{T_{cold}}{T_{hot} - T_{cold}}$$

4.1.2.2 Comparison of COP between GHPs and Air Source Heat Pumps

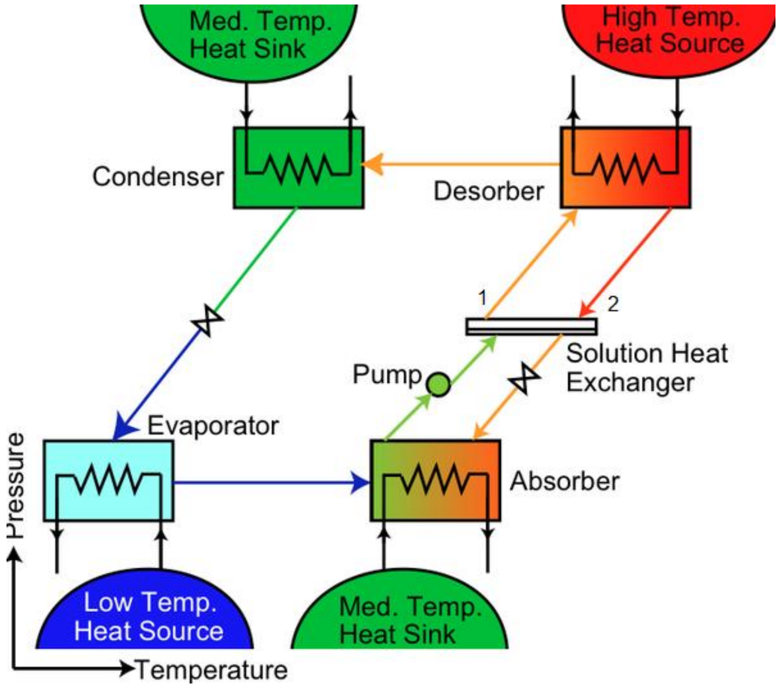
The advantage of geothermal heat pumps over air source heat pumps is that air source heat pumps use the ambient air as a heat source whereas geothermal heat pumps use the underground temperature as a heat source [56]. In the first case, during the cooling period the compressor which is exposed to ambient air needs to reject heat in an already hot environment while during heating period the evaporator (which is the same element as the compressor during cooling period) needs to absorb heat from an already cold ambient environment. This according to the above theoretical definition of COP reduces the efficiency of an air pump because the increased difference between the inside and outside temperature has as a result a high denominator value. As a result the COP of an air source heat pump can be around 3.3 and during adverse climatic conditions around 2.3 [57]. On the other hand since the underground temperature is relatively constant and mild, the small difference between the conditioned space temperature and ambient temperature allows for higher theoretical COP values during both heating and cooling periods. True values range between 3 and 6 and are affected by various variables and technical characteristics of each setup [58].

4.2 LiBr-H_2O Absorption Chillers

Solar cooling of buildings is an attractive idea since the cooling loads and intense solar radiation are in phase. More over a combination of solar cooling and solar heating allow for greater use of thermal solar collectors throughout the year which as a consequence may reduce installation costs since solar thermal collectors can be utilized by many systems. An innovative way to achieve solar cooling is by using absorption chillers. These chillers are similar to vapor compression air conditioners but instead of using a compressor in the compression stage they use thermal energy. Absorption chillers have smaller primary energy COP values than split-unit air conditioners, as a result powering them with commercial fuels is not a viable solution [62]. However since they are designed to utilize solar energy which is free, they constitute an interesting alternative solution.

4.2.1 Absorption Cycle Description

The lithium-bromide – water absorption cycle is depicted in picture 27. Initially the liquid refrigerant (water) evaporates in a low pressure environment in the evaporator thus extracting heat from its surroundings. Afterwards the gaseous refrigerant is absorbed by LiBr in the absorber and once this mixture of LiBr and water gets in the desorber through path one it is heated and waters is forced to evaporate out of the mixture. Finally the refrigerant is condensed through a heat exchanger (condenser) and becomes liquid, replenishing the supply of refrigerant in the evaporator. After LiBr and water are separated in the desorber, LiBr returns to the absorber through path two.

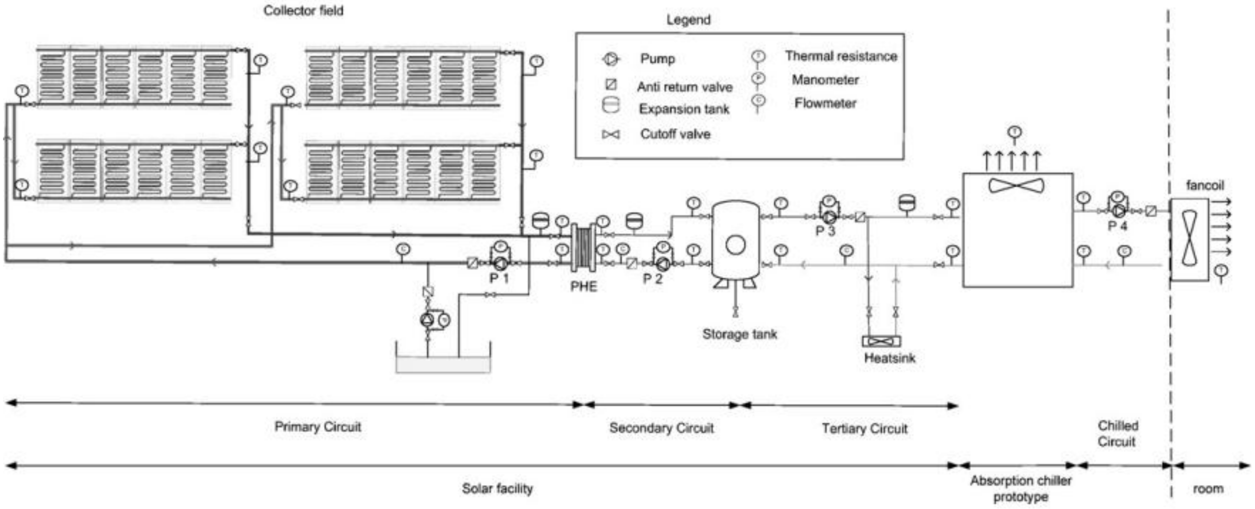


Picture 27: Absorptioncycle

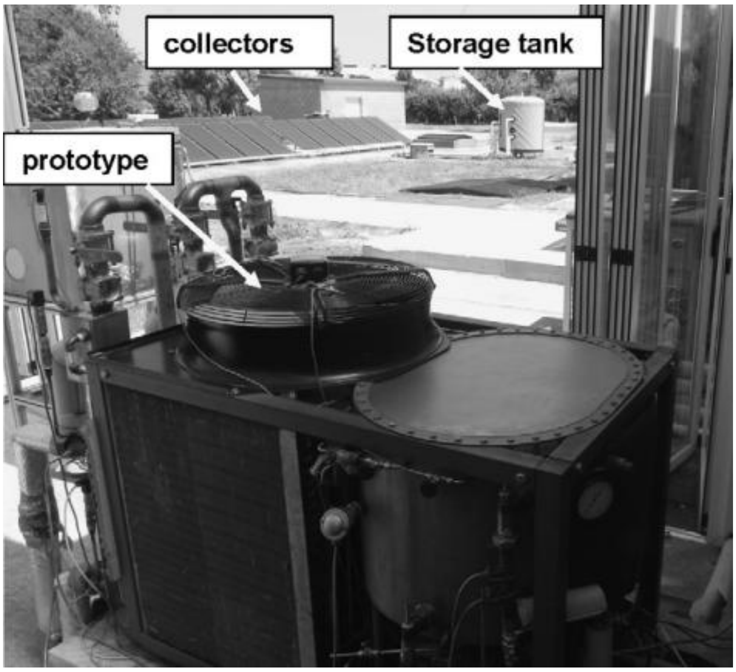
4.2.2 System Assessment

The system under study is a directly air-cooled single effect LiBr-H_2O absorption chiller depicted in picture 28. The system is comprised by three hydraulic circuits. The primary one accommodates 24 vacuum flat-plate solar collectors with a total area of 42.2 m^2 and an optical efficiency of 0.81. The orientation of the collectors is south and their tilt angle 30^O. The heating medium used is a mixture of 70% water and 30% ethylenglycol and it circulates through the solar collectors and a 25 kW plate heat exchanger (PHE) by a 295 Watt pump (P1). In the second circuit the heating medium absorbs heat from the cold side of the PHE, transferred there by the primary circuit and stores it in a 1.5 m^3 storage tank. The heating medium used is 90% water and 10 % ethylenglycol and it is again driven by a 295 Watt pump (P2). The third circuit is comprised by the aforementioned storage tank, a 110 W pump (P3), an 11 kW ancillary fan-coil, used for heat rejection and the generator. The heat medium is the same one used in the second circuit.

The absorption chiller has a volume of one cubic meter and is able to provide 4.5 kW cooling capacity. It differs from other similar systems in the market to the fact that it is directly air cooled whereas the rest use a water tower to reject heat to the environment. More over it uses an adiabatic flat-fan sheets absorber which exhibits a much higher mass transfer coefficient in the absorber chamber compared to falling film and spray absorbers [63]. Parts of the system can be seen in picture 29.

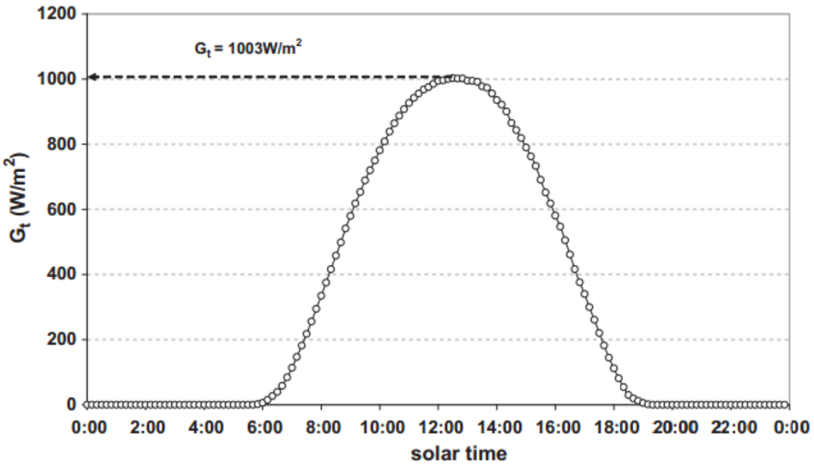


Picture 28: Solar driven absorption cooling facility

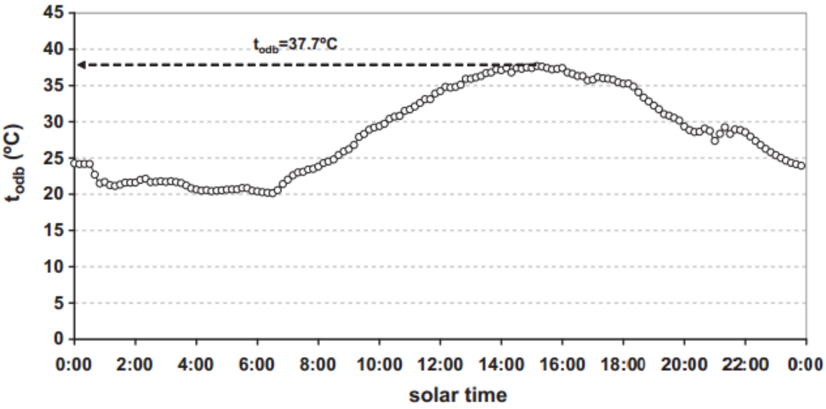


Picture 29: Solar collector field, storage tank and prototype

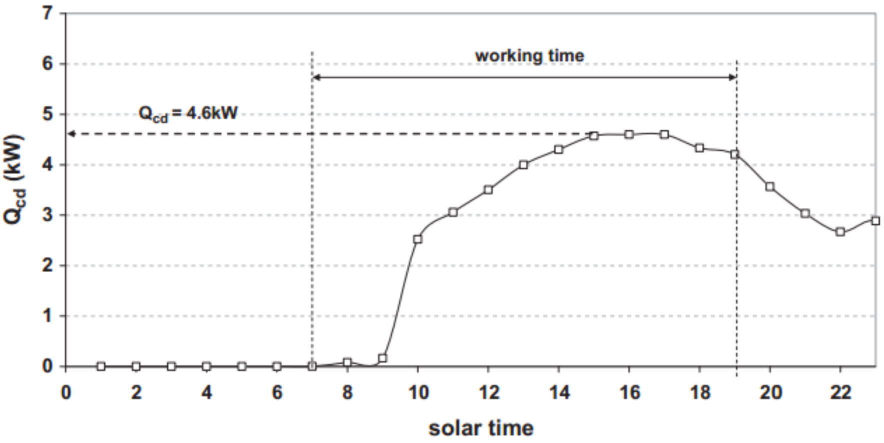
The system was targeted to cool a 40 m^2 room in an 80 m^2 laboratory with a total volume of 240 m^3 located at Argenda del Rey (latitude $40^O18'$) in Spain. The temperature set point was $23\text{-}25^OC$ and the test took place during 28/8/2009. In pictures 30 31 and 32, detailed solar irradiance on the solar collectors, outside temperature and cooling load are depicted for the entire day of 28/8/2009. As for the operation hours, P1 operated from the moment the collector plate temperature was 15^OC above ambient temperature until the difference dropped to 11^OC, P2 operated from the moment the collector outlet temperature was 7^OC higher than that of the collector tank until the difference dropped to 2^OC and P3 operated when the collector tank temperature was above 80^OC and the room needed to be air conditioned.



Picture 30: Solar irradiance on the tilted surface (28/8/2009)



Picture 31: Ambient temperature (28/8/2009)



Picture 32: Cooling load (28/8/2009)

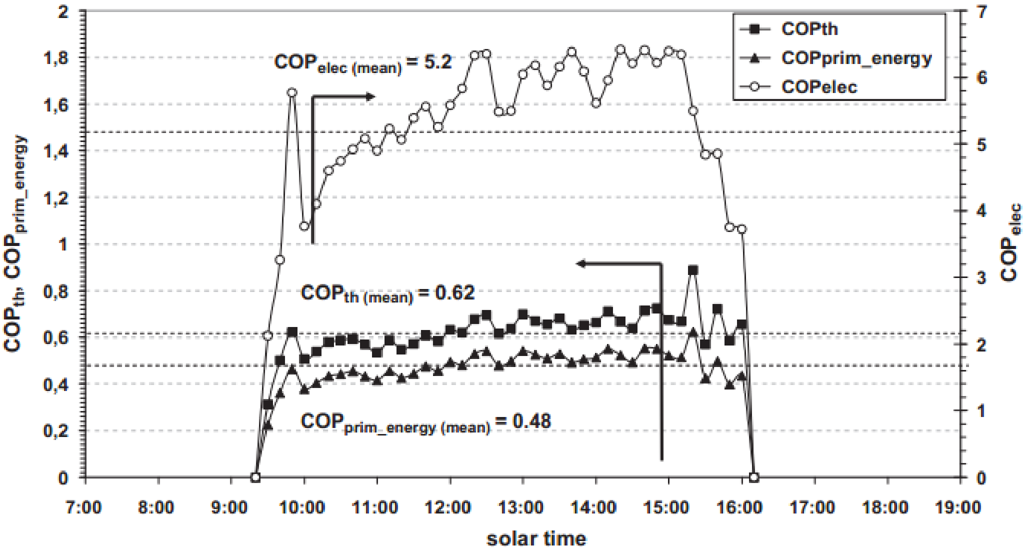
In the following picture the COPs of the system are depicted throughout the day. The thermal, electric and primary energy COPs are defined as following, where η_{conv} is the efficiency of a steam power plant under which it converts primary energy to electric. For Spain η_{conv}=0.38.

$$COP_{th} = \frac{evaporator\ heat\ transfer\ rate}{generator\ heat\ transfer\ rate} = \frac{Q_e}{Q_g}$$

$$COP_{elec} = \frac{evaporator\ heat\ transfer\ rate}{prototype\ electric\ power} = \frac{Q_e}{W_{elec\ prot}}$$

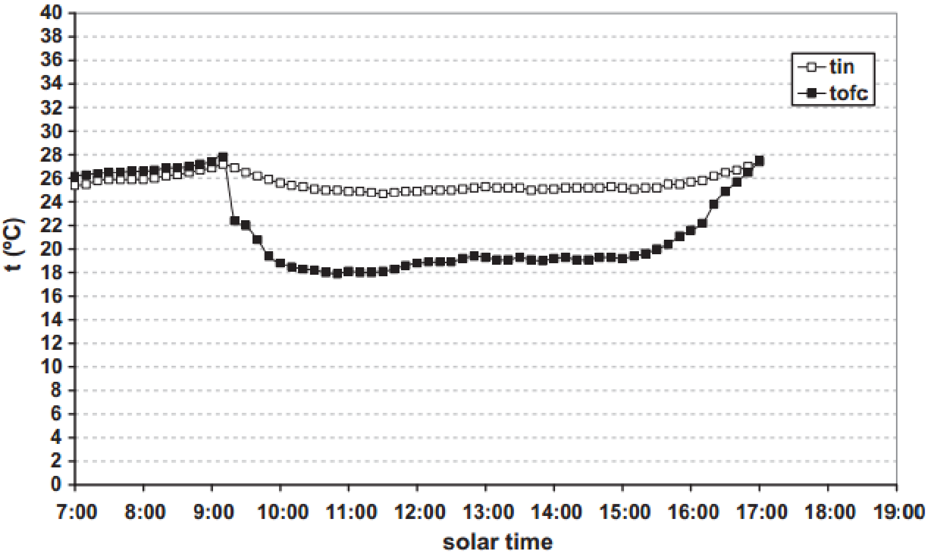
$$COP_{primary\ \ energy} = \frac{Q_e}{Q_g + \frac{W_{elec\ prot}}{\eta_{conv}}}$$

In the $W_{elecprot}$ value, the electric power of all pumps and fans are taken into account, totaling 700 W. Daily the system consumed 4.8 kWh of electricity and its mean COP_{elec} was 5.2 which is higher of the equivalent residential conventional air conditioners which, as already mentioned is around the value of 3; the mean daily $COP_{prim\ energy}$ is found to be 0.48.



Picture 33: COP_{th}, COP_{elec}, $COP_{primary\ energy}$ for 28/8/2009

Finally the inlet and outlet temperatures of the fan-coil are presented in picture 34. It is observed that during operation hours the difference between the temperature of the conditioned space and fan coil outlet temperature is pretty much constant and around 5-6^{O}C.



Picture 34: Fan coil inlet and outlet temperatures for 28-8-2009

Although there aren’t any air cooled LiBr absorption chillers present in the market, this study shows that there is potential for the production of models addressed to residential buildings [64].

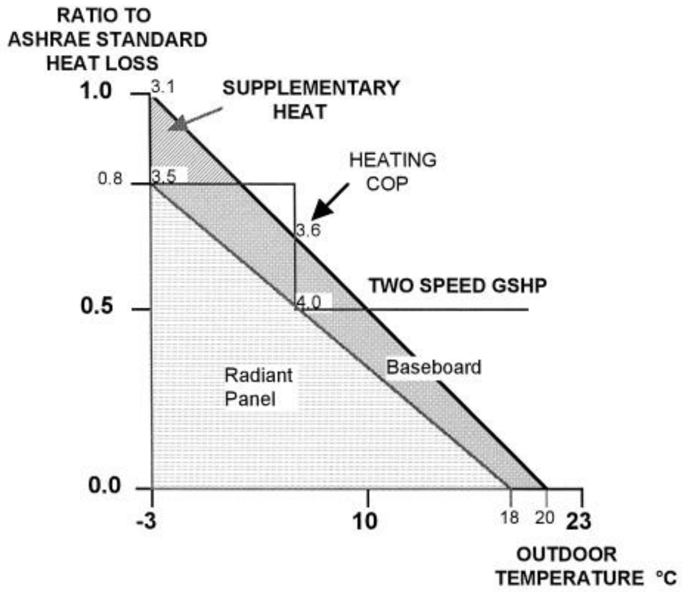
4.3 Combination of Wind Energy with Ground Source Heat Pump for HVAC

In this study a small wind turbine is used to drive a ground source heat pump which combined with a mixture of radiant and convective systems and in-space thermal energy storage aims to provide space conditioning for a home in a climatic zone where heating and cooling loads are roughly equal. Initially the differences between convective and radiant systems will be discussed and the advantages of thermal energy storage will be presented.

4.3.1 Convective and Radiant Panels

Convective panels such as baseboards, heat a space using the principal of convection. Usually thin metallic fins are heated using an electric resistance or hot heating medium provided through pipes by a heat pump or boiler. The hot fins heat the surrounding air which rises because of its reduced density and is replaced by colder air entering from the bottom. This process continues until the conditioned space reaches its desired temperature. Radiant panels on the other hand use infrared radiation to deliver heat to its surroundings. Another system of radiant heating is radiant floor heating, which despite what the name suggests uses a combination of convection and radiation to heat a space. Floor heating will be further discussed below.

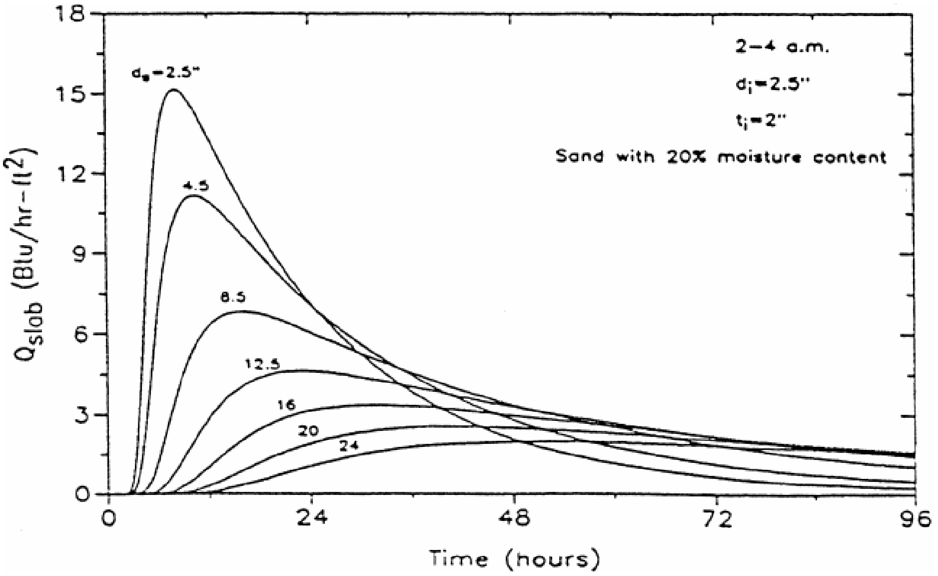
The main difference between convective panels and radiant panels is that when convective panels are used, occupants feel warmth because of the contact with the warm air surrounding them, while when radiant panels are used; occupants feel warmth because of the infrared radiation emitted by the panels which is transformed into heat when absorbed by their bodies. This allows for equal thermal comfort with lower room temperatures compared to convective heating. In picture 35 a heat pump performance comparison when using radiant or convective panels is presented for the heating period. It is observed that when using radiant panels thermal comfort is achieved with internal temperature of 18^{O}C, while with convective ones an air temperature of 20^{O}C is required. Lower internal temperature translates to lower heating medium temperature which according to the theoretical COP formula allows for greater efficiency of heat pumps. As is shown from picture 35, the two stage ground source heat pump used in this study achieves at 50% load a COP of 4 when radiant panels are used whereas with convective ones COP drops to 3.6. Accordingly for 100% load COP is 3.5 for radiant panels and 3.1 for convective. Additionally lower temperature difference between the conditioned space and the environment, results into reduced heat losses. Apparent is the reduced heat loss when radiant panels are used which corresponds to 80% of the losses when convective panels are used. As a result using radiant heating allows for reduced thermal loads of about 20% during heating and 10% during cooling periods.



Picture 35: Comparison of GSHP performance with radiant and convective heating systems

4.3.2 Radiant Floor Heating

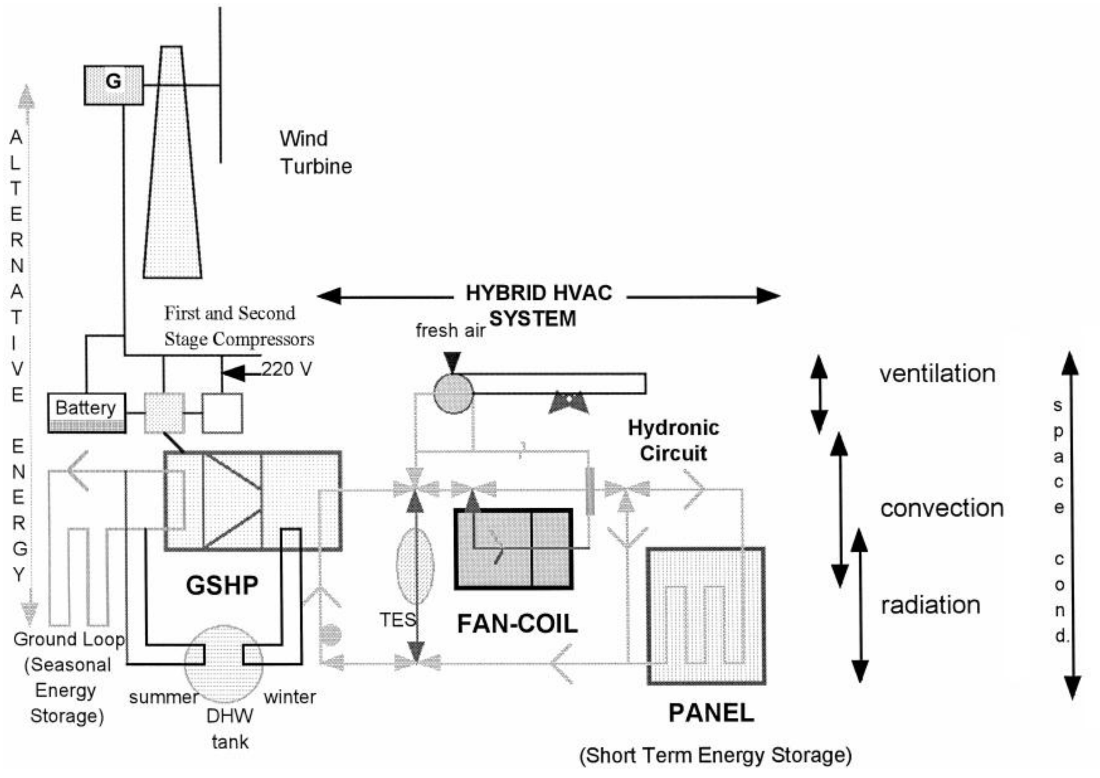
Flood heating is achieved by placing a network of pipes, through which a hot heating medium is flowing, under the floor. This heat is absorbed by the flood and through convection and radiation is transferred to the conditioned space. Some degree of thermal storage can be achieved with the integration of high thermal mass materials. In this study, a 63mm thick layer of sand in combination with a 63mm layer concrete will be used for thermal storage and a 51mm thick layer of back insulation to reduce losses. Picture 36 shows the heat flux for various sand layer thicknesses. This inertia in heat transfer allows for shifting of heating and cooling loads for several hours which means that better utilization of intermittent renewable energy sources such as wind and solar becomes possible.



Picture 36: Radiant panel heat flux as a function of slab thickness

4.3.3 System Description

A 6kW wind turbine is used to drive a GSHP or to store electricity in a 7 kWh battery. The GSHP, which uses two compressors to fulfill the heating and cooling loads, has a hydronic interface which is used by radiant panels and radiant floor heating and an undersized forced-air convective system which has as a main purpose to aid the radiant panels during the cooling period. Fan coils are also able to operate during winter at reduced water temperatures like radiant panels do. Heating loads and domestic hot water are covered by the heat extracted from the ground which afterwards is upgraded by the compressors to a useful temperature. During summer, it is intended for cooling loads to be primarily covered by the hydronic system and when this proves insufficient fan coils would cover the rest of the load. Fan coils use lower temperatures than radiant panels do during summer; as a result they reduce the COP of the GSHP. Finally, heat extracted from the conditioned space is rejected to the ground. The combination of the heat mass of the floor, the heat mass of the building shell and an optional water tank that is used as a thermal energy storage system (TES) can provide sufficient thermal inertia, which coupled with the electricity stored in the battery that is able to drive the GSHP when no wind is present, allow for enough tolerance in the availability of wind energy. The system described is depicted in picture 37 and is intended for a 100 m^2 single-family house.



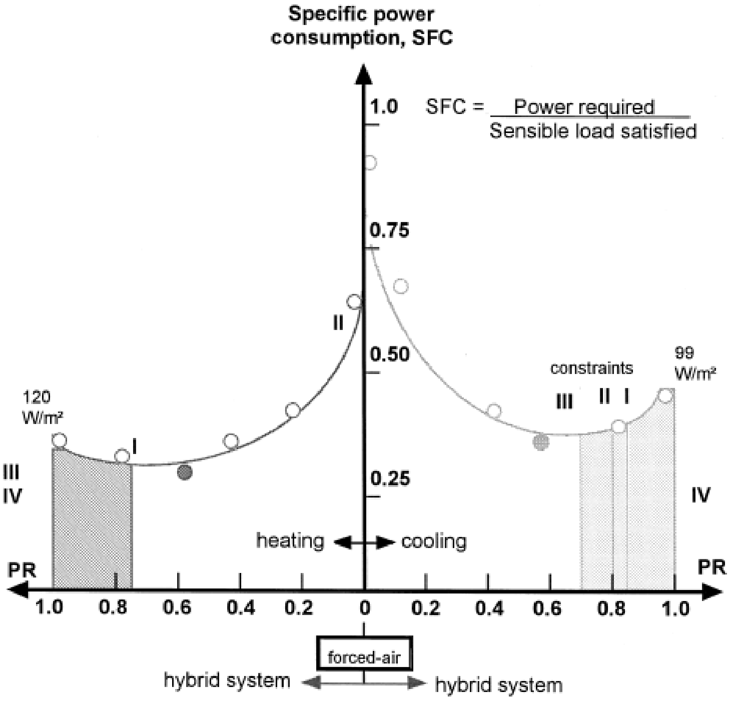
Picture 37: Wind energy GSHP driven coupled to a hybrid HVAC system

The design conditions are listed in table 6. Is should be stated at this point that sensible loads refer to the dry bulb temperature of the building and latent loads to wet bulb temperature of the building.

Table 6: Design specifications

Winter	
Ambient temperature	-3^{O}C
Indoor temperature	18^{O}C
Floor panel area	80 m^2
Sensible panel heating load	80 W/m^2 (80% of standard load)
Summer	
Ambient temperature	26 ^{O}C
Indoor temperature	26 ^{O}C
Sensible panel cooling load	-40 W/m^2 (90% of standard load)

Since the system used is a hybrid one, utilizing a hydronic and a forced-air convective system, the percentage of operation of each system must be found in order to attain optimum performance. When ventilation is demanded, it is achieved by the forced-air convection system, as a results this system can cover part of the sensible load of space conditioning. In the following picture the diagram of specific power consumption as a function of PR (ratio of the sensible load assigned to the radiant panel over total sensible load) is depicted. According to it when 60% of the sensible load is covered by the hydronic system, the specific power consumption is the minimum one for both heating and cooling, therefore when 40% of the load is covered by the forced-air convection system and 60% of the hydronic one, optimum performance is achieved.



Picture 38: Diagram of specific power consumption compared to PR

It is found that during winter, in order to achieve the desired temperature of 18^{O}C, the water temperature must be at 31^{O}C for the radiant panels. However fan coils require a much higher temperature to operate, so water at 55 ^{O}C will be supplied at them and after the temperature drops 20 ^{O}C it will move the radiant panel system. Moreover, as it can be exported form picture 36, the thermal mass of the floor allows for a peak load shifting period of up to 7 hours.

4.3.4 System Assessment

During summer in order to achieve an inside temperature of 26 ^{O}C the water supplied will be at a temperature of 15 ^{O}C. Fan coils need to operate at a temperature range of 8-13 ^{O}C and will do so only when dehumidification is required. In the rest period the heat pump will bypass the fan coils, returning to a temperature of 15-18 ^{O}C and as a result increasing the COP.

Minimum COP during cooling period is found to be 0.7 while during heating period it is 3.5. This translates to electric power requirement of 1.46 kW during winter and 4.9 kW during summer. The 6kW wind turbine and 7 kWh battery are sufficient for winter use and electrical power may be also provided for the house's appliances. For summer however the load is much higher and a combination of wind turbine and solar panels could be considered, since solar irradiance is much more intense during that period. As a conclusion this hybrid wind turbine GSHP driven system can be considered a viable solution for locations with roughly equal heating and cooling loads throughout the year [65].

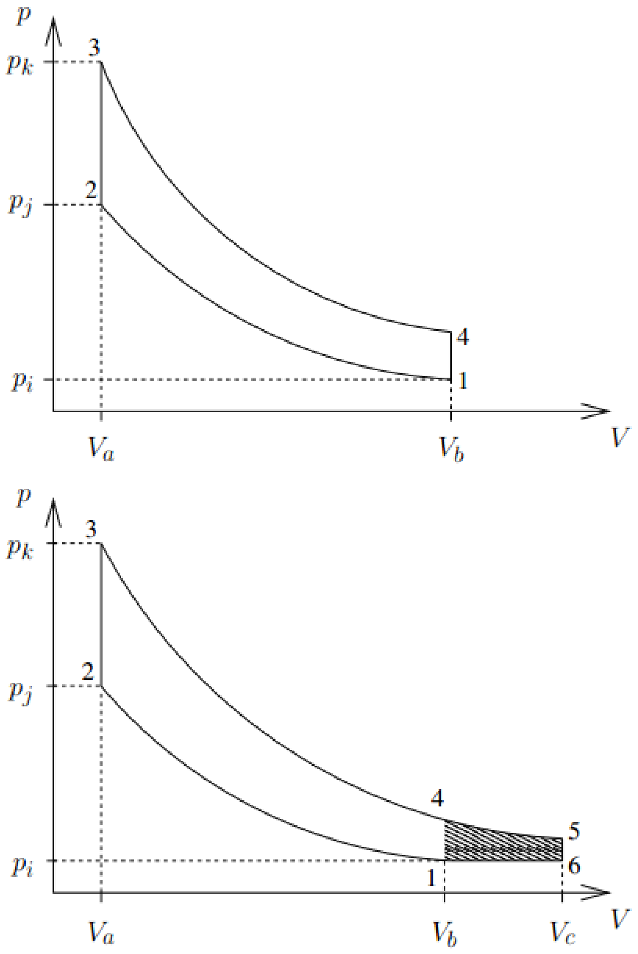
4.4 Combined Heat and Power Systems

A combined heat and power system (CHP) is able to produce electricity and simultaneously use the rejecting heat for useful purposes such as space heating and DHW. Although usually the efficiency of electricity production of such a unit is lower than that of a large power plant, the additional utilization of the rejected heat of the CHP results on grater overall efficiency compared to that of a separate energy production unit that dissipates its thermal energy to the atmosphere and heat production unit for space conditioning purposes. Moreover the fact that the electricity is produced very close to the demand results in the avoidance of the electricity transmission and distribution network which means avoidance of electricity losses during transmission and distribution and less network load, thus reduced maintenance cost.

Two cases that include CHP utilization will be described; one in Japan and one in the UK. The system described in Japan use ether a gas engine or a fuel cell, so initially their operation will be disused.

4.4.1 Gas Engines

A gas engine is an internal combustion engine that uses a gaseous fuel to operate such as natural gas. Such engines, although they are well proven and reliable, they are characterized by high level noise and vibrations and as a result they are not considered as the best choice for CHP. It usually operates under Otto or Miller thermodynamic cycles which are very similar. Miller cycle achieves higher engine efficiency than Otto, by over expanded cycles as it can be observed in picture 39. The shaded area is the theoretical extra work produced by the miller cycle compared to the Otto cycle under the same pressure values.

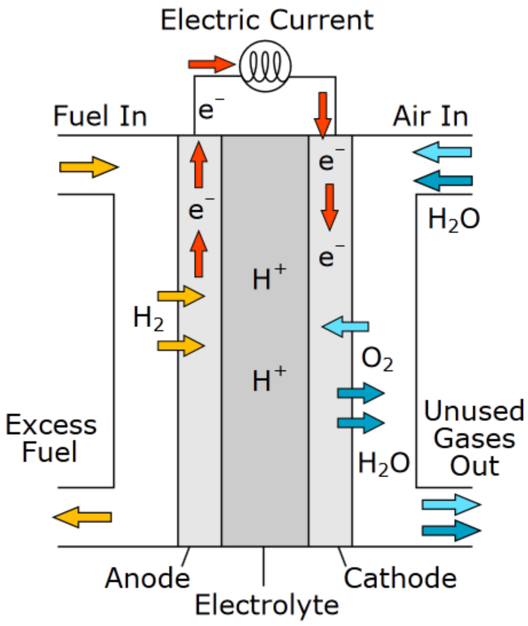


Picture 39: Otto cycle (top) and Miller cycle (bottom). The shaded area is the additional work that can be achieved by Miller cycle

The improved efficiency of Miller engines has as a drawback a reduced power to weight ratio. However for stationary applications such as CHPs this shouldn't be a problem [66].

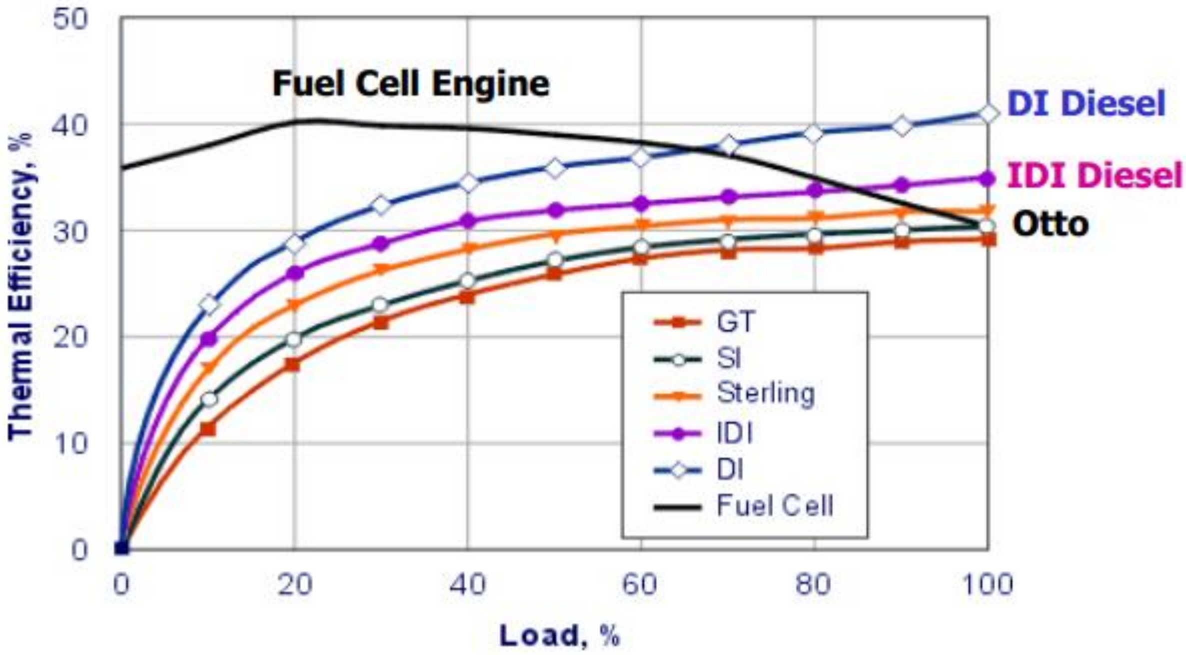
4.4.2 Fuel Cells

Fuel cells produce electricity by utilizing the chemical energy of a fuel through a chemical reaction with an oxidizing agent. They can operate using hydrogen or various gaseous hydrocarbons such as natural gas, methanol etc. A fuel cell consist of an anode (-), a cathode (+) and an electrolyte in between (picture 40). In hydrogen powered fuel cells, the molecule of the hydrogen is separated to two hydrogen atoms in the anode and likewise the oxygen molecule is separated to two oxygen atoms. Each hydrogen atom is oxidized by a catalyst in the anode. The free electrons travel though a wire creating electric current while the protons travel through the electrolyte to the cathode side. Once in the cathode, the protons and the electrons are recombined and with the presence of oxygen they produce H_2O.



Picture 40: Hydrogen burning fuel cell

Since fuel cells are not internal combustion engines, they are not bound by the theoretical thermodynamic limitations of the Carnot cycle and can achieve a theoretical efficiency of 83% [67]; however, practically they can achieve efficiencies of up to 40% us is shown in picture 41. Despite that, fuel cells are more efficient than internal combustion Otto engines such as gas engines especially when they are operating at partial loads.

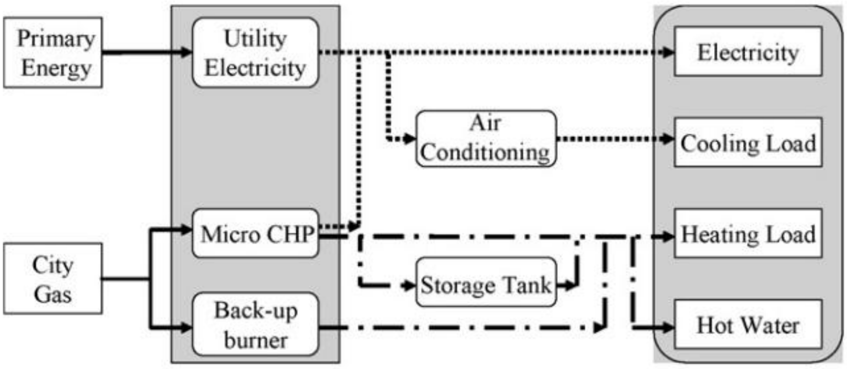


Picture 41: Efficiency of fuel cells compared to various internal engines as a function of load (Asmus, 1995)

4.4.3 System Assessment

4.4.3.1 First Case

The first case is about the environmental benefits of using micro CHPs. Two systems able to produce up to 1 KW of electricity and around 3kW of heat, one using a gas engine and one using a fuel cell which runs on natural gas are examined and their CO_2 emissions are compared to that of a conventional house that uses electricity from the grid and natural gas for space heating and DHW. Cooling loads are covered from a conventional split unit air conditioner which consumes electricity and when the CHP is incapable of meeting the demand, further coverage of electricity loads is done by the utility. A thermal storage tank is also included in order to allow space heating using the CHPs waste heat when it doesn’t operate and any need of heating loads above the CHPs capabilities are met from a natural gas buck up burner. Moreover the demand covered by each CHP is presented and it should be mentioned that the scheduling of the CHPs has the reduction of the environmental impact as its highest priority. This experiment took place in a two stories high single family building in Kitakyushu, Japan (latitude is $33^{O}53'$N). Picture 42 shows the connections end energy flows across all systems.



Picture 42: Structure of the residential CHP system

In Japan the largest portion of electricity produced is from centralized electricity generation plants, 60% of which use fossil fuels and have a mean efficiency of 45%. Because of the long distance between the plants and any residential areas, the waste heat generated cannot be used effectively and is dissipated to the atmosphere through cooling towers.

CHPs on the other hand are right next to thermal demand and their waste heat can be very efficiently utilized. The characteristics of the CHPs used in this experiment can be seen in table 7. The main difference between the gas engine and the fuel cell CHPs apart from the completely different electricity production units is that the fuel cell one uses a fuel processor to produce hydrogen out of natural gas. From the table it is observed that the fuel cell unit has much higher electricity production efficiency while its heat recovery falls short compared to the gas engine unit. It is believed that in modern and future buildings with cable insulation the thermal loads will be reduced and fuel cell CHP systems with their highly efficient electricity conversion will be better utilized.

Table 7: Characteristics of micro CHP systems

	Gas Engine	**Fuel Cell**
Rated capacity (kW)	1	1
Electricity generation efficiency	20%	37%
Heat recovery efficiency	65%	50%
Lifetime (Yr)	10	10

In order to evaluate the environmental benefits of the CHP, the following formula is used, where ERR is the CO_2 emissions reduction ratio, E_{CON} are annual CO_2 emissions of the conventional system and E_{CHP} annual CO_2 emissions of the CHP system.

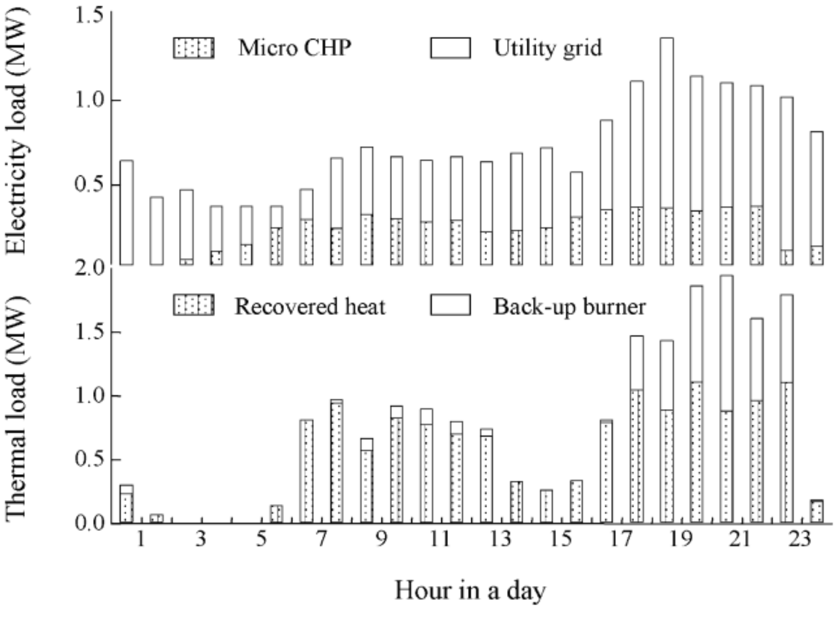
$$ERR = \frac{E_{CON} - E_{CHP}}{E_{CON}}$$

Annual CO_2 emissions of the conventional system include the emissions of the utility electricity consumption and the natural gas consumed to operate the boiler, while CHP CO_2 emissions include that of the utility electricity consumption and the natural gas consumed by the CHP and the backup boiler.

$$E_{CON} = E_{CON}^{ELE} + E_{CON}^{GAS}$$

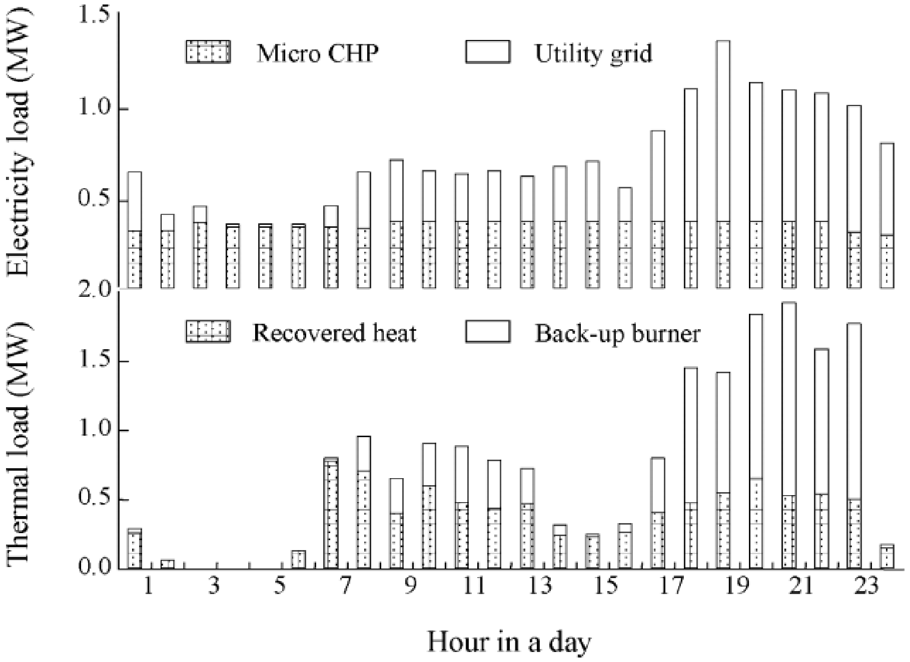
$$E_{CHP} = E_{CHP}^{ELE} + E_{CHP}^{CGAS} + E_{CHP}^{BGAS}$$

The results for the gas engine CHP are depicted in picture 43. Optimal operation for minimum environmental impact dictates that the CHP should operate at high capacity during the day and low capacity during the night because of the reduced thermal load. It manages to cover around 30% of the electric load in the house and around 75% of the thermal load. During midnight the CHP produces more thermal load than the one required. This excess thermal energy is stored in the thermal tank and is used during day time to cover the needs.



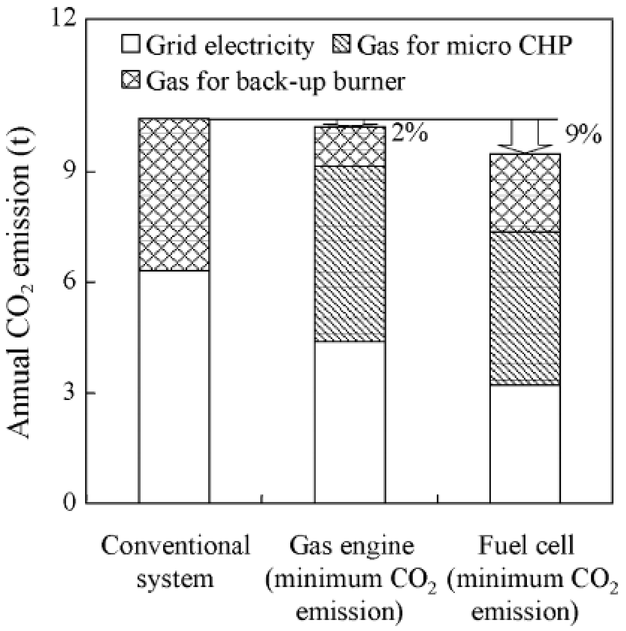
Picture 43: Thermal and Electricity balance for the CHP with gas engine

The fuel cell CHP as shown in picture 44 is operated at full load almost the entire 24 hours of the experiment. Although it manages to surpass the gas engine CHP in the balance of the electric load by generate 49% of the load needed, it falls short in the thermal load by generating only 50% of how much is required. This is because the fuel cell CHP is less efficient at heat recovery as show in table 7 and because of the more intensive use of the thermal storage tank. The fact that this CHP operates during high load at night when there is no demand for thermal load, results in the storage of the thermal loads and their use during daytime. Inevitably this leads to additional losses from the storage tank and consequently around 78% of the recovered heat is used for practical purposes.



Picture 44: Thermal and Electricity balance for the CHP with fuel cell

As illustrated in picture 45 the environmental benefits of the gas engine CHP appear to be marginal with only a 2% reduction of CO_2 emissions, while the fuel cell CHP manages to provide a 9% reduction over the conventional system. The bad performance of the gas engine is attributed to its higher fuel consumption and its small energy production efficiency.

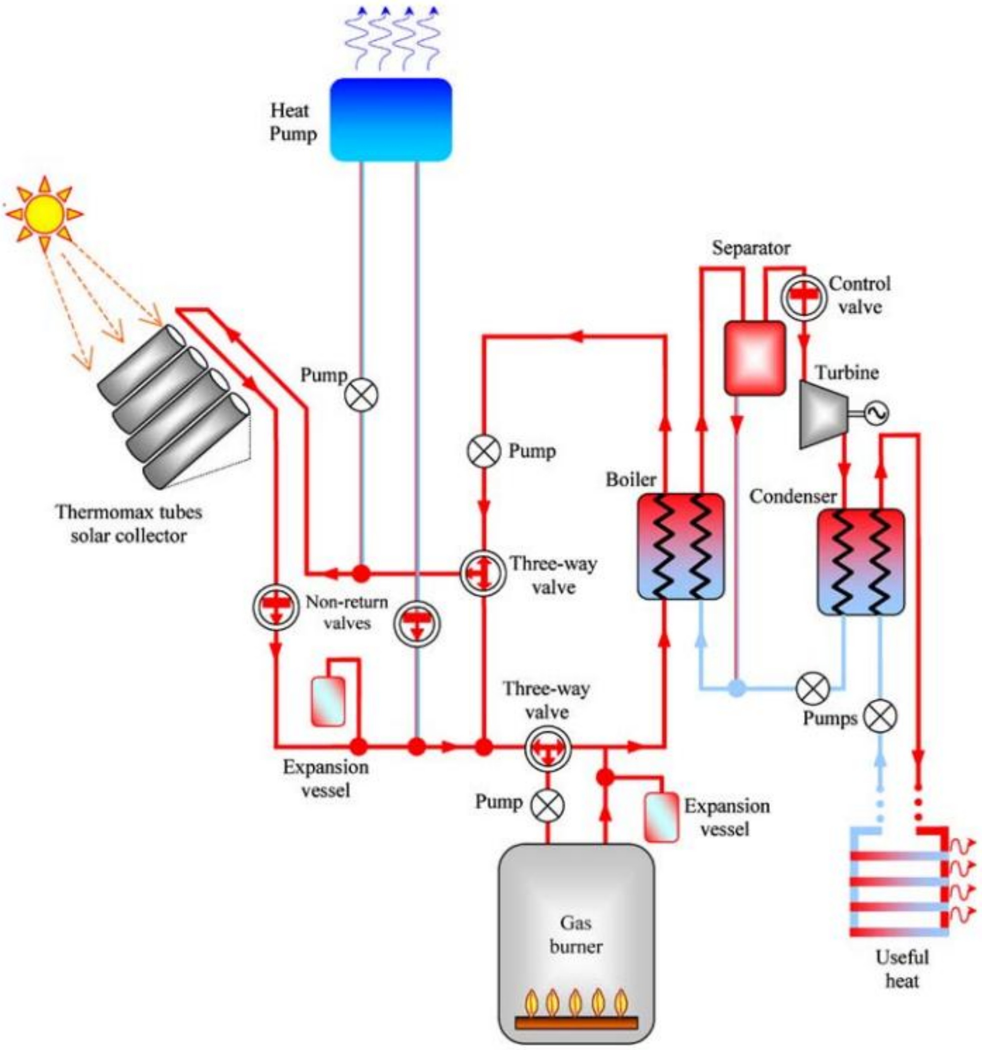


Picture 45: Environmental impact of gas engine CHP and fuel cell CHP compared to the conventional system

The improved performance of the fuel cell CHP along with other advantages such us no vibration or noise, or potentials such as zero CO_2 emissions through the use of H_2 as fuel make it a more attractive choice when it comes to CHPs [68].

4.4.3.2 Second Case

In the second case a hybrid solar-gas driven CHP is tested in a 240 m^2 office building in the Midlands, UK. The system consists of a 1.5 kWe micro turbine electric generator which operates on the Rankine cycle. It is fed by vacuum tube solar thermal collectors with a maximum capacity of 25kW and a condensing gas boiler, also able to provide 25 kW thermal energy, which supplements the thermal solar collectors. Heat from solar collector and the boiler is used to vaporize a working fluid which then enters under high pressure and expands inside the electricity generator turbine, enabling it to produce electricity. After exiting the turbine the low pressure vapor goes through a condenser where it becomes a liquid before it starts a new cycle. The heat extracted in the condenser is used to for space heating. A schematic of the installation is depicted in picture 46.



Picture 46: Schematic of the hybrid CHP system under examination

The average daily electricity consumption of the building is calculated to be 24.5 kWh and the CHP system which operates on an average of 5 hours per day is able to provide around 30% of that load. Additionally it is estimated that annually 42,480 kWh are required for heating purposes. In order to calculate the usable thermal energy, the electricity produced is subtracted from the initial 25 kW of thermal power. On top of that, considering all the losses it is estimated that 10% (2.35 kW) of the heat at the condenser can be considered as usable heat. Therefore, during the 5 hour operation of the system 11.75 kWh of thermal energy will be contributed daily for heating purposes, which is the 10% of the daily heating load. From the results it is found that the electrical cycle efficiency is 7.6% and when the useful heat recovery is added to that the efficiency increases to 17%.

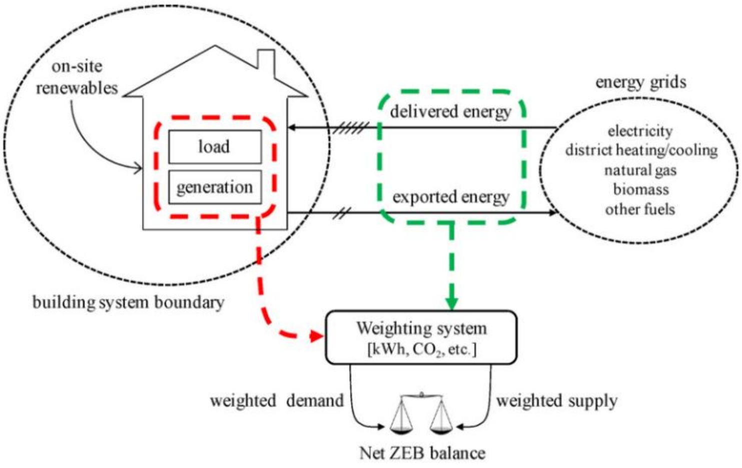
The contribution of the solar thermal system to the energy input is estimated to be 0.14 and it is required in order to calculate any environmental benefits of the system. If only conventional electricity production is used and with the assumption that 0.43 kg of CO_2 is emitted for each kWh produced, the office building is responsible for 4.4 tones of CO_2 annually. Additionally another 8.1 tones are emitted annually from natural gas combustion in order for the heating loads to be covered, resulting to 12.5 tones total. As it has been already mentioned, 30% of the electricity and 10% of the heat load is covered by the CHP with a 0.14 contribution of the solar thermal panels, hence as it is calculated from the following formula 0.3 tones of CO_2 are saved annually [69].

$$CO_2 saved = 4.4 * 0.3 * 0.14 + 8.1 * 0.1 * 0.14 = 0.298\ tones\ of\ CO_2$$

5. Review of Net Zero Energy Buildings

Net Zero Energy Buildings (NZEB) are buildings that produce as much energy as they consume over a typical year. In order for that to be achieved, reduction of energy consumption for space conditioning and electric appliances is mandatory through increased efficiency of appliances and HVAC systems and reduced losses through improved building shells and utilization of hybrid systems that take advantage of the environments' characteristics. Energy production is made ether on site, or off site, for example as part of a community renewable energy system. When the energy produced is insufficient, the remaining demand is satisfied by the grid and respectively when local energy production is higher than the demand it is exported to the grid. Ultimately, this two-way flow of energy should result in zero energy export or import from the building to the grid. A simplified schematic of a NZEB is portrayed in picture 47.

In order to evaluate the energy performance of a building, many building design standards that provide various criteria have been created such as PassivHaus in Germany, BREEAM in the UK, LEED in the U.S.A. Despite that, there is a lack of specific strategies and guidelines for the construction of NZEB which are necessary the massive construction of such buildings.



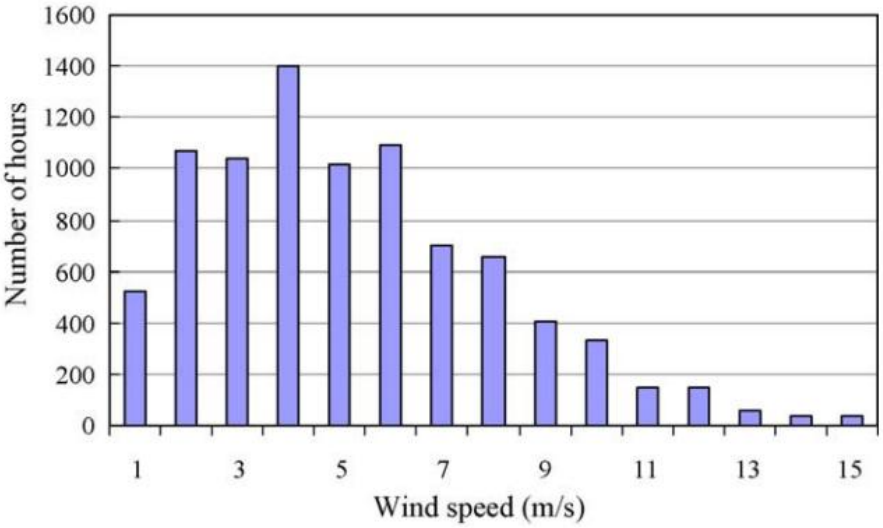
Picture 47: Schematic of a net zero energy building

5.1 Case Study of Net Zero Energy House in the UK

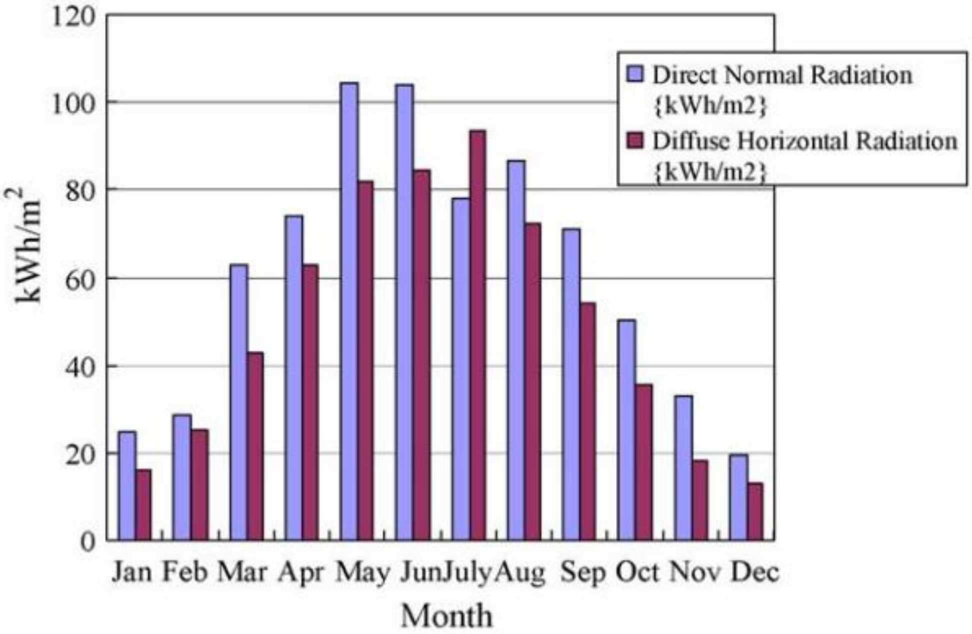
In this study the method followed for the production of a NZEB is presented. Energy consumption is a function of the building shell characteristics, environmental conditions and appliances characteristics, thus various designs are tested in order to find the optimum combination that minimizes energy consumption which is then compensated by on site renewable energy production. The entire process can be divided in three steps and these are weather data analysis, passive design methods to minimize load requirements and finally implementation of energy efficient systems and renewable energy sources.

5.1.1 Weather Data

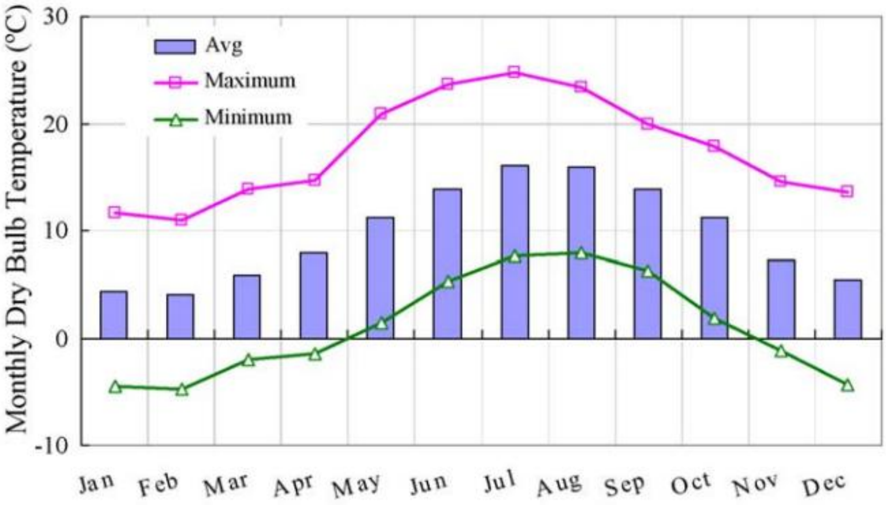
Initially weather data for Cardiff, UK (latitude $51^{O}29'$N) where the house will be constructed are collected. Specifically wind, solar radiation and ambient temperatures are necessary since the orientation and design characteristics of the house are largely affected by them and moreover an optimum solution for wind or solar energy production can be considered. From picture 48 it is extracted that there is frequent wind with speeds ranging from 3 to 7 m/s which indicate that a small wind generator might be a good solution for energy production. In picture 49, solar irradiance throughout the year is presented. Solar irradiance plays decisive role for the use of PV or solar thermal systems and affects the design of the shell of the building as it will be shown later. Average, maximum and minimum dry bulb temperature distribution for Cardiff is presented in picture 50. From the temperature distribution it is apparent that high heating loads and low to none cooling loads are required for houses in Cardiff.



Picture 48: Wind frequency for Cardiff, UK



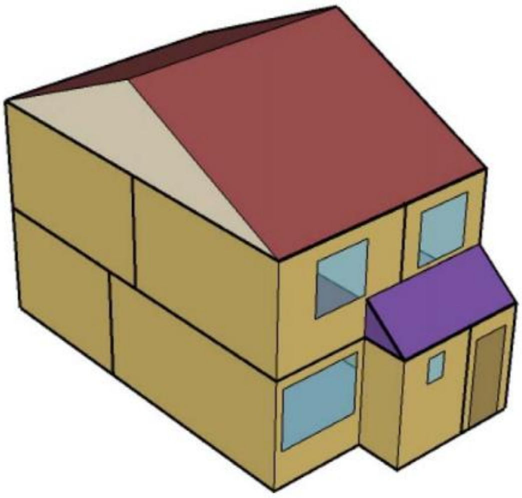
Picture 49: Solar insolation for Cardiff, UK



Picture 50: Temperature distribution for Cardiff, UK

5.1.2 Building shell

The building under study in EnergyPlus software is portrayed in picture 51 and the characteristics of the building elements are listed in table 8.

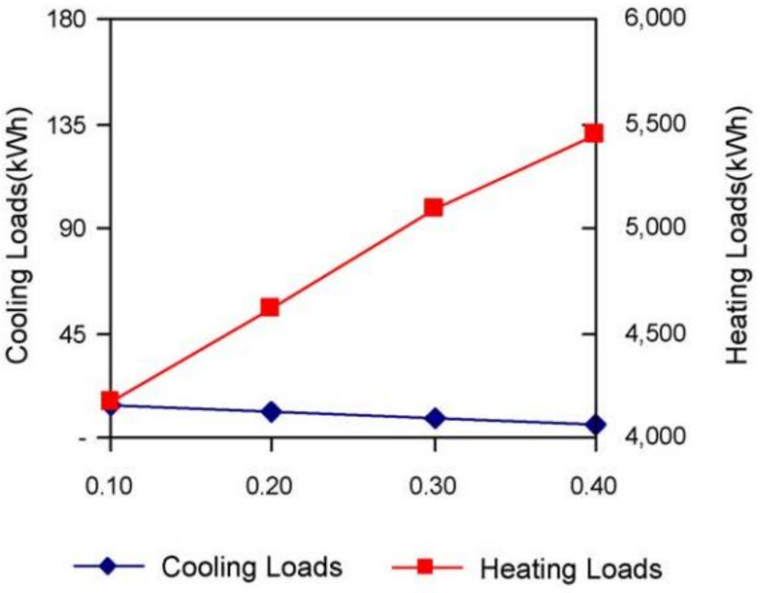


Picture 51: House model under study

Table 8: Characteristics of the building elements

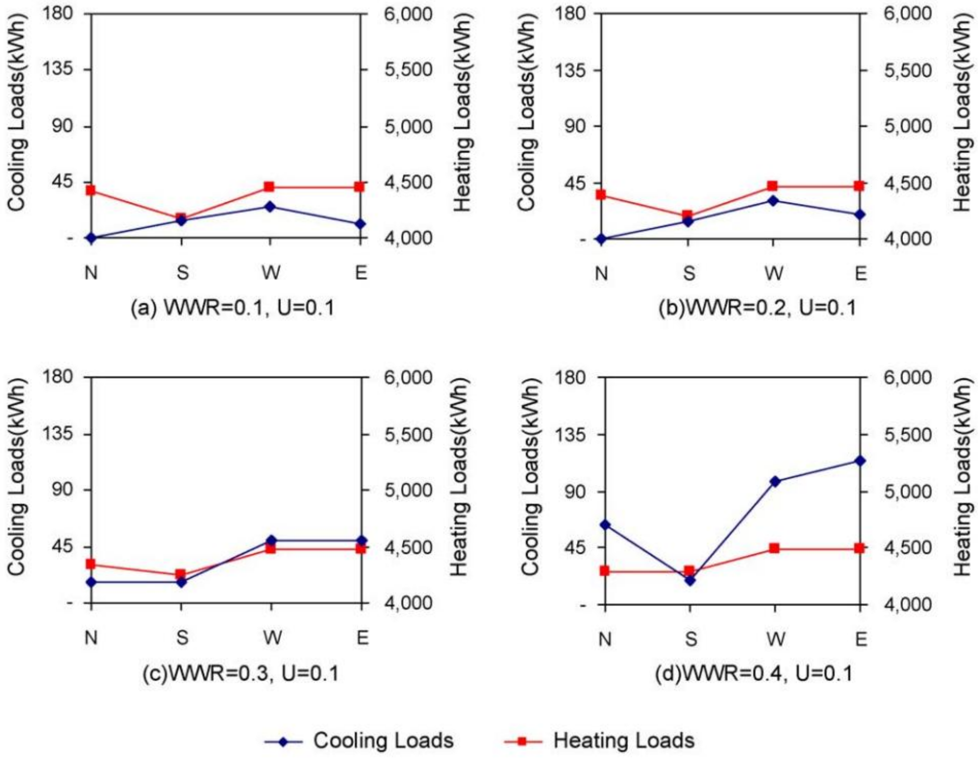
Building element	**Material**	**U value (W/m^{2}C)**
External wall	Concrete block and brick	0.4
Glazing	24mm double glazing	1.78
Internal partition	Plasterboard and insulation	0..71
Roof costruction	Concrete tiles, felt/underlay	4.298

In all cases heating set point is 20^{O}C, cooling set point is 24^{O}C, heating period is from October to March and cooling period from April to September. Initially the space conditioning loads are presented as a function of the U values of the external wall. The results are presented in picture 52 and it is found that with higher U-values, lower cooling loads and higher heating loads are observed. This can be explained because insulation prevents undesirable heat produced by internal heat gains to be rejected to the environment. Despite that the annual energy used for space conditioning is decreased with better insulation.



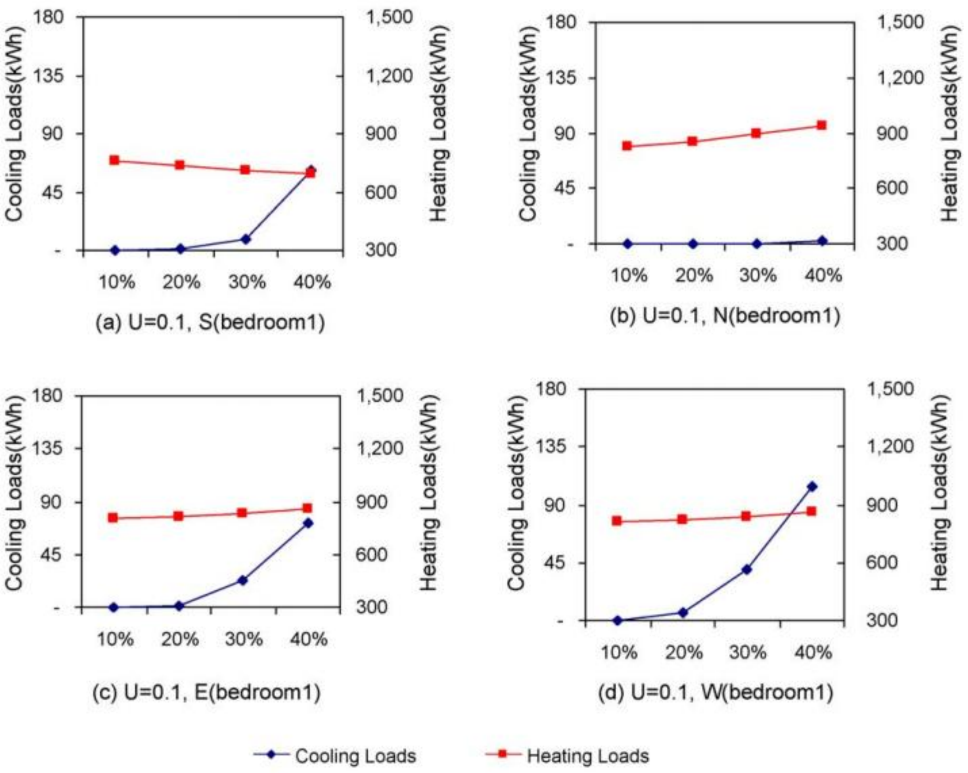
Picture 52: Heating and cooling loads as a function of the U-values of the external walls

Orientation of a building can significantly affect the energy consumed for space conditioning. Since the house in the northern hemisphere, solar thermal gains are much more in the south facing rooms and this should be considered during initial design. Moreover, the window to wall ratio (WWR) is another factor that affects the behavior of the building. In this case various combinations of the orientation and WWR are examined to find the optimum characteristics that allow as to minimize energy consumption. From the results in picture 53 it is observed that south orientation is the optimum one for the reduction of heating loads with the exception of really high WWR value. Large windows allow on one hand greater solar thermal gains to enter the house but on the other hand their bad insulation properties result in greater heat losses. Another interesting observation is that although the north facing orientation is the one with the least solar thermal gains, it requires less heating energy than the west and east orientations. This is because no matter the orientation there will always be conditioned spaces facing in all directions. The arrangement of the rooms in this house is such that although the entrance of the house faces north, other regularly used conditioned spaces face south and take advantage of the solar thermal gains.



Picture 53: Heating and cooling loads for various WWR values and orientations of the house

The results of the heating and cooling loads required for various WWR and orientations of just one room are depicted in picture 54. Examining just one room presents the ability to find an optimum combination for orientation and WWR. It is apparent that higher WWR values result into higher cooling loads regardless of the orientation. As for the heating load, when the orientation is south it decreases with higher WWR values whereas it increases for all other orientations. Therefore it is found that in order to reduce energy consumption for space conditioning a WWR value of 10% should be used for north, east and west orientations and when the goal is the lowest heating load 40% for the south facing walls.



Picture 54: Heating and cooling loads of one room for various orientations and WWR values

After the examination of various orientations and WWR values it is concluded that the south facing wall should have 40% WWR value and the rest facades 10% WWR value. A house with these characteristics provides 26.5% reduction of the heating load and a negligible increase in the cooling load compared to the original house design. Further reduction in energy consumption can be achieved by installing windows with lower U-value and replacing the ventilated roof with an insulated one. By implementing these changes 31% of the initial energy consumption can be saved. The properties of the improved design are listed in table 9.

Table 9: Properties of the improved house shell

Building Elements	**Material**	**U value (W/m^{2}C)**
External wall	Concrete block and brick	0.1
Glazing	19 mm double glazing with low E coating. Suspended plaster board	1.367
Roof	Ceiling insulation, reflective foil, air gap	0.2

5.1.3 Building Systems

In a house energy is used to satisfy the need for heating, DHW and the use of appliances.

A solar thermal plate with circulation pump, heat exchanger and a storage tank are with an auxiliary heater are used to satisfy DHW demands. It is found that for two occupants an average use of 98 liters per day with a temperature of 50^{O}C is required. A significant portion of this can be provided with a 5 m^2 solar flat plate collector which is enough for 78.9% of total DHW consumption, while the rest is provided by the auxiliary heater and is found to be 401.7 kWh per year.

For heating an under floor heating system is used. This is a radiant system and as discussed earlier it can provide the same thermal comfort with a convective system and at the same time keep the ambient temperature two degrees lower. For a temperature set point of 18^{O}C 2805.6 kWh per year are required while if a convective heating system were to be used a set point of 20^{O}C would be required and the consumption would rise to 3666.7 kWh per year. By implementing an air source heat pump with 3.0 COP the energy consumed falls to 935.2 kWh and this could be further reduced with a ground source heat pump which generally have higher COP values.

Finally for the appliances it is assumed that 12.8 kWh are consumed daily which results to 4672 kWh per year.

To achieve net zero energy balance energy production on site is mandatory in order to cover all aforementioned loads. In this case a combination of PVs able to produce up to 1.32 kW and a 2.5 kW wind turbine placed 15 meters high are used. Large amount of the energy produced during summer comes from PVs whereas the wind turbine dominates the energy production the rest seasons. Annually the wind turbine produces 91% of total energy production and the rest is provided by the PVs. The results of the energy balance are listed in table 10.

Table 10: Energy production and consumption for the house under study

Annual Electricity	**kWh**
Lighting and appliances	4672
Auxiliary heating for DHW	401.7
Heating load	935.2
Electricity generated by PVs	687.8
Electricity generated by wind turbine	6618.1
Sum	1297

It is concluded that it is theoretically possible to construct NZEB or even positive energy buildings in the UK. In this case an extra 1297 kWh are produced which can be sold back to the grid [70].

5.2 Feasibility Study of a Solar Powered NZEB in Southern Europe

This feasibility study takes place for a 110 m^2 one floor single family house in Lisbon, Portugal (latitude $38^O43'$). For hot climates like the Portuguese one, both heating and cooling loads are considerable and as a result highly efficient solutions must be considered for both tasks. Moreover since solar irradiance in southern climates is much more intense, a combination of solar thermal panels and photovoltaics will be considered to cover the heating cooling and electrical loads of the house.

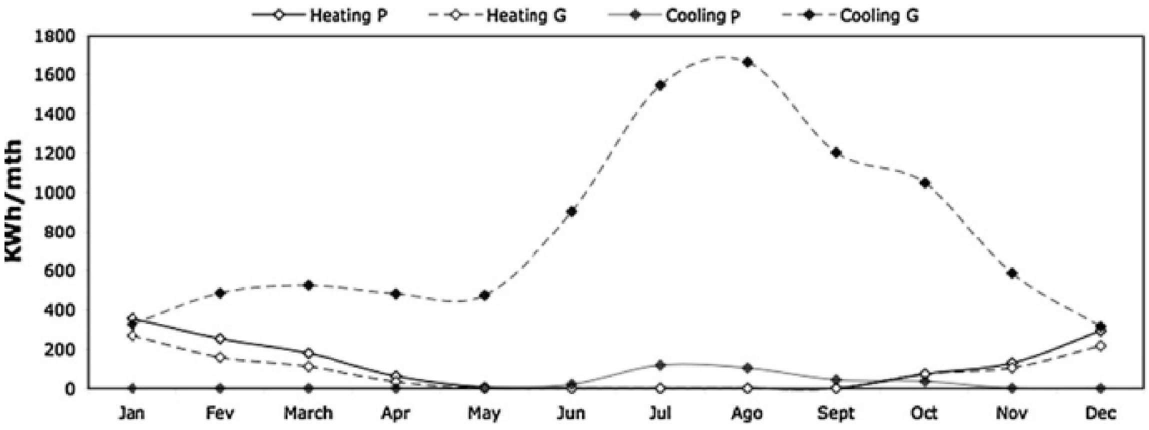
5.2.1 Building Shell

In order to test the importance of the building shell in a NZEB house two different designs are tested. The passive design (P) represents a house with low heating and cooling loads. The window to floor area ratio for this case is 21% and its insulation is superior to that of the current Portuguese standard. The glazed design (G) has the same arrangement with the passive one but a window to floor area ratio of 55% which results in insufficient insulation and inadequate shading mechanism that increase the cooling load during summer months. The U-values of the elements in both cases are listed in table 11. Moreover, to further differentiate the results, different orientations were tested and it was found that the orientations under which the passive design requires the least energy is 350^{O} and the orientation under which the glazed design requires the most energy is 300^{O}. These orientations will be used to calculate further results.

Table 11: U-values of the building elements for this feasibility study

Element	**Total U-value W/m^{2}K)**
Roof	0.23
Floor	0.41
Exterior walls	0.32
Windows	1.8

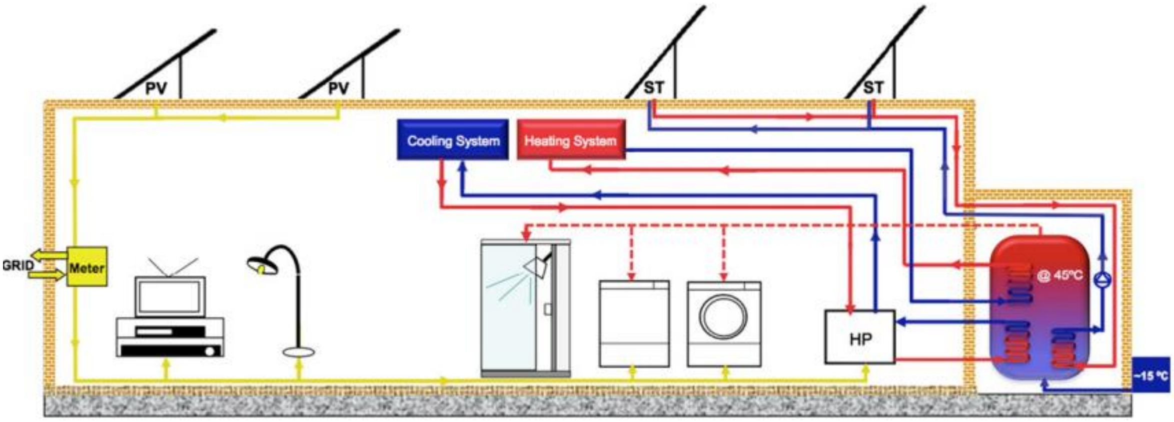
For the aforementioned characteristics and orientations the heating and cooling demands were calculated and are depicted in picture 55. Finally DHW is not affected by the building shell, thus it is the same for both cases and requires roughly 3556 kWh/year.



Picture 55: Monthly energy demand for heating and cooling calculated for the two designs.

5.2.2 Building Systems

All systems in this case are powered by electricity. Electrical appliances used in the glazed design are the ones used by a typical family with no provisions for energy efficiency, while the ones used in the passive house are all class A as defined by European Council in 1992. For example highly efficient laundry and dishwasher machines have the ability to use preheated water from external sources such as solar thermal collectors. For heating and cooling an electrically powered heat pump with a COP of 2.5 is used, which feeds a radiant flood heater.



Picture 56: Energy systems used in this study

The renewable energy system integrated in this design is illustrated in picture 56. It consists of a 4 m^{2} south facing solar thermal panel tilted to 50^{O} which provides hot water in a 300 liter thermal reservoir. When the solar thermal system is incapable of satisfying the demand, the heat pump covers the rest of the load. Also PV panels tilted at 35^{O} were used. In this case 11 m^{2} are sufficient for the passive house since the appliances are highly efficient and the heating and cooling loads are much less than those of the glazed design while for the glazed house 38 m^{2} are required to cover the demand. This large difference in the PV requirement shows the importance of a thoroughly designed house. When orientation, building elements and appliance efficiencies are taken into account overall energy consumption can be significantly reduced [71].

5.3 Case Study of a Positive Net Energy Residential Building in Serbia

In this case study the energy balance of a family building with integrated PVs is examined using the EnergyPlus software. Every need in this building, including space heating and DHW, is fulfilled by electricity consuming appliances and systems. In this city the climate is moderate continental with gradual transition between all four seasons.

Summers are worm and humid and temperatures up to 37^{O}C have been reported, while during winter the temperature can drop to -12^{O}C.

5.3.1 Building Shell

The building under study is located in Kragujevac, Serbia (latitude 44^{O}1’). It is a two floor two apartment building with a total area of 130.6 m^2 and each apartment is occupied by a four member family. The design of the building is such that minimizes heat losses during the winter and the lighting and appliances used are highly efficient. In table 12 are listed the U values of the building elements. Finally the temperature set point during the heating period is set to 19^{O}C.

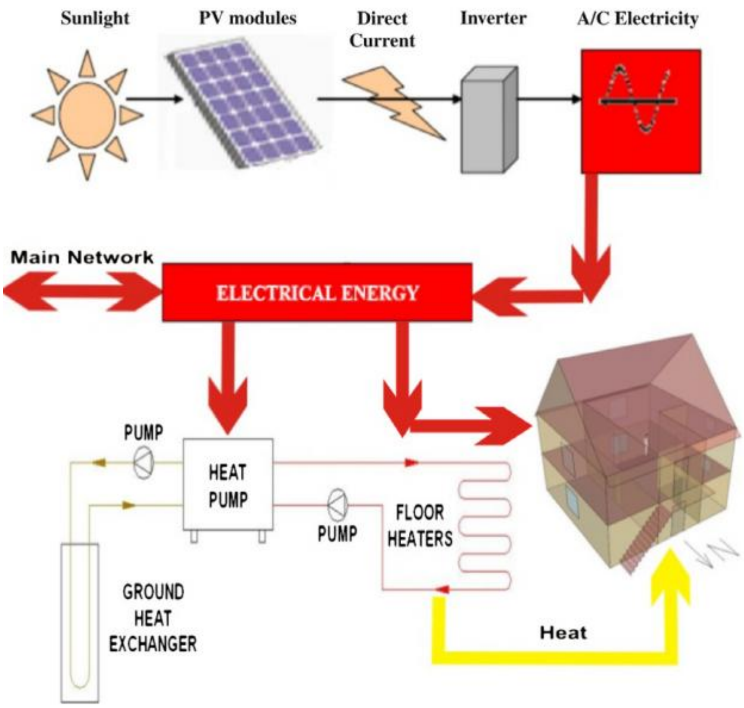
Table 12: U-values of building elements

Building element	**U-value (W/m^{2}K)**
Windows	3.19
Conditioned space wall	0.21
Conditioned space floor	0.265
Conditioned space ceiling	0.11

5.3.2 Building Systems

For space heating a 50 kW geothermal water to water heat pump is used with a COP of 3.5. The ground heat exchanger is a vertical U-tube one and the building is heated via radiant floor heating. Moreover DHW is provided by an electric water heater.

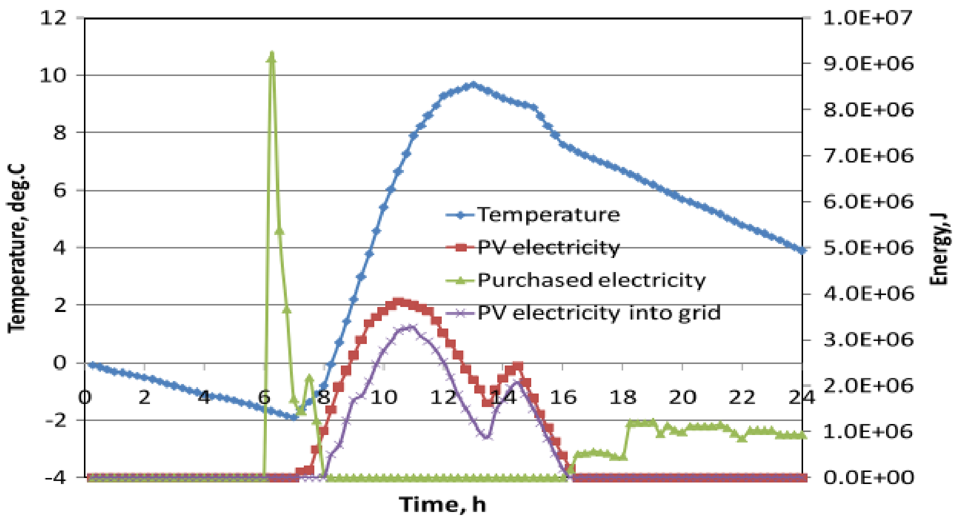
The renewable energy source of this building is chosen to be photovoltaic panels. An array of PVs covering a total area of 45.6 m^2 and able to produce up to 5 kWe is used along with a highly efficient inverter. The panels face south and have a tilt angle of 45^{O}. The heating and renewable energy systems are illustrated in picture 57.



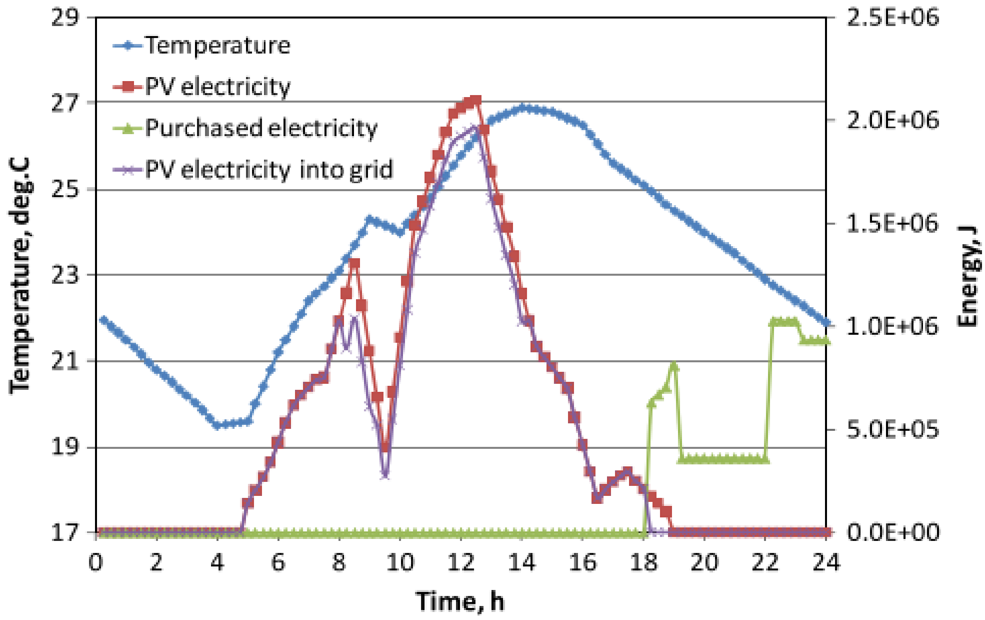
Picture 57: Schematic of the PNEH systems under study

5.3.3 Energy Balance

In pictures 58 and 59 the ambient temperature and electricity flows in the house are depicted for January 21st and July 21st respectively. In picture 58 it is clear that from 7:30 until 16:15 the PV array is able to provide sufficient electricity for the building needs and large amount of the electricity produced is exported into the grid. The remaining hours electricity is purchased by the grid to satisfy the demand. The spice in consumption at 6:15 is when the heat pump starts to operate. A similar pattern appears in picture 59, although in this case greater amounts of energy are produced and exported and for a longer period of time due to higher insolation. Additionally there is no space heating during July so overall energy consumption is lower.

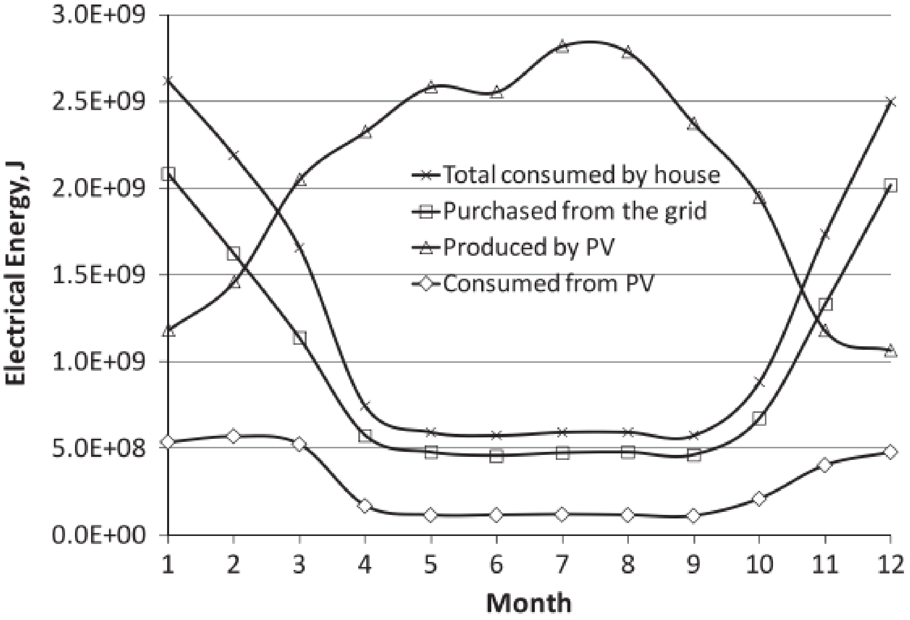


Picture 58: Ambient temperature and energy flows for the building under study at January 21st



Picture 59: Ambient temperature and energy flows for the building under study at July 21st

Annual demand energy flows is illustrated in picture 60. As expected during summer months there is significantly more energy production than during winter, while energy consumption behaves the other way around. It is safe to say from these to picture that electricity production from PVs and electricity demand from the house are not in phase at all. Most of the energy produced during summer is sold to the grid while during winter when there is low electricity production, high demands requires purchase from the grid.



Picture 60: Energy production and consumption for the building under study

In conclusion, annually this house will produce around 6500 kWh/year from which around 700 kWh are used by the house and the rest 5800 kWh are exported to the grid. The amount of the electricity consumed by the house is calculated to be around 4200 kWh/year, so this can be characterized as a positive net energy building [72].

6. Description of a near NZEB in Athens, Greece

Despite the fact that net zero energy buildings present many advantages regarding both energy consumption and quality of life, the cost of constructing such buildings in commercial scale is still considered forbidding. However noteworthy efforts emerge around the globe that integrate various of the systems and techniques presented earlier, in an attempt to achieve performance as close as that of a NZEB while also preventing the cost from becoming exorbitant. Such an attempt that after studies resulted in a highly efficient residential building has been made in Athens, Greece. This building along with various energy consumption data and the results of an energy audit will be presented in this chapter. This case stands out from the ones described earlier because it is a materialized and fully functional residential building, thus measurements take into account all these variables introduced by daily life and many more factors that are not taken under consideration in simulation programs.

6.1 Introduction

In 2011 electricity consumption in Greece reached 52,452 GWh from which 49,219 GWh were produced domestically;83% of the electricity produced in Greece originated from fossil fuels which means that pollution and ghg emissions due to electricity generation are relatively high [73]. Since Greece is a typical European country, its building sector is responsible for around 40% of its annual electricity consumption so in order for Greece to achieve the 20-20-20 goal set by EU, state of the art energy solutions must be introduced in the building sector.

The building under examination focuses in highly efficient appliances and HVAC systems and effective shell insulation to reduce overall energy consumption. The solutions incorporated do not demand anything unusual such as specific orientation for use of passive solar thermal systems such as the Trombe wall or large and open areas for the installation of wind turbines etc; as a result the systems described can be utilized in most of the buildings located in urban areas.

6.2 Building Description

The structure which is depicted in picture 61 is a three floor high residential building with six apartments. There is an underground garage and pilotis at the ground level; additionally there is a seventh studio-apartment located between the ground level and the basement. The entire building was constructed by C. BAKALAS S.A. construction company with energy efficiency in mind; however the description will focus on the studio-apartment which incorporates separate, more advanced hybrid systems and thicker insulation to achieve even lower energy consumption compared to the rest of the building.A top down view of the studio-apartment is depicted in picture 62. Total conditioned area for the six apartments is 800 m^2 and for the studio apartment 249 m^2.

Picture 61: Front view of the residential building under examination

Picture 62: Top down view of the studio-apartment

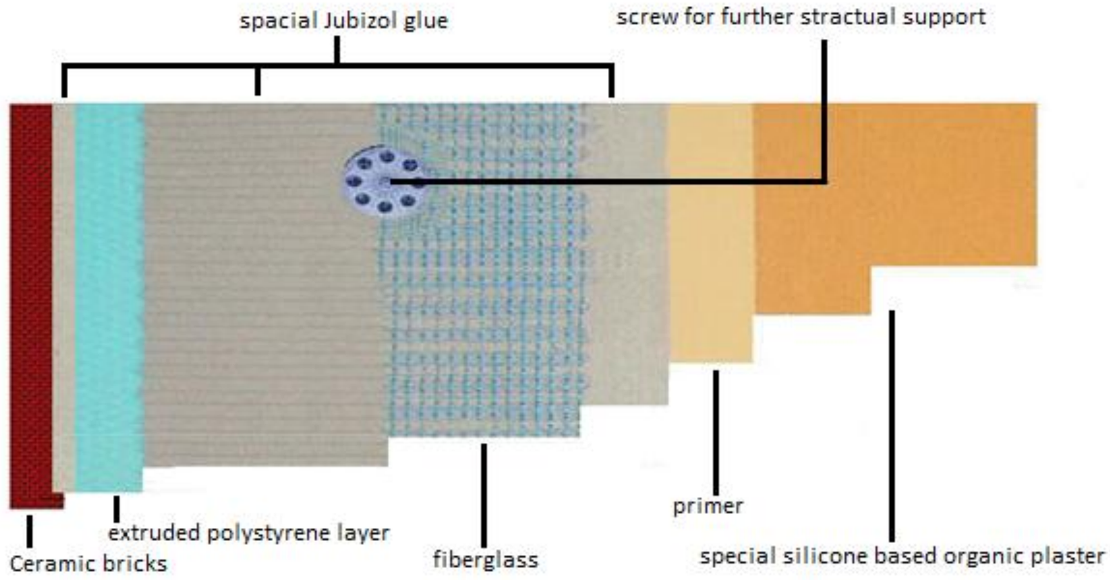
It was build in 2010 and is located in Athens (latitude 37^{O},58’ N) where the climate is subtropical Mediterranean and it is characterized by hot and dry summers which are followed by mild and wet winters [74]. Temperatures range from below zero during winter to above 40^{O} C during summer. Moreover the city is affected by the urban heat island effect during summer which increases energy consumption for space cooling.

6.2.1 Building Shell

The insulation installed is a product manufactured by the companies Jubiland and Fibran and it is used in all external surfaces including the ground level pilotis. It is called thermocoat and it consists of extruded polystyrene plates which are characterized by great thermal insulation properties because of the air trapped inside many closed bubbles (picture 63). Moreover extruded polystyrene plates appear to be resilient against humidity. This type of insulation is installed from the outside of the external wall, its thickness ranges between 6 and 8 cm and it is protected by a special silicone based organic plaster. Special brackets with thermal insulation properties are used to mount the extruded polystyreneplates on ceramic bricks. A schematic of the above layout is depicted in picture 64.

Moreover another significant characteristic is that this type of insulation is ETAG 04 certified. ETAGs are certifications concerning various construction products and are provided by the European Organization for technical Approvals (EOTA). A product with an ETAG certification can carry the “CE” marking and can be traded in any EEA (European Economic Area) country.

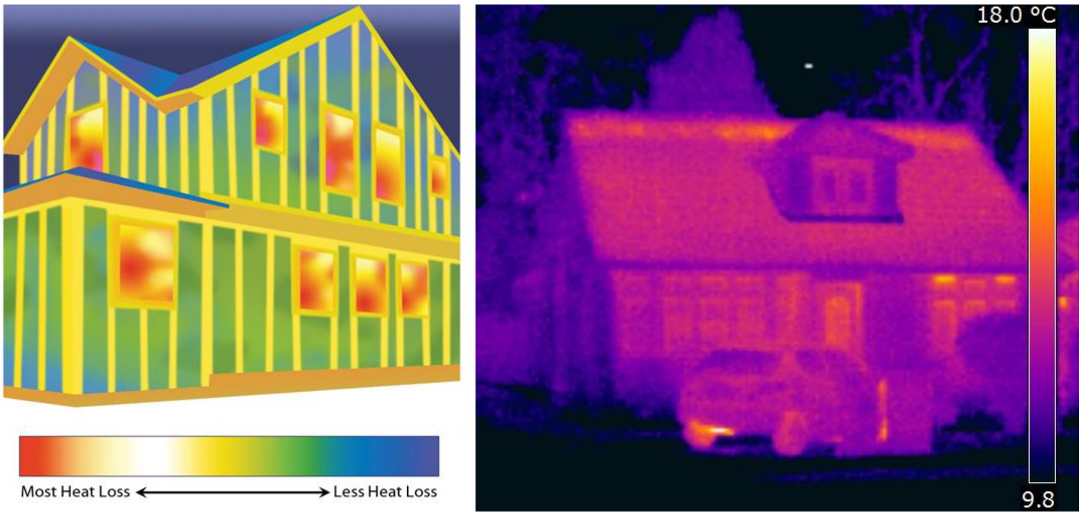
Picture 63: Installation of extruded polystyrene plates in the outer cell during construction



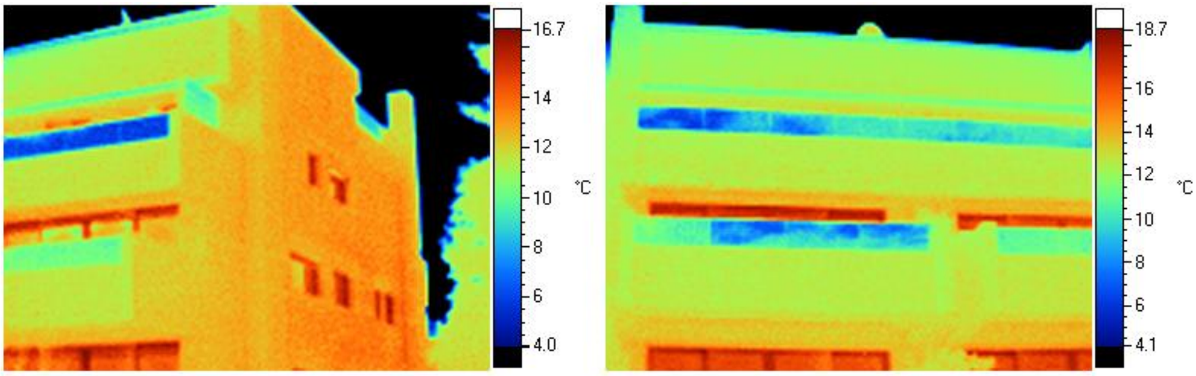
Picture 64: Layers of the external insulation

Modern methods on insulation indicate that it is advantageous when insulation is applied on the external surface of the wall compared to the previous perception where insulation was usually applied in the middle between layers of bricks. To begin with, when the insulation is applied in the external surface of the wall, full advantage of the thermal mass of the entire wall is taken. This way the insulation layer which comes in contact with the external environment permits only a fraction of the temperature difference between the outside and the conditioned space to affect the heat content of the wall thus reducing its rate of temperature change and as a result postponing the effects of the external environment to the conditioned space. On the other hand when the insulation is applied in the middle, the part of the wall exposed to outside conditions is affected severally from them and its temperature closely follows that of the outside. As a result only about half of the entire thermal capacity of the wall is used effectively to prevent external weather conditions from affecting the conditioned space.

Another significant advantage of this insulation technique is that it eliminates thermal bridges. Thermal bridges occur when the insulation applied to the wall is interrupted usually due to construction characteristics. Applying insulation to the external surface can be done uniformly and continuously since there are no obstacles, while with the old method insulation layers would be usually applied in deferent depths and thicknesses to facilitate ether brick or concrete walls or other structural elements. An example of thermal bridging is illustrated in picture 65. Two houses have been photographed with an infrared camera which shows the thermal losses from the hotter conditioned space to the cold environment. It is apparent from the color differences that the left house experiences significant heat losses (bright lines) due to the intermittent insulation which causes thermal bridging. On the contrary the uniformly colored wall of the right building is an indication of continuous insulation that prevents thermal bridging as already explained. Moreover in pictures 66 some infrared images of the building under examination are presented. The color uniformity reveals that the building is correctly and completely insulated and no thermal bridges are apparent.



Picture 65: Comparison between a poorly insulated building and a building which is uniformly insulated



Picture 66: Infrared images of the building under examination

Stone wool is the second type of insulation material used in the inside surface of the external wall (picture 67) which consists of 5 cm thick stone-wool plates with a density of 40 kg/m^3. Stonewool besides its thermal insulation properties, is characterized by good sound insulation properties as well which improves the comfort in living spaces and provides protection against fires since it is difficult to catch fire thus enhancing the safety of the occupants.

Finally, for the internal walls a 5 cm thick stonewool layer is used.

Picture 67: Stonewool plates

The studio-apartment insulation consists of different materials. The outside of the external wall is covered with 10 cm of stonewool with 150 kg/m^3 density that provides thermal and sound insulation along with fire protection. On top of this there is a 5 cm layer of extruded polystyrene plates which is protected by silicone based plaster. The combination of stone-wool and extruded polystyrene plates razes the thickness of the external insulation to 15 cm and it is again mounted on ceramic bricks with the same brackets used to mount the external insulation as mentioned earlier.As already mentioned, there are two important advantage of focusing on external insulation rather than the internal. With 15 cm of external insulation the heat content of concrete or brick walls are much less affected from the outside conditions. As a result the thermal mass of the walls helps to sustain a constant temperature in the inside and delay or even avoid extreme weather conditions affecting the conditioned spaces. From the inside the same type of insulation is used as with the rest of the building. The external insulation layers of the studio-apartment are visible in picture 68.

Finally the insulation of the roof consists of an 8 cm thick layer of extruded polystyrene.

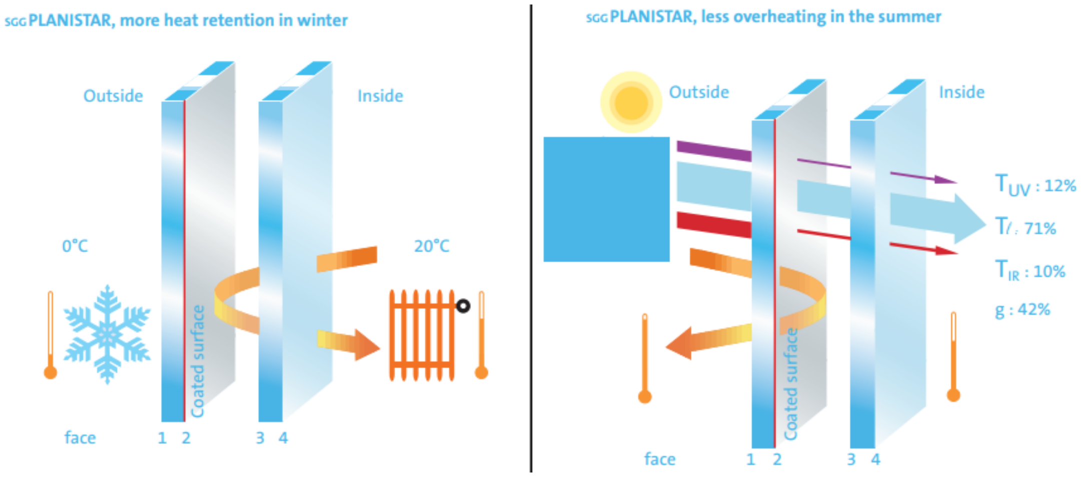
Picture 68: External insulation of the studio-apartment; from left to right, 5 cm of extruded polystyreneplates, 10 cm of stone-wool and ceramic bricks

6.2.2 Windows and Frames

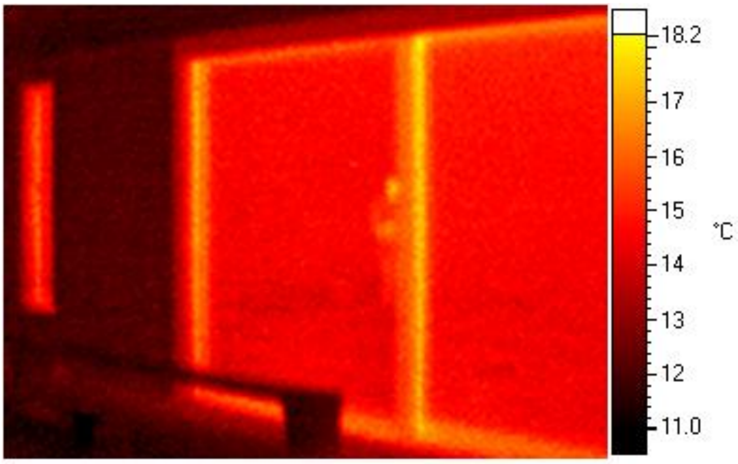
In all apartments Europa window frames have been installed. In the studio apartment the models 5500 hybrid and 10.000 hybrid were used while in the rest the models 5.500 and 600 (picture 69). In table 13 the U-values of all frames are listed according to measurement taken during the energy audit. A significant component that aids in these low U-values is that the frames feature thermal breaking which reduces heat transfer through the aluminum frame.

For glazing, in the apartments the model PlanithermFuturis used and is provided by Saint Gobain. These are 4mm thick (4+6+4 mm) and are made by materials with good thermal insulation properties providing a U-value of 1.6 W/m^{2}K. For the studio the model Planistar from Saint Cobain was chosen with a U-value of 1.1 W/m^{2}K. This model consists of a 4mm thick glass, 16mm gap filled with argon and finally a second 4mm thick glass. Planistar glass is coated with a low emissivity metallic oxide film as seen in picture 70. During the winter it reflects infrared radiation from the heated conditioned space back into the conditioned space thus preventing heat to escape. Respectively during summer it prevents UV radiation from entering and heating the conditioned space having as a result a reduced cooling load. An estimation of the thermal insulation provided by the frames and glazing can be obtained from picture 71 which depicts an infrared image of one of the windows. From the shade of color red on the glazing, the temperature in the glazing from the outside is calculated around 14^{O}C.

Picture 69: Europa frames used in the building. Models 5500 (left) and 600 (right)



Picture 70: The effect of the low emissivity coating during winter (left) and during summer (right) of the Planistar glazing model



Picture 71: Infrared image of one of the windows used in the building under review

Table 13: U-values of the frames used in the building

Frame model	U-value (W/m^{2}K)
Europa 600	2.73
Europa 5500	2.51
Europa 5500 hybrid	2.81
Europa 10000	4.17

6.2.3 Heating System

Heating in the conditioned space of the six apartments is provided through an Ergon floor heating system. Under the floor heating grid, a 2 cm thick layer of stone-wool with a density of 275 kg/m^3 is installed, mainly to provide sound insulation. The heat transfer medium is heated by a Viessmann Vitola 200 oil-fired boiler which can be retrofitted to operate with natural gas and is capable of up to 57 KW of power and an efficiency of up to 98%. Besides its high efficiency, Vitola 200 is a “low temperature boiler” which means that it is able to regulate the amount of heat required each moment. This allows for highly efficient operation even when the boiler operates at partial load which is most of the time.

The heating grid consists of PP-R80 Type 3 pipes made of polypropylene. Polypropylene pipes offer good thermal and sound insulation, thus reducing the cost for any extra insulation needed. Also they are certified with the German standard DIN 8077/78. Finally the pumps that are used for the circulation of the heating medium are Inverter type made by Grundfos and their energy rating is A’. The boiler used for space heating and part of the piping can be seen in picture 72.

Picture 72: Oil fired boiler Vitola 200 and part of the heating grid. Notice how the pipes use extra insulation to minimize heat losses during the heating medium transfer

6.2.4 DHW

For domestic hot water a second Vitola 200 boiler is used able to provide up to 47 kW of power. DHW is stored in two Vitocell V-100 tanks, with combined capacity of 500 lt, where the usable water is heated through a heat exchanger in which hot water provided by the Vitola 200 boiler is flowing. The boiler used for the DHW has the same characteristics with the one used for space heating.

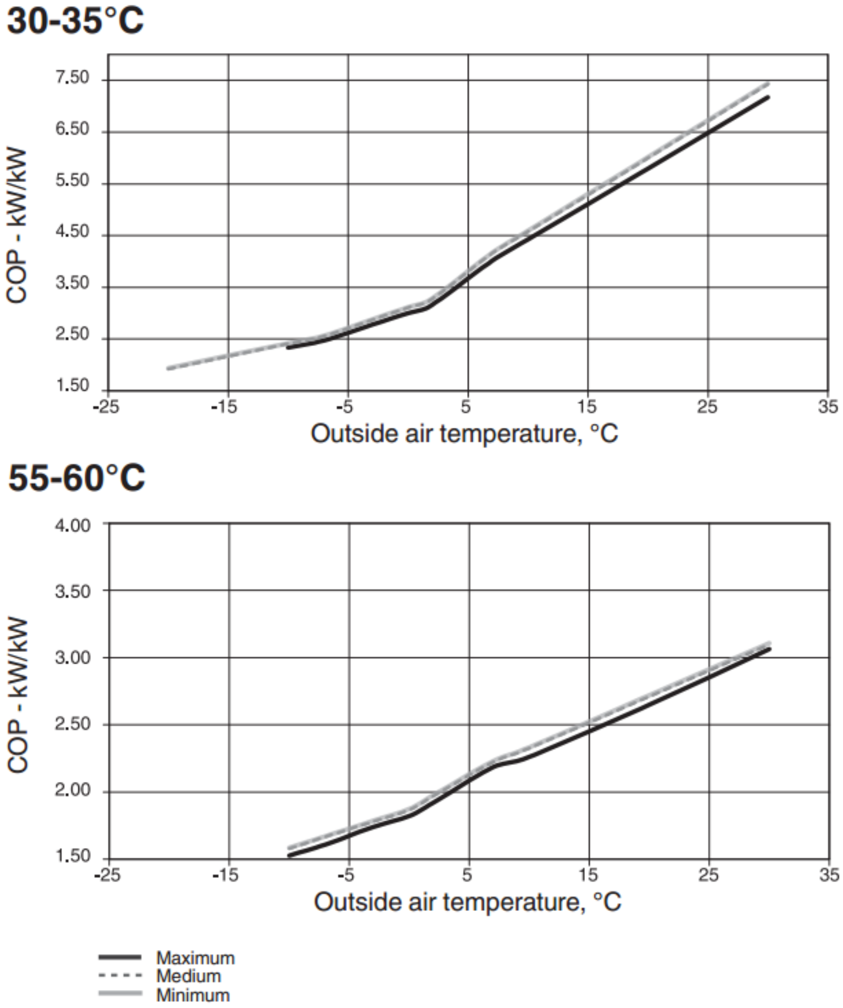
6.2.5 Cooling System

Cooling is achieved with VRV air to air heat pumps manufactured by Daikin. Variable refrigerant volume (VRV) heat pumps have the ability to adjust the volume of the refrigerant sent to the evaporator to the heating needs at each moment thereby providing more accurate control and increased efficiency at part-load conditions compared to conventional heat pumps. Conditioned spaces are finally cooled through fan coils.

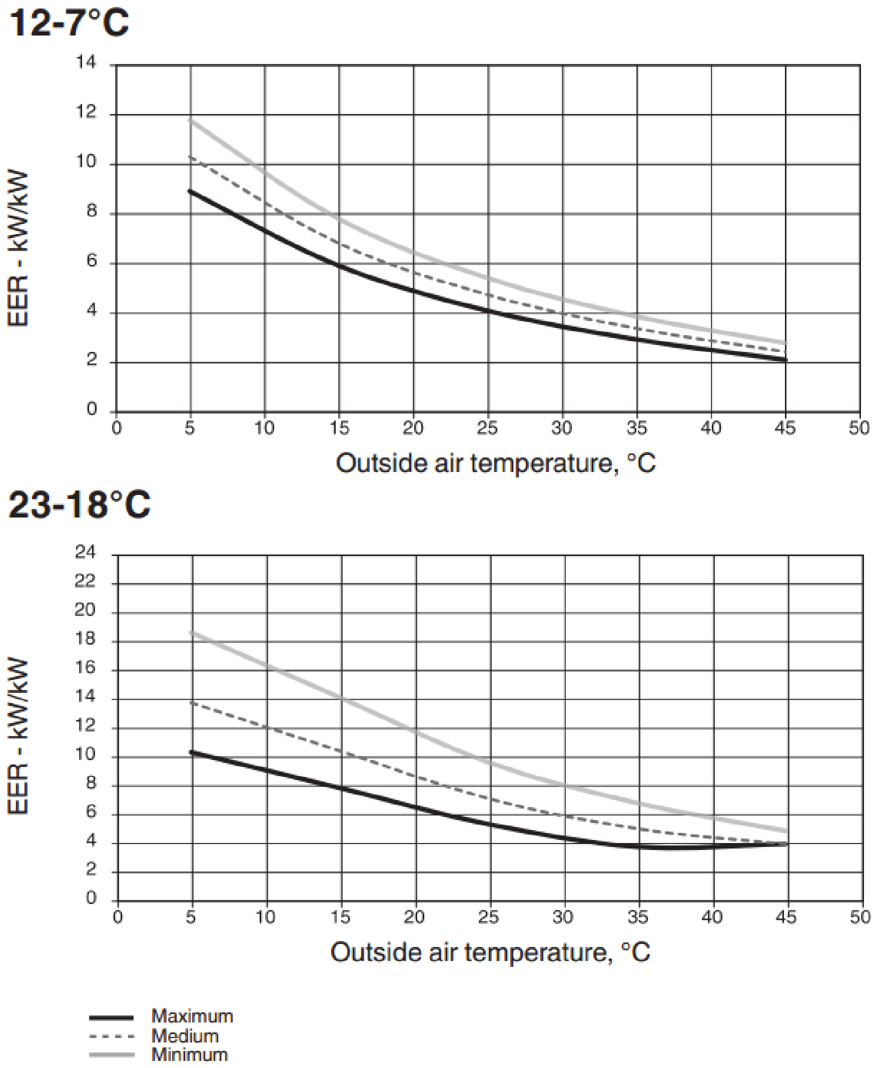
6.2.6 Studio Space Conditioning

For heating and cooling of the studio-apartment a radiative ceiling manufactured by Karo has been installed (picture 73). During the heating period, the pipes in the ceiling are fed with hot water through a heat exchanger by a combination of solar thermal panels and a heat pump. The heat pump model is 30AWH015X manufactured by Carrier with an average COP of 4.32. According to Eurovent Classification, which certifies the performance ratings of air-conditioning and refrigeration products according to European and international standards, this heat pump corresponds to a class A product. The heat pump’s COP as a function of ambient temperature for various output temperatures is depicted is pictures 74 and 75. The solar thermal panels occupy an area of 8 m^2 and when the heat provided by them to the heat exchanger is insufficient for space heating the system is supplemented by the heat pump. Hot water from the heat pump is stored in a Vitocell 360-M tank with a capacity of 750 lt which integrates stratification for more efficient use of the stored water. The water stored in the tank can either be used for space heating or as DHW which increases the utilization of the system. As observed in pictures 74 and 75 the heat pump’s COP is largely affected by the ambient temperature. For that reason, in the event of extremely adverse weather conditions during the winter, the heat pump’s reduced efficiency may render it incapable of providing enough output to satisfy the heating and DHW needs; in this case an oil-fired boiler supplements the heating system in order to meet the demand. The heat pump is also used for space cooling through the same radiative panels.

Picture 73: Karo radiative ceiling during installation



Picture 74: Carrier 30AWH015X COP as a function of ambient temperature during heating operation.



Picture 75: Carrier 30AWH015X COP as a function of ambient temperature during cooling operation.

6.2.7 Systems Control

The above systems are controlled via a Building Energy Management System (BEMS). Monitoring and control are even possible from a distance through a computer when internet connection is available. The system used is the Instabus KNX/EIB manufactured by Gira where KNX is a standardized network protocol for such applications. The fuse panel and the control box of the studio-apartment HVAC system are depicted in picture 76.

Picture 76: Fuse panel and the control box of the studio-apartment HVAC system

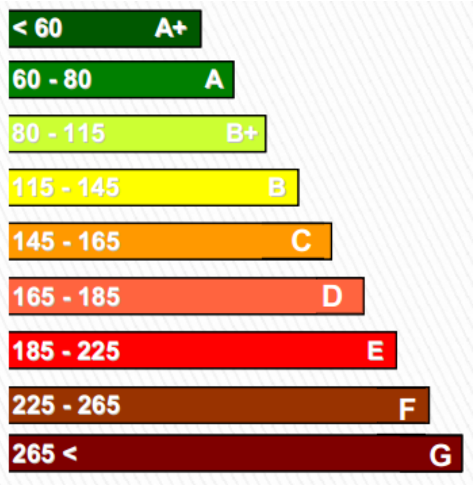
6.2.8 Miscellaneous Systems

Lighting of commonly used spaces is achieved with LED and PL lights whereas in the studio only LED lights are used. LED lights although much more expensive compared to fluorescent light bulbs are considerably more efficient and have a significantly longer lifespan.

The elevator installed in the building is manufactured by Orona and uses machine roomless (MRL) technology. The motor uses inverter technology and while it is rated to consume up to 4.6 KW it can perform equally well with a 13 KW conventional elevator motor. In MRL elevators most of the components are placed in the shaft with the elevator car.

6.3 Energy Audit

The purpose of the energy audit is to classify the building's energy performance according to 2002/91 Energy Performance of Buildings Directive. The classification of a building depends on the amount of primary energy consumed per square meter per year, where primary energy is an energy form that has not been subjected to any conversion or transformation processes. The classifications and the minimum performance for each classification are presented in picture 77 [75].



Picture 77: Energy performance classifications. Energy is measured in kWh/m^2y

In tables 14 and 15 are listed the characteristics of one of the six apartments and the studio apartment respectively according to the energy audit.

Table 14: Energy audit characteristics of one of the apartments

Boiler characteristics	Heating: bimetallic boiler used in combination with floor heating Manufacturer: Viessmann Model: Vitola 200 Power output: 50-57 KW	DHW: bimetallic boiler Manufacturer: Viessmann Model: Vitola 200 Power output: 40-47 KW
Heat pumps characteristics	Manufacturer: Daikin Model: Mini VRV R-410A / 14-16	
Windows and frames	Frame Manufacturer: Europa Model: 600 Type: Aluminum with thermal braking U-value = 2.73 W/m^{2}k	Glazing Manufacturer: Saint Gobsin Model: Future N (6mm+12mm+6mm)
	Frame Manufacturer: Europa Model: 5500 Type: Aluminum with thermal braking U-Value = 2.51 W/m^{2}k	
Glazing reflectivity	LRe (Light reflectance) 12 U-value = 1.4 W/m^{2}k LT (light transmittance) 80 Solar factor 0.63 SC 0.69	
Infrastructure Material	Reinforced concrete	
External wall materials	Starting from the inside: Plasterboard, stone wool 3cm – 50 Kg/m3, brick 18 cm, extruded polystyrene Fibran 6cm, glue, fiberglass, silicon based plaster	U-value = 0.28 W/m^{2}k
Floor materials	Plasterboard, armed concrete 20 cm, stone wool 2 cm – 175 Kg/m^3, layer of expanded polystyrene, floor heating system with heat concrete 6 cm, wooden floor 22 mm	
Lighting specifications	28 pieces of iodine lumps 4 pieces of PL4 lamps	28 x 36Watt = 1008 Watt 4 x 26Watt = 104 Watt
Heating system pumps	Manufacturer: Grundfos Model: Magna inverter cat A.	
Shading	Tents at the east and west side of the building with solar and wind sensors	

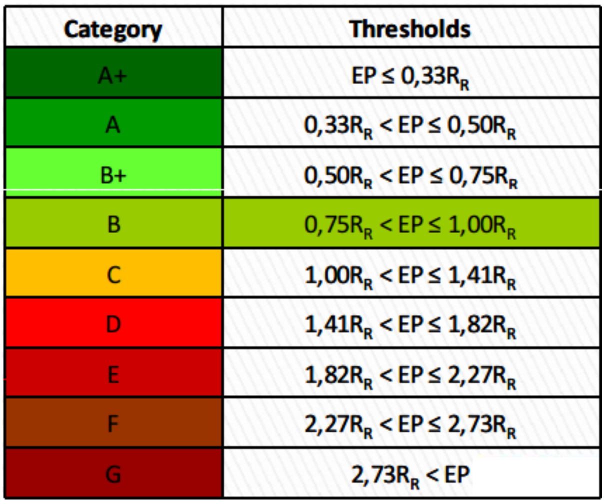
Table 15: Energy audit characteristics of the studio-apartment

Boiler characteristics	Heating and DHW: bimetallic boiler Manufacturer: Viessmann Model: Vitola 200 Power output: 40-47 KW Heating/cooling system manufacturer: Karo (ceiling pipe grid)	Stratification tank for support of the space heating and DHW system Manufacturer: Viessmann Model: Vitocell 360-M Capacity 750 liters
Heat pumps	Internal unit: XBI 300-3, Plus solar thermal system Control panel	External units: 2x 30 RHX 011 Manufacturer: Carrier Power output: 11.41 KW COP: 4.32
External insulation	Type: 10 cm stone wool (150 kg/m^3) + 5cm extruded polystyrene U-Value = 0.2 W/m^{2}k	
Windows and frames	Frame Manufacturer: Europa Model: 10000 hybrid Type: Aluminum with thermal braking U-Value = 4.17 W/m^{2}k	Glazing Manufacturer: Saint Gobsin Model: Planistar (6mm+16mm gap with 90& argon+6mm)
	Frame Manufacturer: Europa Model: 5500 hybrid Type: Aluminum with thermal braking U-Value = 2.81 W/m^{2}k	
Glazing reflectivity	LRe (Light reflectance) 12 U-value = 1.1 W/m^{2}k LT (light transmittance) 69 Solar factor 0.42 T (solar radiant heat transm) 37 RE (external solar radiant heat reflectance) 29 UV (radiancetransmitance) 10	
Infrastructure Material	Reinforcedconcrete	
External wall materials	Starting from the inside: Plasterboard, stone wool 3cm – 50 Kg/m^3, brick 18 cm, two layers of stone-wool 150 Kg/m^3, extruded polystyrene Fibran5cm, glue, fiberglass, silicon based plaster	U-value = 0.17-0.22 W/m^{2}k
Roof materials	1.5 cm coating with integrated Karo pipe grid for heating/cooling,	

	plasterboard, 5 cm stone wool 75 kg/m^3, 20 cm armed concrete, 2 cm stone wool 175 Kg/m^3, insulation plate of expanded polystyrene 30 Kg/m^3, 6 cm of heat concrete integrated with floor heating system, 22 mm wooden floor	
Floor materials	5 cm extruded polystyrene Fibran, 25 cm GrosBeton with fiberglass, top layer made of resin	
Lighting specifications	Ground level roof: 19 LED lights and 5+9 PL lights Ground level floor: 5 led lights Ceiling: 31 PL lights	19 x 14Watt = 266 Watt 5 x 55Watt = 275 Watt 9 x 2 x 18 Watt = 324 Watt 5 x 9Watt = 45 Watt 31 x 26Watt = 806 Watt
Heating system umps	Manufacturer: Grundfos Model: Magna inverter cat A.	
Shading	Tent with solar and wind sensor, across the living room shading is provided through a special metal pergola 1.65 m wide	
Thermal solar panels	Area: 8 m^2	

Another concept in the energy audit is the reference building. This is a B class building with the same geometrical characteristics of the building under study, for which the U-values of many elements are known. The classification of the building under study can be found by comparing the energy it consumes with the energy consumed by the reference building. This is achieved with the help of table 16 below, where EP is the energy consumed by the building under study and RR the energy consumed by the reference building [75]. Moreover, for comparison purposes, in table 17 are listed the U-values of the reference building, one of the apartments and the studio apartment of the building under study for climatic zone B which corresponds to Athens climatic characteristics.

Table 16: Energy classification according to the reference building energy consumption



Category	Thresholds
A+	$EP \leq 0{,}33R_R$
A	$0{,}33R_R < EP \leq 0{,}50R_R$
B+	$0{,}50R_R < EP \leq 0{,}75R_R$
B	$0{,}75R_R < EP \leq 1{,}00R_R$
C	$1{,}00R_R < EP \leq 1{,}41R_R$
D	$1{,}41R_R < EP \leq 1{,}82R_R$
E	$1{,}82R_R < EP \leq 2{,}27R_R$
F	$2{,}27R_R < EP \leq 2{,}73R_R$
G	$2{,}73R_R < EP$

Table 17: U-values of the reference building, an apartment and the studio apartment.

Components	U-value (W/m^2K)		
	Reference Building	Apartment	Studio Apartment
Exterior walls	0.5	0.28	0.2
Openings	3	1.4	1.1

The energy audit classified the studio apartment as **class A** with a primary energy consumption of 65.2 kWh/m^2y, which corresponds to 46.4% of the 140.4 kWh/m^2y consumed by the reference building. With the exclusion of some rare occasions where a boiler is used to aid heating and DHW, all energy used, is electric energy. It can be observed from table 18, where the amount of energy consumed for each purpose is listed, that around two thirds of the primary energy consumption is used for cooling, while the rest is used for heating and DHW. This can be attributed to the solar thermal collectors that contribute hot water to the 750 liter tank whose water is used for heating the studio apartment and DHW. Moreover, it is calculated that the studio apartment emits 17.11 kg/m^2y of CO_2 in the atmosphere.

Table 18: Energy consumption of the studio apartment for various purposes in kWh/m^2y

Purpose	Energy consumed	Percentage
Total	65.2	100%
Heating	12	18.4%
Cooling	45.5	69.8%
DHW	7.7	11.8%

Finally, the rest six apartments, with their thinner insulation and more conventional HVAC systems compared to the studio apartment, are classified as **class B+** which means that they consume less than 115 kWh/m^{2}y each.

6.4 Net Zero Energy Building Scenario

Having calculated the energy consumption of the building under study, a scenario will be examined regarding the implementation or photovoltaic panels in order to achieve zero energy balance for the studio apartment. The calculations were made with RetScreen program. This is a Microsoft Excel based program which is used to assess the feasibility of renewable energy installations. By taking into account the specifications of all the components and the local weather data It is able to determine the energy output for a photovoltaic panel installation quite accurately.

In Greece according to ministerial decision YEK/1079/B/04.06.2009, home owners have the ability to produce electricity by installing photovoltaic panels with power output of up to 10 kW. The energy produced is injected to the power grid where it is sold at a subsidized premium price in order to promote renewable energy production.

In this scenario a photovoltaic panel installation will be considered on the roof of the building under examination. The major components used are 45 Mitsubishi Electric UJ-220GA6 photovoltaic panels and a Costal Solar Electric Pico 10.1 inverter with a maximum efficiency of 96% and able to facilitate the production of up to 11 kW power. The specifications of the PVs are listed in table 19. The panels will be placed at 30^O tilt angle, 0^O azimuth angle and it is assumed that there are no losses because of shading. Total panel area is 74.25 m^2 and since each panel produces up to 220 Watt of power, the maximum power output is:

$$45 * 220 = 9.9\ kW$$

With the meteorological data taken from Hellenikon weather station in Athens it is calculated that a capacity factor of 18.7% is achieved and a total of 16,213 kWh/y of electric energy can be produced.

Table 19: Photovoltaic panel specifications

Manufacturer/Model	Mitsubishi Electric/UJ-220GA6
Type	Polycrystalline Silicon
Area per Panel	1.65 m^2
Efficiency	13.3%
Normal output power	220 Watt

The energy audit determined that the studio apartment consumes 65.2 kWh/m^2y, therefore total annual consumption is:

$$65.2\ {}^{kWh}/_{m^2 y} * 249\ m^2 = 16235\ {}^{kWh}/_{y}$$

The annual energy produced is almost equal to the annual energy consumed; therefore with a 10 kW photovoltaic installation the studio apartment becomes a Net Zero Energy Building and since the studio apartment consumes nearly 100% electricity there are no inconsistencies with the power produced and the primary energy consumed. Although the energy produced is not in phase with the energy consumed, the power grid can be considered as an energy storage medium in order to overcome that problem. When excess energy is produced it is injected into the grid and is consumed by others and when the energy produced is insufficient to cover the studio apartment's demand, additional energy from the grid is consumed; however as already mentioned the annual energy balance is zero.

7. Conclusions

In previous decades the building sector, influenced by the universal energy policies, used to disregard energy efficient designs in favor of reduced production costs. Presently that energy policies focus largely in the reduction of energy consumption, many innovative systems appeared to exploit the huge potential for increased energy efficiency in the building sector.

Following this trend, this dissertation presents many ideas for efficient space conditioning and DHW. The operational principle of many passive and hybrid systems, as well as the influence of each system on the conditioned space and the energy balance of the building is described. Furthermore, some NZEB demonstration projects are presented, where combinations of these systems with the addition of local clean energy production installations are put together in order to achieve net zero energy balance.

These systems achieve the reduction of energy consumption by taking advantage of the environmental characteristics such as insolation or wind. This implies a strong connection between a system’s behavior and the local environmental characteristics which might lead to undesirable effects such as increased power consumption as it is observed for the green roof under cold and sunny days. As a result, thorough investigation should take place for each area, to determine which systems would be appropriate for installation. Additionally some systems are usually followed by specific requirements which often include large open areas exposed to insolation such as the Absorption Chillers, or specific building orientations to operate efficiently such as the Trombe Wall. This implies that such systems are not convenient for use in densely populated areas where open and exposed areas are rare and building orientation is subjected to urban regulations. This dramatically reduces their potential benefit in the building sector since it restricts their use in sparsely populated areas.

From the NZEB demonstration projects it is concluded that each design element should be determined by complicated decision making methods. Great attention should be given to the initial reduction of energy demand by applying the optimum orientation, design of openings and internal layout along with thick and effectively installed insulation. This energy demand can be further reduced when followed by the installation of appropriate HVAC systems that will provide the desired space conditioning by taking advantage of the local environmental characteristics. Additionally the use of modern and highly efficient appliances and lighting can further reduce the amount of energy consumed. After applying all these energy saving measures, a local clean energy production system is chosen to provide energy equal to the amount consumed. In interconnected buildings, when there is a positive energy balance energy is injected to the grid and when there is negative energy balance energy is consumed from the grid thus eliminating any need for energy storage solutions or keeping production and consumption in phase.

In the description of the near NZEB in Athens build by C. BAKALAS S.A. Construction Company many of the aforementioned design principals are evident. Thick and externally installed insulation along with highly performing windows and frames provide a great reduction of the initial energy demand for space conditioning. This is satisfied by the combination of solar thermal panels and a highly efficient heat pump which provide space conditioning and DHW throughout the year. The utilization of a single system for many purposes is desirable compared to many individual systems, since it reduces the initial cost and allows for increased efficiency when the heat pump operates at higher loads to satisfy more than one needs. The building is supplemented by highly efficient led lighting and devices which further reduce energy demand.

An Energy Audit conducted to the studio apartment determined that the annual primary energy consumption is 65.2 kWh/m^2 which classifies it as **class A'**. The low portion of just one third of the total energy consumed for heating and DHW shows how hybrid systems, the solar thermal panels in this case, can significantly reduce energy consumption. On the downside, the studio apartment uses almost exclusively electricity which in Greece is mostly produced inefficiently by coal fired power plants. As a result the conversion coefficient of electricity to primary energy is 2.9 [76], which is high and increases the primary energy consumption. Therefore if a more efficiently produced form of energy were consumed instead of electricity, it could further reduce the primary energy consumption.

The highly efficient studio apartment can be easily converted in to a NZEB by installing a 10 kW photovoltaic panel system. In Greece there is a lot of insolation for the most part of the year which allows the annual production of 16,213 kWh of electric energy which is equal to the annual consumption of the studio apartment.

The conclusion can be made that “Net Zero Energy Buildings” is not a mature concept and since the building sector is a very large one, obstacles arise when such a significant change takes place. Moreover, the relatively new passive and hybrid HVAC systems are not widely spread and are still considered expensive for broad commercial use, making the construction of a NZEB financially unadvisable. However the potential for improvement of these systems exists and with the standardization and massive production they could become affordable and compete with conventional systems in the near future. Finally, the importance of the implementation of decision making methods in the design of NZEBs is highlighted, as the design of the building plays a major role in its energy consumption.

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