THERMAL PERFORMANCE OF DWELLINGS IN CYPRUS AND APPROACHES FOR ENERGY CONSERVATION

A thesis submitted for the degree of Doctor of Philosophy

By

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Abstract

Energy has always been the dominant driving force for the socio-economic development of mankind. Nowadays, the global energy system is highly depended on fossil fuels. A great share of the final energy consumption, over 40%, in the EU-27 is consumed by the existing building stock whereas dwellings account for 66.62% of this. Thus, the need to increase the energy performance of dwellings is an important instrument in the efforts to lessen Europe's energy dependency.

In order to define measures to increase the energy performance of dwellings a deeper understanding of their characteristics should be gained. Unfortunately, in Cyprus there is a gap in knowledge on this aspect. In this thesis the characteristics of the dwellings in Cyprus are defined through a sample of 500 dwellings. The results revealed that more than 80% of dwellings in Cyprus do not have thermal insulation installed on their envelope. From this it is clear that the definition of the optimum thermal insulation material to be applied in dwellings is very important. Thus, the commercially available thermal insulation materials and topologies used in Cyprus were reviewed and defined through a market survey and the typical dwelling was modelled. The effect of the application of thermal insulation to its energy behaviour was simulated using TRNSYS. This resulted in the definition of the optimum thermal insulation materials and topologies to be applied in both new and existing dwellings.

Accordingly, the application of advanced commercially available materials such as Phase Change Materials (PCM) to the envelope of the typical dwelling was investigated. The energy savings achieved by the addition of a PCM layer on the envelope of the typical dwelling was found to be 28.6%. The optimum PCM case was also combined with the optimum thermal insulation combination and an energy saving of 68% was predicted.

The incorporation of Renewable Energy Sources (RES) to the typical dwelling was also simulated and studied. Specifically, two types of standalone RES systems were initially evaluated; a solely photovoltaic (PV) system and a hybrid PV-Wind system. The results showed that the solely PV system is a much better option due to the very high solar potential of Cyprus in comparison to the poor wind profile of the island. Subsequently, a grid-connected PV system was also evaluated and the results showed that when a RES system is grid-connected the cost of the system is reduced to half of that of the standalone cases.

This research has revealed that the optimum topology combinations to be applied in both new and existing dwellings in Cyprus is thermal insulation plaster or thermal insulation bricks (only for new dwellings) on the external walls combined with expanded polystyrene on the roof. These results will provide valuable information that will assist both engineers and architects in the efficient design of dwellings in Cyprus. The investigation of the application of macroencapsulated PCM showed that these materials are not yet an economically viable solution for application in Cyprus The findings also show that a solely PV system is the optimum RES system to be applied in Cyprus especially when it is grid-connected.

The findings of this project are useful for individuals, house builders and designers as well as policy makers for the design of energy saving subsidy schemes.

to my son,

Author's Declaration

'I hereby declare that no part of this thesis has been previously submitted to this or any other University as part of the requirement for a higher degree. The work described herein was conducted solely by the undersigned except where otherwise specified, or where acknowledgments are made by references'.

Gregoris P. Panayiotou
Monday 28th April, 2014

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Nomenclature

Latin letters

A_R	Area of the rotor	[m^2]
A_W	Area far downstream in the rotor wake	[m^2]
C_{ij}	Specific heat	[J/kg K]
C_m	Effective thermal capacity	[kJ/kg K]
C_p	Power coefficient	[-]
$c_{p,liquid}$	Specific heat capacity of PCM at liquid state	[J/kg K]
$c_{p,solid}$	Specific heat capacity of PCM at solid state	[J/kg K]
D	Thrust force	[N]
d_i	Material width	[m]
d_{ij}	Width of the material of surface i on the element j	[m]
e_{qc}	Open circuit voltage extrapolated from V vs I curves during charge volts	[V]
F	Fractional state of charge	[%]
g_c	Small-valued coefficient of H in voltage-current state of charge formulas	[V]
H	1-F	[%]
I	Electric current	[A]
m_c	Cell-type parameter which determine the shapes of the I-V-Q characteristics;	[-]
m_{PCM}	Mass of the PCM	[Kg]
P	Power output	[W]
q_1	Quantity of energy entering the PCM from layer 1	[J]
q_2	Quantity of energy entering the PCM from layer 2	[J]
Q_c	Capacity parameter on charge	[Ah]
Q_{cool}	Energy demand for cooling	[$kWh/m^2/yr$]
Q_{heat}	Energy demand for heating	[$kWh/m^2/yr$]
Q_m	Rated capacity of battery cell	[Ah]
r_{qc}	Internal resistance at full charge when charging	[Ohm]
R_{se}	External surface resistance between the external environment and the external surface of the structural element	[m^2K/W]

R_{si}	Internal surface resistance between the internal environment and the internal surface of the structural element	[m^2K/W]
T_{final}	Final temperature	[^oC]
$T_{initial}$	Initial temperature	[^oC]
U_0	Velocity in the free stream	[m/s]
Ui:	Heat loss coefficient	[W/m^2K]
U_R	Velocity of the rotor	[m/s]
U_W	Velocity far downstream in the rotor wake	[m/s]
V	Voltage	[V]
A	Surface of the element j	[m^2]

Greek letters

λ_i	Material thermal conductivity	[W/mK]
ρ	Air density	[kg/m^3]
ρ_{ij}	Density of the material of surface i on the element j	[kg/m^3]

Abbreviations

BTU	British Thermal Units
CIBSE	Chartered Institution of Building Services Engineers
DHW	Domestic Hot Water
ECM	Energy Conservation Measure
ED	Existing Dwelling
EAC	Electricity Authority of Cyprus
EPBD	Energy Performance of Buildings Directive
EPIQR	Energy Performance, Indoor Environment Quality, Retrofit
HCR	Horizontal Concrete Roof
HCITR	Horizontal Concrete with Inclined clay Tile Roof
HVAC	Heating, Ventilation and Air-Conditioning
IEA	International Energy Agency
IRR	Internal Rate of Return
ITR	Inclined clay Tile Roof
LCC	Life Cycle Cost
LOLP	Loss of Load Probability
LPG	Liquefied Petroleum Gas
MAEPB	Methodology for Assessing the Energy Performance of Buildings
MCIT	Ministry of Commerce, Industry and Tourism
MPPT	Maximum Power Point Tracker
MW	Mineral Wool
ND	New Dwelling
NPV	Net Present Value
NG	Natural Gas
PCM	Phase Change Material
PUR	Polyurethane
PV	Photovoltaic
RES	Renewable Energy Sources
SBEM	Simplified Building Energy Model
SC	Scenario
SOC	State Of Charge
SPBP	Simple Pay Back Period
TESS	Thermal Energy System Specialists
TMY	Typical Meteorological Year
TRNSYS	TRNsient SYstem Simulation software
WECS	Wind Energy Conversion System
XPS	Extruded polystyrene

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Energy has always been the dominant driving force for the socio-economic development of mankind. Nowadays the global energy system is highly depended on fossil fuels (i.e. petroleum, natural gas, and coal) with all the consequent disadvantages such as fossil fuel energy dependency and environmental pollution.

A large share of the final energy consumption, over 40%, in the EU-27 is consumed by the existing building stock while dwellings are responsible for 66.62% of this (European Union, 2012). According to EuroACE (2004) 57% of the consumed energy in dwellings is used for space heating, 25% for the production of domestic hot water (DHW), 11% for electronic devices and lighting and 7% by electric ovens and cookers. Thus, the consequent need to increase the energy performance of dwellings is an important instrument in the efforts to reduce Europe’s dependency on energy imports and reduce carbon dioxide (CO_2) emissions. As a result the European Commission prepared a number of legislative tools one of which is Directive 2010/31/EU where the impact of buildings on energy consumption in the long-term is emphasised. Due to their long renovation cycle, buildings should meet minimum energy performance requirements adapted to the local climate of each Member State. Consequently, it is stated that Member States should set minimum requirements for the energy performance of buildings and building elements with a view to achieving a cost-optimal balance between the investments involved and the energy savings throughout the lifecycle of the building. Member States should also enable and encourage architects and engineers to properly consider the optimal combination of Energy Conservation Measures (ECM) when planning, designing, building and renovating industrial buildings or dwellings.

In the last two decades considerable work has been carried out by the international scientific community on the evaluation of various ECM for domestic dwellings. Some of the main studies are summarised as follows.

In their work Balaras *et al.* (2007) identified the most efficient ECM for application in domestic dwellings in Greece as follows: thermal insulation of external walls (savings 33-60% for space heating), thermal insulation of roofs (savings 2-14% for space heating), installation of double glazing with inert gas filling in the gap (savings 14-20 % for space heating), installation of external shading (savings 10-20% for electric energy consumption for cooling), installation of ceiling fans (savings 60% of electric energy consumption for cooling) and replacement of old A/C units (savings of 72% of electric energy consumption for cooling).

Hasan (1999) evaluated the optimum application of thermal insulation (rock wool and polystyrene) in a dwelling in Palestine and several general charts were drawn for the selection of optimum thickness of insulation as a function of Degree Days (DD). The parameter used for evaluation of the effectiveness of thermal insulation was the Life Cycle Cost (LCC). The results showed a LCC saving of: i) 21$/m^2 of wall area and payback periods between 1.3 and 2.3 years for polystyrene insulation and between 1.0 and 1.7 years for rock wool insulation. These results may be very optimistic if current insulation costs and energy prices are used for the calculations.

Jaber and Ajib (2011) discussed the implementation of several ECM such as building orientation, size of windows, shading, and insulation thickness (rock wool) to a typical dwelling in Jordan. In this work the TRaNsient SYstem Simulation software (TRNSYS) was used and the optimisation parameter was LCC. The results showed that a reduction of 28% on the annual energy consumption of the dwelling could be achieved by combining best orientation (passive façade facing South), optimum size of windows and shading device (window area 30% of the South facade area, 20% of the East facade and 10% for both North and West facades), and optimum insulation thickness (0.22 m of rock wool on both walls and ceilings).

Palmero-Marrero and Oliveira (2010) studied the effect of external louver shading devices on buildings in different geographic locations (Mexico, Cairo, Lisbon, Madrid and London). The calculation of the internal temperatures was performed using TRNSYS while EES (Engineering Equation Solver) was used for the analysis of shading devices. The work showed that the installation of external louver shading devices in buildings could lead to improvement in the internal comfort conditions and can result in significant energy savings (55-60% in Cairo, 38-50% in Lisbon, and 3-9% in Madrid. In contrary, in Mexico and London the annual energy demand was increased by 32-58% and 20% respectively compared with that without shading, due to the lower solar gains in the heating season.

Cabeza *et al.* (2010) studied the performance of insulation materials in Mediterranean constructions. An experimental setup consisting of four test cubicles was constructed in Puigverd de Lleida (Spain) for the investigations. The test cubicles were conditioned using oil radiators in winter and air conditioners in summer. The results of this study showed that with optimum insulation levels, energy reduction of up to 64% could be achieved for cooling in the summer and 37% for heating in winter.

In Cyprus the dwelling stock at the end of 2007 was 357,870 units and 63.3% of these dwellings were in urban areas (Statistical Service, 2007). As it is expected these dwellings have a significant impact on energy consumption of the building sector and therefore a better understanding of their characteristics is important for policy makers, engineers, and homeowners. It is very important to note that until 2010 the use of thermal insulation on the envelope of new dwellings in Cyprus was not mandatory and hence most of the dwellings in Cyprus do not have thermal insulation.

Florides *et al.* (2001) presented the evolution of domestic dwellings in Cyprus during the twentieth century with respect to their heating and cooling requirements. In another work Florides *et al.* (2002) studied the energy flows in modern dwellings in Cyprus and examined measures to reduce the thermal load using TRNSYS. Kalogirou *et al.* (2002) investigated the effects of thermal mass on the heating and cooling loads of dwellings in Cyprus using a four zone dwelling with an insulated roof which was also simulated using TRNSYS.

None of these studies has evaluated all types of commercially available thermal insulation materials in all possible topologies for such a climate. It is also important to note that the application of several ECM such as small size RES installations (photovoltaic, domestic wind turbines etc) and innovative materials such as Phase Change Materials (PCM) have not yet been extensively studied for the environmental conditions of Cyprus.

1.2 AIM AND OBJECTIVES

The main aim of this project is to identify the typical type of domestic dwelling in Cyprus and theoretically investigate the most important ECM with the view to identifying the cost-optimal approaches to improve its energy performance.

The main objectives of this thesis are:

- Investigate the characteristics of the dwelling stock of Cyprus using data obtained from 500 questionnaires. The purpose is to define the typical dwelling to be used in the investigations of the effectiveness of thermal insulation and renewable energy systems.
- Review and define the commercially available thermal insulation materials in Cyprus along with the most commonly used topologies of their application to domestic dwellings.
- Model the typical dwelling and simulate the effect of applying the defined thermal insulation material topologies on its energy behaviour and define the optimal topologies for application in both new and existing dwellings.
- Theoretically evaluate the effect of applying Phase Change Materials (PCM) to the building fabric for load shifting and identify optimal ways for their application.
- Theoretically investigate the incorporation of RES to the typical dwelling so as to define the optimum type and size of system for dwellings in such weather conditions.

1.3 STRUCTURE OF THE THESIS

In **Chapter 1** an introduction to the subject of the thesis is presented together with the main aim and objectives of this research.

In **Chapter 2** a detailed literature review of previous research on the subject of the thesis is provided.

In **Chapter 3** the characteristics of the residential building stock of Cyprus are identified through a sample of 500 dwellings. The results of this Chapter led to the definition of the typical dwelling of Cyprus which is used for the simulations in Chapters 5 and 6. Additionally, the results of this Chapter reveal the weaknesses of dwellings in Cyprus concerning their energy efficiency.

In **Chapter 4** the available thermal insulation materials in Cyprus along with their most commonly used topologies, for walls and roofs, are reviewed and defined.

In **Chapter 5** the previously defined thermal insulation material topologies were initially evaluated using a simpler method than the one used in the detailed simulation of Chapter 6. The software used was the iSBEM-Cy. The results are evaluated using the Simple Pay Back Period (SPBP) method in order to define the best cases to be modelled in detail in Chapter 6.

In **Chapter 6** the typical dwelling is modelled in detail using TRNSYS. The best thermal insulation material topologies from Chapter 5 are evaluated theoretically against the criteria of: i) total energy demand for heating and cooling and ii) indoor temperatures for a non-mechanically thermal controlled building.

In **Chapter 7** the effect of applying suitable commercially available PCM on the envelope of the typical dwelling is theoretically investigated. The simulation was carried out using TRNSYS and for this purpose a suitable model, Type 1270, is utilised.

In **Chapter 8** the incorporation of RES to the typical dwelling is considered. More specifically, two types of RES systems were theoretically evaluated: a solely photovoltaic (PV) system and a hybrid PV-Wind system.

Finally, in **Chapter 9** the overall conclusions of the Thesis and recommendations for future work are presented.

1.4 CONTRIBUTION TO KNOWLEDGE

The main contributions to knowledge of the current research work can be summarised as follows:

- The characteristics of the dwellings in Cyprus are identified and their weaknesses in terms of energy performance are revealed.
- The optimum thermal insulation material topologies for application on the envelope of a new and an existing dwelling in Cyprus are defined.
- The effectiveness of application of macroencapsulated PCM on the envelope of domestic dwellings in Cyprus is theoretically evaluated.

- The optimum type and size of RES systems to be used in typical dwellings for the specific climatic conditions of Cyprus are defined.

Most of the work presented in this thesis has been published in International Journals and presented in a number of peer-reviewed International Conferences. These publications are listed below.

Journal Publications:

G.P. Panayiotou, S.A. Kalogirou, S.A. Tassou, Design and simulation of a PV and a PV–Wind standalone energy system to power a household application, Renewable Energy, Volume 37, Issue 1, January 2012, Pages 355–363

P.A. Fokaides, C.N. Maxoulis C.N., **G.P. Panayiotou**, M.K.A. Neophytou, S.A.Kalogirou, Comparison between measured and calculated energy performance for dwellings in a summer dominant environment, Energy and Buildings, Volume 43, Issue 11, November 2011, Pages 3099-3105

G.P. Panayiotou, S.A. Kalogirou, G.A. Florides, C.N. Maxoulis, A.M. Papadopoulos, M. Neophytou, P. Fokaides, G. Georgiou, A. Symeou, G. Georgakis, 'The characteristics and the energy behaviour of the residential building stock of Cyprus in view of Directive 2002/91/EC', Energy and Buildings, Volume 42, Issue 11, November 2010, Pages 2083-2089

Conference Publications:

G.P. Panayiotou, S.A. Kalogirou, S.A. Tassou, 'Investigation of the effect of applying Phase Change Materials (PCM) on the envelope of a test cubicle in Cyprus', 2nd International Conference on Sustainable Energy Storage, June 19-21, Trinity College Dublin, Ireland, 2013

G.P Panayiotou, C.N. Maxoulis, S.A. Kalogirou, G.A. Florides, A.M. Papadopoulos, M. Neophytou, P.A. Fokaides, G. Georgiou, A. Symeou, N. Hadjinikolaou, G. Georgakis, 'Cyprus building energy performance methodology: A comparison of the calculated and measured energy consumption results', Central Europe towards Sustainable Building (CESB10) Conference, Prague, Czech Republic, 30th June – 2nd July, 2010

S.A. Kalogirou, C.N Maxoulis, G. A. Florides, **G.P. Panayiotou**, A.M Papadopoulos, M. Neophytou, P. Fokaides, G. Georgiou, A. Symeou, G. Georgakis, ‘The energy behaviour of the residential building stock in Cyprus in view of the Energy Performance of Buildings Directive implementation’, Central Europe towards Sustainable Building (CESB10) Conference, Prague, Czech Republic, 30th June – 2nd July, 2010

C.N. Maxoulis, S.A. Kalogirou, G.A. Florides, **G.P. Panayiotou**, A.M Papadopoulos, M. Neophitou, P. Fokaides, G. Georgiou, A. Symeou, G. Georgakis, ‘Classification of residential buildings in Cyprus based on their energy performance’, 2nd MSE International Conference on Renewable Energy Sources & Energy Efficiency, Nicosia, Cyprus, October 24-24, 2009

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

It is widely acknowledged that the contribution of domestic dwellings to the final energy consumption is significant and this has attracted considerable research and development effort over the last twenty years. This chapter provides a review of literature on energy conservation measures for domestic dwellings, particularly for climatic conditions similar to those of Cyprus and places the research in this thesis into context.

2.2 DWELLINGS IN EUROPE AND CYPRUS

According to the Housing Statistics of the European Union (Dol and Haffner, 2010) the total number of dwellings in the EU-27 is about 204 millions distributed as follows: 19.59 % Germany, 13.22 % Italy, 13.2 % France, 12.32 % UK, 8.18 % Spain, 6.52 % Poland, 3.57 % Netherlands and 23.4 % in the remaining twenty countries. It is interesting to compare the number of dwellings with their final energy consumption in EU 27 countries as shown in Figure 2.1 (EU, 2010).

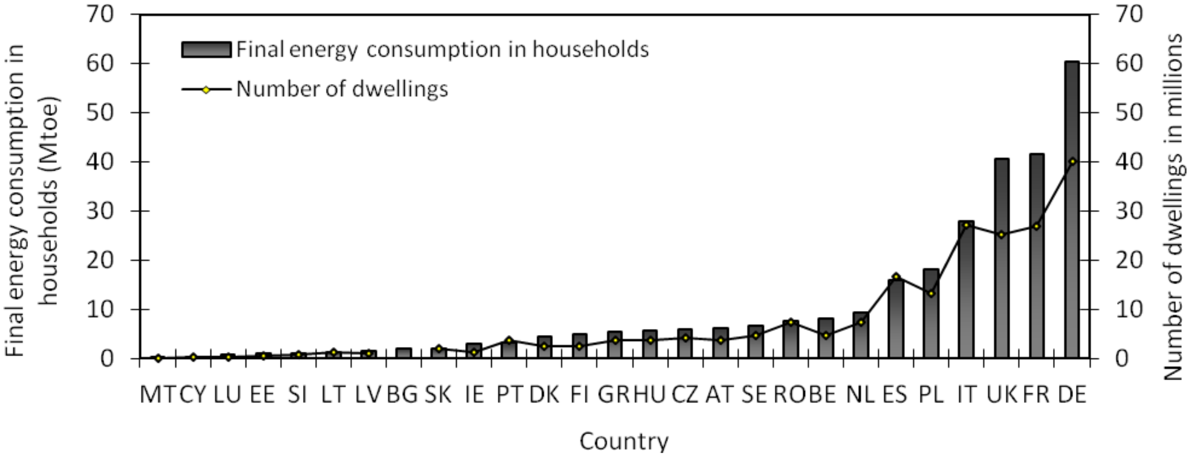

Figure 2.1 Final energy consumption and number of dwellings in EU-27 countries (Data obtained from Dol and Haffner (2010) and EU (2010))

As can be observed the countries with the highest final domestic energy in million tonnes oil equivalent (Mtoe) correspond to the countries with the highest number of dwellings, as it would be expected.

It is expected that by 2060 the total number of dwellings in Europe will increase by 2.5 times the number in 2000 and this makes energy conservation in the domestic sector very important (Uihlein and Eder, 2010). The total dwelling stock in Cyprus at the end of 2011 was 433,212 (Statistical Service of Cyprus, 2011) which only represents 0.21% of the total dwelling stock of Europe. However, domestic dwellings are responsible for 35.6 % and 149.4 ktoe of the energy consumption of Cyprus (IEA, 2010) so energy conservation in the domestic sector is very important for the island. Another important factor is that due to the lack of building regulations that governed thermal performance until 2007, dwellings exhibit a wide variety of design characteristics such as shape, layout, and building materials. (Lambrou, 2010).

The built environment in Cyprus is characterised by low density city centres, which apart from multi-storey office buildings and apartments also comprise multi-storey (most commonly three storeys) domestic dwellings. In the suburbs the dominant dwelling is the detached single-family single storey dwelling, which accounts for the largest share in the total dwelling stock of Cyprus. This most common dwelling typology has a bearing structure made of reinforced concrete. The walls are constructed from hollow bricks covered with plaster on both sides; the floors are made of concrete slabs; the floor finishing consists of a layer of mortar usually covered with tiles, marble, or granite sheets. The building has a flat roof made of a concrete slab, usually 0.2 m in thickness, with a layer of plaster of 0.02-0.03 m thick on the underside. The concrete slab is normally water-proofed with a thin layer of bitumen and painted with white paint for heat reflection (Florides *et al.*, 2001).

2.3 EUROPEAN DIRECTIVES

On 16 December 2002 the European Community released Directive 2002/91/EC on Energy Performance of Buildings (EPBD) which mainly concerns minimum energy performance requirements of new buildings and large (more than 1,000 m^2) existing buildings subject to major renovation.

Directive 2002/91/EC was revised by Directive 2010/31/EU which places specific emphasis to the impact of buildings on long-term energy consumption. The directive acknowledges the significance of major renovations of existing buildings, regardless of size, as an opportunity to take cost-effective measures to enhance energy performance. The definition of the term 'major renovation' is an obligation of each Member State and it can be defined either in terms of a percentage of the surface of the building envelope or in terms of the value of the building. Additionally it is highlighted that Member States shall take the necessary measures to ensure that when buildings undergo major renovation, the energy performance of the building or the renovated part thereof is upgraded in order to meet minimum energy performance requirements set in accordance with Article 4 in so far as this is technically, functionally and economically feasible. Furthermore, when a building element that forms part of the building envelope and has a significant impact on the energy performance of the building envelope, is retrofitted or replaced, the Member States should ensure that the energy performance of the building element meets minimum energy performance requirements in so far as this is technically, functionally and economically feasible.

An additional Directive related to the energy renovation of existing buildings is Directive 2012/27/EU which acknowledges that the existing building stock represents the biggest potential sector for energy savings and thus Member States should establish a long-term strategy beyond 2020 for mobilising investment in the renovation of residential and commercial buildings with a view to improving the energy performance of the building stock.

2.4 ENERGY CONSERVATION MEASURES (ECM)

Many studies have been carried out during the last decade evaluating the effect of various ECM in dwellings in Europe. Most of these studies concern conventional ECM such as the application of thermal insulation, glazing type and size, shading systems and heating and cooling equipment. There are also studies that investigated more sophisticated ECM such as the application of Phase Change Materials (PCM) on the envelope of dwellings to reduce internal temperature variations and energy consumption for both heating and cooling. An additional category of ECM is the on-site utilisation of Renewable Energy Sources (RES) such as solar, wind and geothermal energy. Important studies are summarised below.

The effect of thermal insulation, age and condition of heating system on the energy consumption for space heating and the resulting environmental impact was studied by Balaras *et al.* (2005). In their study they used a sample of 349 residential buildings in seven European countries following the INVESTIMMO methodology as part of the European project INVESTIMMO. The data concerning the heating energy consumption came from 193 European residential buildings from five European countries namely Denmark, France, Greece, Poland, and Switzerland. The results showed that 38% of the audited buildings had higher annual heating energy consumption than the European average of 174.3kWh/m^2.

Jaber and Ajib (2011) examined the optimum type and size of windows in terms of both energy and investment cost for three different climatic zones (Amman, Aqaba and Berlin) using the building simulation software TRNSYS. The results indicated that triple glazing provided the best energy performance of all glazing types investigated but was not economically feasible for all the climates examined. Double glazing with U-value equal to 2.83 W/m^{2}K achieved the minimum life cycle cost in locations with hot summer and mild winter climates while double glazing with U-value equal to 1.4W/m^{2}K was the best choice for locations with mild summers and cold winters. It was also shown that optimised glazing could achieve energy savings of 21%, 20% and 24% for Amman, Aqaba and Berlin, respectively.

Palmero-Marrero and Oliveira (2010) studied the effect of external louver shading devices on buildings in Mexico City, Cairo, Lisbon, Madrid and London. The calculations of the internal temperatures were conducted using TRNSYS software while EES software was used for the geometric study of the shading systems. A vertical louver layout was considered for east/west façades and a horizontal layout was used for the south façade (Figure 2.2). Three different window and louver areas (A, B and C) were studied for three different window heights for the south façade (1.0, 1.3 and 1.5 m) and one window height (1.0 m) for the east and west façades.

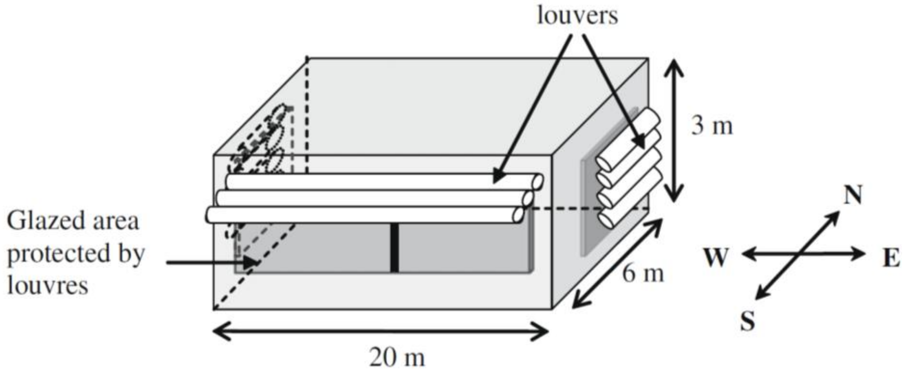

Figure 2.2 Use of louvers to protect glazed surfaces (horizontal layout in a south façade and vertical layout in east or west façades (Palmero-Marrero and Oliveira, 2010)

The results of this study showed that the integration of louver shading devices in buildings may lead to significant energy savings. Energy savings were shown to be higher for cases B and C in cities like Cairo (55% and 60%), Lisbon (38% and 50%) and Madrid (3% and 9%), which have high ambient temperatures and solar insolation in the summer months. In cities such as London, which have relatively lower ambient temperatures and solar insolation, the use of louver shading devices all year round may increase annual energy demand due to reduced solar gains in the heating season.

Muslum and Hasan (2010) determined the optimum air layer thickness of double glazed windows for different climate zones of Turkey (Iskenderun, Kocaeli, Ankara and Ardahan) using the degree days method. During their calculations the heating cost was calculated for different energy sources namely natural gas, coal, fuel-oil, electricity and LPG. The optimum air layer thickness was obtained for three different base temperatures 18, 20 and 22^{o}C. The results reviled that the optimum thickness of the air layer ranges between 12 and 15mm depending on the climate zone, fuel type and base temperature (Figure 2.3). The effect of the fuel type and the base temperature (T_b) on the optimum air layer thickness diminishes in cold zones. Finally, in this study it is shown that by installing a double glazed window optimized according to the specific conditions of the area of the building energy savings of up to 60% are possible.

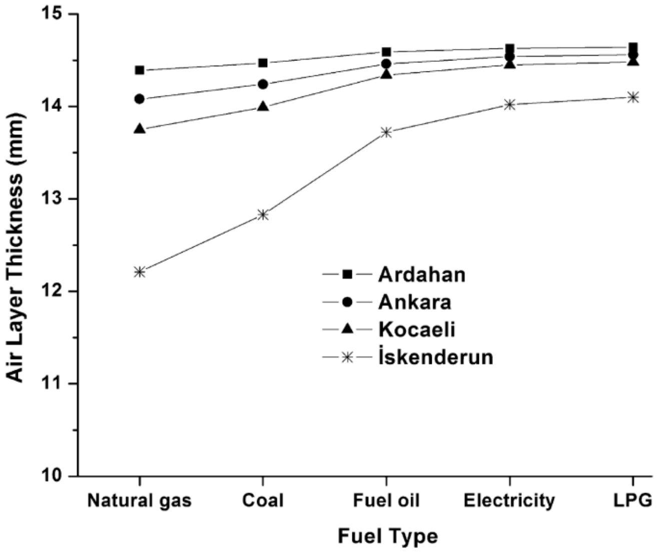

Figure 2.3 Effect of the fuel type on the optimum air layer thickness for different cities (T_b=18^{o}C) (Muslum and Hasan, 2010)

Bolatturk (2008) investigated the optimum insulation thickness on external walls of buildings based on annual heating and cooling loads for the city of Bursa, Turkey. The method employed was the degree-hours method which is one of the simplest methods of estimating the annual energy consumption of a building. The structure of wall consists of (inside to outside) 0.02 m plaster, 0.2 m hollow clay brick, insulation material layer, and 0.03 m plaster. The results showed that the use of insulation on building walls had greater impact for cooling rather than for heating for the climatic conditions investigated. The results show that for heating load, the optimum insulation thickness is between 0.016 and 0.027 m, the energy savings vary between 2.2 and 6.6 \$/m^2, and the payback periods vary between 4.2 and 5.5 years depending on the city. On the other hand, for cooling load, the insulation thickness is between 0.032 and 0.038 m producing annual energy savings of the order of 8.47 and 12.19 \$/m^2 and payback periods of between 3.4 and 3.8 years.

Papadopoulos *et al.* (2002) studied a representative sample of 42 buildings (residential, public and mixed use) in Northern Greece over a 6 year period in order to determine the potential of the most efficient energy saving measures taking into consideration their economic viability. The two major areas for energy savings in these buildings were found to be the improvement of the central heating system and the improvement of the thermal insulation of the envelope of the building. The results of this work showed that an average energy saving of 28% was possible. The significance of energy prices to the economic viability of all energy saving measures was also highlighted in the study.

Another study for Greece was carried out by Nikolaides *et al.* (2009). The study evaluated the economic viability of various ECM for a detached dwelling in Larissa (Central Greece). Specifically, the reference dwelling has an area of 100 m^2, uses a heating oil burner with water radiators for heating and an electric water heater is used to cover the need for hot water. The U-value of the building's envelope is 2.3 W/m^2K and that of the single glazing windows and doorframes 5.6 W/m^2K. The ECM examined included thermal insulation on the envelope of the dwelling, upgrading of the heating system, use of thermal solar systems, upgrading of lighting, upgrading of electric appliances and upgrading of the cooling system. The economic evaluation methods used for ranking the energy saving measures were the Net Present Value, the Internal Rate of Return, the Savings to Investment Ratio and the Depreciated Payback Period. According to the results of the study, when using the IRR as the evaluation criterion the upgrading of artificial lighting was the most effective investment, while the insulation as well as the installation of an automatic temperature control system at the burner – boiler system follow next. The use of solar heaters is economic enough and profitable, contrary to the replacement of windows and doorframes and the partial upgrading of heating systems that constitute very low return investments. On the other hand when the NPV is used as the evaluation criterion the insulation of the roof or the pilotis of the building constitute the most effective interventions. The replacement of windows and doorframes are once again very low return investments.

Kolaitis *et al.* (2013) performed a comparative assessment of internally and externally installed thermal insulation for energy efficient retrofitting of residential buildings for different locations. For this purpose TRNSYS software was used to simulate a 99.6 m^2 one-storey apartment located at a mid-level of a multi-storey building. The climates used for the simulation were the “Csa” and the “Cfb” Koeppen classification region (Kottek *et al.,* 2006) corresponding to a warm Mediterranean climate and a moderate Oceanic climate (characterised by warm but not hot summers, cool but not cold winters and relatively narrow annual temperature range), respectively. The parameters examined were the annual heating and cooling energy requirements; the effect of insulation layer location, meteorological conditions and “energy conscious” occupant behaviour. Two different occupant behaviour scenarios were examined the passive the active occupant behaviour. In the first case, no movable shadings are installed and all window panes are assumed to remain closed during the entire year while in the second case external shadings (retractable vertical mats) are assumed to be installed in the eastern kitchen and the western living room windows and night ventilation is also utilized. According to the results of this study both cases of insulation (internal and external) were found to significantly reduce the total energy requirements by 56–89% in the Mediterranean climate region and by 21–47% in the Oceanic climate while on average, external insulation outperformed the internal insulation configuration by 8%.

Cabeza *et al.* (2010) experimentally evaluated the influence of the application of three typical insulation materials (polyurethane, polystyrene, and mineral wool) on the envelope of a building in a Mediterranean region (Lleida, Spain). For the experiments four house-like cubicles were constructed (with a size of 2.4m x 2.4m x 2.4 m, Figure 2.4). In all cases examined the width of the insulation layer was kept the same at 0.05m. Tests were performed for: (i) Free floating conditions, where no heating/cooling system was used and the air temperature was allowed to vary with external conditions; (ii) Controlled conditions, where an air conditioning system was used in summer and an electrical oil radiator was used in winter to control the internal air temperature of the cubicle. For the controlled conditions different set points were investigated 21 and 24°C in winter and 16, 20 and 24°C in the summer. In this study energy savings of up to 64% in summer and up to 37% in winter were measured experimentally (Table 2.1). The differences between insulation materials are small but significant (less than 25% in most of the cases). Nevertheless, the results show that the cubicle with polyurethane is the one with the lowest energy consumption.

Table 2.1 Monthly energy consumption of electric heaters in winter and heat pumps in summer for different set points for the four cubicles studied (Cabeza *et al.*, 2010)

CASE	**Winter**				**Summer**					
	Set point, 21°C		**Set point, 24°C**		**Set point, 16°C**		**Set point, 20°C**		**Set point, 24°C**	
	Energy (kWh)	Savings (%)	Energy (kWh)	Savings (%)	Energy (kWh)	Savings (%)	Energy (kWh)	Savings (%)	Energy (kWh)	Savings (%)
Ref.	395.6	0	618.3	0	123.1	0	107.6	0	98.2	0
PUR	276.6	30	388.6	37	63.9	48	38.4	64	49.9	49
MW	278.7	30	410.9	34	68.1	45	46.2	57	52.8	46
XPS	283.2	28	427	31	67.5	45	44.1	59	53.7	45

Figure 2.4 Test cubicles: (a) Reference cubicle; (b) cubicle insulated with PUR; (c) cubicle insulated with mineral wool; (d) cubicle insulated with polystyrene (Cabeza *et al.,* 2010)

The evolution of the domestic dwellings in Cyprus during the twentieth century with respect to their heating and cooling requirements was described by Florides *et al.* (2001). In this study the methods of construction employed and materials used were also presented. The modeling and simulation procedures were carried out using TRNSYS. The results showed that the temperature inside a high thermal mass traditional house without heating or cooling could vary between 16-20°C in winter and 25-35°C in the summer compared to 11-20°C for winter and 33-46°C for summer for a non-insulated modern house with a flat roof.

In another work Florides *et al.* (2002) studied the energy flows in modern dwellings in Cyprus and examined measures to reduce the thermal load using TRNSYS. The measures examined were natural and controlled ventilation, solar shading, various types of glazing, orientation, shape of building, and thermal mass. The results showed that a maximum reduction of annual cooling load of 7.7% for maintaining the house at 25^{o}C could be achieved by ventilation. The saving in annual cooling load could be as much as 24% when low emissivity double glazing windows are used. Additionally, when overhangs of 1.5 m are used over windows about 7% of the annual cooling load could be saved for a house constructed from single walls with no roof insulation. An elongated shape of the house leads to an increase in the annual heating load, by between 8.2 and 26.7% depending on the construction type, compared with a square-shaped house. In respect to orientation, the best position for a symmetrical house is to face the four cardinal points and for an elongated house to have its long side facing south. Finally, the analysis of the results showed that the roof is the most important structural element of buildings in a hot environment. LCC analysis showed that using roof insulation (0.025-0.05m of polystyrene) could lead to short pay-back periods of between 3.5 and 5 years.

Kalogirou *et al.* (2002) investigated the effects of thermal mass on the heating and cooling loads of dwellings in Cyprus. A typical four zone dwelling with an insulated roof was modeled using TRNSYS. The south wall was replaced by a thermal wall (a wall with large thermal mass). The simulation results showed a 47% reduction in heating load requirements, and a slight increase in the cooling load requirements.

2.5 PHASE CHANGE MATERIALS (PCM)

Besides the conventional ECM discussed above thermal energy storage (TES) in buildings is also important due to the fact that it can both reduce the energy demand for heating and cooling and also smooth out daily temperature fluctuations of the dwelling. A way to increase the TES of buildings is by integrating or including PCM on the building's envelope and thus store heat in latent form. The main advantage of latent heat storage is its high storage density over a small range of phase change temperature interval (Cabeza *et al.*, 2011). PCM suitable for building applications should have a melting temperature range between 20-32^{o}C.

PCM have been investigated by many researchers around the world for over 30 years (Salyer *et al.*, 1985; Shapiro *et al.*, 1987; Babich *et al.*, 1994; Zalba *et al.*, 2003; Khudhair *et al.*, 2004). Some PCM are also commercially available from some companies such as BASF, DuPont and Phase Change Energy Solutions.

The main categories of PCM for building applications are organic, inorganic and eutectics. In a comprehensive work Cabeza *et al.* (2011) reviewed all available PCM along with their classification, problems and possible solutions for their application to buildings. In another work Baetens *et al.* (2010) also reviewed the state-of-the-art on the current knowledge of PCM applications in buildings. Tyagi and Buddhi (2007) reviewed the ways PCM can be incorporated in buildings such as trombe wall, wallboards, shutters and building blocks. The results showed that there is significant potential to reduce the energy for both heating and cooling of buildings by using PCM. In order to avoid direct contact of the PCM with the surrounding environment and to hold the liquid phase of the PCM these should be encapsulated. There are two ways to encapsulate a PCM either in a macroscopic containment (macroencapsulated) which can contain from several ml up to several litres or within a solid shell of 1μm to 1000μm diameter (microencapsulated).

A very promising application of microencapsulated PCM is their inclusion into construction materials such as concrete. This technology has been under study at the University of Lleida, Spain since 2004. One of the main drawbacks of this technology is the severe influence of summer weather conditions (high ambient temperature and solar radiation) over the PCM, which prevented its solidification during night and thus reduced its effectiveness during the day. Arce *et al.* (2012) examined the possibility of introducing sunshades to the building in order to decrease the number of hours of direct solar radiation on the walls and thus reduce wall temperatures and thus allow the PCM to solidify at night. The experimental procedure was carried out using two identically shaped cubicles (Figure 2.5) which were initially constructed in the work of Cabeza *et al.* (2007). One cubicle was made of conventional concrete and the other with concrete containing about 5% in weight of microencapsulated PCM (Micronal® PCM, from BASF with a theoretical melting point of 26^{o}C, and a phase change enthalpy of 110kJ/kg. The PCM was included in South and West walls and roof. No wall insulation was installed to enable the evaluation of the influence of PCM alone. To evaluate the dimensions of the awning the Sun trajectory in June, July, and August was assessed using the solar altitude and the solar azimuth. Results indicated that a 4.4 x 4 m awning installed 0.12 m above the roof of the cubicles (3 m x 3 m) would be appropriate. With this awning the East wall was partially shaded during the morning ,the East and West walls were totally shaded from 1 pm to 3 pm, the West wall was partially shaded in the afternoon and half of the South wall was shaded at 10 am, was totally shaded at noon, and partially shaded again in the afternoon. The roof was protected all day long. Two sets of experiments were carried out as follows: (i) Free cooling: windows remained opened at night and closed during the day and (ii) Open windows: only windows on the South wall were open at all times. The results showed that peak temperature was reduced by 3-4^{o}C, their appearance delay was increased by 50 minutes (free-cooling), but decreased 15 minutes (open windows), and the time in comfort conditions increased between 10-21%. However, despite the PCM remained active for a longer period of time (4-10%), the effect of high outdoor temperatures was not overcome completely as PCM did not complete full phase change cycles everyday as desired.

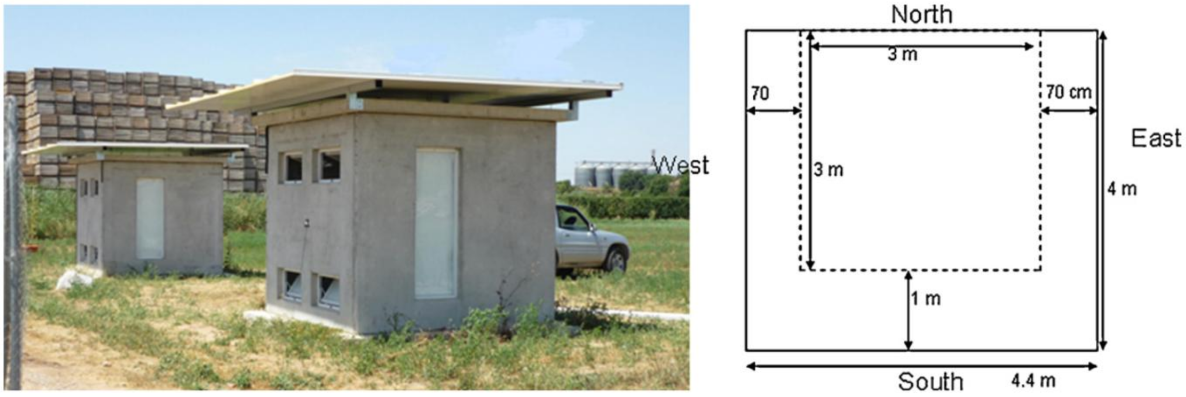

Figure 2.5 Outer view of the cubicles with sunshades (left) and bird's eye view of the roof with a sunshade (right) (Arce *et al.*, 2012)

Although the inclusion of PCM into building materials such as concrete is considered to have a number of advantages it also has drawbacks as it can only be used in new buildings during the construction phase and not in existing buildings during their renovation.

Additionally, in spite of the fact that a number of studies have been performed on the incorporation of PCM in several construction materials, only a few cases have studied the use of macroencapsulated PCM in brick constructions. Alawadhi (2008) carried out a thermal analysis of a building brick containing phase change material (PCM) to be used in hot climates. A brick with cylindrical holes filled with PCM (Figure 2.6) was considered and a 2-D finite element model was used. The thermal effectiveness of the proposed brick-PCM system was evaluated by comparing the heat flux at the indoor surface of the wall with and without PCM during typical working hours. A parametric study considered the effect of different design parameters, such as the PCM quantity, type, and location in the brick. The results indicated that the heat transfer through the wall reduces when the PCM is incorporated into the brick due to heat storage in the

PCM. PCM located in the centreline of the brick provided best results and n-eicosane was found to perform best amongst the PCM investigated.

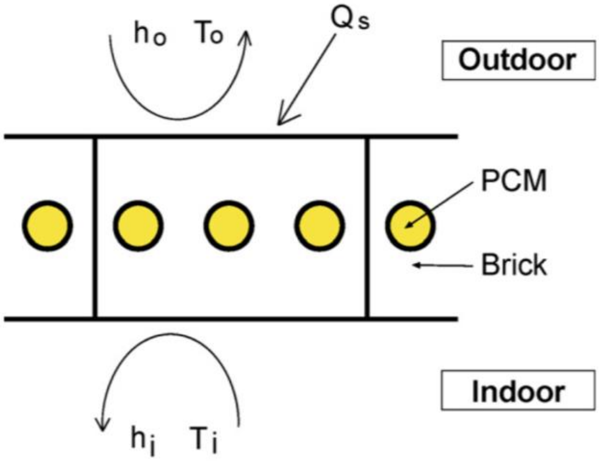

Figure 2.6 Schematic representation of the brick-PCM system and the boundary conditions (Alawadhi, 2008)

Silva *et al.* (2012) evaluated the effect of incorporation of macroencapsulated PCM into a typical Portuguese clay brick masonry enclosure wall. Two wall specimens were used in the experiments (one with macroencapsulated PCM and one without PCM). Both were constructed with horizontally hollowed clay bricks (0.03m x 0.02m x 0.15m) and cement mortar for horizontal and vertical mortar joints. In order to incorporate the PCM into the brick wall, steel macro capsules (0.30m x 0.17m x 0.028m and 0.0075m mean thickness) were filled with PCM and inserted into the middle brick voids (Figure 2.7). The test programme utilized two climatic chambers (CC): CC1, was used to simulated external boundary conditions and the temperature of CC2, was allowed to float. The results of the study showed that with the use of PCM the amplitude of the fluctuation of the indoor temperature was reduced from 10^{o}C to 5^{o}C and the time of maximum temperature in CC2 was shifted by about 3 h. The test results were also used for the validation of the numerical modelling which will be used to explore the influence of incorporation of PCM into wall envelopes.

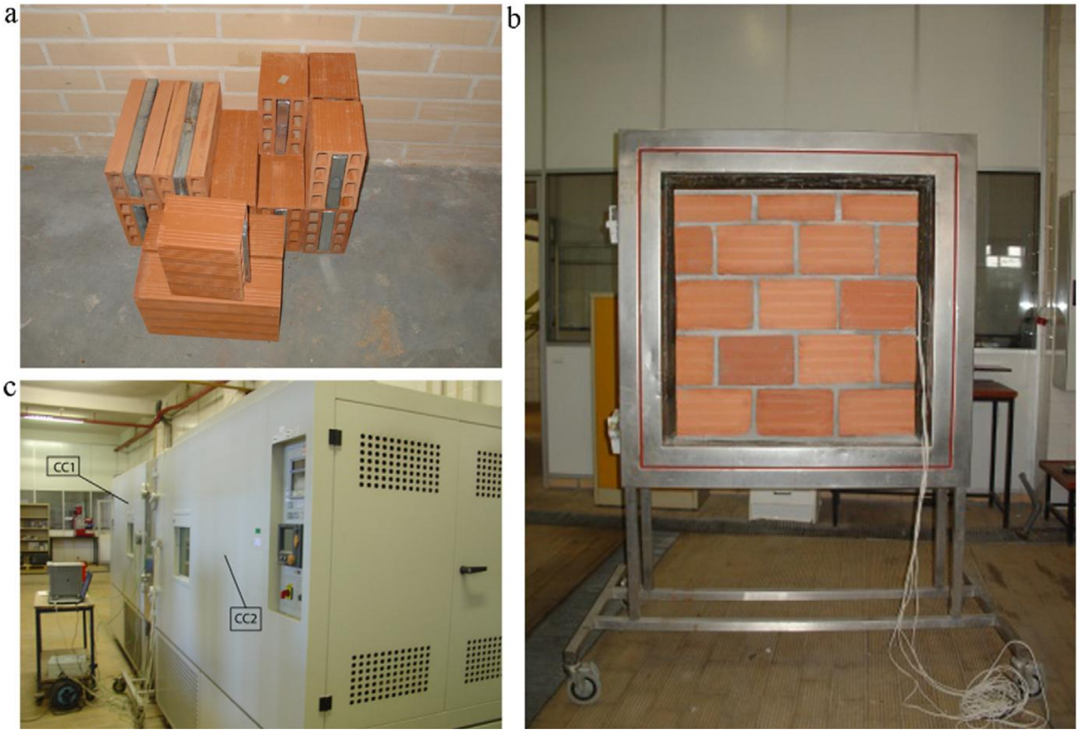

Figure 2.7 (a) Bricks with PCM macro capsules; (b) wall specimen into ring structure; (c) climatic chambers and data acquisition (Silva *et al.*, 2012)

Castell *et al.* (2010) experimentally investigated the application of macroencapsulated PCM in two types of brick a hollow clay brick and a thermal insulation brick (alveolar brick) which has a special design providing thermal insulation. The tests were performed under ambient conditions using five different cubicles located in Puigverd de Lleida, Spain. The five cubicles comprised of the following: (i) Reference cubicle (hollow clay brick, no insulation), (ii) Polyurethane cubicle (hollow clay brick with 0.05 m of spray foam polyurethane everywhere on the envelope), (iii) PCM cubicle RT27 (Figure 2.8) (hollow clay brick with RT27 in the southern and western walls and the roof and PU foam everywhere) (Figure 2.9), (iv) Reference cubicle (Alveolar, no insulation) and (v) PCM cubicle (Alveolar brick with SP-25 A8 hydrate salt panels located between the alveolar brick and the plaster in the southern and western walls and the roof). Two types of experiments were performed: the free-floating temperature test and the controlled temperature test. The free-floating experiments showed that the use of PCM can reduce peak temperatures by up to 1^{o}C and smooth out daily fluctuations (Figure 2.10). The controlled temperature tests showed that the energy consumption of the cubicles containing PCM reduced by about 15% compared to the cubicles without PCM. This demonstrates the significant potential of PCM in building envelopes for energy savings and thermal comfort.

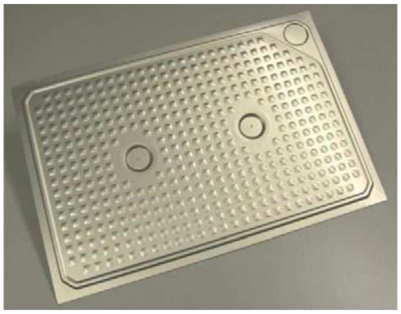

Figure 2.8 Panel containing the PCM (RT-27) (Castell *et al.*, 2010)

Figure 2.9 Brick cubicle with RT-27 and polyurethane (Castell *et al.*, 2010)

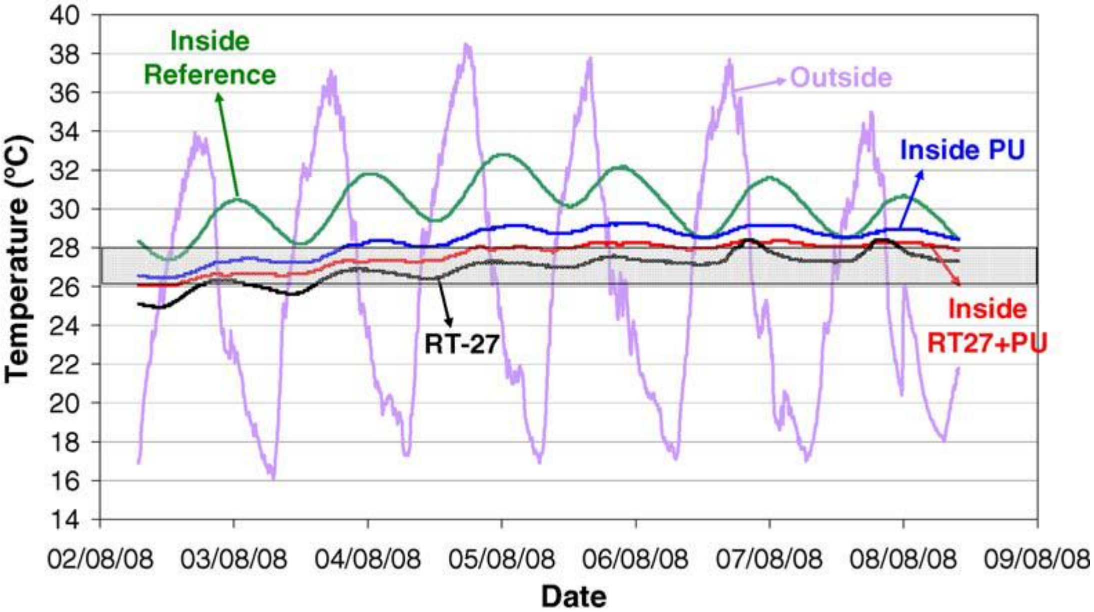

Figure 2.10 Ambient temperature variation and temperature variation inside the test cubicles examined (Castell *et al.*, 2010)

In a different study concerning office buildings, Ascione *et al.* (2014) investigated the effect of PCM plaster on the exterior building envelope during a cooling season in Mediterranean climates through simulation using EnergyPlus (Athens, Naples, Marseille, Seville). The advantage of application of PCM to the external surface of the wall is that it offers non-invasive energy retrofit possibilities for existing buildings. The reduction of the cooling energy demand was evaluated for different parameters which are shown in Figure 2.11. The results showed that with reference to each climatic condition the highest cooling energy savings were obtained by installing 0.03m of PCM plaster on all exposures of the building vertical envelope and the most important parameter is the PCM melting temperature. Results for natural ventilation of the building showed that the comfort hours increased by between 7% and 12% depending on the climatic conditions.

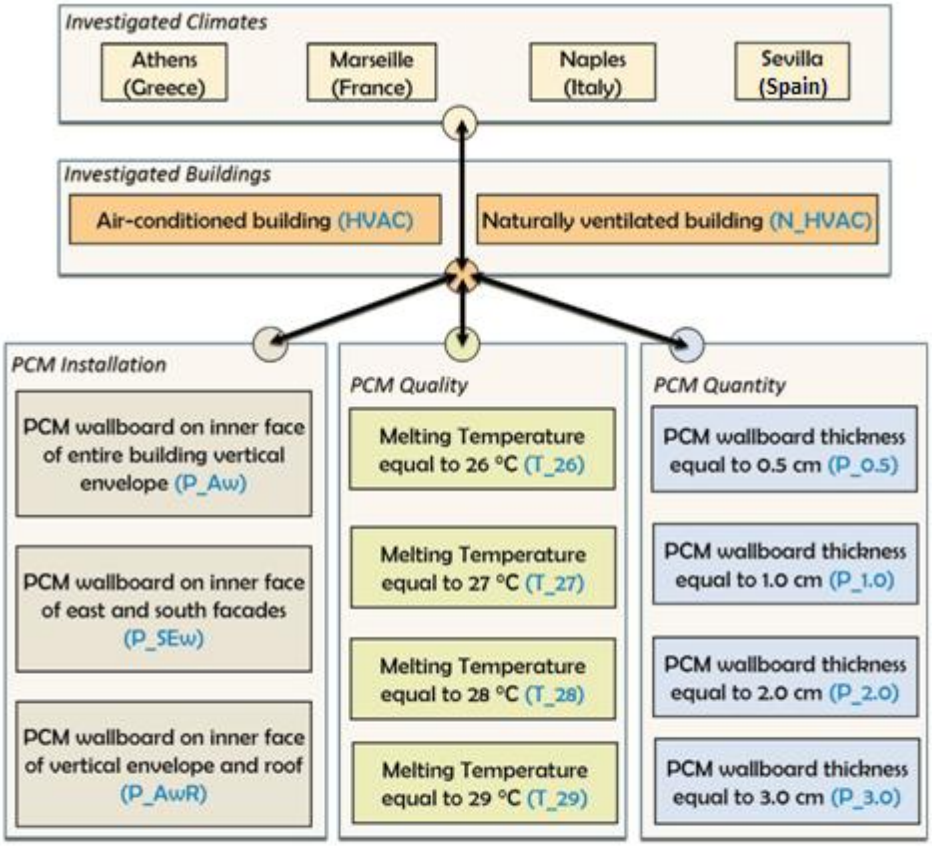

Figure 2.11 Use of PCM as energy efficiency measure. Analyzed climates, building typologies, PCM materials and installed quantity (Ascione *et al.*, 2014)

2.6 SUMMARY

The literature review has provided essential background information to the research project. A brief review of dwellings in Europe and in Cyprus has been presented while also the European Directives concerning the energy efficiency of dwellings have been reviewed. Accordingly, some of the main studies concerning the application of ECM in dwellings in countries with similar climatic conditions to those of Cyprus have been reviewed. None of the reviewed studies used a typical dwelling for the country or location for the analysis but rather relied on dwellings selected in an ad-hoc manner. Studies relating to Cyprus were carried some time ago and did not evaluate modern insulation materials. The application of innovative materials such as PCM on the walls of buildings has been researched for different climates, including climates similar to that of Cyprus. However, there are no studies in the literature considering the application of PCM to typical dwelling and commercial buildings in Cyprus. This fact emphasises the relevance of the present study in providing essential data and relevant interpretations in relation to the application of such materials in Cyprus.

The next chapter will identify the characteristics of the residential building stock of Cyprus and consequently define the typical dwelling that will provide the basis for the investigations in this PhD research project.

CHAPTER 3

CHARACTERISTICS OF THE RESIDENTIAL BUILDING STOCK OF CYPRUS

The significance of the energy consumption of the residential building sector in Cyprus is well acknowledged but unfortunately knowledge in this area is rather limited. This Chapter details the methodology followed for the characterisation of the domestic building stock of Cyprus to enable the investigation of effective energy conservation measures (ECM) and quantification of their effectiveness in subsequent Chapters.

3.1 METHODOLOGY

The methodology followed is shown schematically in Figure 3.1. The first step involved analysis of the existing database of the Cyprus residential building stock, according to the Census of Population Vol. III (2001) and the Construction and Housing Statistics (2006) of the Statistical Service of Cyprus, in order to classify the dwellings in terms of several parameters that are defined accordingly. This classification was carried out in order to minimise the systematic statistical error by ensuring that the sample obtained in the next step behaves in the same way as the total number of dwellings in Cyprus. Consequently, the required residential building sample was determined on which the research was undertaken. The target sample comprised of about 500 dwellings. The next step was the data collection of the sample of 500 dwellings based on a formulated questionnaire detailed in Appendix I. The collected data was then analysed and led to the definition of the characteristics of the residential building stock of Cyprus and to the typical dwelling.

3.2 DETERMINATION OF THE CHARACTERISTICS OF THE SAMPLE

The methodology for the specification of the characteristics of the sample was based on the basic principle that the sample should follow the same trend in terms of the predefined parameters as the total number of dwellings in Cyprus. Thus, the basic parameters on which the sample was specified were determined according to the Census of Population Vol. III (2001) and the Construction and Housing Statistics (2006) of the Statistical Service of Cyprus.

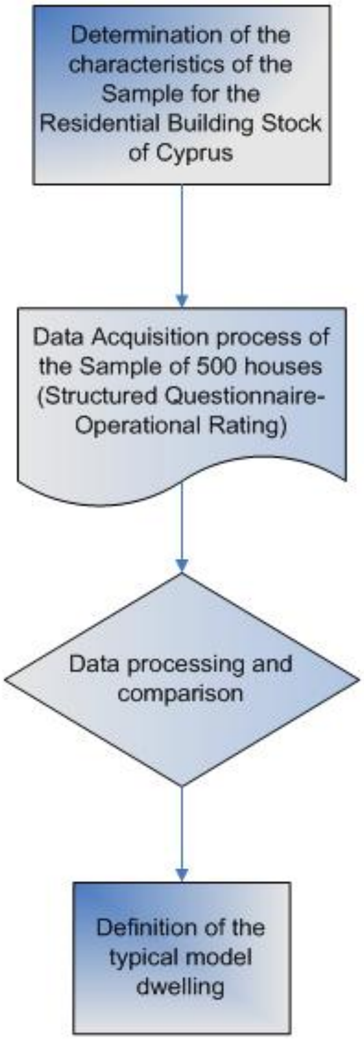

Figure 3.1 Process flow chart showing the methodology followed in this chapter

These parameters are the following:

i. The distribution of dwellings in climatic zones.

ii. The type of the dwelling.

iii. The year of construction.

iv. The size of the dwelling.

In the following sections the determination of the actual distribution in terms of these parameters is presented.

3.2.1 Distribution of dwellings in climatic zones

The climatic zone in which the dwelling is located is crucial in terms of weather conditions, architectural style, and therefore energy behaviour. The Cyprus Energy Service acknowledges four major climatic zones, shown in Figure 3.2, namely coastal, low land, semi-mountainous and mountainous areas.

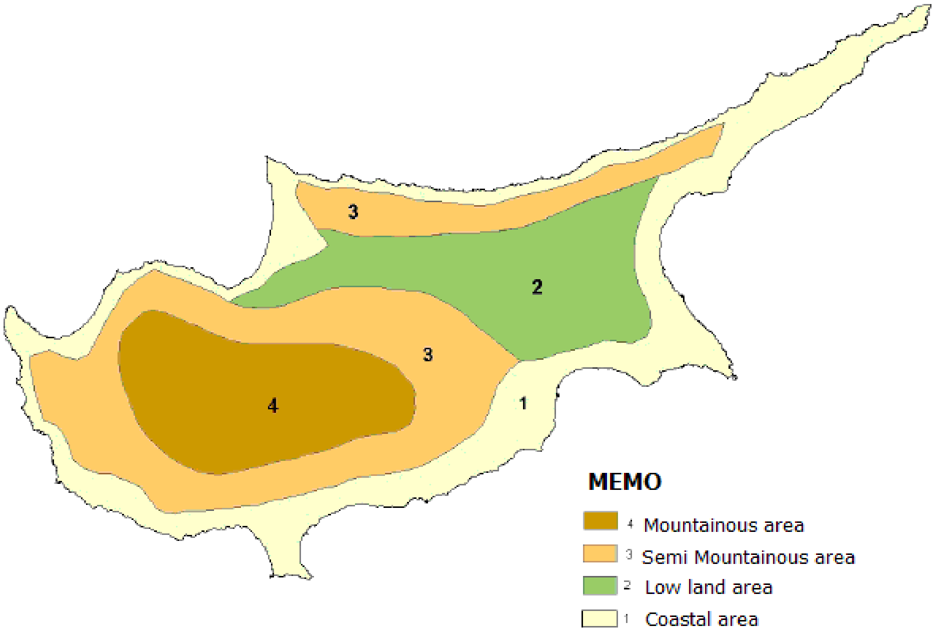

Figure 3.2 Map of Cyprus showing the four major climatic zones

Based on data of the Census of Population Vol. III (2001) and the Construction and Housing Statistics (2006) the dwelling distribution in Table 3.1 was obtained.

Table 3.1 Actual distribution of dwellings in climatic zones

District	**Number of dwellings in each climatic zone**			
	Zone 1 ***(Coastal area)***	**Zone 2** ***(Low land area)***	**Zone 3** ***(Semi mountainous area)***	**Zone 4** ***(Mountainous area)***
Nicosia	485	60,063	26,219	2,642
Limassol	57,233	0	2,996	4,049
Paphos	16,615	0	4,488	1,064
Larnaca	34,544	0	1,756	0
Famagusta	11,619	0	0	0
Total	**120,496**	**60,063**	**35,459**	**7,755**
Percentage	**54%**	**27%**	**16%**	**3%**

3.2.2 Type of the dwelling

The type of the dwelling is also very important as it essentially defines the actual structure and its influence on thermal behaviour. In the Census of Population Vol. III (2001) the main types of dwellings in Cyprus are categorised as detached, semi-detached, apartment, mixed use, terraced and auxiliary (a typical dwelling of each category is depicted in Figure 3.3). If we exclude the last type, since it is not an actual dwelling but a kind of storage room and it is not considered in Directive 2002/91, then the actual distribution is as follows (Table 3.2).

Table 3.2 Actual distribution according to the type of dwelling

	Detached	**Semi-detached**	**Apartment**	**Mixed use**	**Terraced**
Count	124,526	47,752	60,042	21,844	28,605
Percentage	44%	17%	21%	8%	10%

Figure 3.3 Types of dwellings in Cyprus: (a) Detached, (b) Semi-detached, (c) Mixed use, (d) Terraced and (e) Apartment

3.2.3 Year of construction

The age of the dwelling is also crucial for its energy behaviour since many parameters depend on the year of construction such as the architectural style and the building regulations at that time. Considering these parameters, the year of construction is separated into the following three time periods:

- Dwellings built before 1960
- Dwellings built between 1961 - 1990
- Dwellings built after 1990

According to the available sources, the distribution of dwellings for the three time periods is shown in Table 3.3.

Table 3.3 Actual dwelling distribution according to year of construction

Year of construction period	**Count**	**Percentage**
Dwellings built before 1960	30,972	14%
Dwellings built between 1961 - 1990	134,210	61%
Dwellings built after 1990	56,496	25%

3.2.4 Size of the dwelling

The size of the dwelling is the last of the parameters to be defined and due to lack of data in the Census of Population Vol. III (2001) and the Construction and Housing Statistics (2006) concerning the actual size of the dwelling in square meters (m^2) the categorisation was done according to the number of rooms present in the dwelling (excluding bathrooms, toilettes and storage rooms) as follows:

- Less than 3 rooms
- Between ≥3 and ≤6 rooms
- More than 6 rooms

The analysis of dwellings per number of rooms is shown in Table 3.4.

Table 3.4 Actual distribution according to the size of the dwelling

Number of rooms	**Count**	**Percentage**
Less than three	25,715	12%
Between three and six rooms	152,373	68%
More than six rooms	44,735	20%

3.3 DATA COLLECTION PROCESS

The data collection process was based on a field survey using a questionnaire (Appendix I) specifically formulated for the needs of this work that took place between May and October 2009 in all climatic zones according to the predefined distribution (Table 3.1). It should be noted that the data of each questionnaire were given by the owner of the dwelling so as to be as reliable and representative as possible.

The initial number of the collected questionnaires was 530 and the number collected in each climatic zone is shown in Table 3.5. After preliminary validation and evaluation, the useful questionnaires (questionnaires for which all data were present) were reduced to 482. In comparison to the total stock this sample was judged to be adequate.

Table 3.5 Required sample distribution of dwellings in climatic zones

Number of dwellings in each climatic zone			
Zone 1 ***(Coastal area)***	**Zone 2** ***(Low land area)***	**Zone 3** ***(Semi mountainous area)***	**Zone 4** ***(Mountainous area)***
286 (54%)	143 (27%)	85 (16%)	16 (3%)

The main data collected using the questionnaires were focused on the characteristics of the residential building stock of Cyprus. Specifically, the main parameters were the climatic zone in which the dwelling is located, the area of the dwelling (m^2), the number of occupants per dwelling, the year of construction, the type of dwelling, the presence of thermal insulation on the envelope of the dwelling (external walls and roof), the type of the heating/cooling system, the type of the domestic hot water (DHW) system, the presence of double glazing, the occupation time and the number of floors.

3.4 CHARACTERISTICS OF THE RESIDENTIAL BUILDING STOCK OF CYPRUS

The data obtained by the sample of the 482 complete questionnaires were analysed and led to the definition of the characteristics of the residential building stock of Cyprus which are presented below.

The sample distribution according to the area of the dwelling is graphically represented in Figure 3.4. It can be observed that most of the dwellings (75%) are between 51 and 200 m^2 with the mean area being 172.9 m^2. With a rough approximation the average area per occupant is 57m^2/occupant. The equivalent average European numbers according to the Housing Statistics of the European Union 2005/2006 (2006) are much lower than those in the present sample and are equal to 84.5 m^2 and 33.8 m^2/occupant, respectively.

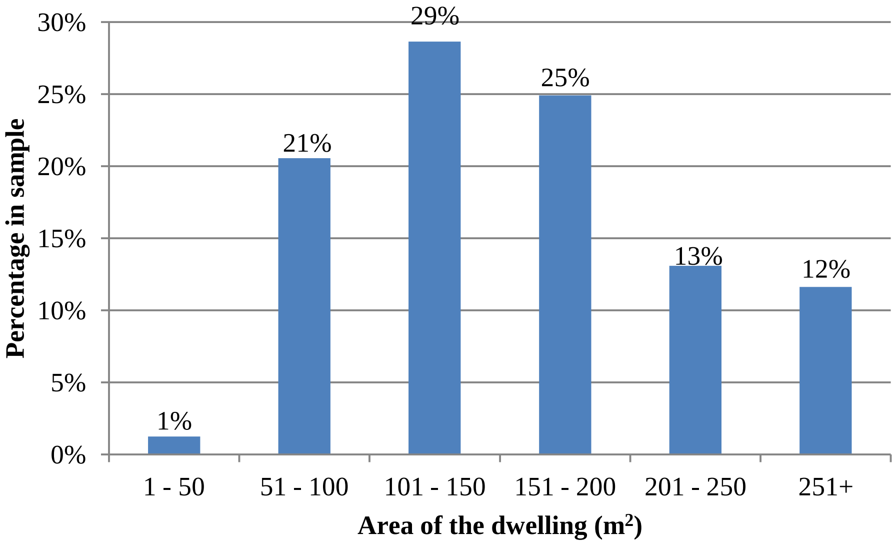

Figure 3.4 Sample distribution according to the area of the dwelling (m^2).

The number of occupants in a dwelling is also important and directly related to its overall energy behaviour. Figure 3.5 shows the number of occupants per dwelling and as it can be seen 68% of the dwellings have 2 to 4 occupants. The average number of occupants per house is 3.3 while the corresponding average European number is 2.5 (Housing Statistics in the European Union 2005/2006, 2006).

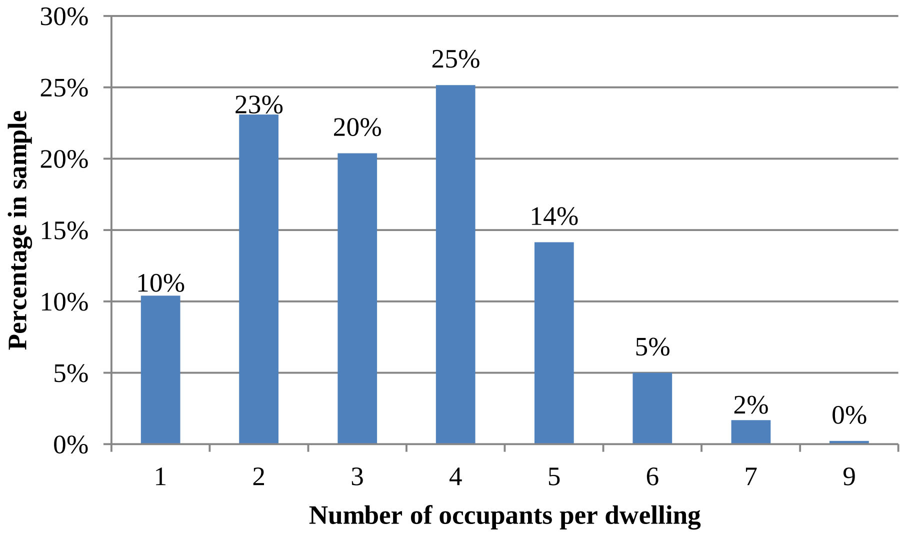

Figure 3.5 Sample distribution according to the number of occupants per dwelling

The sample distribution according to the year of construction is shown in Figure 3.6. As can be observed the majority (~90%) of the residential building stock in Cyprus was constructed after 1971. A rapid increase in dwelling construction occurred between 1970 and 1990 as a result of the construction of refugee settlements to house refugees caused by the Turkish invasion of 1974.

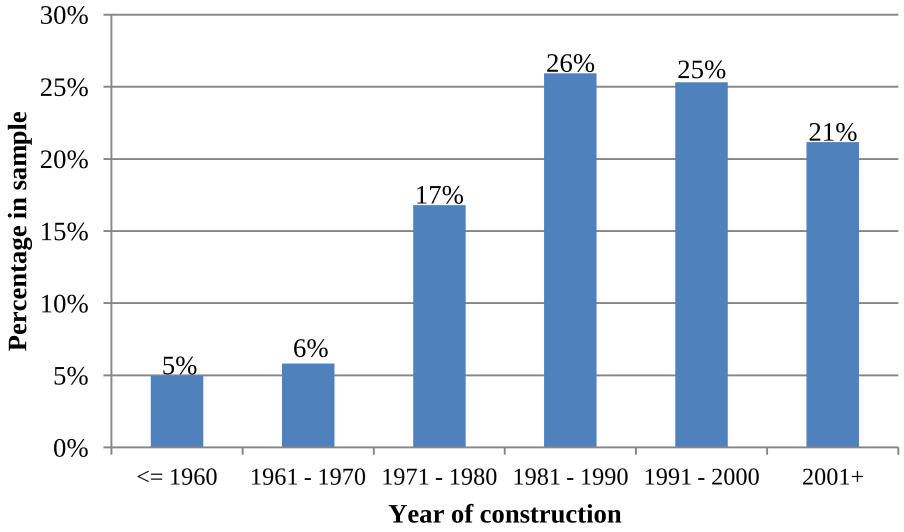

Figure 3.6 Sample distribution according to the year of construction.

The dominant type of dwelling in the sample is that of the detached dwelling which represents 68% of the total number while the second most common type is the apartment with a share of 23% (Figure 3.7). It should be noted that the terraced dwellings in our sample only accounts for 1% while there weren't any mixed use dwellings in the sample. This distribution differs from that of the available database analysed previously in this Chapter. This can be attributed to the fact that the available database was constituted in 2001 and 2006 while this sample was collected in 2009. Nevertheless, this is not a problem for this study since the main objective of this Chapter is to identify the typical dwelling to be used in the analysis. This is the detached dwelling which represents 68% of the sample.

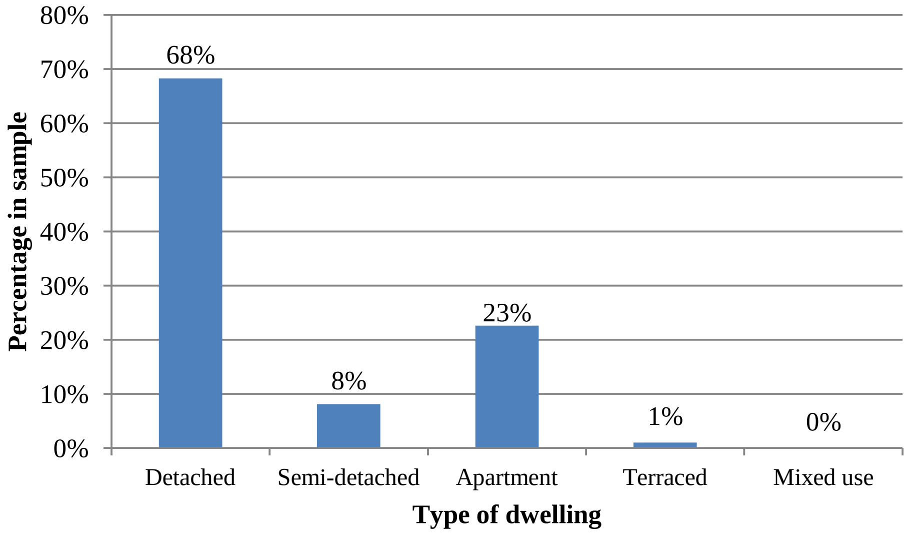

Figure 3.7 Sample distribution according to the type of the dwelling.

The types of heating systems used in dwellings as primary and secondary source are shown in Figure 3.8. The primary source system is the most commonly used one while the secondary source is the backup system which is only occasionally used. The dominant heating system used as primary representing 37% of the sample is a central heating system with water radiators and oil fired boiler. The second most commonly used system is the split type air conditioning/heat pump units system which can be used for both heating and cooling. The category 'Other' includes central electrical storage heating systems which represent the majority of other systems. Additionally, it should be noted that due to the economic crisis and the consequent increase of the price of heating oil most people interviewed stated that despite the fact that they have a central heating system installed as primary system they do not use it. Instead they use their backup heating systems which can serve only the space occupied at a particular time like fireplaces, individual electric heaters, LPG heaters and split type air conditioning/heat pump units.

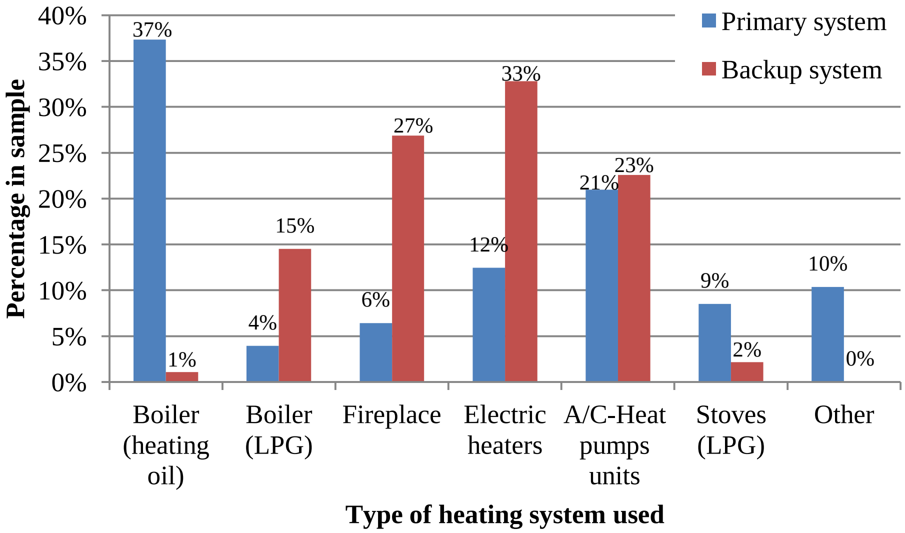

Figure 3.8 Sample distribution according to the type of the heating system used.

According to Maxoulis and Kalogirou (2008) people in Cyprus extensively use solar energy for water heating. This is also reflected by the results in our sample (Figure 3.9) since solar thermal systems are used in more than 82% of houses in Cyprus for the production of domestic hot water (DHW). This is close to the estimated 90% coverage of dwellings with DHW systems (Maxoulis and Kalogirou, 2008). This high percentage should be credited to the favourable weather conditions, to a pioneering thermal solar industry and to the coordinated efforts of the various stakeholders. The main backup system is the boiler using electricity with a share of 87% while the heating oil boiler has a share of 13%.

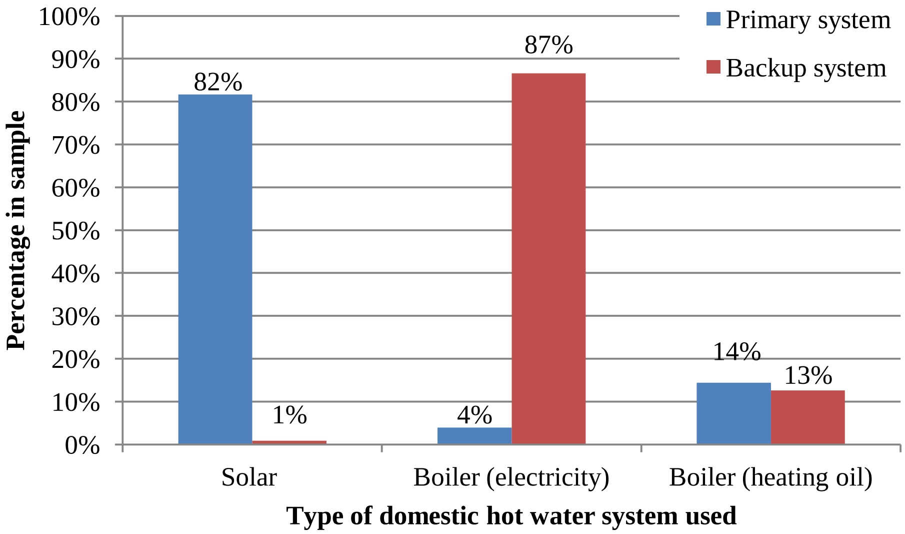

Figure 3.9 Sample distribution according to the type of the domestic hot water system used.

A very disappointing fact is that 82% and 95% of the dwellings in the sample do not have thermal insulation installed on the external walls and the roof, respectively (Figure 3.10). The results also show that 49% of the dwellings in the sample do not have double glazed windows. These results are mainly attributed to the fact that until 2010 there were no regulations to cover the thermal performance of domestic dwellings.

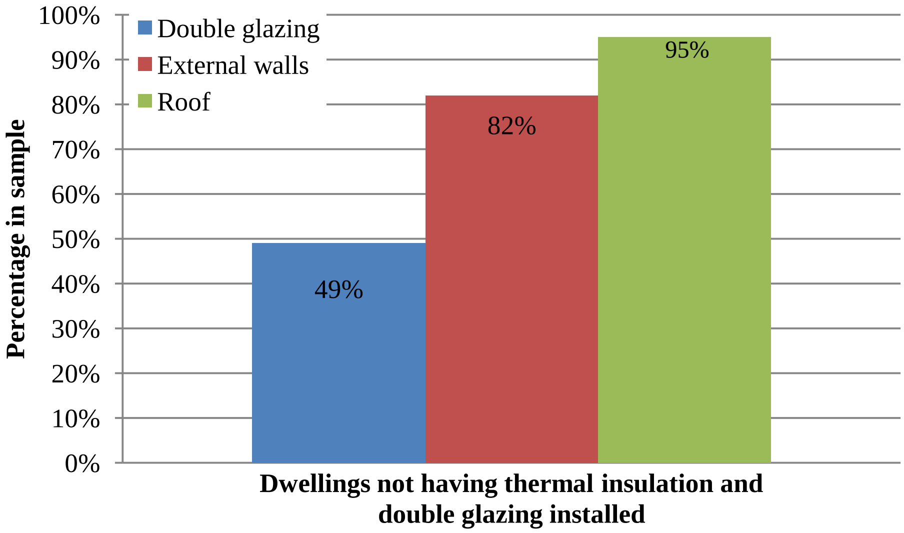

Figure 3.10 Sample distribution according to the number of dwelling which do not have thermal insulation (external walls and roof) and double glazing installed

The distribution of the dwellings in the sample according to the location (climatic zone) of the dwelling (Figure 3.11) shows that 52% of the dwellings are located in Zone 1, 29% in Zone 2, 15% in Zone 3 and only 4% in Zone 4. The reason for which the majority of the dwellings are located in Zone 1 is that three out of four major cities in Cyprus are coastal (Limassol, Paphos and Larnaca) while only Nicosia is located in Zone 2 (low land area). As it can be seen the distribution of the sample is identical to the predefined required distribution shown in Table 3.5 and thus it can be said that the sample provides a good representation of the actual distribution of dwellings in the four climatic zones.

The occupation time is also very important for the energy behaviour of dwellings since it essentially shows the period when the occupants are present and the need for energy (heating/cooling, lighting etc) exists. The sample distribution (Figure 3.12) according to the mean occupation time of all occupants of the dwelling shows that 52% of the sample corresponds to 10-12 hours while 83% corresponds to 10-15 hours. For an occupation time over 15 hours the share in the sample corresponds to 12% and for less than 10 hours corresponds to 3%. It should be noted that the occupation time with the highest share (27%) is 12 hours.

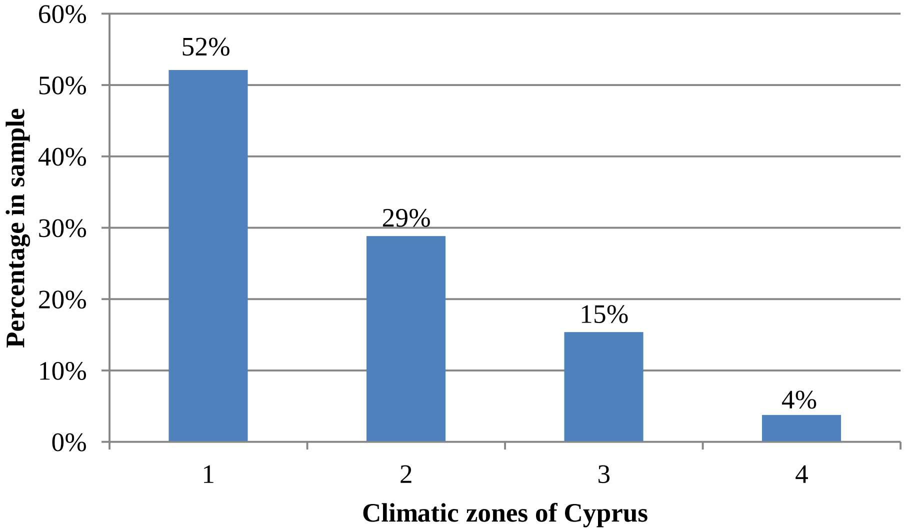

Figure 3.11 Sample distribution according to the location of the dwellings

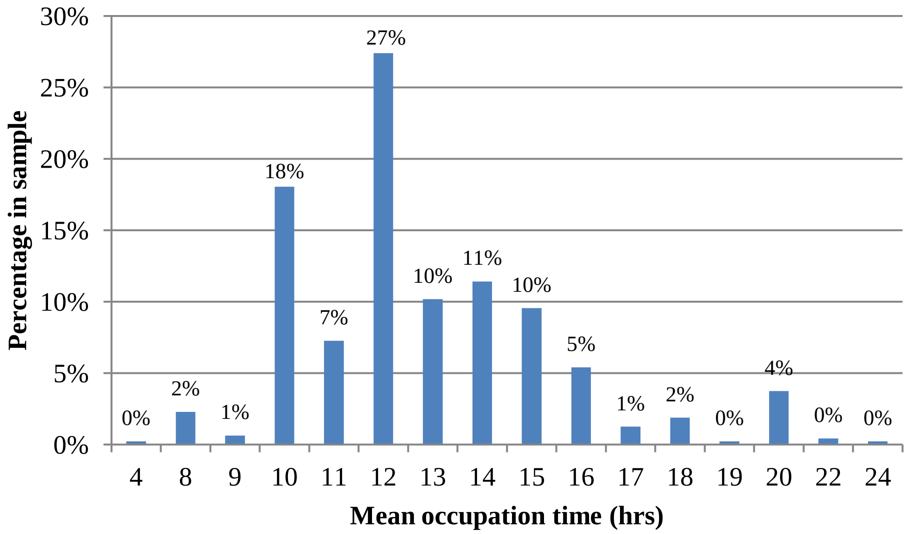

Figure 3.12 Sample distribution according to the mean occupation time

The results concerning the number of floors in detached dwellings (Figure 3.13) show that the majority (66%) of the detached dwellings only have one floor (ground floor), 30% have two floors and only 3% have three floors.

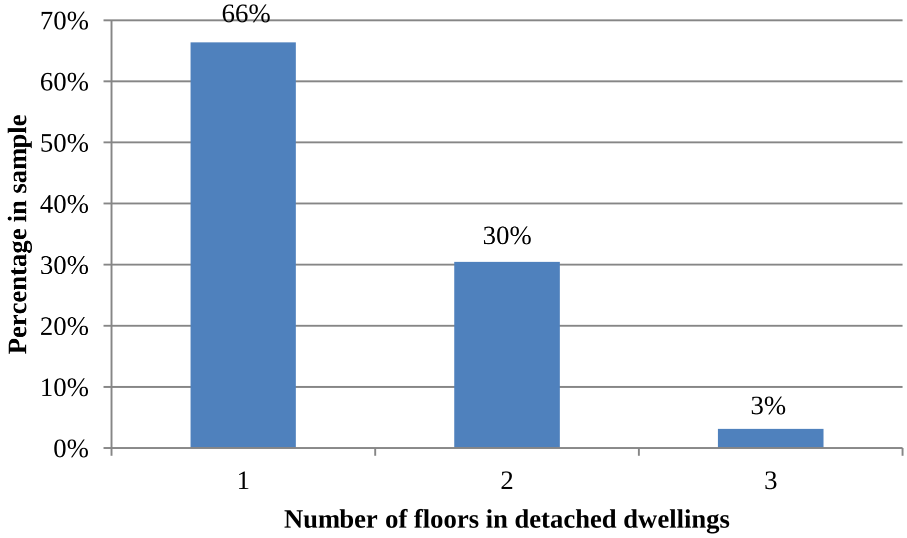

Figure 3.13 Sample distribution according to the number of floors in detached dwellings

In the question if the dwelling has undergone major renovation during the last 5 to 10 years the vast majority of the homeowners (98%) responded negatively and only 2% responded positively. The term major renovation was used to describe any interventions made to improve the energy efficiency of the dwelling such as installation of thermal insulation, replacement of the glazing.

3.5 SUMMARY

According to the results presented in this Chapter, the typical dwelling is a single floor (ground floor) detached house located in Zone 1 (Coastal area) with a total area of 133 m^2. However, due to the lack of available weather data for Zone 1 (Coastal area) the dwelling will be modelled for Zone 2 (Low land area) for which weather data are available in literature (Kalogirou, 2003). The differences between these two Zones concerning the temperature variation are considered to be very small and thus the modelling and simulation can be carried out sufficiently. There are 4 occupants living in the dwelling and the mean occupation time is 12 hours. The dwelling does not have thermal insulation installed on its envelope (external walls and roof). It consists of the following rooms: three bedrooms, kitchen, living room, bathroom, and dining room. A solar water heating system is used for domestic hot water production. The demand for heating and cooling is met by split type A/C – Heat pump units. The windows of the dwelling are double-glazed with aluminium frame. Finally, the floor consists of marble tiles. The layout of the dwelling is shown in Figure 3.14.

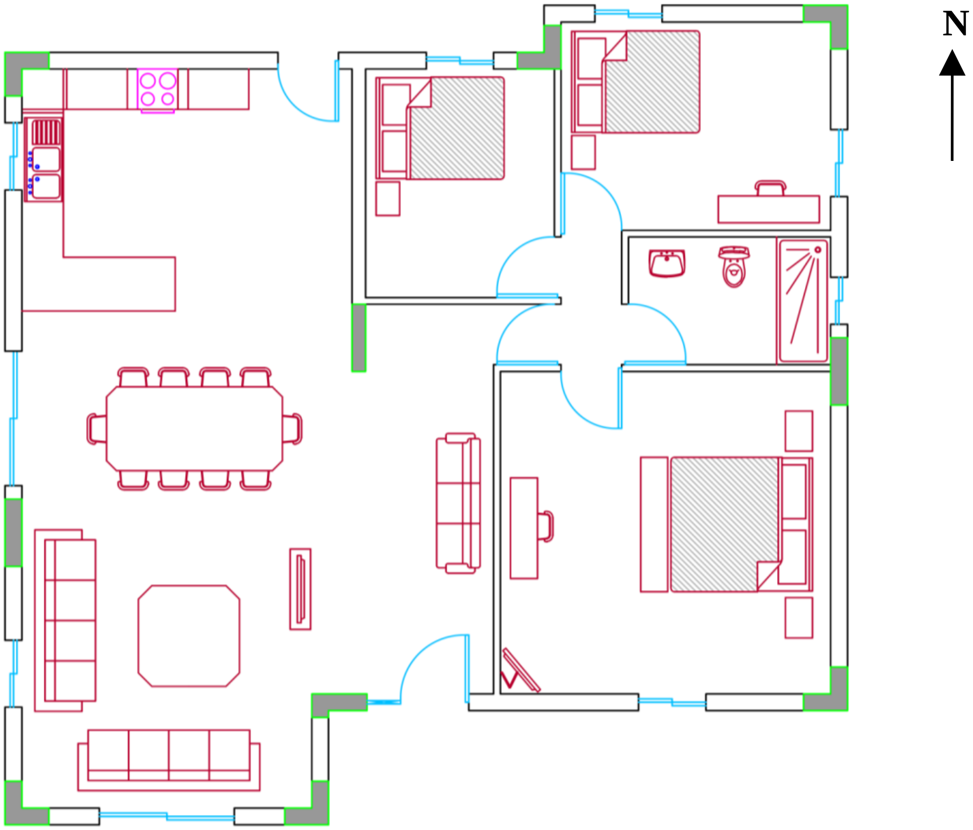

Figure 3.14 Plot of the typical dwelling.

CHAPTER 4

DEFINITION AND REVIEW OF COMMERCIALLY AVAILABLE THERMAL INSULATION MATERIALS IN CYPRUS

The results of the previous chapter indicated that more than 80% of the dwellings in Cyprus do not have thermal insulation installed on their envelope. Under these circumstances the need for reviewing and defining the available thermal insulation materials and their most commonly used topologies in Cyprus is important. This is the main aim of this Chapter.

4.1 COMMERCIALLY AVAILABLE THERMAL INSULATION MATERIALS IN CYPRUS

The commercially available thermal insulation materials, suitable for installation on a dwelling's envelope in Cyprus, have been identified through a market survey and are summarised in Table 4.1. The main sources of information during the market survey were the thermal insulation suppliers and producers while the main data collected concerned the type of the material, the available thicknesses, the cost of the material per square meter and its thermal conductivity. It is worth noting that most of these materials are imported and only thermal insulation bricks and thermal insulation plaster are locally produced.

Additionally, it should be clarified that the cost of each material presented in Table 3.1 refers to the cost of purchasing the material only. It is also not within the scope of this thesis to investigate the application of insulation materials that are not commercially available in Cyprus such as aerogel or vacuum insulation panels (VIP) and are currently too expensive for application in domestic dwellings. According to Cabot (2014) the cost for a product that can be applied in buildings (Cabot Aerogel Thermal Wrap) is around 270 €/m^2 while according to Alam, Singh and Limbachiya (2011) the cost of VIP is 70-80 £/m^2.

Table 4.1 Main types of commercially available thermal insulation materials in Cyprus

Type of material	Available thicknesses (m)	Thermal conductivity (W/mK)	Material cost (€/m^2)
Extruded polystyrene (ρ = 32 kg/m^3)	0.02	0.029	3.25
	0.03	0.035	3.60
	0.03	0.029	4.15
	0.04	0.035	4.80
	0.04	0.029	5.55
	0.05	0.035	6.00
	0.05	0.029	6.80
Expanded polystyrene (ρ = 12 kg/m^3)	0.02	0.04	1.60
	0.03	0.04	2.10
	0.04	0.04	2.80
Stone wool (ρ = 50 kg/m^3)	0.03	0.035	2.50
	0.04	0.035	3.35
	0.05	0.035	4.20
Thermal insulation bricks (ρ = 600 kg/m^3)	0.20	0.18	17.96
	0.23	0.18	20.00
	0.25	0.18	20.52
	0.28	0.18	25.00
Thermal insulation plaster (ρ = 175 kg/m^3)	0.025	0.051	3.13
	0.03	0.051	3.75
	0.035	0.051	4.38

4.2 CALCULATION OF THE U-VALUE FOR DIFFERENT TOPOLOGIES OF WALLS AND ROOFS

In order to have a more complete and realistic view of the effect of thermal insulation materials on the thermal characteristics of a dwelling’s envelope, these should be evaluated by calculating the overall heat transfer coefficient (U-value) of several different topologies of external walls and roofs where they can be applied. The types of walls and roofs to be evaluated are briefly summarised below:

- Wall Topologies:
  - Single leaf wall with external insulation.
  - Double wall with insulation in-between, without air gap.
  - Double wall with insulation in-between, with air gap.
  - Wall with thermal insulation bricks.
  - Wall with thermal insulation plaster installed outside.

- Roof Topologies:
  - Horizontal concrete roof (HCR).
  - Inclined clay tile roof (ITR).
  - Horizontal concrete with inclined clay tile roof (HCITR) on top.

The methodology used to calculate the U-value is that indicated by the "Building Thermal Insulation Guide" (MCIT, 2010). More analytically, the method used to calculate the U-value of each structural element is based on standard CYS EN ISO 6946: 2007, using the following equation:

$$Uvalue = \frac{1}{R_{si} + \sum \frac{d_i}{\lambda_i} + R_{se}} \tag{4.1}$$

Where,

R_{si}: internal surface resistance between the internal environment and the internal surface of the structural element (m^2K/W),

R_{se}: external surface resistance between the external environment and the external surface of the structural element (m^2K/W),

d_i: material thickness (m),

λ_i: material thermal conductivity (W/mK).

The values of the surface resistances (R_{si} and R_{se}) are taken from the "Building Thermal Insulation Guide" (MCIT, 2010) and can be seen in Table 4.2. According to the methodology the values of the thermal resistances used in the calculations should have an accuracy of at least three decimal places. During the calculation of the U-value of each structural element (topology) the materials taken into consideration are only those that essentially contribute to the formation of the thermal resistance of the element, whereas materials with insignificant thermal conductivity such as paints, glues etc. have been neglected.

Table 4.2 Values of the surface resistances (R_{si} and R_{se}) according to the heat flow direction for common non-reflective surfaces (MCIT, 2010).

Heat flow direction	R_{si} (m^2K/W)	R_{se} (m^2K/W)
Horizontal	0.13	0.04
Downwards	0.17	0.04
Upwards	0.10	0.04

4.2.1 Wall with external insulation.

In this wall topology the suitable thermal insulation materials that can be effectively applied are those of extruded and expanded polystyrene of several different thicknesses. The typical detail of this topology is presented in Figure 4.1 and consists of (internal to external):

1. 0.025 m Portland cement plaster
2. 0.20 m hollow clay brick
3. Insulation layer (0.02-0.05m)
4. 0.025 m Portland cement plaster

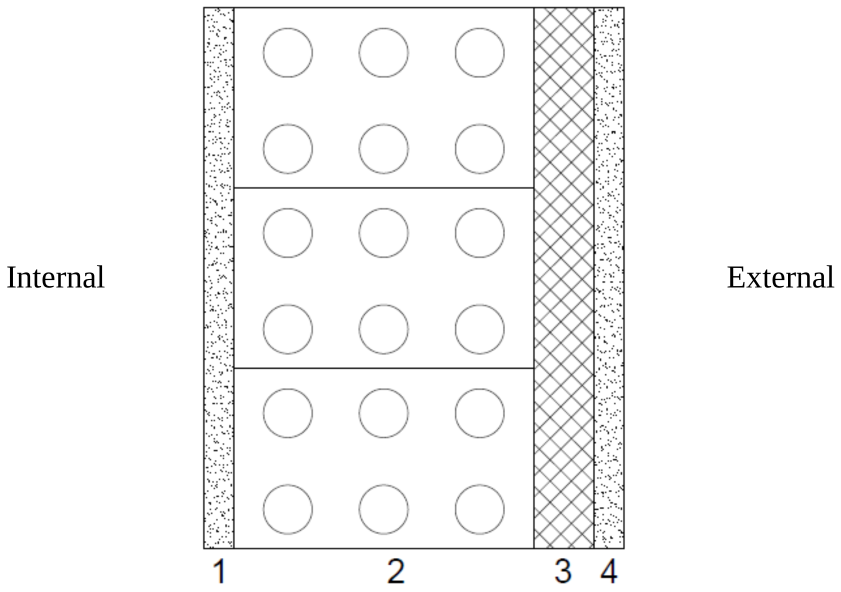

Figure 4.1 Typical topology detail of an externally insulated wall

An example of a U-value calculation for this type of wall is presented below for the case where the wall is insulated with 0.02m of expanded polystyrene. Specifically, the calculation is performed by applying the data for each material shown in Table 4.3 in Eq. 4.1. The numbering of the material layers is same as in Figure 4.1.

Table 4.3 Data required for the calculation of the U-value for an externally insulated wall with 0.02m of expanded polystyrene

Nº of layer	Material (internal to external)	Material thickness (m)	Thermal conductivity (W/mK)
1	Portland cement plaster	0.025	1.39
2	Hollow clay brick	0.2	0.4
3	Expanded polystyrene	0.02	0.04
4	Plaster	0.025	1.39
	Heat flow direction	Horizontal	
	Rsi (m^2K/W)	0.13	
	Rse (m^2K/W)	0.04	

$$Uvalue = \frac{1}{R_{si} + \sum \frac{d_i}{\lambda_i} + R_{se}}$$

$$\rightarrow Uvalue = \frac{1}{0.13 + \frac{0.025}{1.39} + \frac{0.2}{0.4} + \frac{0.02}{0.04} + \frac{0.025}{1.39} + 0.04}$$

$$\rightarrow Uvalue = \frac{1}{0.13 + 0.018 + 0.5 + 0.5 + 0.018 + 0.04}$$

$$\rightarrow Uvalue = \frac{1}{1.206} \rightarrow Uvalue = \mathbf{0.829}\, W/m^2K$$

The results of the calculation for this type of wall together with the total additional cost per m^2 of wall area are presented in Table 4.4. The total additional cost includes the cost for purchasing the material together with labour cost for installing it.

Table 4.4 U-values and total additional cost of externally insulated walls

Insulation thickness (m)	U- Value (W/m^{2}K)	Total additional cost (€/m^2)
Expanded polystyrene		
0.02	0.829	30
0.03	0.687	30.5
0.04	0.586	31.2
Extruded polystyrene		
0.02 *(0.029 W/mK)*	0.717	31.7
0.03 *(0.035 W/mK)*	0.640	32
0.03 *(0.029 W/mK)*	0.575	32.6
0.04 *(0.035 W/mK)*	0.541	33.2
0.04 *(0.029 W/mK)*	0.480	34
0.05 *(0.035 W/mK)*	0.468	34.4
0.05 *(0.029 W/mK)*	0.412	35.2

4.2.2 Double wall with insulation in-between, without air gap.

In this wall topology suitable thermal insulation materials that can be effectively applied are those of extruded polystyrene, expanded polystyrene and stone wool of several different thicknesses.

The typical detail of this topology is presented in Figure 4.2 and consists of (internal to external):

1. 0.025 m Portland cement plaster
2. 0.10 m hollow clay brick
3. Insulation layer (0.02-0.05m)
4. 0.10 m hollow clay brick
5. 0.025 m Portland cement plaster

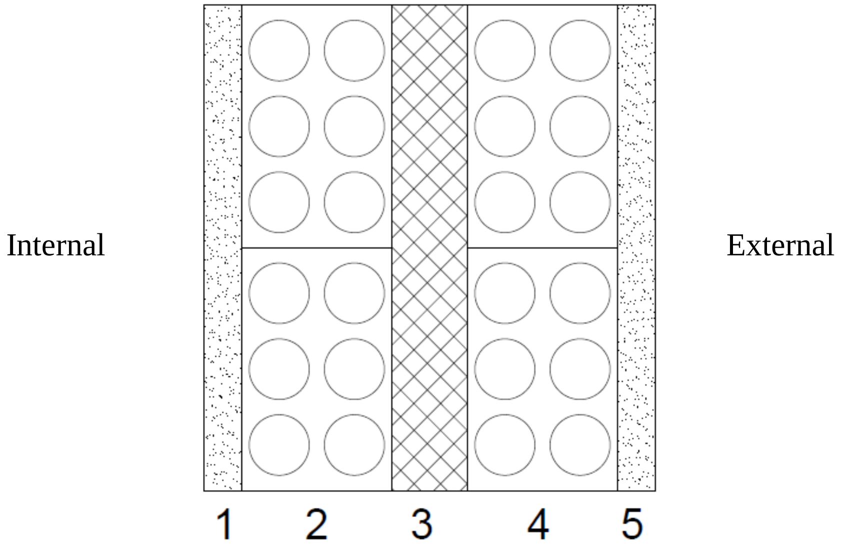

Figure 4.2 Typical topology detail of a double wall with insulation in-between without air gap

The results of the calculation for this type of wall together with the total additional cost per m^2 of wall area are presented in Table 4.5.

Table 4.5 U-values and total additional cost of a double wall with insulation in-between without air gap

Insulation thickness (m)	U- Value (W/m^2K)	Total additional cost (€/m^2)
Expanded polystyrene		
0.02	0.829	14.1
0.03	0.687	14.6
0.04	0.586	15.3
Extruded polystyrene		
0.03 *(0.035 W/mK)*	0.640	16.1
0.03 *(0.029 W/mK)*	0.575	16.6
0.04 *(0.035 W/mK)*	0.541	17.3
0.04 *(0.029 W/mK)*	0.480	18
0.05 *(0.035 W/mK)*	0.468	18.5
0.05 *(0.029 W/mK)*	0.412	19.3
Stone wool		
0.03	0.640	15
0.04	0.541	15.8
0.05	0.468	16.7

4.2.3 Double wall with insulation in-between, with air gap.

In this wall topology the suitable thermal insulation materials that can be effectively applied are those of extruded polystyrene, expanded polystyrene and stone wool of several different thicknesses. The typical detail of this topology is presented in Figure 4.3 and consists of (internal to external):

1. 0.025 m Portland cement plaster
2. 0.10 m hollow clay brick
3. Insulation layer (0.02-0.05m)
4. 0.025 m air gap
5. 0.10 m hollow clay brick
6. 0.025 m Portland cement plaster

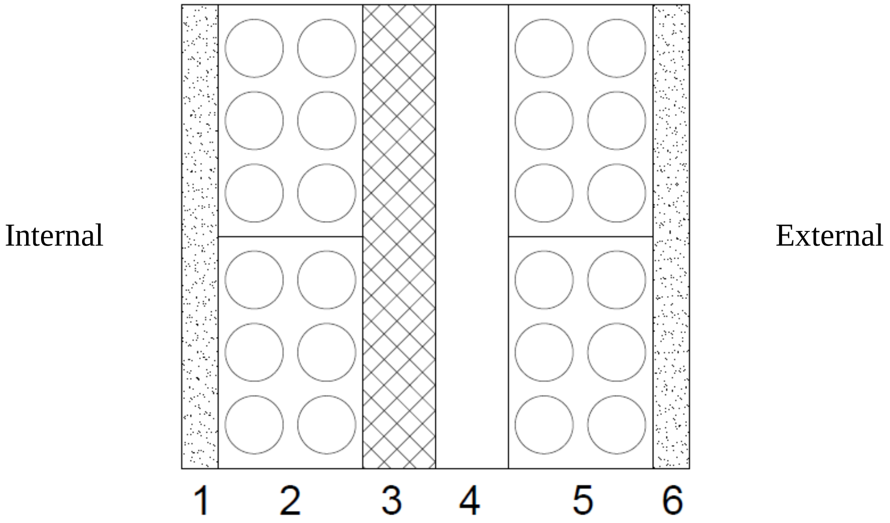

Figure 4.3 Typical topology detail of a double wall with insulation in-between with air gap

The resulting U-value for this type of wall together with the total additional cost per m^2 of wall area are presented in Table 4.6.

Table 4.6 U-values and total additional cost of double wall with insulation in-between with air gap

Insulation thickness (m)	U- Value (W/m^{2}K)	Total additional cost (€/m^2)
Expanded polystyrene		
0.02	0.744	20.1
0.03	0.627	20.6
0.04	0.542	21.3
Extruded polystyrene		
0.02 *(0.029 W/mK)*	0.652	21.7
0.03 *(0.035 W/mK)*	0.588	22.1
0.03 *(0.029 W/mK)*	0.521	22.6
0.04 *(0.035 W/mK)*	0.493	23.3
0.04 *(0.029 W/mK)*	0.441	24
0.05 *(0.035 W/mK)*	0.432	24.5
0.05 *(0.029 W/mK)*	0.383	25.3
Stone wool		
0.03	0.574	21
0.04	0.493	21.8
0.05	0.432	22.7

4.2.4 Wall with thermal insulation bricks.

In this wall topology thermal insulation bricks of several different thicknesses are used. The thermal insulation bricks considered are manufactured by a Cypriot company named ‘United Brickworks Ltd’ and their typical structure is shown in Figure 4.4. As can be seen their structure is much different than that of common hollow clay brick and according to the CE certificate provided by the manufacturer their thermal conductivity (λ) is 0.18 W/mK. The typical detail of this topology is presented in Figure 4.5 and consists of (internal to external):

1. 0.025 m Portland cement plaster
2. Thermal insulation bricks (0.20-0.28m)
3. 0.025 m Portland cement plaster

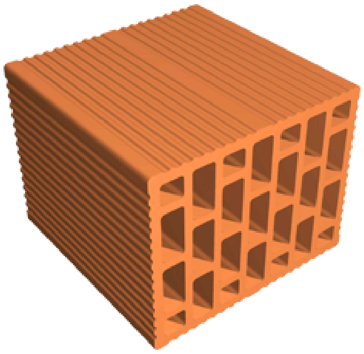

Figure 4.4 Thermal insulation brick used in the calculations.

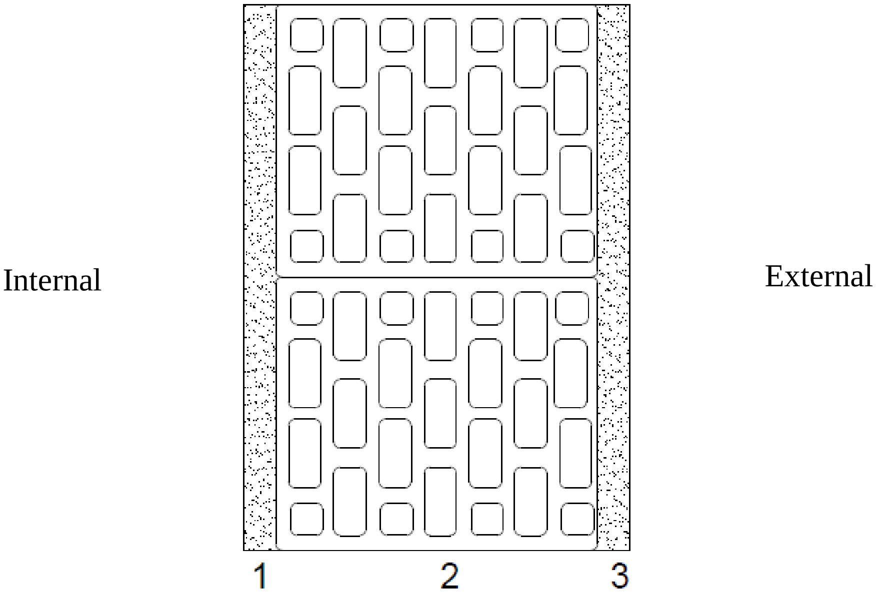

Figure 4.5 Typical topology detail of a wall with thermal insulation bricks

The results of the calculation for this type of wall together with the total additional cost per m^2 of wall area are presented in Table 4.7.

Table 4.7 U-values and total additional cost of wall with thermal insulation bricks

Thermal insulation bricks thickness (m)	U- Value (W/m^{2}K)	Total additional cost (€/m^2)
0.2	0.759	3.6
0.23	0.674	5.6
0.25	0.627	6.1
0.28	0.568	10.6

4.2.5 Wall with thermal insulation plaster.

In this wall topology thermal insulation plaster of several different thicknesses is used. The thermal insulation plaster used in this study is manufactured by a Cypriot company named ‘Moustick Products Ltd’ and its product name is Mektotherm. This product is based on Portland cement and expanded polystyrene beads. According to the CE certificate provided by the manufacturer its thermal conductivity (λ) is 0.051 W/mK compared to the common Portland cement plaster which has a thermal conductivity of 1 W/mK. The typical detail of this topology is presented in Figure 4.6 and consists of (internal to external):

1. Thermal insulation plaster (0.025-0.035m)
2. 0.20 m hollow clay brick
3. 0.025 m Portland cement plaster

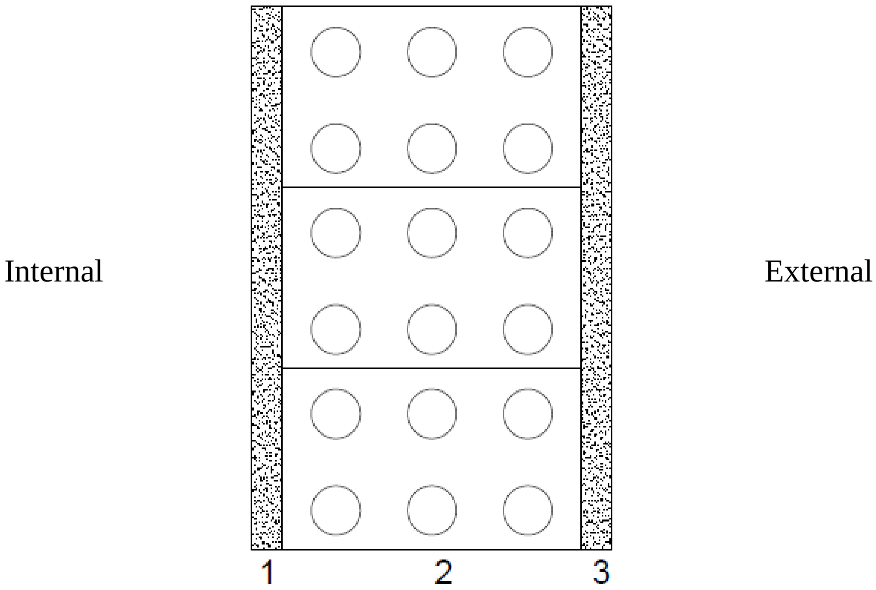

Figure 4.6 Typical topology detail of a wall with thermal insulation plaster

The results of the calculation for this type of wall together with the total additional cost per m^2 of wall area are presented in Table 4.8.

Table 4.8 U-values and total additional cost of wall with thermal insulation plaster

Insulation thickness (m)	U- Value (W/m^{2}K)	Total additional cost (€/m^2)
0.025	0.843	3.1
0.03	0.779	3.8
0.035	0.676	4.4

4.2.6 Horizontal concrete roof (HCR)

The most commonly used thermal insulation materials in the case of a horizontal concrete roof are extruded polystyrene, expanded polystyrene and stone wool of several different thicknesses. The typical detail of the topology of this roof is presented in Figure 4.7 and consists of (external to internal):

1. 0.004 m bitumen hydro insulation layer
2. 0.05 m screed
3. Insulation layer (0.03-0.05 m)
4. 0.15 m reinforced concrete (2% steel)
5. 0.025 m Portland cement plaster

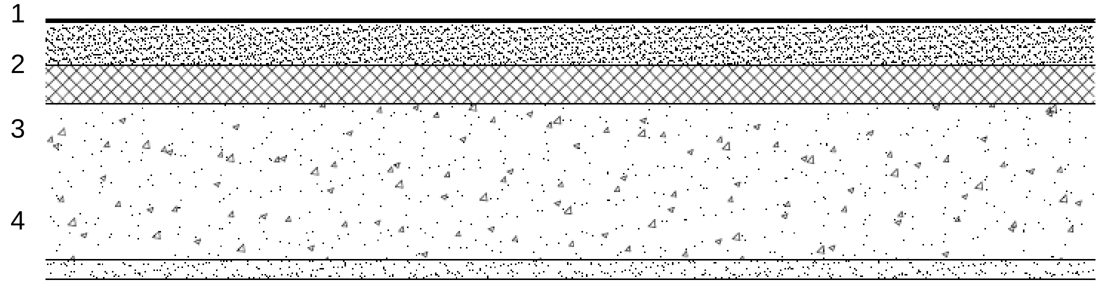

Figure 4.7 Detail of an insulated horizontal concrete roof

The results of the calculation for this type of roof together with the total additional cost per m^2 of roof area are presented in Table 4.9.

Table 4.9 U-values and total additional cost of an insulated horizontal concrete roof

Insulation thickness (m)	U- Value (W/m^{2}K)	Total additional cost (€/m^2)
Expanded polystyrene		
0.04	0.795	17.8
0.05	0.664	18.5
Extruded polystyrene		
0.03 *(0.029 W/mK)*	0.774	19.2
0.04 *(0.035 W/mK)*	0.714	19.8
0.04 *(0.029 W/mK)*	0.611	20.6
0.05 *(0.035 W/mK)*	0.593	21
0.05 *(0.029 W/mK)*	0.505	21.8
Stone wool		
0.04	0.714	18.4
0.05	0.593	19.2

4.2.7 Inclined clay tile roof (ITR)

In the case of inclined roof with clay tiles the most commonly used thermal insulation materials are extruded polystyrene, expanded polystyrene and stone wool of several different thicknesses. The typical detail of the structure of the dwelling is presented in Figures 4.8 and consists of (external to internal):

1. 0.02 m clay tiles (Spanish type)
2. 0.004 m bitumen hydro insulation layer
3. Insulation layer (0.03-0.05 m)
4. 0.20 m reinforced concrete (2% steel)

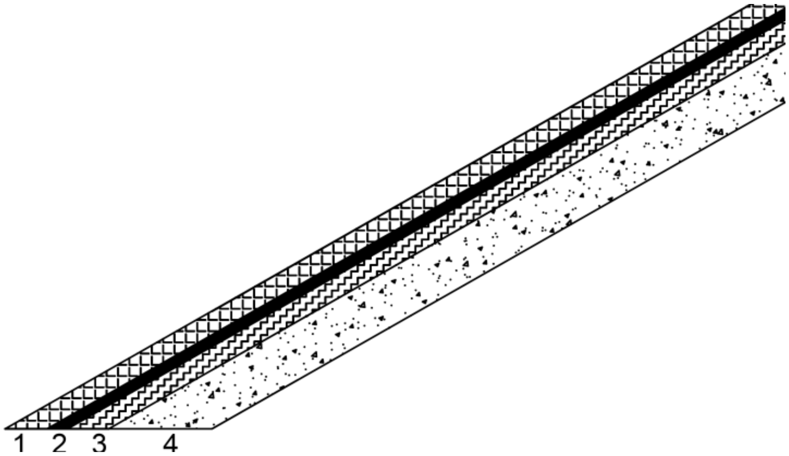

Figure 4.8 Typical topology detail of an insulated inclined clay tile roof

The results of the calculation for this type of roof together with the total additional cost per m^2 of roof area are presented in Table 4.10.

Table 4.10 U-values and total additional cost of an insulated inclined roof with clay tiles

Insulation thickness (m)	U- Value (W/m^2K)	Total additional cost (€/m^2)
Expanded polystyrene		
0.04	0.748	17.8
0.05	0.630	18.5
Extruded polystyrene		
0.03 *(0.029 W/mK)*	0.730	19.2
0.04 *(0.035 W/mK)*	0.676	19.8
0.04 *(0.029 W/mK)*	0.583	20.6
0.05 *(0.035 W/mK)*	0.567	21
0.05 *(0.029 W/mK)*	0.485	21.8
Stone wool		
0.04	0.676	18.4
0.05	0.567	19.2

4.2.8 Horizontal concrete roof and inclined clay tile roof (HCITR)

This roof concerns an insulated horizontal concrete roof in combination with a ventilated inclined clay tile roof (the angle of inclination is approximately 35^o). Suitable thermal insulation materials considered in this topology are extruded polystyrene, expanded polystyrene and stone wool of several different thicknesses. It should be noted that during the calculation of the U-value of this topology the thermal resistance of the void (air) between the inclined roof and the horizontal concrete roof is taken into consideration. According to the "Building Thermal Insulation Guide" (MCIT, 2010) this can be done by adding a thermal resistance, R_u, which takes into consideration both the air space resistance and the clay tiles and wooden structure resistance and for the case examined is equal to 0.06 m^2K/W.

The typical detail of this topology is presented in Figure 4.9 and consists of (external to internal):

1. 0.02 m clay tiles
2. Wooden structure

Pitched roof structure

3. 0.004 m bitumen hydro insulation layer
4. 0.05 m screed
5. Insulation layer (0.03-0.05m)
6. 0.15 m reinforced concrete (2% steel)
7. 0.025 m Portland cement plaster

Horizontal roof structure

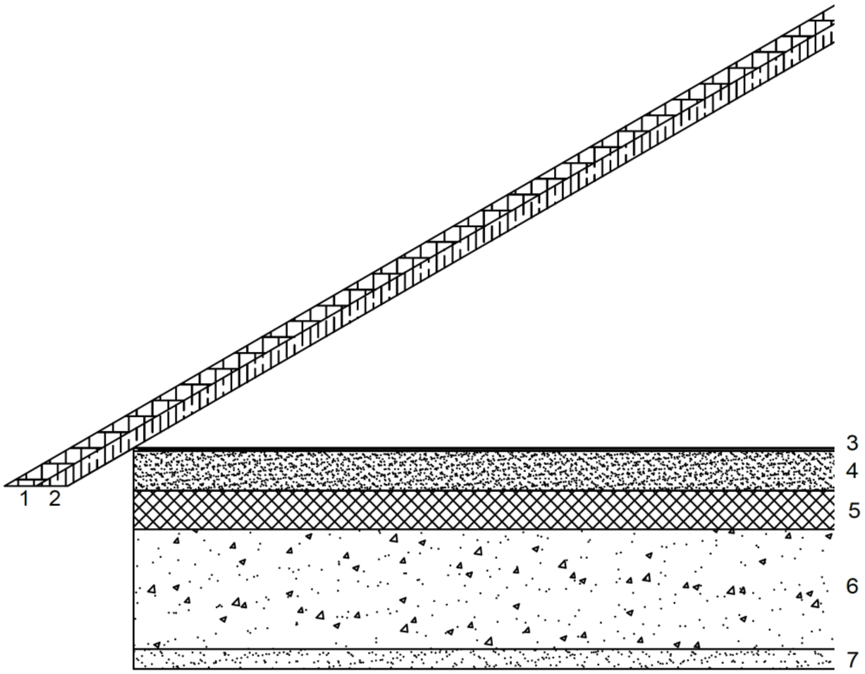

Figure 4.9 Typical topology detail of an insulated horizontal concrete and inclined clay tile roof

An example of a U-value calculation for this type of roof is presented below using Eq. 4.1 for the case where the wall is insulated with 0.04m expanded polystyrene. Specifically, the calculation is performed by applying the data for each material shown in Table 4.11 in Eq. 4.1.

Table 4.11 Data required for the calculation of the U-value of an insulated horizontal concrete and inclined clay tile roof with 0.02m of expanded polystyrene

Nº of layer	Material (internal to external)	Material thickness (m)	Thermal conductivity (W/mK)
1	Bitumen hydro insulation layer	0.004	0.19
2	Screed	0.05	1.35
3	Expanded polystyrene	0.04	0.04
4	Reinforced concrete (2% steel)	0.15	2.5
5	Portland cement plaster	0.025	1.39
Heat flow direction		Vertical	
Rsi (m^2K/W)		0.100	
Rse (m^2K/W)		0.040	

$$Uvalue = \frac{1}{R_{si} + \sum \frac{d_i}{\lambda_i} + R_{se}}$$

$$\rightarrow Uvalue = \frac{1}{0.10 + \frac{0.004}{0.19} + \frac{0.05}{1.35} + \frac{0.04}{0.04} + \frac{0.15}{2.5} + \frac{0.025}{1.39} + 0.06 + 0.04}$$

$$\rightarrow Uvalue = \frac{1}{0.10 + 0.021 + 0.037 + 1 + 0.06 + 0.018 + 0.06 + 0.04}$$

$$\rightarrow Uvalue = \frac{1}{1.336} \rightarrow Uvalue = \mathbf{0.748}\, W/m^2K$$

The results of the calculation for this type of roof together with the total additional cost per m^2 of roof area are presented in Table 4.12.

Table 4.12 U-values and total additional cost of an insulated horizontal concrete roof with inclined clay tile roof

Insulation thickness (m)	Overall U- Value for combined roof (W/m^2K)	Total additional cost (€/m^2)
Expanded polystyrene		
0.04	0.748	17.8
0.05	0.630	18.5
Extruded polystyrene		
0.03 *(0.029 W/mK)*	0.730	19.2
0.04 *(0.035 W/mK)*	0.676	19.8
0.04 *(0.029 W/mK)*	0.583	20.6
0.05 *(0.035 W/mK)*	0.567	21
0.05 *(0.029 W/mK)*	0.485	21.8
Stone wool		
0.04	0.615	18.4
0.05	0.567	19.2

4.3 SUMMARY

The results presented in this Chapter provide details of 42 wall topologies and 27 roof topologies which give 1,203 topology combinations. Due to their very large number these are evaluated in Chapter 5 using a simpler method to determine the most appropriate for further evaluation in Chapter 6.

CHAPTER 5

PRELIMINARY EVALUATION OF THE TOPOLOGIES FOR APPLYING THERMAL INSULATION MATERIALS

Due to the large number of insulation materials and topology combinations these were initially evaluated in this Chapter using a simple method instead of the detailed simulation conducted and presented in Chapter 6. The software used for the preliminary evaluation is SBEM-Cy which is the dedicated software for the calculation of the energy performance of buildings approved by the Energy Service of Cyprus (MCIT, 2009). The results were evaluated using the Simple Payback Period (SPBP) method in order to select the optimum topologies in terms of energy savings, cost, and benefit to be modelled in detail subsequently.

5.1 SIMPLIFIED BUILDING ENERGY MODEL (SBEM-CY) SOFTWARE

Article 3 of the Energy Performance of Buildings Directive (EPBD) 2002/91/EC of the European Parliament and Council requires that all EU Member States develop a methodology of calculation of the integrated energy performance of buildings, Methodology for Assessing the Energy Performance of Buildings (MCIT, 2009).

In response to this, the Energy Service of the Ministry of Commerce, Industry and Tourism (MCIT) of Cyprus commissioned BRE/Infotrend to develop a calculation tool in compliance with the requirements of the Directive. BRE/Infotrend developed SBEMcy (Simplified Building Energy Model) to be the default calculation tool for domestic and non-domestic buildings in Cyprus to enable energy ratings to be carried out on a consistent basis.

This calculation tool comprises several modules as follows:

- SBEM, the core calculation engine
- iSBEM, an interface based on Microsoft Access®
- Standardised databases and report format

SBEM-CY, iSBEM-CY and the associated databases and files can be applied to both domestic and non-domestic buildings. The software is available free of cost via the MCIT website.

5.2 CALCULATION OVERVIEW AS IMPLEMENTED IN SBEM-CY

SBEMcy requires a number of inputs to be defined by the software user via the iSBEM interface. Also, several other inputs are taken from various built-in databases of the software.

In general the user interacts with the interface module, iSBEM, and sets up a model of the building by describing its size, the way it is constructed and used, and how it is serviced (HVAC, domestic hot water and lighting system). More specifically, the inputs required are the following: the location, orientation and geometry of the building (physical configuration of the different areas of the building); the separation of the building into different activity zones; the internal conditions of each activity zone; the areas and construction of the building components of each activity area; the heating, cooling, lighting and other building services systems and the activity areas they serve.

After the calculations are performed, the results and output reports become accessible through the interface. When the user inserts the necessary inputs into the system the following actions are performed by the SBEM calculation tool:

1. Calculates lighting energy requirements taking into account the glazing area, shading, light source, and lighting control systems.
2. Establishes the standardised heat and moisture gains in each activity area, from the database.
3. Calculates the heat energy flows of each activity area with the outside environment using CEN standard algorithms.
4. Applies appropriate HVAC system efficiencies to determine the delivered energy requirements to maintain thermal conditions.
5. Aggregates the delivered energy by source, and converts it into primary energy.
6. Determines, on the same basis, the primary energy of a reference building which has the same geometry, usage pattern, heat gains, temperature, lighting, ventilation conditions and weather but building component construction, HVAC and lighting systems specified by MCIT.

7. Based on the primary energy the carbon emissions rate are estimated for both the building being evaluated and those of the reference building.

Results produced by SBEMcy can be produced for diagnostic checks on the proposed building and include:

- Monthly profiles of energy expenditure by each end use activity and fuel type.
- Total electricity and fossil fuel use, and resulting carbon emissions.

5.3 INPUT DATA AND METHODOLOGY

5.3.1 Input data

The model house used for the simulations is the one defined in Chapter 3. This house was chosen from the examined statistical sample due to its characteristics which can be used to describe it as a typical dwelling of Cyprus. The model house is a single storey detached house located in Nicosia (Zone 2 - Low mainland area) with a total floor area of 133 m^2. The house is occupied by a four person family. The house consists of three bedrooms, a kitchen, a living room, a bathroom, and a dining room. It does not incorporate thermal insulation installed on its envelope (external walls and roof). For the production of DHW a solar water heating system is used while the heating and cooling energy demands are served by split type air-conditioning units. The windows of the house are double-glazed with aluminium frame without thermal break; the main entrance door is made of solid wood while the kitchen door is made of aluminium and glass. The floor is in contact with the ground and consists of concrete, screed and marble. A 3D plot of the model house is depicted in Figure 5.1.

As described in section 5.2 SBEMcy requires a number of inputs to be defined by the user via the iSBEM interface. Some of the main inputs such as the activity zones, the heating, ventilation and air conditioning (HVAC) and lighting system serving each activity zone are listed in Table 5.1. As it can be seen the dwelling is separated into seven different activity zones according to the usage of each space, the HVAC system serving the space, and the lighting systems used.

Figure 5.1 3D plot of the typical dwelling.

Table 5.1Activity zones, HVAC system and lighting

Activity zones	Description	HVAC system	Lighting
Zone 1	Kitchen	Split type AC unit	Fluorescent
Zone 2	Dining room	Split type AC unit	Compact fluorescent
Zone 3	Circulation area	- No HVAC -	Compact fluorescent
Zone 4	Bedroom	Split type AC unit	Compact fluorescent
Zone 5	Bathroom	- No HVAC -	Fluorescent
Zone 6	Bedroom	Split type AC unit	Compact fluorescent
Zone 7	Bedroom	Split type AC unit	Compact fluorescent

The U-values of the structural elements of the model dwelling are presented in Table 5.2.

Table 5.2 U-values of the structural elements of the model dwelling

Structural element	**U-value (W/m^{2}K)**
External walls	1.416
Windows	3.889
Main entrance door	2.92
Roof	1.527
Floor	0.753
Internal wall	1.786

5.3.2 Methodology for the analysis of the results

At first the typical model dwelling is created into the software as presented in the previous section. Once all necessary inputs and parameters are inserted into the software the results are calculated. The results are in the form of energy consumption (end-use energy) per square meter of floor area per year (kWh/m^2/yr).

Subsequently, by changing the construction details and material properties of various elements like the wall, roof or both, the energy expenditure for each topology examined is calculated. Then the difference between the energy use of each topology to that of the typical model dwelling determines the effectiveness of each change in the construction detail.

Then, the economic benefit of each modification is determined by assuming a lifetime for the building of 30 years (CYS EN 15459, 2007) and a cost of electricity of 0.1461 €/kWh$_e$ which is the current price of electricity in Cyprus (EAC, 2013). The Simple Payback Period (SPBP) method is used for the calculations.

The initial results of the simulation procedure were focused on the energy saving achieved by each topology combination and comprised of 1,203 cases (42 wall topologies, 27 roof topologies and 1,134 combinations). In the sections below only the most important results are presented. It should be noted that these are separated for application in new and existing dwellings. In the case of an existing dwelling the main differences compared to a new one rely on the fact that several thermal insulation materials and topologies (i.e. double wall with insulation in-between with and without air gap) cannot be applied as this will require the complete reconstruction of the building element. Furthermore, the cost of the available solutions also differs due to the fact that in this case the cost concerns the entire cost for purchasing and applying each material while in the case of the new dwelling the cost is calculated for each topology as the additional cost compared to a typical topology without insulation.

5.4 CASE I: NEW DWELLING (ND)

5.4.1 Cost of the examined topology combinations

The topology combinations with the highest cost are those which combine the application of external insulation on the walls and extruded polystyrene on the roof. As it can be seen in Table 5.3 the highest cost is almost the same for the three combinations presented (~5,500 €). On the contrary the topology combinations with the lowest cost are those combining thermal insulation plaster or thermal insulation bricks on the walls with expanded polystyrene or stone wool on the roof (Tables 5.4).

Table 5.3 Highest cost topology combinations (ND)

Wall Topology	**Roof topology**	**Total Cost (€)**	**Cost per floor area (€/m^2)**
External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^{2}K)*	All types of roof with Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.505 W/m^{2}K)*	5,572	42.04
External Insulation Extruded polystyrene 0.05 m (0.035 W/mK) *(Uvalue = 0.468 W/m^{2}K)*	All types of roof with Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.505 W/m^{2}K)*	5,465	41.24
External Insulation Extruded polystyrene 0.04 m (0.029 W/mK) *(Uvalue = 0.480 W/m^{2}K)*	All types of roof with Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.505 W/m^{2}K)*	5,405	40.79

Table 5.4 Lowest cost topology combinations (ND)

Wall Topology	**Roof topology**	**Total Cost (€)**	**Cost per floor area (€/m^2)**
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^{2}K)*	All types of roof with Expanded Polystyrene 0.04 m *(Uvalue = 0.795 W/m^{2}K)*	469	3.61
Thermal Insulation Bricks 0.20 m *(Uvalue = 0.759 W/m^{2}K)*	All types of roof with Expanded Polystyrene 0.04 m *(Uvalue = 0.795 W/m^{2}K)*	827	6.36
Thermal Insulation Plaster 0.03 m *(Uvalue = 0.779 W/m^{2}K)*	All types of roof with Stone wool 0.04 m *(Uvalue = 0.714 W/m^{2}K)*	838	6.55

5.4.2 Energy Savings

The energy consumption (end-use energy) of the ‘base case’ (without thermal insulation installed either on the external walls or the roof) is 604kWh/m^2/yr. The highest energy savings are around 155kWh/m^2/yr or 20,654kWh/yr and are achieved by the topology combinations shown in Table 5.5.

Table 5.5 Highest energy savings topology combinations (ND)

Wall Topology	**Roof topology**	**Energy Savings (kWh/m^2/yr)**	**Total Energy Savings (kWh/yr)**
Double wall with insulation in-between with air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.383 W/m^{2}K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^{2}K)*	156	20,851
Double wall with insulation in-between with air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.383 W/m^{2}K)*	HCR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.505 W/m^{2}K)*	154	20,654
External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^{2}K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^{2}K)*	154	20,576
Double wall with insulation in-between without air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^{2}K)*			

The range of energy savings for the various topology combinations analysed per type of wall topology is summarised as follows:

- External insulation: 100 to 154 kWh/ m^2/ yr
- Double wall with insulation in-between without air gap: 100 to 154 kWh/ m^2/ yr
- Double wall with insulation in-between with air gap: 107 to 156 kWh/ m^2/ yr
- Thermal Insulation Bricks: 105 to 142 kWh/ m^2/ yr
- Thermal Insulation Plaster: 99 to 140 kWh/ m^2/ yr

5.4.3 Economic benefit

The economic benefit resulting is investigated in terms of money saving per year (€/ yr) and per 30 years period (€/ 30 yrs). As it can be seen in Table 5.6 the highest economic benefit achieved by the examined topology combinations is around 2,750 €/ yr or 82,500 €/ 30yrs.

Table 5.6 Highest economic benefit topology combinations (ND)

Wall Topology	**Roof topology**	**Economic benefit (€/ yr)**	**Economic benefit (€/ 30 yrs)**
Double wall with insulation in-between with air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.383 W/m^{2}K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^{2}K)*	2,774	83,209
Double wall with insulation in-between with air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.383 W/m^{2}K)*	HCR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.505 W/m^{2}K)*	2,747	82,423
External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^{2}K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^{2}K)*	2,737	82,107
Double wall with insulation in-between without air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^{2}K)*			

The economic benefit range of each topology combinations analysed per type of wall topology is summarised as follows:

- External insulation: 1,790 to 2,737 €/ yr (53,692 to 82,107 €/ 30 yrs)
- Double wall with insulation in-between without air gap: 1,790 to 2,737 €/ yr (53,692 to 82,107 €/ 30 yrs)
- Double wall with insulation in-between with air gap: 1,900 to 2,774 €/ yr (56,986 to 83,209€/ 30 yrs)
- Thermal Insulation Bricks:1,880 to 2,539 €/ yr (56,403 to 76,156 €/ 30 yrs)
- Thermal Insulation Plaster: 1,772 to 2,495 €/ yr (53,146 to 74,851 €/ 30 yrs)

5.4.4 Simple Payback Period (SPBP)

Due to the fact that the main aim of the results presented in this Chapter is the evaluation of the topology combinations to define the optimum only to be investigated in detail subsequently in the next Chapter, the method of SPBP is chosen. Thus, monetary terms such as the future value of money, the internal rate of return and discount rate are not taken into consideration here.

The lowest SPBP according to the results is 0.4 years and is achieved by the topology combinations with thermal insulation plaster of various widths (0.025-0.03m) or thermal insulation bricks (0.20m) on the walls as presented in Table 5.7. The roof topologies that achieve the lowest SPBP concern the use of expanded polystyrene and stone wool in all roofs topologies.

Table 5.7 Lowest SPBP topology combinations (ND)

Wall Topology	**Roof topology**	**SPBP (yrs)**
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.748 W/m^{2}K)*	0.4
Thermal Insulation Bricks 0.20 m *(Uvalue = 0.759 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.04 m & 0.05 m *(Uvalue = 0.748 W/m^{2}K and 0.630 W/m^{2}K)*	
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^{2}K)*	HCR Expanded polystyrene 0.04 m *(Uvalue = 0.795 W/m^{2}K)*	
	ITR & HCITR Expanded polystyrene 0.05 m *(Uvalue = 0.630 W/m^{2}K)*	
	ITR & HCITR Stone wool 0.04 m *(Uvalue = 0.676 W/m^{2}K)*	
Thermal Insulation Bricks 0.20 m *(Uvalue = 0.759 W/m^{2}K)*	HCR Expanded polystyrene 0.04 m & 0.05 m *(Uvalue = 0.795 W/m^{2}K and 0.664 W/m^{2}K)*	
	ITR & HCITR Stone wool 0.04 m *(Uvalue = 0.676 W/m^{2}K)*	
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^{2}K)*	HCR Expanded polystyrene 0.05 m *(Uvalue = 0.664 W/m^{2}K)*	
Thermal Insulation Plaster 0.03 m *(Uvalue = 0.779 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.664 W/m^{2}K)*	

5.4.5 Benefit-Cost Ratio (BCR)

The Benefit-Cost Ratio (BCR) is an indicator attempting to identify the relationship between the benefits and costs of a proposed project, measure or investment. Both benefits and costs are expressed in monetary terms. BCR is most often used in corporate finance to detail the relationship between possible benefits and costs of undertaking new projects or replacing old ones. In this project BCR is used in order to give a more comprehensive view of each topology combination by identifying the relationship between the economic benefits over the lifetime of the materials (30 years) and their initial cost.

The equation for calculating BCR is:

$$BCR = \frac{EB_{30\ years}}{CTC} \tag{5.1}$$

Where,

$EB_{30years}$: is the economic benefit of the investment after a period of 30 years

CTC: is the current total cost of the investment

The highest and lowest BCR achieved by topology combinations are illustrated in Tables 5.8 and 5.9 respectively.

Table 5.8 Highest BCR topology combinations (ND)

Wall Topology	**Roof topology**	**BCR**
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m²K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.748 W/m²K)*	71.6
Thermal Insulation Bricks 0.20 m *(Uvalue = 0.759 W/m²K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.748 W/m²K)*	70.5
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m²K)*	ITR & HCITR Expanded polystyrene 0.05 m *(Uvalue = 0.630 W/m²K)*	69.9
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m²K)*	ITR & HCITR Expanded polystyrene 0.05 m *(Uvalue = 0.630 W/m²K)*	69.8
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m²K)*	HCR Expanded polystyrene 0.04 m *(Uvalue = 0.795 W/m²K)*	69.1

As expected the wall topologies that achieve the highest BCR, which is around 70, are those of thermal insulation plaster of various widths (0.025-0.03m) and thermal insulation bricks of 0.20m width due to their very low initial cost compared to the very high economic benefit achieved over their lifetime. In general, higher BCR means better investment and thus these combinations are much more attractive for application.

Table 5.9 Lowest BCR topology combinations (ND)

Wall Topology	Roof topology	BCR
External Insulation Expanded polystyrene 0.02 m *(Uvalue = 0.829 W/m^{2}K)*	HCR Extruded polystyrene 0.03 m *(Uvalue = 0.774 W/m^{2}K)*	12
External Insulation Expanded polystyrene 0.02 m *(Uvalue = 0.829 W/m^{2}K)*	HCR Expanded polystyrene 0.04 m *(Uvalue = 0.795 W/m^{2}K)*	12.3
External Insulation Expanded polystyrene 0.02 m *(Uvalue = 0.829 W/m^{2}K)*	HCR Extruded polystyrene 0.04 m *(Uvalue = 0.714 W/m^{2}K)*	

The lowest BCR is a result of the wall topologies which have external insulation (expanded polystyrene of 0.02m width) installed due to their high initial cost.

The BCR range of topology combinations analysed per type of wall topology is summarised as follows:

- External insulation: 12.3 to 15
- Double wall with insulation in-between without air gap: 24 to 28.1
- Double wall with insulation in-between with air gap: 18.7 to 22
- Thermal Insulation Bricks: 33.1 to 70.5
- Thermal Insulation Plaster: 42.7 to 71.6

5.5 CASE II: EXISTING DWELLING (ED)

In this section the wall topologies investigated are those that are applicable for an ED namely external insulation and thermal insulation plaster while in the case of roof topologies the results are the same as in the case of the new dwelling since nothing has changed and are not presented here.

5.5.1 Cost of the examined topology combinations

The topology combinations with the highest cost are those combining external insulation on the walls and extruded polystyrene on the roof (Table 5.3). Meanwhile, the lowest cost which is ~2,800€ corresponds to the combination of thermal insulation plaster on the walls with expanded polystyrene or stone wool on the roof as illustrated in Table 5.10.

Table 5.10 Lowest cost topology combinations (ED)

Wall Topology	**Roof topology**	**Total Cost (€)**	**Cost per m^2 (€/m^2)**
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^2K)*	All types of roof with Expanded Polystyrene 0.04 m *(HCR: Uvalue = 0.795 W/m^2K ITR & HCITR: Uvalue = 0.748 W/m^2K)*	2,779	20.93
Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^2K)*	All types of roof with Stone wool 0.04 m *(HCR: Uvalue = 0.714 W/m^2K ITR & HCITR: Uvalue = 0.676 W/m^2K)*	2,848	21.48
Thermal Insulation Plaster 0.03 m *(Uvalue = 0.779 W/m^2K)*	All types of roof with Expanded Polystyrene 0.04 m *(HCR: Uvalue = 0.795 W/m^2K ITR & HCITR: Uvalue = 0.748 W/m^2K)*	2,863	21.55

5.5.2 Energy Saving

The highest energy savings are ~152 kWh/m^2/yr or ~20,380 kWh/yr and are achieved by the topology combinations having external insulation on the walls as shown in Table 5.11.

Table 5.11 Highest energy savings topology combinations (ED)

Wall Topology	Roof topology	Energy Saving (kWh/ m^2/ yr)	Total Energy Saving (kWh/ yr)
External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^2K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^2K)*	154	20,482
External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^2K)*	HCR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.505 W/m^2K)*	152	20,216
External Insulation Extruded polystyrene 0.05 m (0.035 W/mK) *(Uvalue = 0.468 W/m^2K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^2K)*	150	19,950

The energy saving range of topology combinations analysed per type of wall topology is summarised as follows:

- External insulation: 100 to 154 kWh/ m^2/ yr
- Thermal Insulation Plaster: 99 to 140 kWh/ m^2/ yr

5.5.3 Economic benefit

The highest economic benefit in the case of the ED is ~2,700 €/ yr or 81,500 €/ 30 yrs and is achieved by the topology combinations implementing external insulation (0.05m of extruded polystyrene) on the walls and 0.05m of extruded polystyrene on the roof (Table 5.12).

Table 5.12 Highest economic benefit topology combinations (ED)

Wall Topology	Roof topology	Economic benefit (€/ yr)	Economic benefit (€/ 30 yrs)
External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^2K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^2K)*	2,737	82,107
External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^2K)*	HCR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.505 W/m^2K)*	2,711	81,321
External Insulation Extruded polystyrene 0.05 m (0.035 W/mK) *(Uvalue = 0.468 W/m^2K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^2K)*	2,666	79,979

The economic benefit range of topology combinations analysed per type of wall topologies is summarised as follows:

- External insulation: 1,790 to 2,737 €/ yr (53,692 to 82,107 €/ 30 yrs)
- Thermal Insulation Plaster: 1,772 to 2,495 €/ yr (53,146 to 74,851 €/ 30 yrs)

5.5.4 Simple Payback Period (SPBP)

It should be noted that in the case of an ED the SPBP is higher (1.4 years instead of 0.4 years) from that of the ND since the initial cost of each intervention is higher (Table 5.13).

Table 5.13 Lowest SPBP topology combinations (ED)

Wall Topology	**Roof topology**	**SPBP (yrs)**
Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	ITR & HCITR Stone wool 0.05 m *(Uvalue = 0.567 W/m^{2}K)*	1.4
Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.05 m *(Uvalue = 0.630 W/m^{2}K)*	
Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	HCR Stone wool 0.05 m *(Uvalue = 0.593 W/m^{2}K)*	
Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	HCR Expanded polystyrene 0.05 m *(Uvalue = 0.664 W/m^{2}K)*	
	ITR & HCITR Stone wool 0.04 m *(Uvalue = 0.676 W/m^{2}K)*	
Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	ITR & HCITR Stone wool 0.05 m *(Uvalue = 0.567 W/m^{2}K)*	
Thermal Insulation Plaster 0.03 m *(Uvalue = 0.779 W/m^{2}K)*		

From the results presented in Table 5.13 it can be observed that the topology combinations that achieve the lowest SPBPs, as expected, are thermal insulation plaster of larger width than that of the new dwelling (0.035-0.05 m instead of 0.025-0.03 m) combined with expanded polystyrene or stone wool in all three roof topologies.

5.5.5 Benefit-Cost Ratio (BCR)

The BCR in the case of the existing dwelling is much lower than that of the new dwelling (22 instead of 70) since the initial cost of the insulation materials and topologies is significantly higher.

The highest and lowest BCR achieved by topology combinations are presented in Tables 5.14 and 5.15 respectively.

Table 5.14 Highest BCR topology combinations (ED)

Wall Topology	Roof topology	BCR
Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	ITR & HCITR Stone wool 0.05 m *(Uvalue = 0.567 W/m^{2}K)*	22
	ITR & HCITR Expanded polystyrene 0.05 m *(Uvalue = 0.630 W/m^{2}K)*	21.9
	ITR & HCITR Stone wool 0.05 m *(Uvalue = 0.567 W/m^{2}K)*	21.7
	ITR & HCITR Expanded polystyrene 0.05 m *(Uvalue = 0.630 W/m^{2}K)*	21.4
	ITR & HCITR Stone wool 0.04 m *(Uvalue = 0.676 W/m^{2}K)*	

Table 5.15 Lowest BCR topology combinations (ED)

Wall Topology	Roof topology	BCR
External Insulation Expanded polystyrene 0.02 m *(Uvalue = 0.829 W/m^{2}K)*	HCR Extruded polystyrene 0.03 m *(Uvalue = 0.774 W/m^{2}K)*	12
	HCR Expanded polystyrene 0.04 m *(Uvalue = 0.795 W/m^{2}K)*	12.3
	ITR & HCITR Extruded polystyrene 0.04 m (0.029 W/mK) *(Uvalue = 0.583 W/m^{2}K)*	

The BCR range of topology combinations analysed per type of wall topologies is summarised as follows:

- External insulation: 12 to 15
- Thermal Insulation Plaster: 18.3 to 22

From the results presented in Table 5.15 it can be concluded that in the case of an existing dwelling the optimum thermal insulation material to be applied to the wall topology is that of thermal insulation plaster of 0.035 m width.

5.6 SUMMARY - OPTIMUM TOPOLOGIES

By carefully analysing the results of the previous sections it is decided that the criteria for choosing the optimum topology combinations to be further analysed are the highest economic benefit and the highest BCR. The reason for this is because the highest economic benefit defines the most profitable investment and the highest BCR indicates which investment is more efficient in terms of the initial cost and the total economic benefit. This applies for the case of both new and existing dwellings. Thus, the optimum topology combinations are presented in Figure 5.2 and Table 5.16.

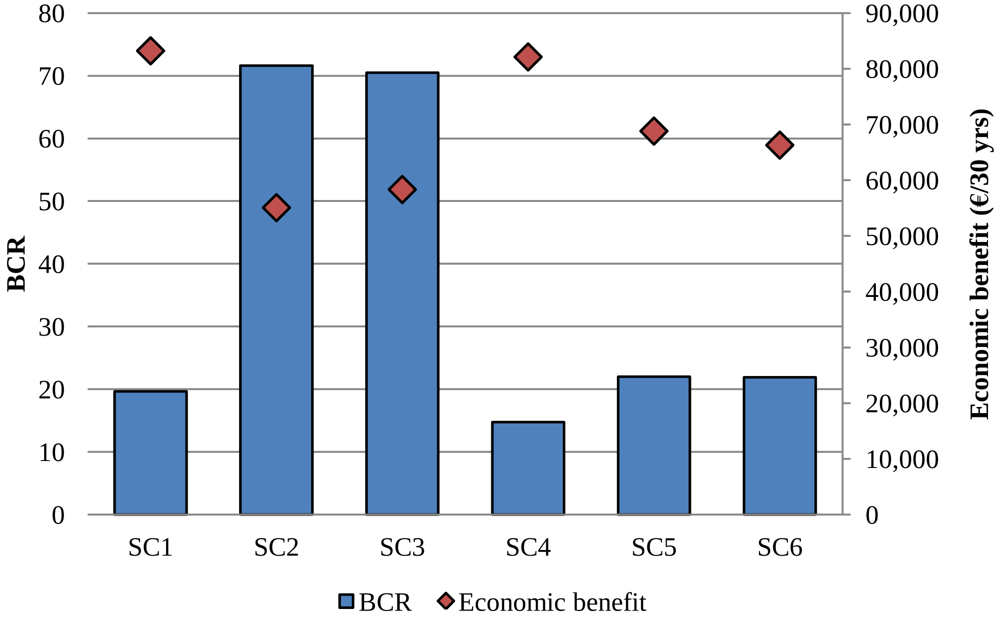

Figure 5.2 Graphical representation of the BCR and the economic benefit of the optimum topology combinations.

Table 5.16 Optimum topology combinations to be modelled and evaluated further in the next chapter

Nº	Wall Topology	Roof topology	Criterion
New Dwelling			
1	Double wall with insulation in-between <u>with</u> air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.383 W/m^2K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^2K)*	Highest Economic Benefit
2	Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^2K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.748 W/m^2K)*	Highest BCR
3	Thermal Insulation Bricks 0.20 m *(Uvalue = 0.759 W/m^2K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.748 W/m^2K)*	Highest BCR
Existing Dwelling			
4	External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^2K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^2K)*	Highest Economic Benefit
5	Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^2K)*	ITR & HCITR Stone wool 0.05 m *(Uvalue = 0.567 W/m^2K)*	Highest BCR
6	Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^2K)*	ITR & HCITR Expanded polystyrene 0.05 m *(Uvalue = 0.630 W/m^2K)*	Highest BCR

CHAPTER 6

DETAILED SIMULATION AND EVALUATION OF THE OPTIMUM THERMAL INSULATION TOPOLOGY COMBINATIONS

In this Chapter the typical dwelling, previously defined in Chapter 3, is modelled in detail using the TRaNsient SYstem Simulation (TRNSYS) software environment. The optimum topologies defined in Chapter 5 were applied to the typical dwelling and simulated. Two types of simulations were carried out namely: temperature control where the heating and cooling system is assumed to maintain the indoor temperature at the control set-point, and free floating building where the temperature is not controlled by a mechanical system and is allowed to vary in response to variation in external and internal gains/losses. The results are evaluated using the Life Cycle Cost (LCC).

6.1 DETAILED MODEL DESIGN

The model design process was carried out using TRNSYS. The detailed model of the typical dwelling is depicted in Figure 6.1 and consists of the following components:

- Type 109 - TMY2 (weather data processing model)
- Type 33 - Psychrometrics
- Type 69 - Effective sky temperature for long-wave radiation exchange
- Type 2 - ON/OFF Differential controller
- Type 65 - Online graphical plotter
- Type 25 - Printer - TRNSYS-supplied units printed to output file
- Type 56 - Multi-Zone Building

The model of each component listed above is analytically presented according to TRNSYS 16 - Standard Component Library Overview (Solar Energy Laboratory, 2006).

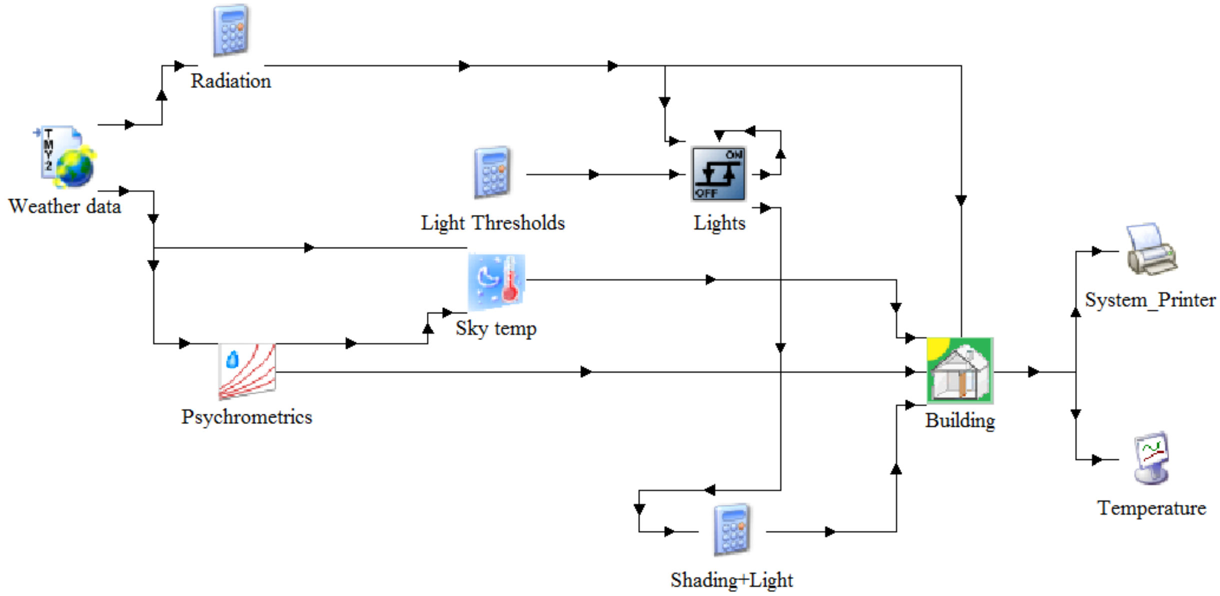

Figure 6.1 Configuration of the complete model of the typical dwelling

- **TMY-2 model – Type 109**

Type 109 model reads the Typical Meteorological Year (TMY-2) type 2 for Nicosia, Cyprus and generates the weather data at the orientations needed by other components, such as the multi-zone building. Specifically, this model provides all weather related data required by other models which include ambient temperature, relative humidity, total radiation on both horizontal and inclined surfaces, beam radiation on both horizontal and inclined surfaces, diffuse radiation on horizontal surfaces and angle of incidence for both horizontal and inclined surfaces. The TMY-2 used for the simulation process was developed by Kalogirou (2003).

- **Type 33 - Psychrometrics**

This component is used to give several moist air properties corresponding to a dry bulb temperature and relative humidity of moist air. This is done by the TRNSYS Psychrometrics routine. The outputs of this type are the following: dry bulb temperature, dew point temperature, wet bulb temperature, relative humidity, absolute humidity ratio, and enthalpy.

- **Type 69 - Effective sky temperature for long-wave radiation exchange**

This component is employed to determine an effective sky temperature, which is subsequently used to calculate the long-wave radiation exchange between an arbITRary external surface and the atmosphere.

- **Type 2 - ON/OFF Differential Controller**

This component is a simple on/off differential controller which generates a control function having a value of either 1 or 0. In the case of the model examined, this controller is used to control the lighting system of the dwelling. Specifically, this controller receives the total radiation on a horizontal surface value as an input and according to the light thresholds in return it turns the lights ON or OFF.

- **Type 65 - Online graphical plotter**

This component is used to graphically display several selected system variables while the simulation is running. The selected variables are displayed in a separate plot window on the screen which can be modified in such a way as to present the selected variables in the best possible way.

- **Type 25 - Printer - TRNSYS-supplied units printed to output file**

The printer component is used to output selected system variables at specified intervals of time.

- **Type 56 - Multi-Zone Building**

The material presented in this subsection is based on TRNSYS 16 - Multizone Building modelling with Type56 and TRNBuild (Solar Energy Laboratory, 2005). This component models the thermal behaviour of a building having up to 25 different thermal zones.

TRNBuild is used to provide the necessary data files to be used in Type 56 - Multi-Zone Building component. Initially, the user creates a file using the interactive interface TRNBuild describing the building. The user defines simple building blocks, called Types, which are used to describe the building. Types represent unique descriptions that can be used many times to either define other Types or to construct the building. For instance, a layer Type represents a material description of an individual wall layer. Several layer Types may be used to define a unique wall Type, which in turn may be used in the description of the building. Other necessary Types include windows, orientations, gains, comfort, infiltration, ventilation, heating, and cooling and zone definition. Each of these Types is characterized by a name that is assigned to it and its associated data. Inputs might be used to consider gains from heating or cooling equipment whose performance depends upon the conditions of the zones. After the definition of all parameters the completed building description file is converted by TRNBuild into suitable files required by Type 56.

6.2 INPUT DATA AND METHODOLOGY

6.2.1 Input data

The main input data necessary for the modelling of the typical dwelling are required by Type 109 (TMY-2 model) and Type 56 (Multi-Zone Building). Specifically, Type 109 requires the definition of the Typical Meteorological Year (TMY2) for the location of the dwelling (Nicosia, Cyprus) while Type 56 requires the definition of the structure of the dwelling and the systems serving the dwelling (heating, cooling, lighting etc).

The structure of the typical dwelling and the separation into several different activity zones used as inputs in the detailed simulation are the same as the ones used in Chapter 5 and may not be repeated again.

In the model used for the detailed simulation in this Chapter many of the variables in each activity zone vary with time. Specifically, these variables are the heat gains due to the presence of occupants, the occupant activity, the state of function (ON/OFF) of the lighting system and of the electrical appliances (i.e. PC, printers, refrigeration, TV etc.). Thus, in order to realistically represent the variation of each of these variables through time, periodic functions are defined with five different schedules shown in Figures 6.2-6.6. In these the y-axis represents the number of the unit concerned in each case (people or devices) and the x-axis the time of the day.

The use of a heating or cooling system in each zone together with the consequent set temperature is also defined. At the beginning of the simulation the initial temperature and relative humidity of the air in the dwelling are 20^{o}C and 50% respectively.

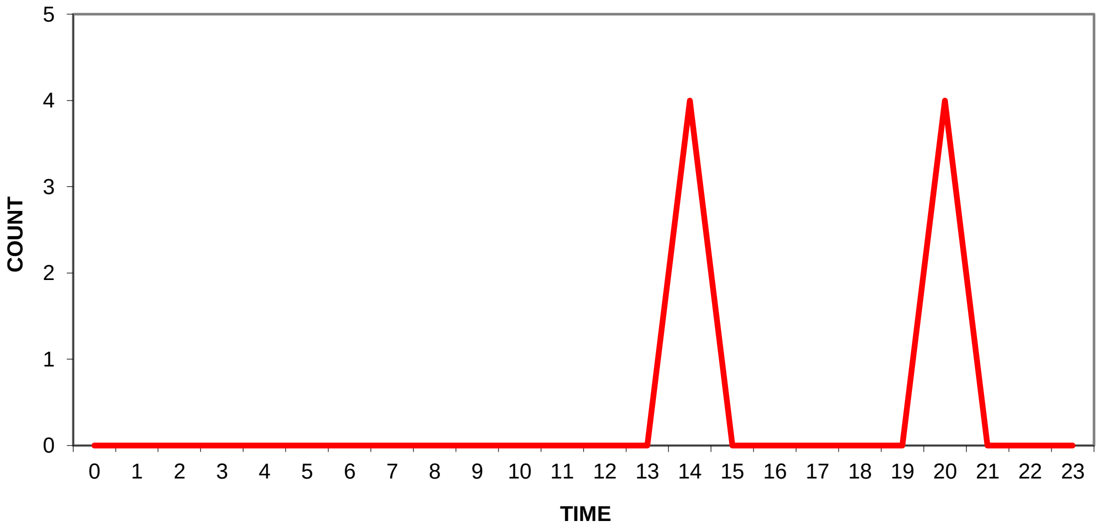

Figure 6.2 Periodic function 1 (SCHED001)

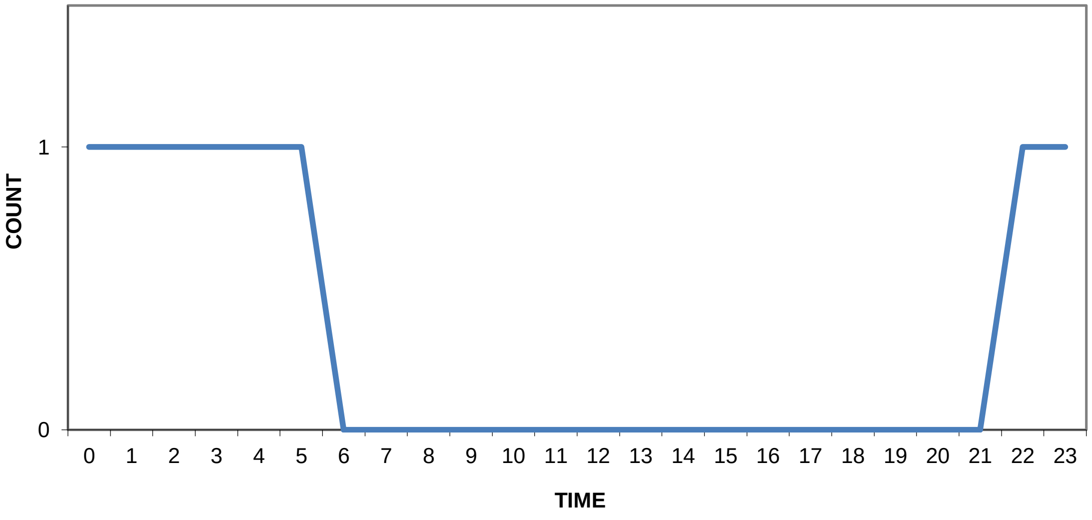

Figure 6.3 Periodic function 2 (SCHED002)

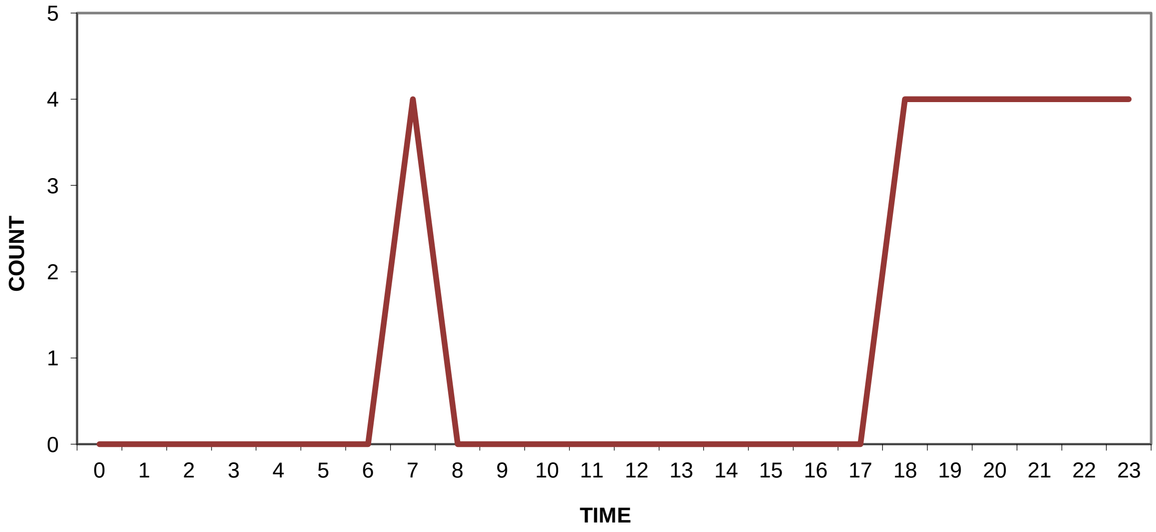

Figure 6.4 Periodic function 3 (SCHED003)

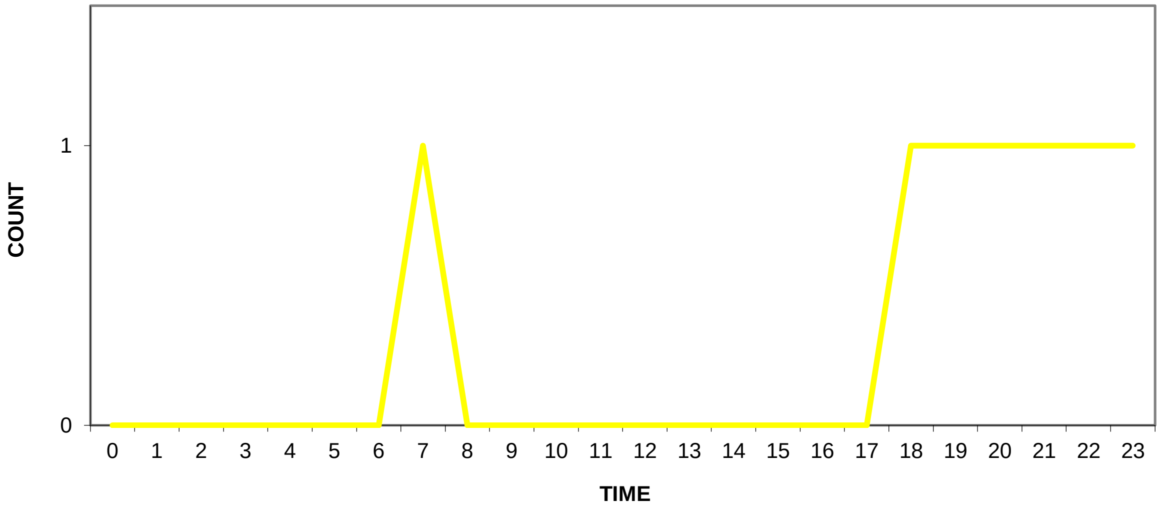

Figure 6.5 Periodic function 4 (SCHED004)

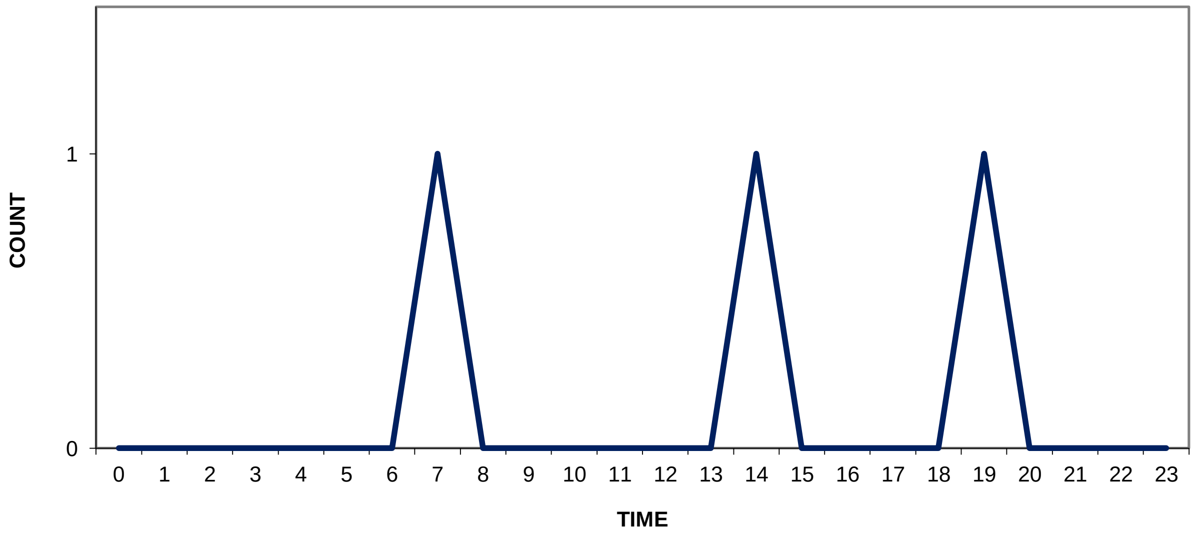

Figure 6.6 Periodic function 5 (SCHED005)

Accordingly, the heat gains of each activity zone are presented in Tables 6.1-6.7 below. It should be noted that the heat gain due to the degree of activity of the occupants was taken from ISO 7730 (2005).

Table 6.1 Heat gains of Zone 1 (Kitchen)

• **Persons**				
Degree of activity	Sensible heat per person (W)	Latent heat per person (W)	Total heat gain per person (W)	Usage Pattern
Seated, eating	75	95	170	SCHED001

• **Lighting**		
Heat gain (W/m^2)	Related floor area (m^2)	Usage Pattern
5	18	SCHED003

Table 6.2 Heat gains of Zone 2 (Dining room)

- **Persons**

Degree of activity	Sensible heat per person (W)	Latent heat per person (W)	Total heat gain per person (W)	Usage Pattern
Seated at rest	60	40	100	SCHED001

- **Lighting**

Heat gain (W/m^2)	Related floor area (m^2)	Usage Pattern
5	35.81	SCHED003

Table 6.3 Heat gains of Zone 3 (Circulation area)

- **Persons**

Degree of activity	Sensible heat per person (W)	Latent heat per person (W)	Total heat gain per person (W)	Usage Pattern
Standing, light work or working slowly	90	95	185	SCHED004

- **Lighting**

Heat gain (W/m^2)	Related floor area (m^2)	Usage Pattern
5	12.89	SCHED004

Table 6.4 Heat gains of Zone 4 (Bedroom)

- **Persons**

Degree of activity	Sensible heat per person (W)	Latent heat per person (W)	Total heat gain per person (W)	Usage Pattern
Seated at rest	60	40	100	SCHED002

- **Lighting**

Heat gain (W/m^2)	Related floor area (m^2)	Usage Pattern
5	24	SCHED002

- **Electronic appliances**

Type of appliance	Number of appliances	Heat gain per appliance (W)	Usage Pattern
PC with monitor	1	230	SCHED004

Table 6.5 Heat gains of Zone 5 (Bathroom)

- **Persons**

Degree of activity	Sensible heat per person (W)	Latent heat per person (W)	Total heat gain per person (W)	Usage Pattern
Seated at rest	60	40	100	SCHED005

- **Lighting**

Heat gain (W/m^2)	Related floor area (m^2)	Usage Pattern
5	8.1	SCHED005

Table 6.6 Heat gains of Zone 6 (Bedroom)

- **Persons**

Degree of activity	Sensible heat per person (W)	Latent heat per person (W)	Total heat gain per person (W)	Usage Pattern
Seated at rest	60	40	100	SCHED002

- **Lighting**

Heat gain (W/m^2)	Related floor area (m^2)	Usage Pattern
5	12.70	SCHED002

- **Electronic appliances**

Type of appliance	Number of appliances	Heat gain per appliance (W)	Usage Pattern
PC with monitor	1	230	SCHED004

Table 6.7 Heat gains of Zone 7 (Bedroom)

- **Persons**

Degree of activity	Sensible heat per person (W)	Latent heat per person (W)	Total heat gain per person (W)	Usage Pattern
Seated at rest	60	40	100	SCHED002

- **Lighting**

Heat gain (W/m^2)	Related floor area (m^2)	Usage Pattern
5	10	SCHED002

- **Electronic appliances**

Type of appliance	Number of appliances	Heat gain per appliance (W)	Usage Pattern
PC with monitor	1	230	SCHED004

6.2.2 Methodology for the analysis of the results

The simulation was carried out for a complete year (8,760 hours) lasting from the 1st of January until the 31st of December.

As aforementioned two types of simulations were carried out namely; the energy rate control and the temperature level control. During the first simulation the set temperatures of the heating and cooling modes were 20°C and 26°C respectively so as to be within the comfort conditions for dwellings according to the CIBSE Guide A: Environmental Design (2006). The capacities of the heating and cooling systems were assumed to be unlimited in order to maintain comfort conditions at all times. The results are expressed as electricity consumption per square meter per year (kWh/m^2/yr). It should be noted that for the conversion of the calculated energy demand into electricity consumption the efficiencies of the air conditioning/ heat pump units was considered to be COP=3.4 and EER=3.2, corresponding to an Energy Class A unit. Subsequently, by using the model of the typical dwelling and altering the structure according to the optimum topology combinations (scenarios) that resulted in the previous Chapter and shown in Table 6.8, the energy expenditure of each scenario was calculated. The difference between the energy consumption of each scenario to that of the typical dwelling determines the energy saving. The results were evaluated using the Life Cycle Cost (LCC).

Table 6.8 Optimum topology combinations previously defined in Chapter 5

Scenario N^{o}	**Wall Topology**	**Roof topology**
New Dwelling		
SC1	Double wall with insulation in-between with air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.383 W/m^{2}K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^{2}K)*
SC2	Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.748 W/m^{2}K)*
SC3	Thermal Insulation Bricks 0.20 m *(Uvalue = 0.759 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.748 W/m^{2}K)*
Existing Dwelling		
SC4	External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^{2}K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^{2}K)*
SC5	Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	ITR & HCITR Stone wool 0.05 m *(Uvalue = 0.567 W/m^{2}K)*
SC6	Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.05 m *(Uvalue = 0.630 W/m^{2}K)*

In the second simulation the dwelling was considered to be unconditioned and thus the heating and cooling systems were assumed to be both switched off. The simulation shows the effect of insulation added in each scenario on the variation of the mean air temperature of the dwelling in comparison to that of the typical dwelling. The maximum, minimum and mean air temperature together with the number of hours where the air temperature was within comfort conditions were determined. The results for the mean air temperature are presented graphically for the coldest day of the winter period (3rd-4th of February) and the hottest day of the summer period (26th-27th of July) according to the TMY-2 data file (Figure 6.7).

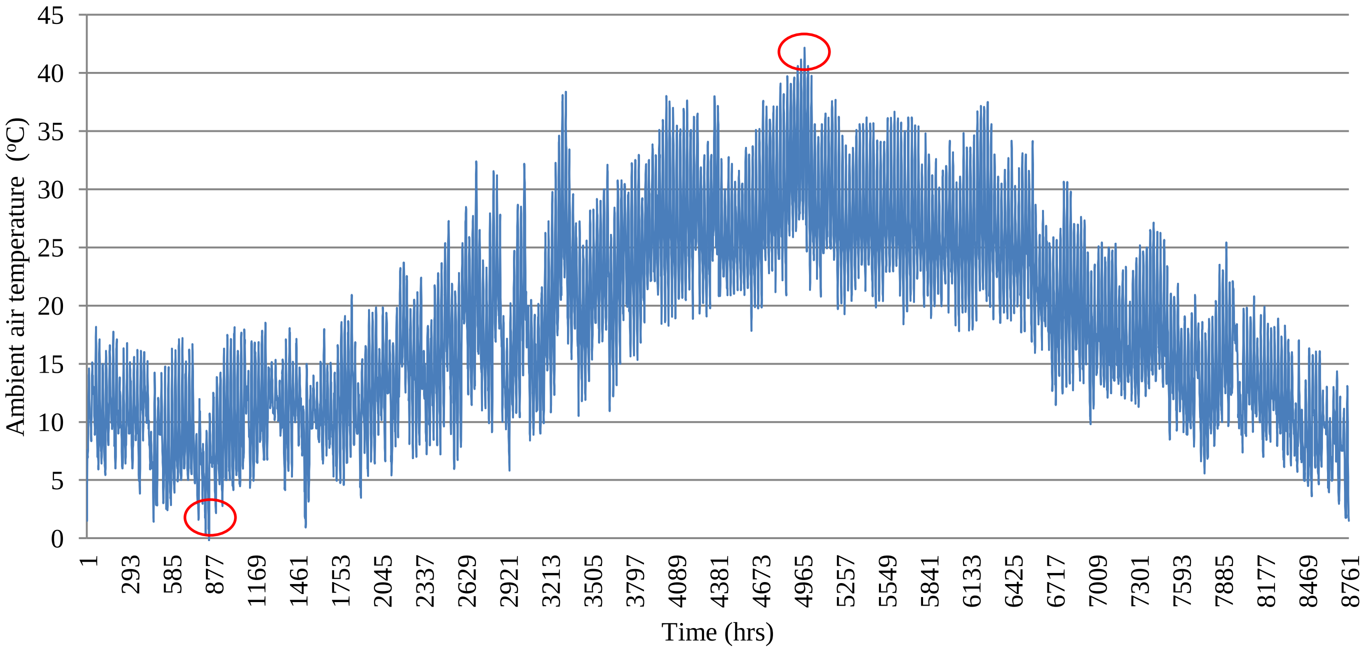

Figure 6.7 Variation of ambient air temperature for one year (8,760 hrs) at Nicosia, Cyprus

The results of both simulations are used to define the optimum topology combination for the case of a new and an existing dwelling. The economic data used in the LCC are listed in Table 6.9.

Table 6.9 Economic data used for the LCC

Current price of electricity in Cyprus without VAT and additional taxes (€/kWh) (EAC, 2013)	0.146
Discount rate (%) (MCIT, 2012)	5.74
Annual increase in electricity price (%) (Capros, 2010)	3.00
Interest rate (%) (MOF, 2012)	5.40

6.3 ANALYSIS OF THE RESULTS

6.3.1 Results for New Dwelling (ND) - Energy rate control simulation

The first step for the analysis of the results of the energy rate control simulation was the calculation of the annual energy consumption of the typical dwelling together with the consequent cost of energy which can be seen in Table 6.10.

Table 6.10 Annual electricity consumption and cost (heating and cooling) of the typical dwelling

Annual consumption of electricity	30,442 kWh
Annual consumption of electricity per floor area	229 kWh/m^2
Annual cost of electricity	€ 4,448

- **Scenario 1 (SC1)**

The results of the energy rate control simulation for SC1 are presented in Table 6.11. As it can be seen these concern the cost of the investment, the annual consumption of electricity, the energy saving, the annual cost of electricity and the annual money saving. From the results presented in Table 6.11 the payback period of the investment of SC1 is calculated to be 1.5 years. The resulting energy saving is 61.5%.

Table 6.11 Results of the economic analysis for SC1

Cost of the investment	€4,238
Annual consumption of electricity	11,710 kWh
Energy saving percentage	61.5 %
Annual cost of electricity	€1,711
Annual money saving	€2,737
Payback period	1.5 years
Net Present Value (NPV)	€119,125
Internal Rate of Return (IRR)	68%

- **Scenario 2 (SC2)**

The results of the energy rate control simulation for SC2 are presented in Table 6.12. The payback period of the investment of SC2 is calculated to be only 0.3 years which is 5 times lower than that of SC1 due to the much lower initial cost (€769 instead of €4,238). The energy saving achieved by SC2 is 59.4% which is only 2.2% lower than that of SC1. Finally, the economic benefit at the end of the 30 years period expressed as NPV is €118,041.88 which is only €1,084 less than SC1. The consequent IRR is 346% which is also 5 times larger than that of SC1.

Table 6.12 Results of the economic analysis for SC2

Cost of the investment	€769
Annual consumption of electricity	12,374 kWh
Energy saving	59.4%
Annual cost of electricity	€1,808
Annual money saving	€2,640
Payback period	0.3 years
Net Present Value (NPV)	€118,041
Internal Rate of Return (IRR)	346%

- **Scenario 3 (SC3)**

The results of the energy rate control simulation for SC3 are presented in Table 6.13. The payback period of SC3 is calculated to be the same as SC2 (0.3 years) which is again 5 times lower than that of SC1. The energy saving achieved by SC3 is 59.6% which is almost the same as that of SC2 and only 2% lower than that of SC1.

Table 6.13 Results of the economic analysis for SC3

Cost of the investment	€827
Annual consumption of electricity	12,312 kWh
Energy saving	59.6%
Annual cost of electricity	€1,799
Annual money saving	€2,649
Payback period	0.3 years
Net Present Value (NPV)	€118,394
Internal Rate of Return (IRR)	346%

6.3.2 Results for New Dwelling (ND) - Temperature level control simulation

The results of the temperature level control simulation are summarised in Table 6.14. Specifically, these concern the minimum, maximum and average mean air temperature of the dwelling for each scenario investigated and the period for which comfort conditions are maintained inside the dwelling.

Table 6.14 Results of temperature level control simulation for the typical dwelling (No Insulation), SC1, SC2 and SC3.

Mean air Temperature	No Insulation	SC1	SC2	SC3
Minimum	8.6	15.6	13.7	13.4
Maximum	47.8	45.3	44.4	44.9
Average	27.2	29.8	28.4	28.5
Comfort conditions period (hrs/year)	1728 (19.7%)	2652 (30.3%)	2443 (27.9%)	2452 (28%)

During the winter period the highest minimum air temperature is achieved by SC1 followed by SC2 (1.9^{o}C less) and SC3 (2.2^{o}C less). During the summer period SC1 results in the highest air temperature 45.3^{o}C compared to 44.9^{o}C SC2 and 44.4^{o}C SC2. The highest temperature for SC1 is due to the higher level of insulation in SC1 which does not let the heat stored into the dwelling's envelope during daytime to dissipate to the outer environment during night time when the ambient temperature is lower. The scenario with the highest period of comfort conditions is SC1 followed by SC3 (2.3% less) and SC2 (2.4% less). It can also be observed that the results of SC2 and SC3 are almost identical except from the maximum temperature of SC3 during the summer period which is 0.5^{o}C higher than that of SC2.

The variation of the mean air temperature of the typical dwelling for all scenarios investigated during the coldest days of winter period (3rd - 4th February) is depicted in Figure 6.8. As can be seen the mean air temperature of the typical dwelling without insulation is fluctuating between 8.6-11.9^{o}C and thus the variation range is larger than that of the insulated scenarios (3.3^{o}C instead of 1.4-2.4^{o}C).

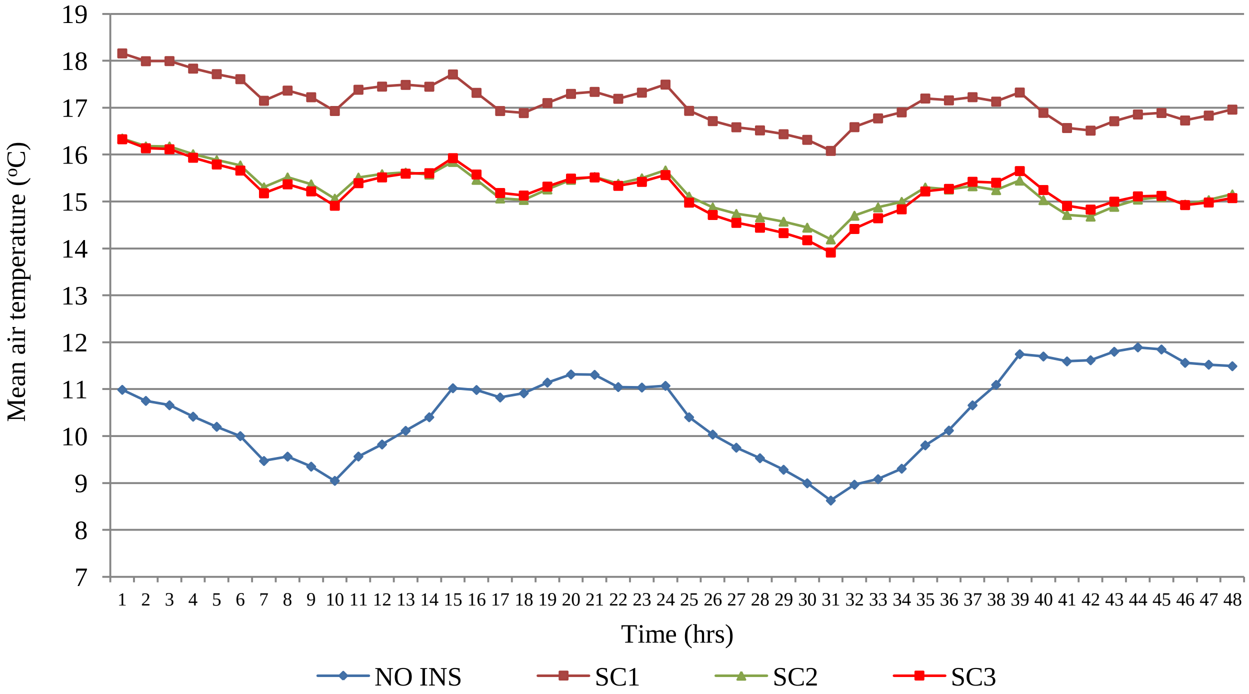

Figure 6.8 Variation of mean air temperature for the typical dwelling (No insulation), SC1, SC2 and SC3 during the coldest days of winter period (3rd-4th February)

It can also be observed that the mean air temperature of SC1 is fluctuating between 16.1-18.2^{o}C while those of SC2 and SC3 are fluctuating between 14.2-16.3^{o}C and 13.9-16.3^{o}C respectively (2^{o}C lower than SC1).

The variation of the mean air temperature of the typical dwelling during the hottest days of the summer period (26th-27th of July) is depicted in Figure 6.9. As it can be seen the mean air temperature of the typical dwelling is fluctuating between 41-47.8^{o}C and the variation range is larger than the insulated scenarios (7^{o}C instead of 4-4.5^{o}C). It can also be observed that the mean air temperature of SC1 is fluctuating between 41.3-45.3^{o}C, SC2 between 40.3-44.4^{o}C and SC3 between 40.3-44.9^{o}C. A very interesting result is that the most well insulated scenario (SC1) results to the highest temperature of all three scenarios (SC1, SC2 and SC3) while during the time period between 07:00-11:30 it also exceeds the mean air temperature of the typical dwelling.

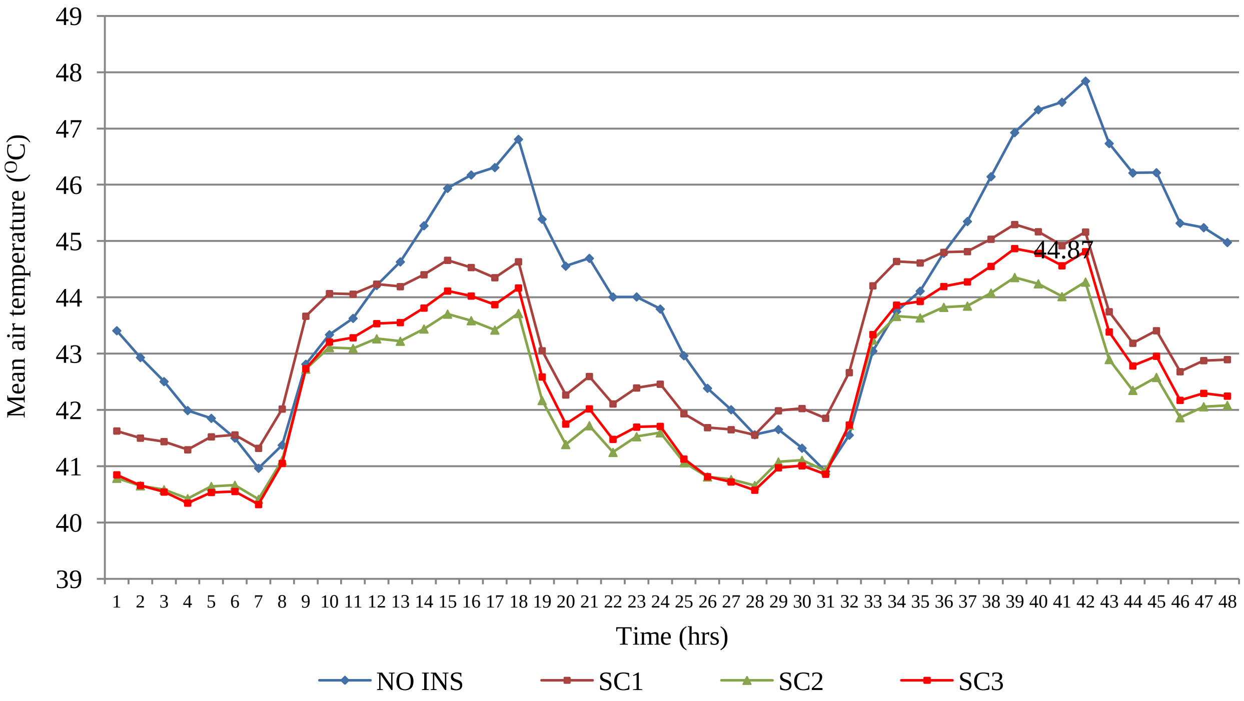

Figure 6.9 Variation of mean air temperature for the typical dwelling (No insulation), SC1, SC2 and SC3 during the hottest days of the summer period (26th-27th of July)

6.3.3 Optimum topology combinations for ND

In order to define the optimum topology combinations for the case of the New Dwelling the main results of the three scenarios examined (SC1, SC2 and SC3) are summarised in Table 6.15. As it can be observed the highest energy saving is achieved by SC1 (61.5%) followed by SC3 (59.6%) and SC2 (59.4%). Nevertheless, the main disadvantage of SC1 relies on the maximum interior air temperature during summer period which is the highest of all three scenarios by 0.4-1°C. Additionally two other drawbacks of SC1 are its very high cost and low IRR compared to the other scenarios examined. Thus, the choice of the optimum topology combination will be between SC2 and SC3. These two scenarios are identical in terms of the achieved results both energy and economic. Their only difference relies on the fact that during summer time the maximum internal air temperature is higher by 0.52°C in SC3 compared to SC2. However, this difference is small and thus these two scenarios can be considered to be optimum for the case of the ND.

Table 6.15 Main results of the examined SC for the ND

Scenario	Initial cost (€)	IRR	Energy saving	Interior air temperature (^{o}C)		
				Min.	Max.	Avg.
SC1	4,238	68%	61.53%	15.56	45.3	29.81
SC2	769	346%	59.35%	13.7	44.35	28.43
SC3	827	346%	59.56%	13.39	44.87	28.5

6.3.4 Results for Existing Dwelling (ED) - Energy rate control simulation

- **Scenario 4**

The results of the energy rate control simulation for SC4 are presented in Table 6.16. The payback period of SC4 is calculated to be 2 years and the energy saving 61.5%. The economic benefit expressed as NPV at the end of the 30 years period is calculated to be €117,792 and the IRR 52%.

Table 6.16 Results of the economic analysis for SC4

Cost of the investment	€5,572
Annual consumption of electricity	11,721
Energy saving	61.5%
Annual cost of electricity	€1,712
Annual money saving	€2,735
Payback period	2 years
Net Present Value (NPV)	€117,792
Internal Rate of Return (IRR)	52%

- **Scenario 5**

The results of the energy rate control simulation for SC5 are presented in Table 6.17. The payback period of SC5 is calculated to be 1.2 years which is almost half of that of SC4 due to the lower initial cost (€3,122 instead of €5,572). The energy saving achieved by SC5 is 60% which is only 1.5% lower than that of SC5. Additionally, the economic benefit is €117,065 which is only €726 less than SC4 and the consequent IRR is 88% which is 36% higher than that of SC4.

Table 6.17 Results of the economic analysis for SC5

Cost of the investment	€3,122
Annual consumption of electricity	12,184
Energy saving	59.98%
Annual cost of electricity	€1,780
Annual money saving	€2,667
Payback period	1.2 years
Net Present Value (NPV)	€117,065
Internal Rate of Return (IRR)	88%

- **Scenario 6**

The results of the energy rate control simulation for SC6 are presented in Table 6.18. The payback period of the investment of SC6 is the same as that of SC5 which is 1.2 years. The energy saving achieved by SC3 is 59.2% which is 0.8% lower than SC5 and 2.3% lower than that of SC4. The economic benefit expressed as NPV is €115,577 which is €1,487 less than that of SC5 and €2,214 less than that of SC4. The consequent IRR is 90% which is 2% higher than that of SC5 and 38% higher than that of SC4.

Table 6.18 Results of the economic analysis for SC6

Cost of the investment	€3,034
Annual consumption of electricity	12,423
Energy saving	59.19%
Annual cost of electricity	€1,815
Annual money saving	€2,633
Payback period	1.2 years
Net Present Value (NPV)	€115,577
Internal Rate of Return (IRR)	90%

6.3.5 Results for ED - Temperature level control simulation

The results of the temperature level control simulation for the case of the ED are presented in Table 6.19. As it can be seen that during the winter period the highest minimum air temperature is achieved by SC4 followed by SC5 (1.3^{o}C less) and SC6 (1.5^{o}C less). In contrary during summer period SC4 results in the highest air temperature followed by SC3 (0.6^{o}C less) and SC2 (0.7^{o}C less). This is again a result of the higher level of insulation present at SC4 compared to SC5 and SC6. The scenario with the highest period of comfort conditions is SC4 followed by SC5 (1.9% less) and SC6 (2.4% less). It should be noted that SC5 and SC6 behave almost identically with a very slight difference in favour of SC5 due to the use of stone wool in the roof which has better thermal conductivity than the expanded polystyrene used in SC6 (0.035 instead of 0.04 W/mK).

Table 6.19 Results of temperature level control simulation for the typical dwelling (No Insulation), SC4, SC5 and SC6.

Temperature	No Insulation	SC4	SC5	SC6
Minimum	8.6°C	15.4°C	14.1°C	14°C
Maximum	47.8°C	45.2°C	44.5°C	44.6°C
Average	27.2°C	29.7°C	28.7°C	28.7°C
Comfort conditions period (hrs/year)	1728 (19.7%)	2624 (30%)	2456 (28%)	2417 (27.6%)

The variation of the mean air temperature of the typical dwelling for all scenarios investigated during the coldest days of winter period (3rd - 4th February) is depicted in Figure 6.10. The mean air temperature of the typical dwelling is fluctuating between 8.6-11.9°C and thus the variation range is higher than that of the insulated scenarios (3.3°C instead of 2°C). It can be observed that the mean air temperature of SC4 is fluctuating between 16-18°C while those of SC5 and SC6 are fluctuating between 14.6-16.8°C and 14.5-16.6°C respectively (~1.5°C lower than SC1). The slightly better behaviour of SC5 compared to SC6 is once again a result of the better properties of the insulation material used in the roof.

The variation of the mean air temperature of the typical dwelling during the hottest days of the summer period (26th-27th of July) is depicted in Figure 6.11. As it can be seen the mean air temperature of the typical dwelling is fluctuating between 41-47.8°C and thus again the variation range is higher than that of the insulated scenarios (~7°C instead of 4-4.5°C). It is also observed that the mean air temperature of SC4 is fluctuating between 41.2-45.2°C, SC5 between 40.6-44.5°C and SC6 between 40.7-44.6°C (1°C lower than SC1). Similarly, to the case of the new dwelling it can be seen that the most well insulated scenario (SC4) results to the highest temperature of all three scenarios (SC4, SC5 and SC6) while during the time period between 06:00-12:00 it also exceeds the mean air temperature of the typical dwelling. Additionally, during 08:00-10:00 of the first 24 hours the mean air temperature of the typical dwelling is almost the same as that of SC5 and SC6 while during 07:00-10:00 of the second 24h period the mean air temperature of SC5 and SC6 exceeds that of the typical dwelling for 0.3-0.5°C.

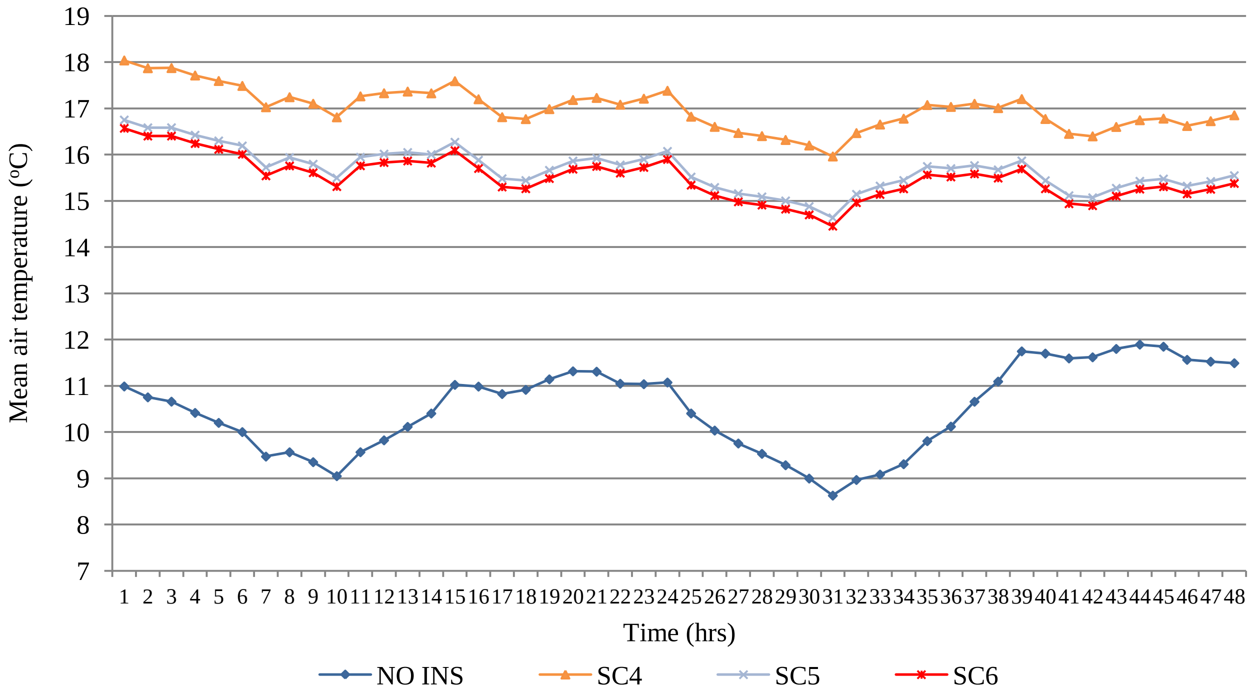

Figure 6.10 Variation of mean air temperature for the typical dwelling (No insulation), SC4, SC5 and SC6 during the coldest days of winter period (3rd-4th of February)

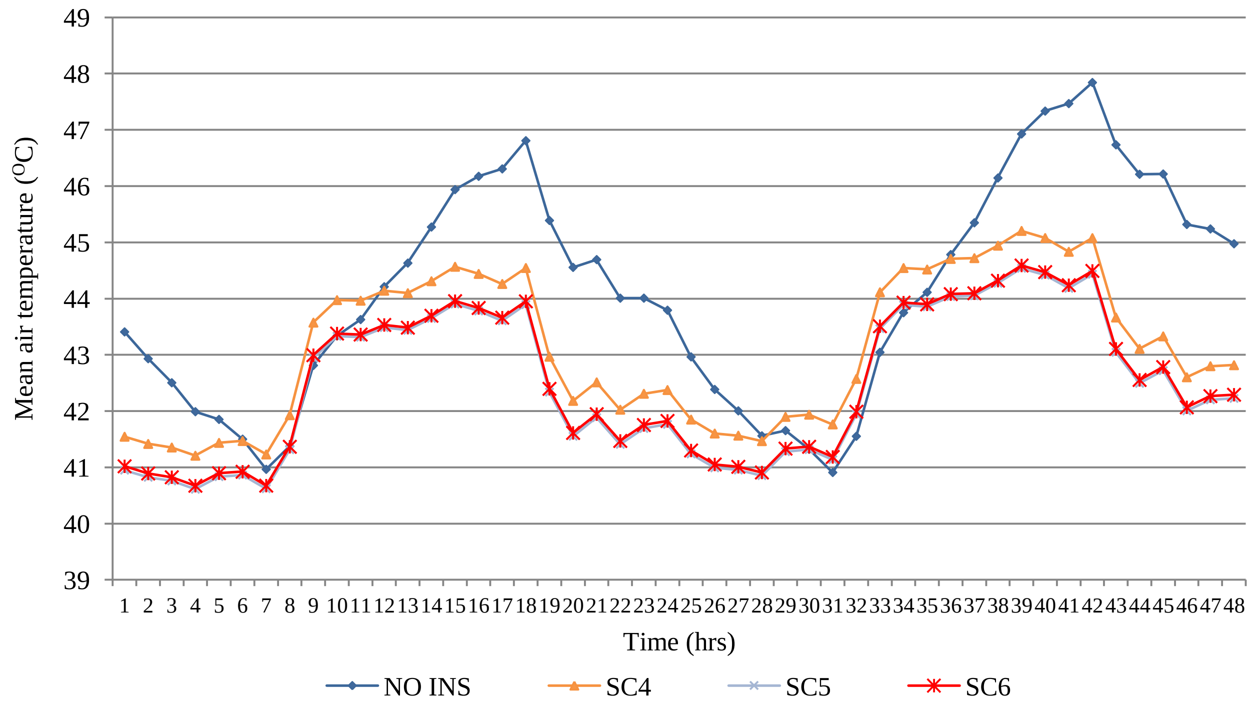

Figure 6.11 Variation of mean air temperature for the typical dwelling (No insulation), SC4, SC5 and SC6 during the hottest days of the summer period (26th-27th of July)

6.3.6 Optimum topology combinations for ED

The main results of the three scenarios examined (SC4, SC5 and SC6) are summarised in Table 6.20. The highest energy saving is achieved by SC4 (61.5%) followed by SC5 and SC6 (60% and 59.2%). Nevertheless, SC4 exhibits several disadvantages such as the highest cost of all three scenarios examined, the lowest IRR and the highest maximum and average interior air temperature. The highest temperature during summer time is a result of the highest level of insulation of SC4. Thus, the optimum topology combination will be chosen between SC5 and SC6. These two scenarios are identical both economically and in terms of energy savings due to the fact that they have the same wall insulation (0.035m of thermal insulation plaster) and their only difference is the type of insulation material used on the roof (stone wool instead of expanded polystyrene). The difference in the thermal conductivity of these two materials causes a very slight difference in both energy savings and temperature behaviour in favour of SC5 in comparison to SC6 (+0.8% in energy saving, +0.18^{o}C in minimum air temperature, -0.05^{o}C in maximum air temperature). Nevertheless, this difference is negligible and both SC5 and SC6 are considered to be the optimum topology combinations for the case of the ED.

Table 6.20 Main results of the examined SC for the ED

Scenario	Initial cost (€)	IRR	Energy saving	Interior air temperature (^{o}C)		
				Min.	Max.	Avg.
SC4	5,572	52%	61.5%	15.4	45.2	29.7
SC5	3,122	88%	60%	14.1	44.5	28.7
SC6	3,034	90%	59.2%	14	44.6	28.7

6.4 VALIDATION OF THE RESULTS

For the validation of the results of this Chapter the results of other studies evaluating the same ECM under similar weather conditions to those of the location examined in this Chapter (Nicosia, Cyprus) are presented in Table 6.21. As it can be seen the results of this Chapter are in very good agreement with the results of the other studies which are both theoretical and experimental results. Thus, it can be concluded that the results of this Chapter are validated.

Table 6.21 Results of other ECM studies for the validation of the results of this Chapter

Studies	Kind of study	Location	ECM examined	Total energy savings percentage
Nikolaides *et al.* (2009)	Theoretical	Larissa, Greece	External walls and roof insulation	57.5%
Kolaitis *et al.* (2013)	Theoretical	Mediterranean Climate region	External walls and roof insulation	56-89%
Cabeza *et al.* (2010)	Experimental	Lleida, Spain	External walls and roof insulation	64% in summer, 37% in winter
Current study	Theoretical	Nicosia, Cyprus	External walls and roof insulation	59.2-69.5%

6.5 SUMMARY

In this Chapter the topology combinations previously defined are modelled in detail using suitable models of TRNSYS simulation tool in order to identify the optimum for the cases of both new and existing dwellings (ND and ED respectively).

In the case of the ND the optimum topology combinations are SC2 and SC3 where the first one concerns the application of thermal insulation plaster in the external walls and the second one the use of thermal insulation bricks instead of hollow clay bricks. In both cases the roof is insulated using 0.04m of expanded polystyrene.

In the case of the ED the optimum topology combinations are SC5 and SC6 where in both cases thermal insulation plaster (0.035m) was used on the walls. Their difference is due to the different insulation material used on the roof (0.05m of stone wool in SC5 and 0.05m of expanded polystyrene in SC6).

It should be noted that the reason for which the optimum topology combinations are different between the ND and the ED is their applicability in the case of the ED and their consequent cost.

A general conclusion is that the use of double wall in ND and external insulation in both ND and ED are not yet economically efficient solutions due to their high initial cost compared to the other solutions examined. Additionally, due to their high level of insulation significantly contribute to the overheating of the dwelling during the summer period which is very important especially for hot environments like Cyprus.

Finally, the optimum way to insulate the external walls of a ND or an ED is by using either a layer of at least 0.025m of thermal insulation plaster or substituting the hollow clay bricks with thermal insulation bricks of the same dimensions which, amongst all other advantages previously described, do not require any specialised personnel for their application The optimum way to insulate the roof of a ND or an ED dwelling is by adding a layer of either stone wool or expanded polystyrene of at least 0.04m thickness.

CHAPTER 7

APPLICATION OF PHASE CHANGE MATERIALS (PCM)

ON THE ENVELOPE OF A TEST CUBICLE

In this Chapter the application of macroencapsulated Phase Change Materials (PCM) on the envelope of a test cubicle in Cyprus is theoretically evaluated. The simulation process is carried out using TRNSYS and a suitable model, Type 1270. Two types of simulations have been carried out namely the energy rate control test and the temperature level control test. The PCM are also compared and combined with the insulation of the optimum cases of Chapter 6. The results of the simulations are used to make an evaluation of their effect when applied to the typical dwelling of Chapter 3.

7.1 MODEL DESIGN

The model design is carried out using TRNSYS. The model used for the simulation of the PCM is Type1270 which is able to model a PCM layer in any part of the dwelling's envelope. This was purchased from Thermal Energy System Specialists (TESS) Company (TESS, 2012). All other components of the model are the same as in Chapter 6 and their description is not repeated here. The configuration of the complete model of the test cubicle with PCM is depicted in Figure 7.1.

Type1270 is a model designed to interact with Type56 and can model a PCM located in any position in the thickness of a Type56 wall. There are two options for setting the physical properties of the PCM: the manual option and the built-in option. In the manual option the physical properties of the PCM such as density, specific heat, melting temperature, freezing temperature, and latent heat of fusion are defined by the user. In the built-in option the user can utilize the built-in values of this component which concern a specific brand of PCM. It should be noted that Type1270 models a pure PCM (as opposed to a mixture of a PCM with an inert material). From a physical point of view, this means that the PCM is assumed to go through its freeze/thaw process at constant temperature and to have a constant specific heat in the solid phase and a constant specific heat in the liquid phase. This is done in order to simplify the analysis of the PCM by treating the phase change layer in bulk.

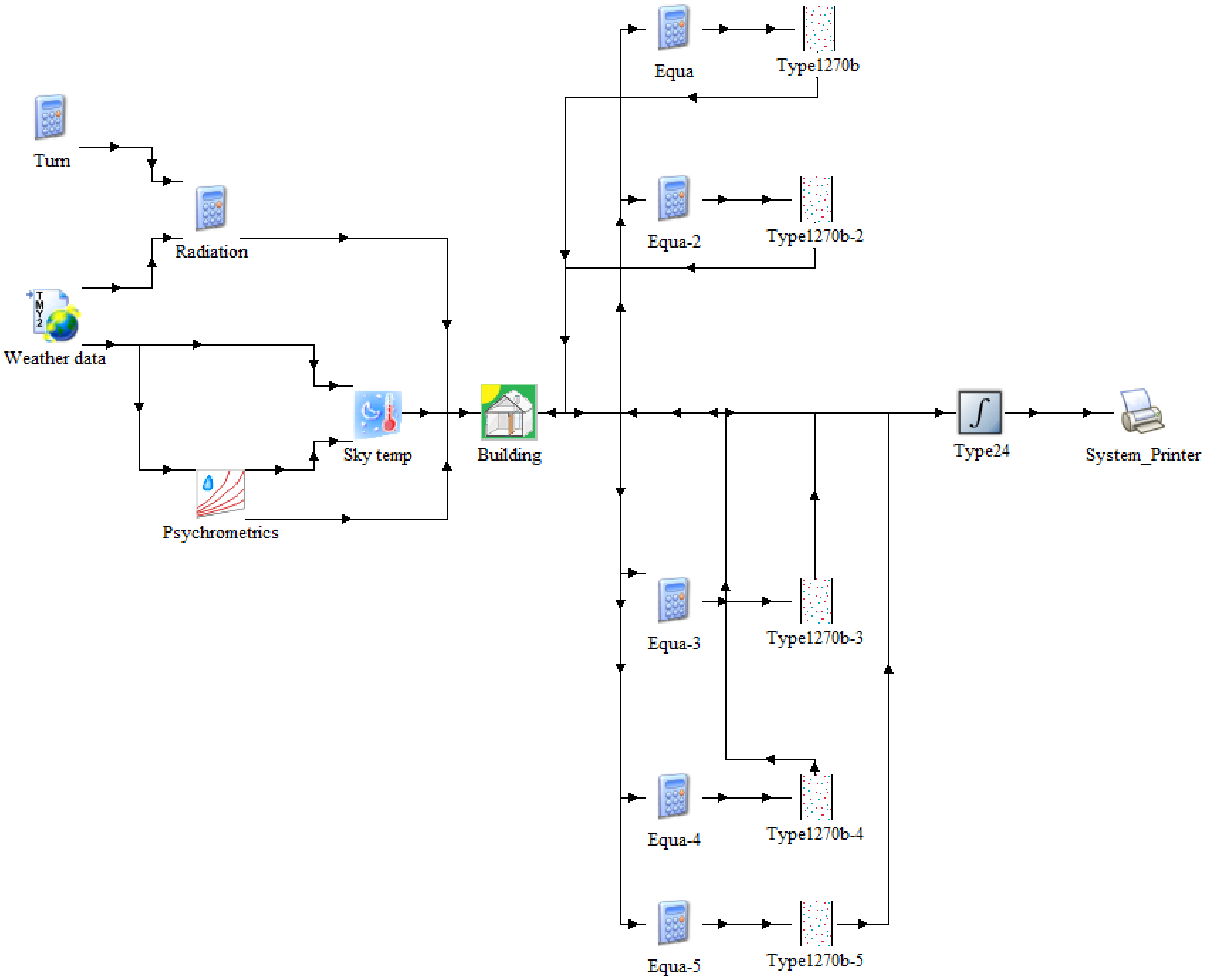

Figure 7.1 Configuration of the complete model of the test cubicle with PCM

7.1.1 Mathematical description of Type1270

According to TESSLibs 3-Mathematical Reference (TESS, 2012) Type1270 is quite simplistic mathematically and it assumes that:

1. The specific heat of the PCM is constant (i.e. it does not change with temperature) when fully solid. The user defines the solid-phase specific heat.

2. The specific heat of the PCM is constant (i.e., it does not change with temperature) when fully liquid. The user defines the liquid-phase specific heat.

3. The thermal contact resistance of energy flow between the PCM layer and the standard material layers adjacent to it is negligible.

4. The freeze/solidification process occurs at a constant temperature.

When the PCM material is fully solidified, the temperature at the end of a time step is given by:

$$T_{final} = T_{initial} + \left(\frac{q_1+q_2}{m_{PCM} \times c_{P,solid}}\right) \tag{7.1}$$

Where q_1 and q_2 are the quantities of energy entering the PCM from the adjacent wall layers, m_{PCM} is the mass of the PCM and $c_{p,solid}$ and $c_{P,liquid}$ are the specific heat capacities at solid and liquid state of the PCM respectively.

When the PCM material is fully thawed, the temperature at the end of a time step is given by:

$$T_{final} = T_{initial} + \left(\frac{q_1+q_2}{m_{PCM} \times c_{P,liquid}}\right) \tag{7.2}$$

When the PCM material is in the transition state, the final temperature and initial temperature are equal as the phase change occurs at a constant temperature. Type1270 simply records how much energy the PCM has absorbed or given off. If the energy absorbed by the PCM during a particular time step exceeds the PCM's latent storage capacity then Type1270 computes how much of the energy was needed to fully melt the PCM, then applies the remaining energy to a temperature change in the liquid phase using Eq. (7.2). Likewise, if the PCM is giving energy to the surrounding wall layers, and it gives more energy than has been stored in a particular time step, then Type1270 computes how much energy was required to fully solidify the PCM and applies the remaining energy to a temperature change in the solid phase using Eq. (7.1).

7.2 INPUT DATA

The complex utilisation of Type1270 and the continuous iterations during the simulation result to a very long simulation time. Thus, it is decided that the simulation is carried out for a test cubicle and consequently the results are used to calculate the savings for the typical dwelling.

7.2.1 Methodology for the utilization of Type1270

When using Type1270 the PCM layer can be applied in any part of a dwelling's envelope such as wall, either internal or external, and roof. For the purposes of this thesis the PCM layer will be applied only to the external walls and the roof and not the internal walls of the dwelling. The reason for this is that the internal walls in a detached dwelling separate conditioned spaces and thus the application of a PCM layer there will not have any effect either on the mean air temperature or the energy demand.

Initially it is required that a direct contact airnode is introduced in each wall and the roof of the cubicle (main zone). The direct contact airnode is essentially a zone that has the same dimensions (height and length) as the examined part (wall or roof) but has a width of only 0.01m. Consequently, the wall or roof containing the PCM is split into three parts: the inner boundary part, the outer boundary part and the external part. The first part is contained in the main zone while the other two in the airnode. The inner boundary part is the part of the wall or roof that is in contact with the inner surface of the PCM layer while the outer boundary part is the part of the wall or roof that is in contact with the outer surface of the PCM layer. The first two parts are set as BOUNDARY in Type56 and the heat transfer coefficient by convection of the side in contact with the PCM layer is set to be 0.0001 kJ/hm^{2}K (0.000028W/m^{2}K) thus indicating direct contact. The separation of each structural element (wall or roof) is depicted in depicted in Figures 7.3-7.6 below. Accordingly, an input named T_{PCM} is defined which represents the boundary temperature of the sides of these walls which are in contact with the PCM layer. Then, the flux of energy that crosses the outside surface of each BOUNDARY wall is connected from Type56. The PCM model takes the two energy inputs from Type56 and computes the temperature of the PCM layer at each time step previously defined. This temperature is then passed back to the Type56 (T_{PCM} input) and the iterations carry on. It should be noted that a BOUNDARY wall in Type56 cannot have an orientation. Nevertheless, since the BOUNDARY wall is in direct contact with an external wall which has an orientation and is subject to incident solar radiation the BOUNDARY wall is indirectly affected by solar radiation.

7.2.2 Test cubicle definition

The dimensions of the test cubicle are 3m x 2m x 3m and the orientation can be seen in Figure 7.2. As already mentioned the introduction of a direct airnode is necessary for the utilisation of Type 1270, therefore a direct airnode is introduced in each orientation with a width of 0.01m as also depicted in Figure 7.2.

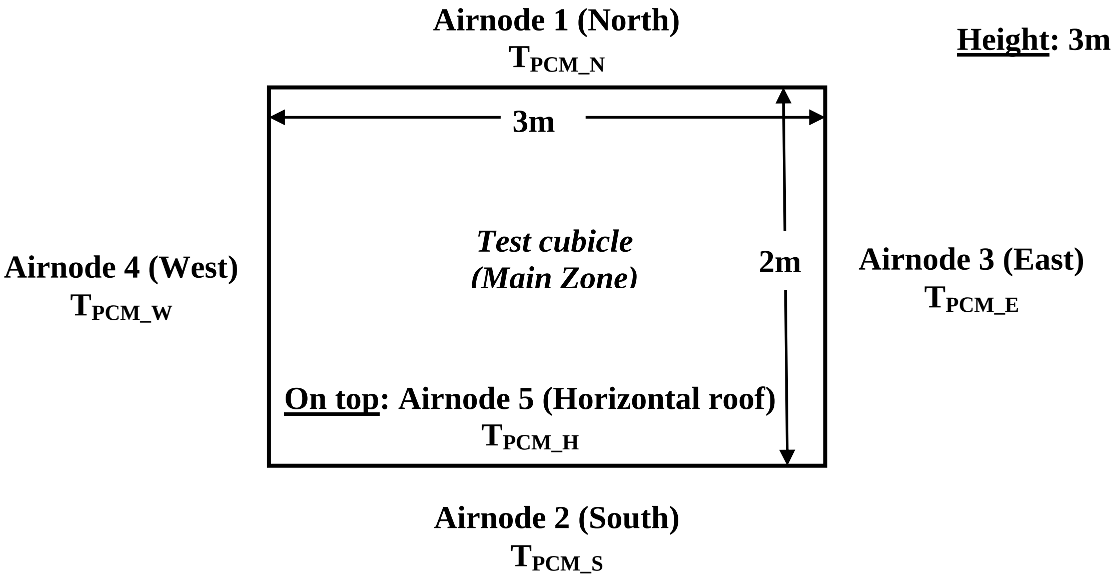

Figure 7.2 Test cubicle dimensions, orientation and adjacent airnodes

7.2.3 Position of the PCM layer

The application of the PCM layer is examined in three different positions in order to be applicable for both new and existing dwellings as follows:

I. The PCM layer is placed in the middle of a double brick wall (applicable only in new dwellings, ND),

II. The PCM layer is placed in the inner side of the wall between the brick and the plaster layer (applicable in both new and existing dwellings, ND and ED).

III. The PCM layer is placed in the outer side of the wall between the brick and the plaster layer (applicable in both ND and ED).

The positions examined are depicted in Figures 7.3-7.5 together with separation of each wall into the required parts. Where the PCM layer was applied on the roof of the building this was positioned in the inner side of the concrete slab just behind the plaster as shown in Figure 7.6. This is done in order to protect the PCM layer and also due to the fact that it cannot be placed inside the concrete slab as this will affect the structural integrity of the slab. It should be noted that in all PCM cases examined the roof is considered to have a PCM layer applied also.

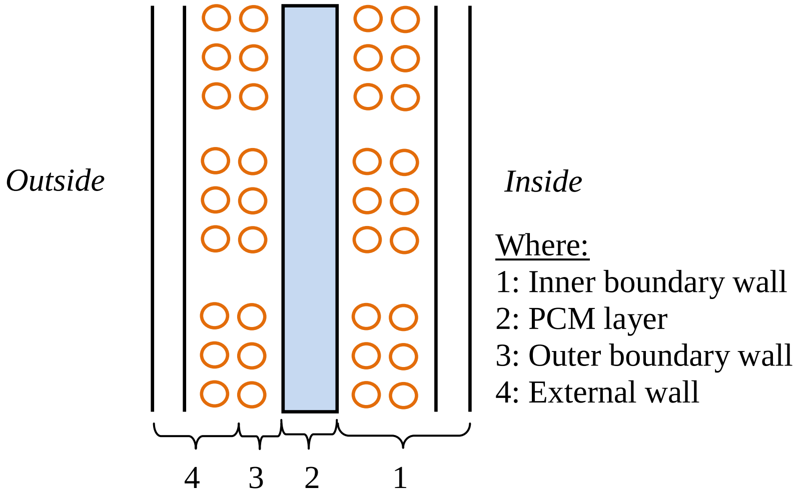

Figure 7.3 PCM layer position I

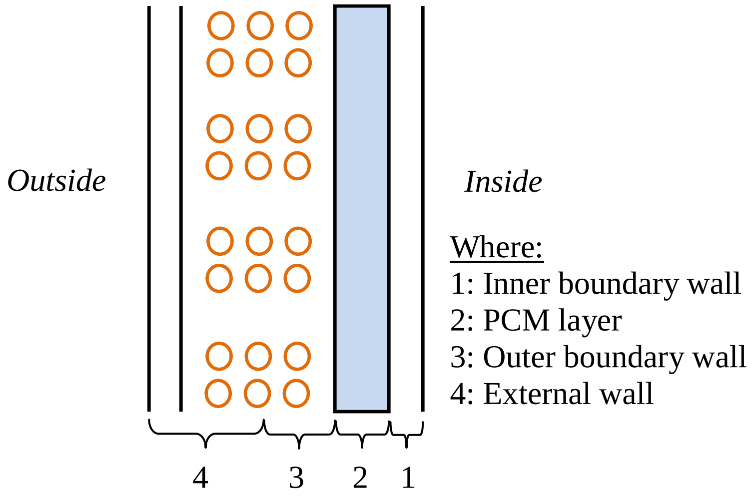

Figure 7.4 PCM layer position II

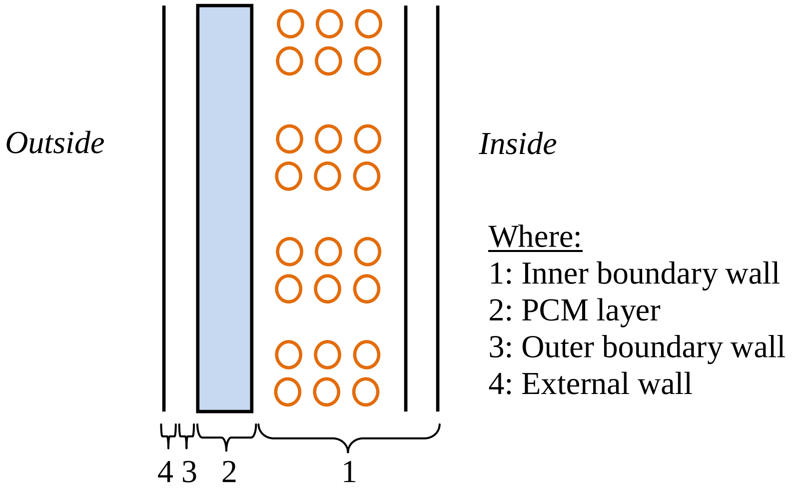

Figure 7.5 PCM layer position III

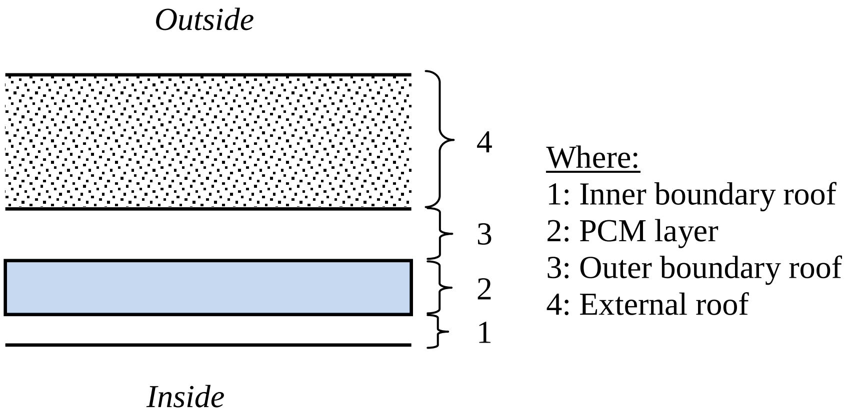

Figure 7.6 PCM layer position on the roof of the test cubicle

7.2.4 Physical properties and characteristics of the PCM used

The PCM investigated were those of the Type 1270 built-in library and concern specific commercial products (BioPCmat™) manufactured by Phase Change Energy Solutions Company. Their product codes are M27, M51 and M91 and their physical properties and characteristics are listed in Table 7.1. These products are offered in four different melting temperatures 23, 25, 27 and 29°C. The main difference between these products is their mass per unit area (kg/m^2) which indicates the mass of the PCM contained within the product. According to literature (Castell *et al.*, 2010; Barreneche *et al.*, 2013; Cabeza *et al.*, 2007; Arce *et al.*, 2012; Ibañez *et al.*, 2005) the most commonly used melting temperatures of PCM applied in buildings located in hot environments is between 26-29°C. Thus, in this thesis since Cyprus has a predominantly hot weather environment the PCM selected were those with a melting temperature of 29°C.

Table 7.1 Physical properties and characteristics of the PCM used during the simulation procedure (Phasechange, 2013)

Melting/Freezing temperatures*	29°C/26°C		
Product	M27	M51	M91
Thickness (mm)	14		
Weight per unit area (kg/m^2)	2.49	3.56	6.15
Dimensions/Width (mm)	419		
Latent heat storage capacity (J/g)**	165 - 200		
* The temperatures shown in the products table are close proximities of the 'true' melting temperatures since PCM are melting within a small range of temperatures ** Depending on formulation and application of the product			

7.3 METHODOLOGY

Once the detailed model of the test cubicle was setup the simulation was carried for a 'basic case' where the dwelling is considered to have no insulation or PCM installed in any part of its envelope. The simulation was carried out for a complete typical year (8,760 hours) from 1st January to 31st December.

For the definition of the optimum PCM layer the energy rate control test is conducted with which the total energy demand for heating and cooling are estimated. Specifically, in this test all three products located in all three positions are examined. The results of each case are compared to those of the 'basic case' in order to calculate the consequent energy savings. The set temperature during heating and cooling periods are 20°C and 26°C respectively according to the comfort conditions for dwellings (CIBSE, 2006) while the power of the heating and cooling system is set to be unlimited in order to maintain comfort conditions at all times. The results are presented as energy consumption per square meter of dwelling area per year (kWh/m^2/yr).

Accordingly, since the optimum topologies of Chapter 6 for both new and existing dwelling are behaving in an almost identical way between them (SC2 with SC3 and SC5 with SC6) it is decided that only SC2 and SC5 will be applied to the test cubicle in this Chapter. This is done in order to compare the optimum PCM case with the optimum insulation cases and also in order to evaluate their combinations (optimum PCM case with the insulation cases).

The second test carried out is the temperature level control which is showing the free floating fluctuation of the mean air temperature of the cubicle. In this test the cubicle is considered to be unconditioned. The maximum, minimum and mean air temperature together with the number of hours where the air temperature is within comfort conditions are examined. As in the previous chapter, the results of this test are presented for the coldest day of winter and the hottest day of summer which are the 3rd-4th of February and 26-27th of July respectively. During this test the cases evaluated are the 'base case', the optimum PCM case, the insulation cases (SC2 and SC5) and the combined cases (PCM-SC2 and PCM-SC5).

The results of the energy rate control test for the optimum PCM layer are used to make an evaluation of the energy savings that will occur if the optimum PCM layer is applied on the envelope of the typical dwelling. These are also compared to the energy savings achieved by the combined cases.

Finally, the results of the optimum PCM layer and the combined cases are economically evaluated using Life Cycle Cost (LCC) in order to define the IRR and the consequent payback period of the investment.

7.4 ANALYSIS OF THE RESULTS

7.4.1 Energy rate control simulation

The results concerning the energy rate simulation are presented in Table 7.2 for all 9 PCM cases examined (three types of materials in three positions). These concerns the energy savings achieved compared to the 'basic case'. It should be noted that the annual energy consumption per floor area of the 'basic case' was 414.5 kWh/m^2 yr.

As it can be seen in Table 7.2 and in Figure 7.7 the optimum position is position III where the PCM layer is located on the outer side of the bricks behind the plaster. Specifically, in positions I and II the achieved energy savings are 21.7-21.8% and 21.4-21.6% while in position III was 28.5-28.6%. It should be noted that in all three positions the differences in the energy savings between the three products examined were negligible (0.1%) and thus it is shown that the difference in the PCM mass per area is not that significant for the examined case. Nevertheless, the PCM case chosen for carrying out the remaining simulations is the 2991 material (29ºC melting temperature, material type 91) located in position III (28.6%, 118.5 kWh/yr/m^2). The reason for which the PCM is working more efficiently in Position III (both in heating and cooling) is because it is more exposed to the outer environment conditions such as temperature variations and solar radiation. As a result it can be observed that an increase of the energy savings from Position I to Position III of 4.1% and 8.2% occurs in cooling and heating, respectively.

As expected, the energy savings in cooling are much higher than those of heating since essentially the PCM melting/freezing procedure is operating much better under summer conditions.

The results of the energy rate simulation concerning the combined (PCM and insulation) and the insulation cases are presented in Table 7.3 and in Figure 7.8 where it can be observed that the combined cases achieve higher overall energy savings than the insulation cases (66.2% and 67.7% instead of 61% and 63.5% respectively). The highest energy savings amongst the combined cases is achieved by the 2991-SC5 case. It should be noted that the insulation only cases achieve better results in energy saving during the heating period (winter) than the combined cases (75.8-77.7% and 66.1-67.4% respectively). The reason for this is that the PCM in winter is absorbing a part of the heat (sensible and latent) from the interior (since the space is conditioned) and thus the heating demand is increased. Additionally, it cannot absorb heat from the exterior due to the existence of insulation. In contrary the combined cases exhibit much better behaviour compared to the insulation only cases during the cooling period (66.3-67.8% and 34.5-38.3% respectively).

Table 7.2 Results of the energy rate control simulation for the PCM materials examined

PCM MATERIAL		2927		2951		2991	
		QHEAT	QCOOL	QHEAT	QCOOL	QHEAT	QCOOL
POSITION I	Heating and cooling demand per m^2 (kWh/yr m^2)	224.9	100	224.8	99.6	224.7	99.3
	Total energy demand (kWh/yr m^2)	324.8		324.4		324	
	Heating and cooling energy savings per m^2 (kWh/yr m^2)	40.6	49.1	40.7	49.5	40.8	49.7
	Total energy savings (kWh/yr m^2)	89.7		90.1		90.5	
	Heating and cooling energy savings percentage per m^2 (% kWh/yr m^2)	15.3%	33%	15.3%	33.2%	15.4%	33.4%
	Total energy savings percentage (% kWh/yr m^2)	21.7%		21.7%		21.8%	
POSITION II	Heating and cooling demand per m^2 (kWh/yr m^2)	225.9	99.8	225.8	99.6	225.7	99.2
	Total energy demand (kWh/yr m^2)	325.7		325.4		324.8	
	Heating and cooling energy savings per m^2 (kWh/yr m^2)	39.6	49.2	39.7	49.4	39.8	49.8
	Total energy savings (kWh/yr m^2)	88.8		89.1		89.7	
	Heating and cooling energy savings percentage per m^2 (% kWh/yr m^2)	14.9%	33%	15%	33.2%	15%	33.4%
	Total energy savings percentage (% kWh/yr m^2)	21.4%		21.5%		21.6%	
POSITION III	Heating and cooling demand per m^2 (kWh/yr m^2)	203	93.4	203	93.3	202.9	93.1
	Total energy demand (kWh/yr m^2)	296.4		296.2		296	
	Heating and cooling energy savings per m^2 (kWh/yr m^2)	62.5	55.6	62.5	55.8	62.9	55.9
	Total energy savings (kWh/yr m^2)	118.1		118.3		118.5	
	Heating and cooling energy savings percentage per m^2 (% kWh/yr m^2)	23.5%	37.3%	23.6%	37.4%	23.6%	37.5%
	Total energy savings percentage (% kWh/yr m^2)	28.5%		28.5%		28.6%	

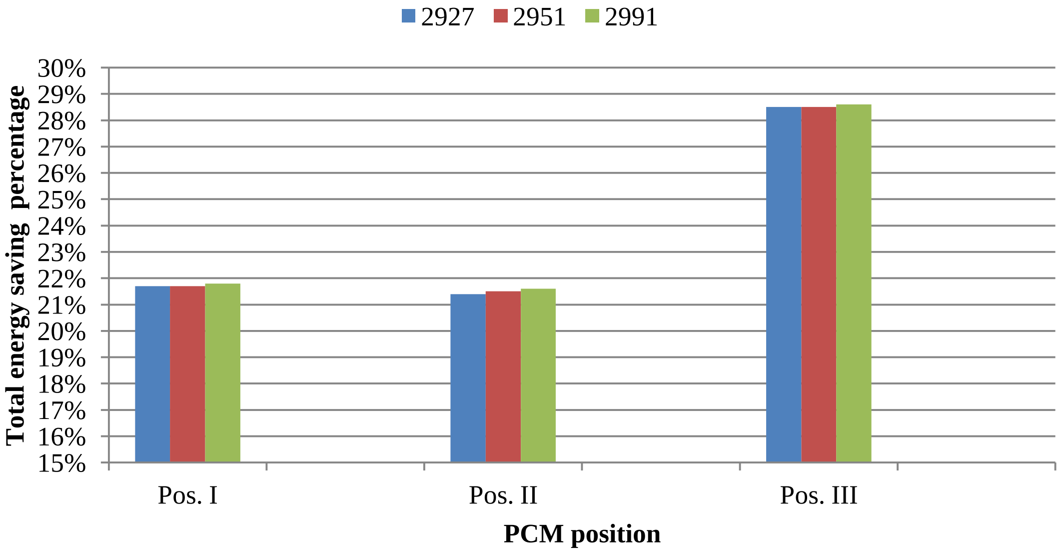

Figure 7.7 Total energy saving percentage for the PCM materials examined

Table 7.3 Results of the energy rate control simulation for the combined and the insulation cases

	Combined cases				Insulation cases			
	2991-SC2		2991-SC5		SC2		SC5	
	QHEAT	QCOOL	QHEAT	QCOOL	QHEAT	QCOOL	QHEAT	QCOOL
Heating and cooling demand per m^2 (kWh/yr m^2)	89.9	50.3	86.5	48	64.3	97.6	59.2	92
Total energy demand (kWh/yr m^2)	140.2		134.5		161.9		151.2	
Heating and cooling energy savings per m^2 (kWh/yr m^2)	175.6	98.7	179	101	201.2	51.4	206.3	57
Total energy savings (kWh/yr m^2)	274.3		280.1		252.6		263.3	
Heating and cooling energy savings percentage per m^2 (% kWh/yr m^2)	66.1%	66.3%	67.4%	67.8%	75.8%	34.5%	77.7%	38.3%
Total energy savings percentage (% kWh/yr m^2)	66.2%		67.6%		61%		63.5%	

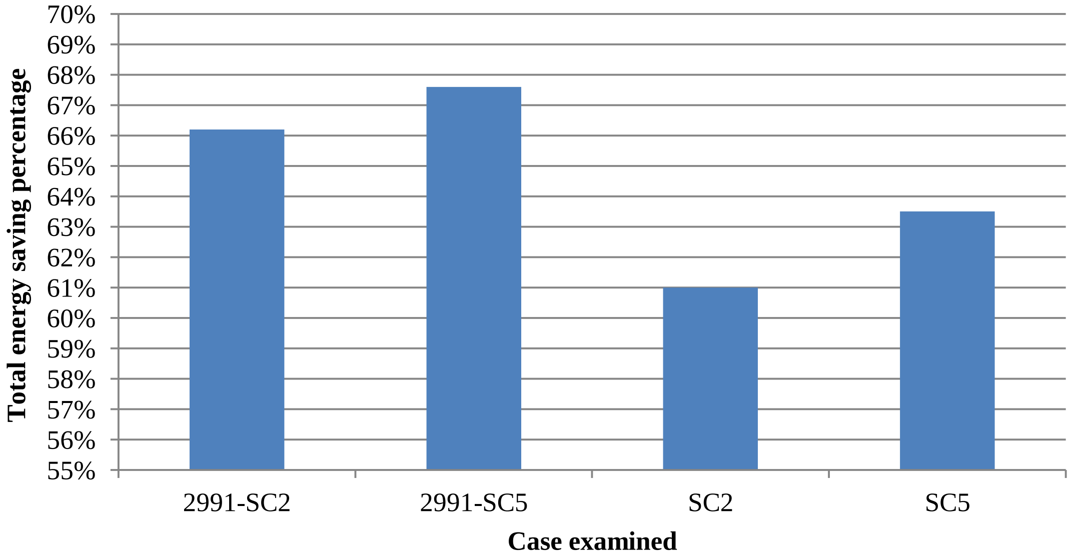

Figure 7.8 Total energy saving percentage for the combined and the insulation cases examined

7.4.2 Temperature level control simulation

The results of the temperature level control simulation for the coldest days of winter (3rd-4th of February) and the hottest days of summer (26-27th of July) are depicted in Figures 7.9 and 7.10 respectively. In these figures the free-floating temperature for the base case, the optimum PCM case, the insulation cases (SC2 and SC5) and the combined cases (PCM-SC2 and PCM-SC5) are plotted.

As can be seen the optimum cases for winter conditions are the insulation only followed by the combined ones. As expected the optimum case is the one where more insulation is used (SC5) which has a difference of 3-4^{o}C when compared with the base case followed by SC2 which has a difference 2.5-3^{o}C. The combined cases have a difference between 0.8-1^{o}C when compared with the insulation cases while between them only have a difference of 0.1^{o}C, which is negligible. The combined cases have a difference of 2-2.5^{o}C compared to the base case. The PCM only case has a difference between (-0.2)-1^{o}C when compared to the base case. As it can be seen between16:00-20:00 the mean air temperature of the PCM case is slightly lower (0.2^{o}C) than that of the base case a fact that can be attributed to the low response time of the PCM layer to the sudden rise of the temperature.

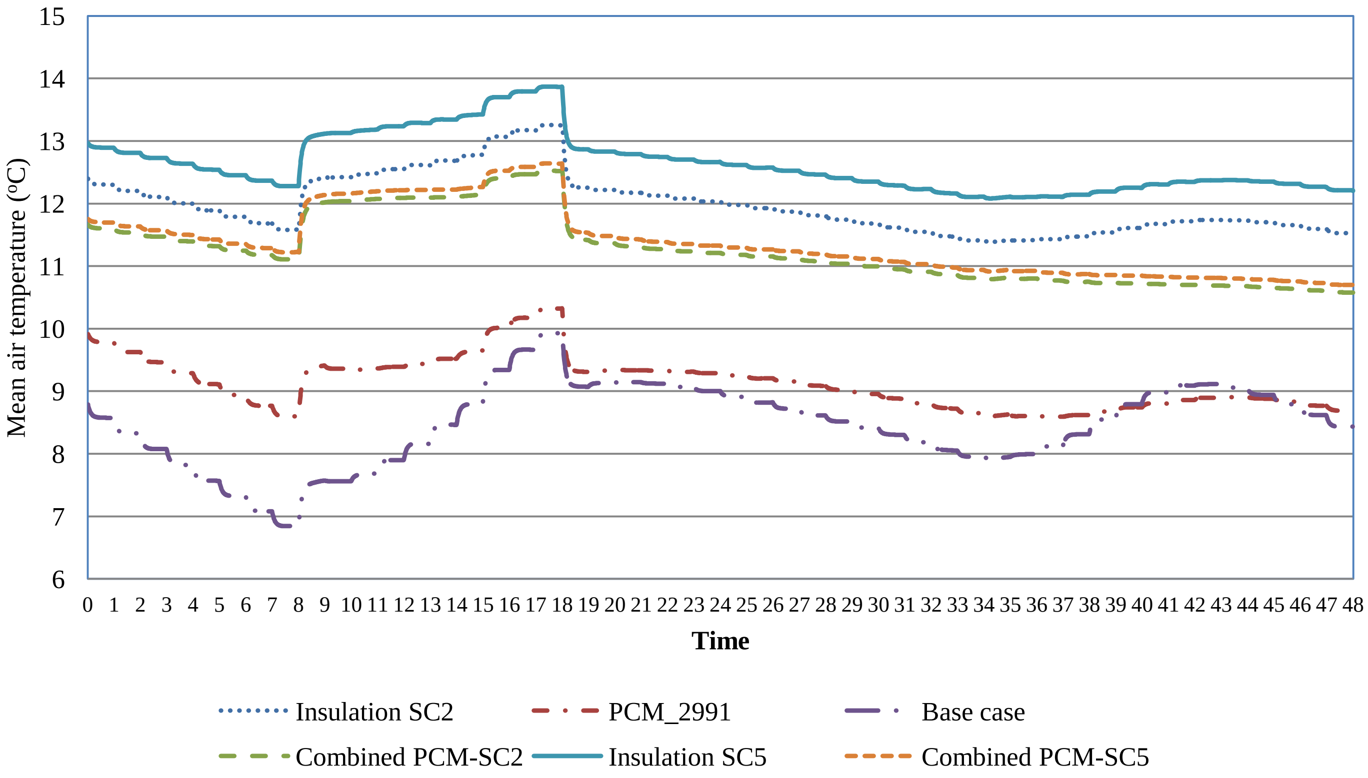

Figure 7.9 Free-floating temperature for all cases examined during the 3rd-4th of February

In the contrary during summer period the optimum cases are the combined ones (PCM-SC2 and PCM-SC5), where the PCM is combined with the insulation, with a very slight difference between them in the range of 0.1-0.2°C. It should be noted that for these two cases the temperature variation is much smoother than the other cases examined due to the application of the PCM layer. A very interesting observation is the fact that the mean air temperature for both insulation cases between 02:00-14:00 exceeds that of the base case due to the fact that the heat that entered the space is trapped into the cubicle and it cannot escape. When comparing the two insulation cases it can be easily observed that the mean air temperature of SC5 is higher than that of the SC2 due to the additional insulation used. However, when a PCM layer is installed on the walls and roof (PCM only case) this is not happening while this case is also slightly better than both insulation cases with a difference between 0.1-1.1°C.

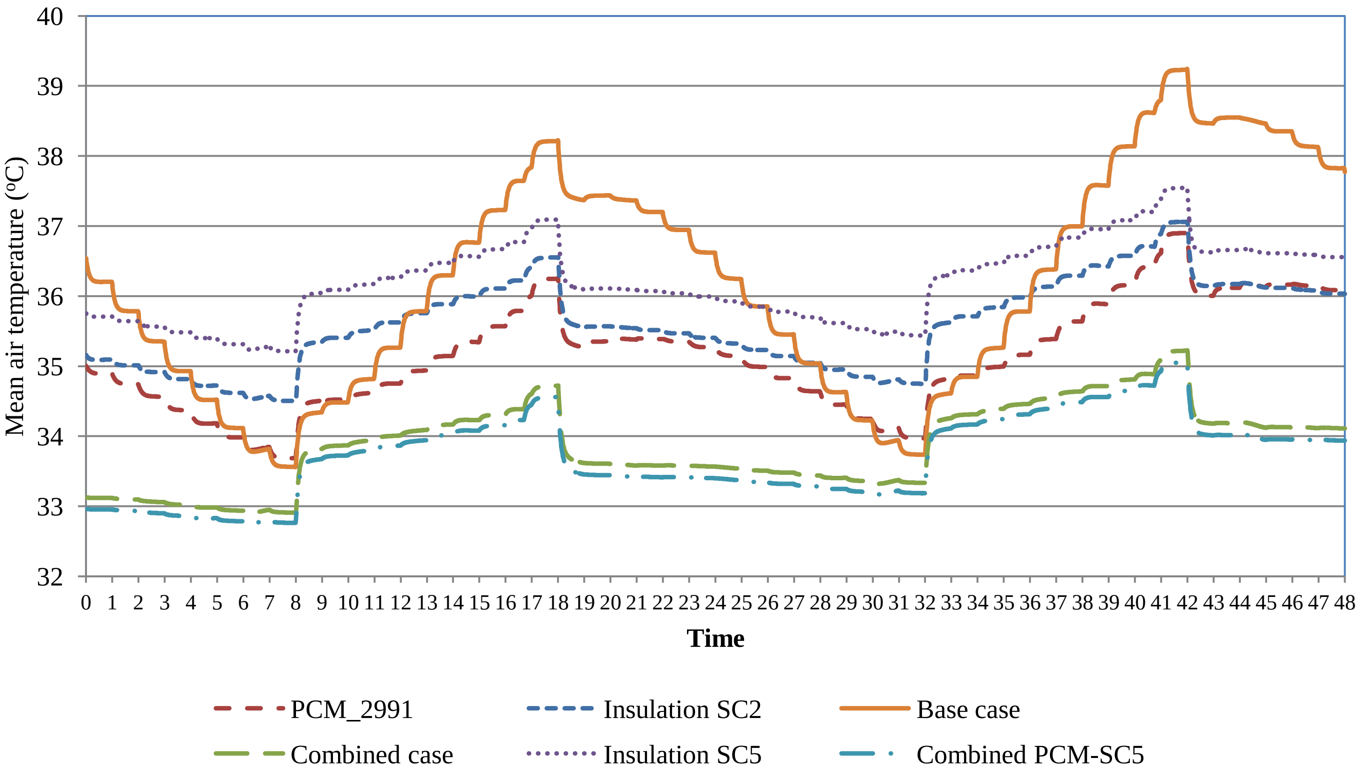

Figure 7.10 Free-floating temperature for all cases examined during the 26-27th of July

7.4.3 Application on the envelope of the typical dwelling

The energy savings that will occur if the cases examined above (optimum PCM case and combined cases) are applied to the model dwelling of Chapter 3 are estimated in this section so as to be used in the LCC analysis. This is done by multiplying the respective energy savings percentage with the energy consumption of the typical dwelling which was calculated in Chapter 6. The results are presented in Table 7.4 in terms of both energy and money savings and are evaluated in the following section.

Table 7.4 Results of the application of the cases examined to the envelope of the typical dwelling

	PCM only	PCM-SC2	PCM-SC5
Energy savings percentage (%)	28.6%	66.2%	67.6%
Total annual energy savings (kWh/yr)	8,703	20,143	20,567
Total annual money savings (€/yr)	1,271	2,941	3,003

7.4.4 Life Cycle Cost (LCC)

By using the results of the previous section concerning the savings (energy and money) that will occur if the examined cases are applied to the typical model dwelling the LCC of each case is carried out and the results are presented below. The economic data used in the LCC are the same as those used in Chapter 6 and are repeated in Table 7.5 below.

Table 7.5 Economic data used for the LCC

Current price of electricity in Cyprus without VAT and additional taxes (€/kWh) (EAC, 2010)	0.146
Discount rate (%) (MCIT, 2012)	5.74
Annual increase in electricity price (%) (Capros, 2010)	3.00
Interest rate (%) (MOF, 2012)	5.40

- **Optimum PCM case (2991)**

The results of the LCC for the optimum PCM case (2991) concern the cost of the investment, the NPV, the Payback period and the annual money savings. For the estimation of the cost of the PCM the online cost calculator provided by the manufacturer is used (Phasechange, 2013). The cost of the PCM material was calculated to be €22,490. The payback period of the investment is calculated to be 14.5 years, the economic benefit at the end of the lifetime of the materials, expressed as NPV, is €35,942 and the IRR is 4%.

- **Combined case (PCM-SC2)**

The cost of the combined case (PCM-SC2) is €23,259 which is only €769 higher than the PCM only case and this represents the additional cost for the insulation of a ND. The results of the LCC show that the payback period of the investment is 7.5 years, the economic benefit at the end of the lifetime of the materials, expressed as NPV, is €110,416 and the IRR is 14%.

- **Combined case (PCM-SC5)**

The cost of the combined case (PCM-SC2) is €25,612 which is €3,122 higher than the PCM only case and in this case represents the additional cost for the insulation of an ED. According to the results of the LCC for the combined PCM-SC5 case the payback period of the investment is calculated to be 7.5 years, the economic benefit at the end of the lifetime of the materials used, expressed as NPV, is €110,972 and the IRR is 13%.

The results of the LCC presented in this section show that the application of only PCM to a dwelling is not yet economically viable due to the high initial cost compared to the insulation cases examined. This results to a rather high payback period and low IRR.

7.5 VALIDATION OF THE RESULTS

The results of this chapter are validated according to that of other studies which are presented in Table 7.6. As it can be seen the calculated energy saving during winter period is slightly higher than that of other studies. During summer period the calculated energy saving is also higher, as expected, than that of other studies. A possible explanation is that the maximum ambient air temperature in Nicosia in summer is much higher compared to the other locations examined and thus the consequent energy saving is also higher. Finally, the results concerning the reduction of the mean air temperature of the interior are in very good agreement with the results of other studies. This fact is very important since this test presents the behaviour of the PCM much more accurately than the energy rating test which inserts many other parameters that might cause differentiation of the results.

Table 7.6 Results of other PCM studies for the validation of the results of this Chapter

Studies	Kind of study	Location	Energy savings		Mean air temperature reduction
			Heating	Cooling	
Zhou et al. (2007)	Experimental	Beijing, China	-	-	1-2°C
Stetiu & Feustel (1998)	Theoretical	California, USA	-	28%	-
Ismail & Castro (1997)	Experimental & Theoretical	Campinas, Brasil	-	31%	-
Athienitis et al. (1997)	Experimental & Theoretical	Montreal, Canada	15%	-	4°C
Chen et al. (2008)	Experimental	Beijing, China	17%	-	-
Kong et al. (2013)	Experimental	Tianjin, China	-	-	1-3°C
Cabeza et al. (2007)	Experimental	Puigverd of Lleida, Spain	-	-	2°C
Ibánez et al. (2005)	Experimental & Theoretical	Puigverd of Lleida, Spain	-	-	3°C
Current study	Theoretical	Nicosia, Cyprus	23.5%	37.4%	2.5-3°C

7.6 SUMMARY

In this Chapter the application of macroencapsulated PCM on the envelope of a test cubicle in Cyprus was theoretically evaluated. The PCM employed during the simulation process had a melting temperature of 29°C.

The results of the energy rate control showed that the optimum position of the PCM layer when applied to an external wall is between the outer side of the brick towards the exterior environment and the plaster layer. This happens due to the fact that in this position the PCM is more exposed to the outer conditions such as temperature and solar radiation and thus it is more active. In this case an energy saving of 28.6% was achieved.

The optimum PCM case was then combined with the optimum thermal insulation topologies of Chapter 6 (SC2 and SC5) and the results showed that the case with the maximum energy savings was PCM-SC5 case with an energy saving of 67.6%. The difference between the insulation only cases and the combined cases ranged between 2.7-6.6%.

In the temperature level control simulation the cases containing PCM performed better in summer while during the winter conditions it did not work very well. Specifically, during winter period the optimum cases are the insulation ones followed by the combined ones. On the contrary during summer time the optimum cases are the combined ones were the mean air temperature is 3-5ºC lower than the base case (PCM-SC2 and PCM-SC5).

The savings that will occur if the optimum PCM layer is applied on the envelope of the typical dwelling were estimated and the results showed that the highest energy and money savings are achieved by the combined case PCM-SC5 and are 20,567kWh/yr, 3,003€/yr respectively.

Finally, the results of the optimum PCM case and the combined cases were economically evaluated using LCC. The results showed that the case employing only PCM is not considered to be a very attractive solution, in monetary terms, due to the combination of the high initial cost and the annual money saving which result to a very long payback time of 14.5 years. This is changing when the PCM is combined with thermal insulation where the payback period is reduced to 7.5 years.

From the results of this Chapter it is concluded that the application of macroencapsulated PCM on the envelope of dwellings in Cyprus is considered to be an attractive solution in terms of energy saving and sustainable development while in monetary terms it is not yet attractive.

CHAPTER 8

INCORPORATION OF RES TO THE TYPICAL DWELLING

The purpose of this Chapter is to evaluate the incorporation of RES to the typical model dwelling. More specifically, the design of several renewable standalone power systems is presented which are consequently evaluated and compared. The systems designed and compared are a standalone PV system and a hybrid standalone PV-Wind system both with battery storage. Finally, the optimum system is also evaluated for the case where it is grid-connected.

8.1 BASELINE SCENARIO CHARACTERISTICS

In order to design a standalone energy system for application in a dwelling the first step is to define a baseline scenario concerning the structure, location, occupancy and energy systems installed in the dwelling examined. The data used to define these characteristics were based on the model dwelling defined in Chapter 3. It is very important to note that the baseline scenario concerns a future situation where all energy for the dwelling is supplied by a RES system and the system is isolated from the grid.

For the design of these systems it should be noted that there are 130 m^2 of free space on the roof of the dwelling for any systems such as solar thermal or PVs to be installed. The heating and cooling is covered with split type air conditioning/heat pump units and the number of units installed are two 9,000 BTU/hr (2.6 kW) in two of the three bedrooms and one 12,000 BTU/hr (3.5 kW) unit in the living room. Additionally, during the winter period a stove and a fire place are also used. For the production of domestic hot water (DHW) a solar water heating system is used while an immersed electric element (3kW) is used for backup. The kitchen is using LPG for cooking while the oven is electric.

8.2 TYPICAL ANNUAL LOAD PROFILE DEFINITION

The typical annual load profile is defined using the findings of Panayiotou *et al.*, (2010) were it was observed that there are two peaks on the consumption of electricity in the domestic sector annually; one in summer (24 kWh/day), which is the highest, and one in winter (21 kWh/day). Autumn and spring periods have more or less the same consumption of electricity (15 kWh/day) which is lower compared to that of summer and winter.

In order to define the load profile of the typical dwelling it is imperative not only to know the occupancy profile of the occupants but also the number and type of electric appliances used along with their specific power which when multiplied by the number of operation hours per day will result to daily electricity consumption. These data can be seen on Table 8.1 and are based on the values given on an informational leaflet published by the Electricity Authority of Cyprus.

Table 8.1 Electric appliances used along with their power.

Device	Quantity	Power [W per device]
Washing machine	1	1,020
Refrigerator	1	65
Oven	1	890
LCD TV	1	200
Iron	1	2,400
PC	1	300
Printer	1	150
Lamps_1	5	60
Lamps_2	5	100
DVD player	1	15
A/C unit (9,000 BTU/hr)	2	2,640
A/C unit (12,000 BTU/hr)	1	3,510

To be more precise on the definition of the typical annual load profile this was split into weekdays and weekends for each one of the four seasons. The months contained in each season are as follows:

- Winter: December, January, February
- Spring: March, April, May
- Summer: June, July, August
- Autumn: September, October, November

The typical load profiles for both weekdays and weekends for each season can be seen in Figures 8.1 to 8.6. It should also be noted that the first day of the typical year examined is assumed to be a Monday and that February has 28 days.

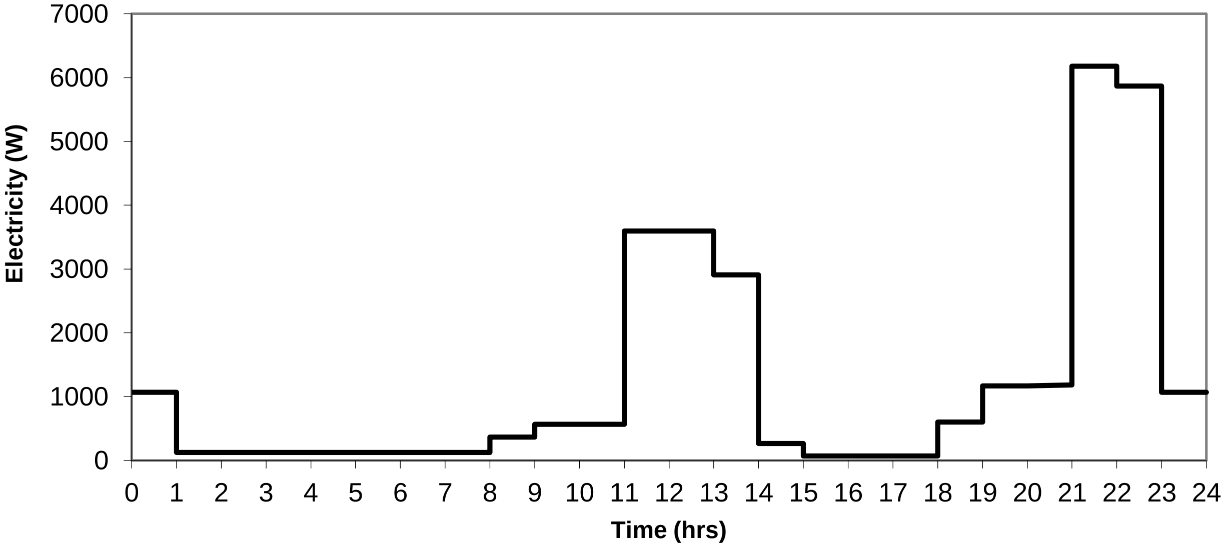

Figure 8.1 Load profile for a typical summer weekday

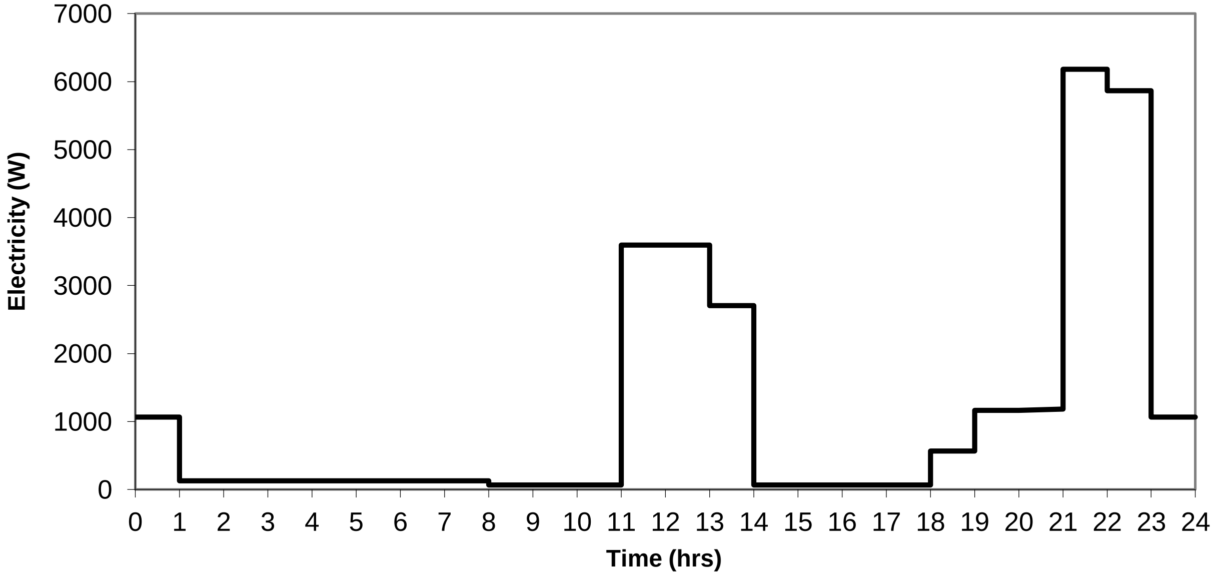

Figure 8.2 Load profile for a typical summer weekend day

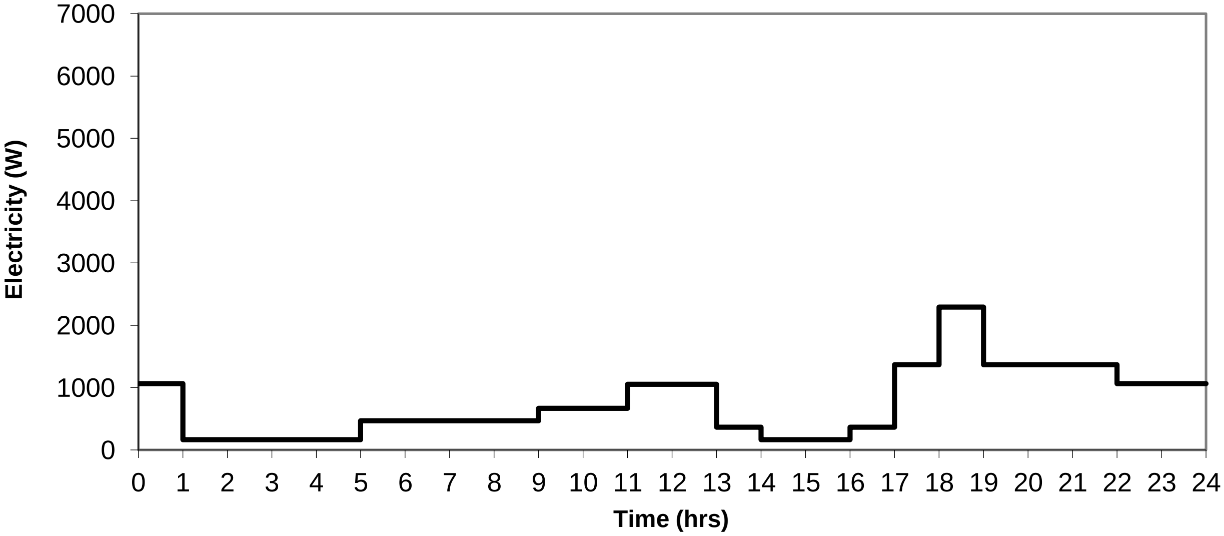

Figure 8.3 Load profile for a typical spring/autumn weekday

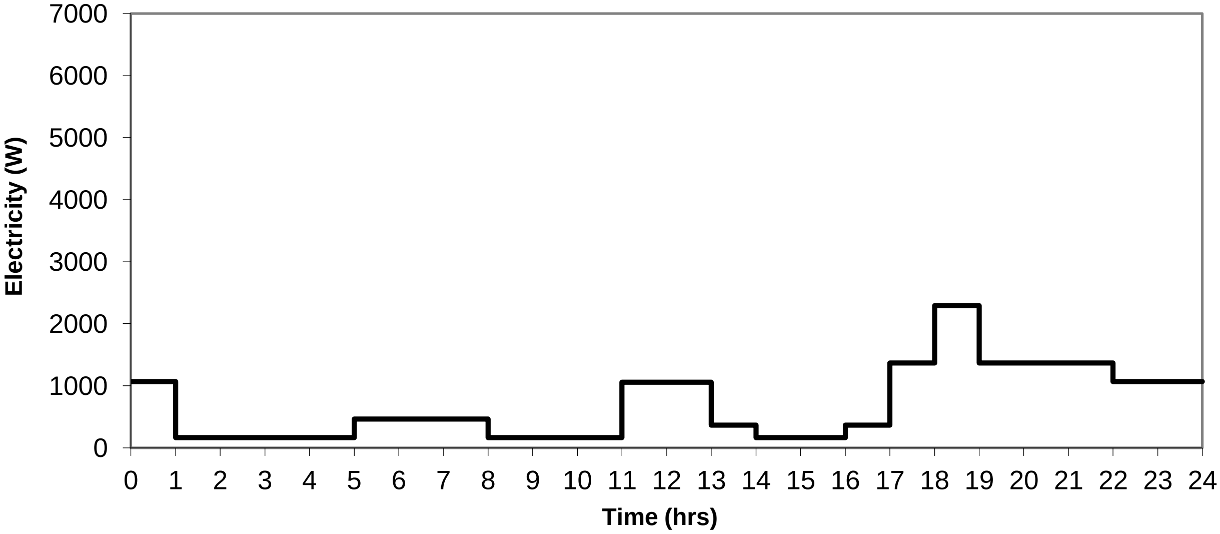

Figure 8.4 Load profile for a typical spring/autumn weekend day

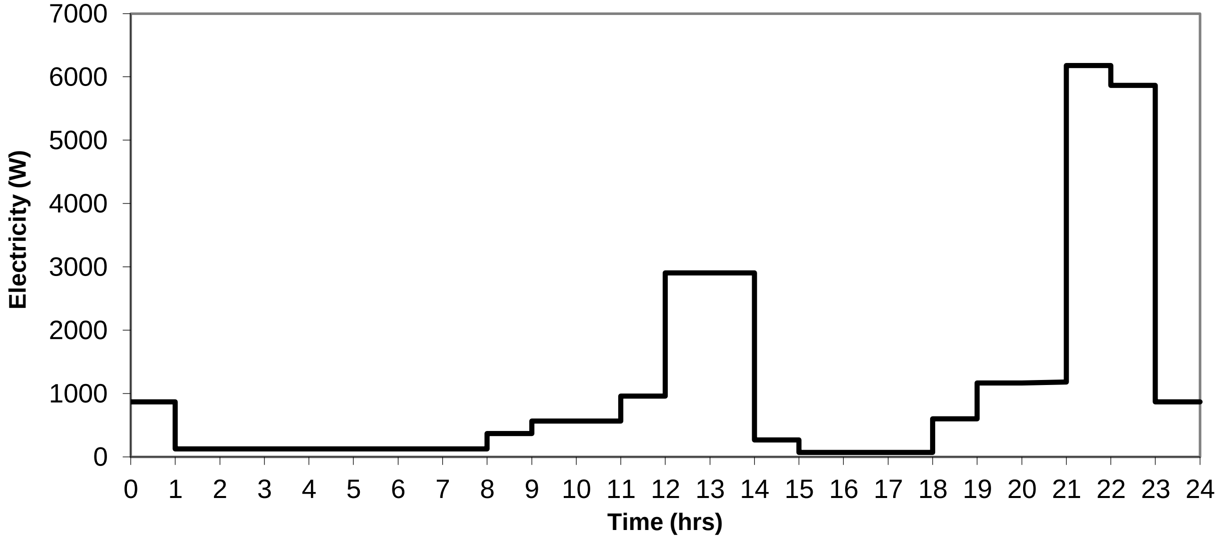

Figure 8.5 Load profile for a typical winter weekday

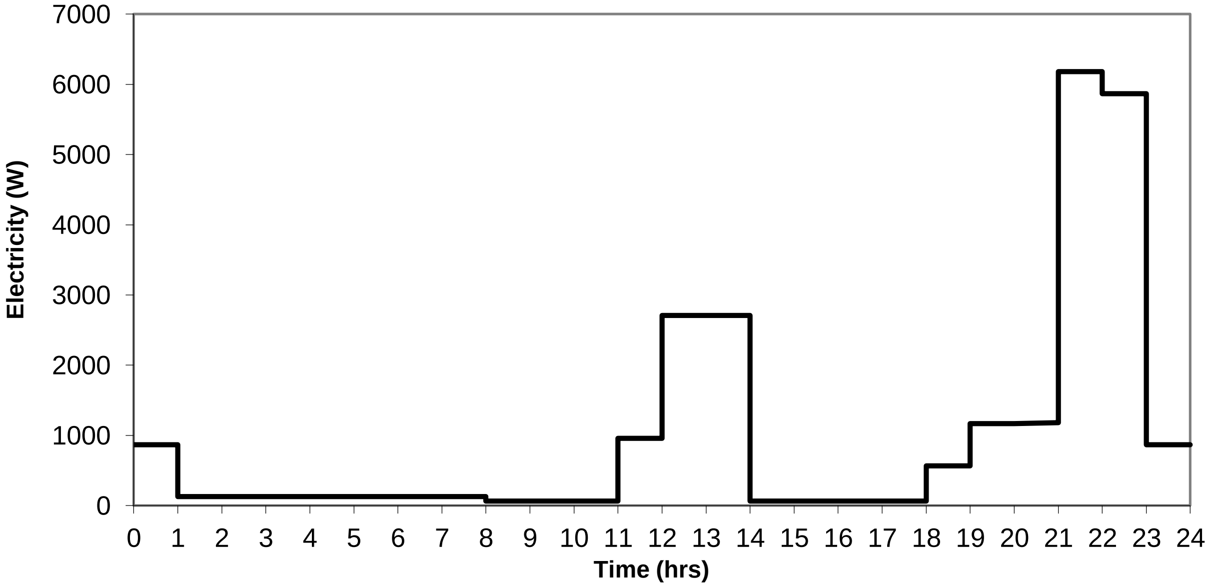

Figure 8.6 Load profile for a typical winter weekend day

8.3 MODEL DESIGN FOR STANDALONE PV SYSTEM

The model design process is carried out using the environment of TRNSYS. The model of the standalone PV system consists of the following components:

- Weather data processing model
- PV model
- Inverter/Regulator model
- Battery model
- Load Profile model

The specific model of each component listed above is analytically presented in the following subsections.

A very important parameter to consider when designing a standalone PV system is the nominal voltage of the battery bank that can be 12, 24 or 48 VDC. The parameters affecting the definition of the suitable nominal voltage for a system are the nominal voltage of the PVs, the size of the system and the input requirements of the inverter. The nominal voltage of the majority of commercially available PVs is around 24 V while the nominal voltage of the battery cells is 2 V.

A general rule when designing such a system is that the bigger the system the highest nominal voltage should be used. But this of course is very general and each system should be designed according to its specific needs. For example inverters which have a power of 6 to 12 kW require the nominal voltage to be 48 V while inverters with a power of 2 to 5 kW require a nominal voltage of 24 V. Since the system examined is neither a large system nor a small one it is decided that the nominal system voltage investigated should be 24 V. The main reason for this decision is that since with a rough estimation the system will not exceed 10-13 kW of PV power it is much better to use three inverters of 4 kW instead of one inverter of 10-13 kW in order to secure basic load coverage in the case of a failure of one of the inverters.

- **TMY-2 model – Type 109**

Type 109 model reads the Typical Meteorological Year (TMY-2) type 2 for Nicosia, Cyprus and generates the weather data needed by other components such as the PVs and the wind turbine. More specifically, the data read are the ambient temperature and wind velocity whereas total radiation on tilted surface is generated for the particular inclination of the solar receiving surface.

The TMY-2 used for the simulation process is developed by Kalogirou (2003) and it is generated from a simple TMY created in the past from available hourly meteorological data recorded during the period 1986–1992 using the Filkenstein–Schafer statistical method. The equations for converting radiation values from horizontal surface to inclined surface of PV are given in Chapter 2 of Kalogirou (2009).

- **PV model – Type 180e**

Type 180 model is a mathematical model for a photovoltaic (PV) generator, based on an equivalent circuit of a one-diode model. The model is primarily intended for PV-arrays consisting of silicon cells, but can also be used for other types of materials. The electrical model employed is described by Duffie and Beckman (1991). A dynamic thermal model has also been included (Ulleberg, 1997).

There are several different modes with which Type 180 can operate. The difference between them is whether a Maximum Power Point Tracking (MPPT) is used or not and the method used to calculate the temperature of the PV-array (TCMODE).

Type 180e corresponds to a PV-array where the MPPT is switched ON and the temperature of the PV-array is calculated based on an overall heat loss coefficient (U_L) and the thermal capacitance (C_T) of the PV-array, usually determined from experiments (TCMODE 3). The equations used in this model can be seen in Chapter 9 of Kalogirou (2009).

It should be noted that Type 180 has been validated by Quesada *et al.* (2011) using experimental data of a 7.2 kWp PV installation. The validation showed that the results of the model were in good agreement with the experimental ones.

It is also essential to know the slope of the PVs. A rule of thumb used in Cyprus is that the slope of PVs should be somewhere between 27-31°. In order to define the optimum slope to be used in the modelling process a small model consisting of a typical meteorological year (TMY) and a single PV was developed and a series of simulations were carried out for slopes between 27-33°. The energy production for each slope is presented in Table 8.2.

Table 8.2 Energy production from PVs in different slopes

Slope of the PV	Energy Produced [Wh/yr]
27 ^{o}	89,516
28 ^{o}	89,650
29 ^{o}	89,748
30 ^{o}	89,810
31 ^{o}	**89,835**
32 ^{o}	89,823
33 ^{o}	89,775

It can be seen that the maximum energy production occurs for a slope of 31^o and thus it is the optimum angle for the location examined.

The technical characteristics of the PVs used are presented in Table 8.3.

Table 8.3 PV characteristics on standard test conditions

(STC: T = 25^{o}C, G = 1000 W/m^2, AM = 1.5)

Technology: **Si-poly**		
Nominal Power	P_{nom}	180 W_p
Max. power point voltage	U_{mpp}	25.3 V
Max. power point current	I_{mpp}	8.11 A
Open circuit voltage	V_{OC}	30.95 V
Short circuit current	I_{SC}	8.69 A
Maximum System Voltage		750 V
Number of cells in series (P)		48
Area of the PV array (P)		1.33 m^2

- **Inverter/Regulator model – Type 48b**

In general, when designing standalone photovoltaic systems two power conditioning devices should be considered a regulator/charge controller and an inverter. The regulator or battery charger, as it is indicated by the name, is the component that regulates the distribution of DC power from the PV-array to and from the battery bank (in systems with energy storage) and to the inverter and subsequently to the load. The inverter on the other hand converts the DC power to AC and sends it to the load and/or feeds it to the utility grid.

Type 48 model includes both a regulator and an inverter routine, and can operate in one of four modes. Modes 0 and 3 are based upon the "no battery/feedback system" and "direct charge system," respectively. Modes 1 and 2 are modifications of the "parallel maximum power tracker system" in the same reference. Type 48b corresponds to Mode 1 where batteries are used for energy storage, the PV includes a MPPT tracker and the regulator is monitoring the state of charge (SOC) of the batteries.

This specific mode of operation gives the user the choice to decide if the priority is going to be given to charge the batteries (‘total charge’ mode) or to meet the load. In order to have a more holistic view of the behaviour of each mode on the system designed, both modes are evaluated. More details are given in section 8.4.

- **Battery model – Type 47a**

Type 47a is the model of a lead-acid storage battery which operates in conjunction with solar cell array and power conditioning components. It specifies how the battery SOC varies over time, given the rate of charge or discharge cycles. Type 47a corresponds to Mode 1, based on a simple energy balance of the battery where the power is simply taken as input. This model does not calculate nor gives any output of current or voltage values.

The variation of the state of charge of the battery during charge and discharge phases according to the model of Shepherd (1965) is given by:

$$V = e_{qc} - g_c H + I r_{qc} \left(1 + \frac{m_c H}{\frac{Q_c}{Q_m} - H} \right) \tag{8.1}$$

Where:

V = voltage;

e_{qc}= open circuit voltage extrapolated from V vs I curves during charge;

F = fractional state of charge;

H = 1-F;

g_c = small-valued coefficient of H in voltage-current state of charge formulas;

I = current;

r_{qc} = internal resistance at full charge when charging;

m_c = cell-type parameter which determine the shapes of the I-V-Q characteristics;

Q_c = capacity parameter on charge and

Q_m = rated capacity of cell.

The parameters required to be specified for the modelling of the batteries are presented in Table 8.4.

Table 8.4 Battery characteristics on standard test conditions

Technology: **Lead-acid, sealed, Gel Per cell Whole battery**		
Number of cells per battery	N_{cells}	1
Nominal voltage	V_{nom}	2.0 V
Nominal capacity (at discharge rate of 10 hours)	C_{nom}	1500 Ah (3.00 kWh)
Internal resistance	Int. Res.	0.1 mOhm
Coulombic efficiency	Eff.	97%
Size	W x H x D	0.28 m x 0.84 m x 0.22 m
Weight		120 kg

- **Load Profile model – Type 9a**

This component serves the purpose of reading data at regular time intervals from a data file, converting it to a desired system of units, and making it available to other TRNSYS components. This component is very general and can read many different types of files such as .txt files.

After the definition of the typical annual load profile in the previous section, the data were extracted into a data file, where in this case was a .txt file, for all 8,760 hours of the typical year.

8.4 EVALUATION AND ECONOMIC ANALYSIS OF STANDALONE PV SYSTEM

The configuration of the complete model of the system, where all components are connected together in the right order so as the system is fully functional, can be seen in Figure 8.7.

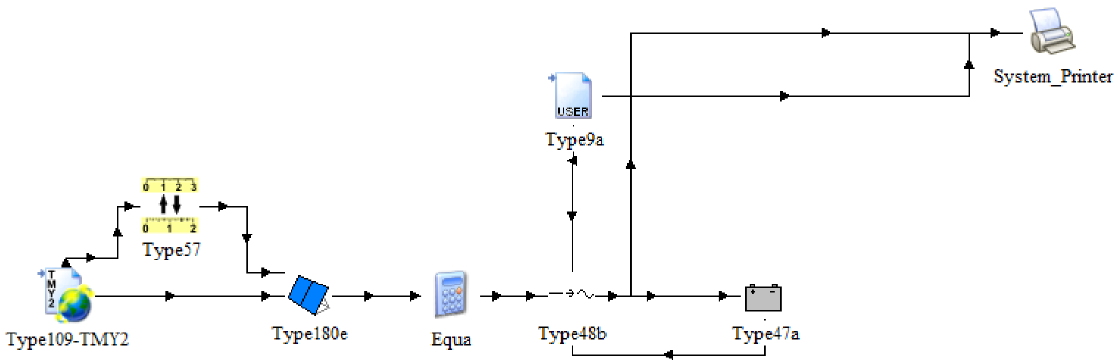

Figure 8.7 Configuration of the complete model for the standalone PV system

Type 57 is a unit conversion model and was used in order to convert the total radiation on a tilted surface from kJ/hr-m^2 to W/m^2 so that it is compliant with the input data of Type 180e. The Equation module is used to convert the power output of Type 180e from W to kJ/hr in order to be compatible with the input units of Type 48b.

When the setup of the complete model for the standalone PV system was complete, a series of simulations was carried out in order to specify the required storage capacity and PV array power necessary to cover the load over the time period of a typical year. Before running the simulations it is essential to decide the acceptable loss of load probability (LOLP) of the specific system which defines the required system autonomy in days. For example, if a 1% acceptable LOLP is chosen it means that during the time period of a year there is probability to have 3.65 days where the load will not be covered. Thus, if we want to design a system where we will have a 100% annual load coverage, then a first estimate for the required battery autonomy should be that of 4 days. It should be noted that the battery capacity must be larger than that calculated for the 4 days of autonomy due to the fact that it is impossible to start the 4 days of autonomy with the batteries fully charged as these always supply electricity to the system during night-time. Thus, in the system examined, it is predefined that one of the most important parameters to consider for the selection of the PV array size and the required storage capacity is to have 100% annual load coverage.

Since the nominal voltage of the battery bank is decided to be at 24 V and the nominal voltage of each battery cell is 2 V then the configurations of the battery bank used during the simulation consisted of 1, 2, 3 or 4 strings in parallel of 12 batteries connected in series. The results of the simulation process were recorded in a data file and subsequently processed to evaluate the load coverage achieved by each configuration. The most important results estimated during the simulation are presented in Table 8.5.The results are separated in two main categories for each mode of the inverter where it is clear that the results for the first mode of operation (Total Charge mode ON) are 2 to 2.5 times larger than the results for the second mode of operation (Total Charge mode OFF) of the inverter for the same system examined each time. For example, Configuration 1 has an energy deficiency of 1063 kWh while Configuration 9 (same as Configuration 1) has only 566 kWh. Additionally, Configuration 2 has an energy deficiency of 805 kWh while Configuration 10 has only 381 kWh. Consequently, it is concluded that the proper mode of operation of the inverter to apply for the system examined is the one that gives the priority on covering the load (Total Charge mode OFF). By using this control system we achieve to reduce both PV array power and energy storage capacity (number of batteries) installed and thus a much more affordable and viable system is designed.

Table 8.5 Results of the simulation process for the standalone PV system

Mode	Configuration Nº	Nº of PVs	PV array power	Nº of Batteries	Battery capacity	Annual Energy Deficiency	Annual period of Energy Deficiency
		[-]	[kW]	[-]	[kWh]	[kWh]	[hrs]
'Total Charge' ON	1	40	8.2	36	108	1063	1543
	2	45	8.1	36	108	805	1269
	3	50	9.0	36	108	665	1054
	4	60	10.8	36	108	446	704
	5	65	11.7	36	108	401	645
	6	40	8.2	48	144	938	1287
	7	45	8.1	48	144	700	991
	8	50	9.0	48	144	546	754
'Total Charge' OFF	9	40	8.2	36	108	566	607
	10	45	8.1	36	108	381	451
	11	50	9.0	36	108	228	220
	12	60	10.8	36	108	25	33
	13	63	11.34	36	108	12	2
	14	65	11.7	36	108	2	10
	15	40	8.2	48	144	496	503
	16	45	8.1	48	144	320	365
	17	50	9.0	48	144	193	186
	18	55	9.9	48	144	80	97
	19	58	10.44	48	144	13	29
	20	59	10.62	48	144	0	0

From the results of Table 8.5 it can be seen that the systems that can achieve 100% annual load coverage over a typical year are those of Configurations 14 and 20. It should be noted that these systems are coming from two different approaches with the difference being that Configuration 20 has larger energy storage capacity and lower PV array power while Configuration 14 has larger PV array power and lower energy storage capacity. This is a very important fact to consider when deciding which is the optimum configuration for the system designed.

In order to decide which is the optimum system configuration Configurations 14 and 20 are evaluated using Simple PayBack Period method (SPBP) for a total system life of 25 years. The reason for using this method is because the LCC cannot be used due to the significant changes in the prices of the systems' components (especially the PVs) over time which cannot be estimated. During this process the lifetime of each component is taken into consideration along with its current cost which comes from various sources and is presented in Table 8.6. The results of this analysis are presented in Tables 8.7 and 8.8 respectively.

Table 8.6 Equipment prices used in the economic analysis

	Equipment Description	**Price**
1	Photovoltaic panels	3.2 € per W
2	Batteries	640 € per pc
3	Inverter (2.5 kW, 12 V)	2,069 €
4	Mounting system (for flat roof)	200 € /kW
5	Electrical equipment (cables etc)	210 € /kW
Sources: **1, 4, 5**: Average current prices in Cyprus given by 'SW Solarwatt Ltd' (13/09/10). **2**: Quotation given by 'Digicom – The UPS company Ltd' on 27th of August 2010. **3**: http://www.eshop.com.gr, accessed on 13/09/10.		

By evaluating the results of the economic analysis it is concluded that the optimum configuration is that of Configuration 14 which consists of 65 PVs (11.7 kW) and 36 batteries. The cost of such a system is 104,271 €. It is very important to notice that in all cases examined the main part of the cost, around 50%, goes to the batteries. A cost analysis of the optimum configuration is presented as a pie chart in Figure 8.8, where despite the fact that we have chosen the system with the lowest possible number of batteries they still represent over 50% of the overall cost.

Since the optimum configuration estimated has 36 batteries it is concluded that the decision for the nominal voltage of the battery bank to be at 24 V was correct due to the fact that if 48 V was chosen then the battery bank configuration should have been either 1 or 2 strings of 24 batteries and it is obvious that the option of 24 batteries (1 string) would be undersized and thus insufficient while the option of 48 batteries (2 strings) would be oversized with a consequent increase of the overall cost of the system.

Table 8.7 Economic analysis results for the system of Configurations 14

Configuration 14						
	Equipment	**Number**	**Power**	**Lifetime**	**Price**	**Price overall**
1	PV	**65**	180 W	25	€ 37,440	€ 37,440
2	Inverter & Controller	**3**	4,500 W	15	€ 7,977	€ 15,954
3	Elec. Equip.	-	-	25	€ 2,457	€ 2,457
4	Mounting system	-	-	25	€ 2,340	€ 2,340
5	Batteries	**36**	1,500 Ah	18	€ 23,040	€ 46,080
					TOTAL	**€ 104,271**

Table 8.8 Economic analysis results for the system of Configurations 20

Configuration 20						
	Equipment	**Number**	**Power**	**Lifetime**	**Price**	**Price overall**
1	PV	**59**	180 W	25	€ 33,984	€ 33,984
2	Inverter & Controller	**3**	4,500 W	15	€ 7,977	€ 15,954
3	Elec. Equip.	-	-	25	€ 2,230	€ 2,230
4	Mounting system	-	-	25	€ 2,124	€ 2,124
5	Batteries	**48**	1,500 Ah	18	€ 30,720	€ 61,440
					TOTAL	**€ 115,732**

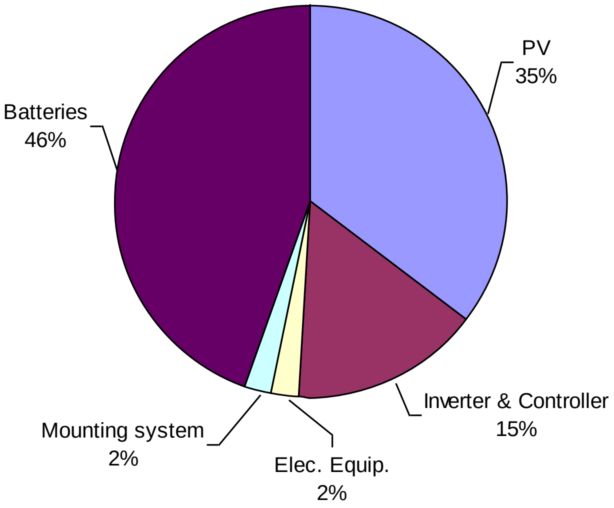

Figure 8.8 Pie chart showing the cost of each component for the optimum system configuration

The load coverage curve of randomly selected 24h periods for each season is presented in Figs 8.9-8.12. In these charts four different curves are plotted as follows:

- Load demand curve (Load),
- Energy generated from the PVs curve (P_{pv}),
- Energy to or from batteries curve (P_{bat})
- Excess energy which is dumped or not collected due to full batteries (P_{dumped}).

The negative part of P_{bat} curve indicates that the batteries are discharging at that moment in order to supply the required electricity to cover the load during periods when the energy generated by the PVs is insufficient for example during a cloudy day or night time. The peak of the P_{pv} curve appears to be around noon time in all seasons except winter period.

In all seasons the energy production by the PVs is higher than the load demand and thus it covers the load while at the same time it charges the batteries with the energy surplus. When the batteries are fully charged and there is no load to cover, then the excess energy is either not collected or dumped. The only season where the energy production by the PVs is lower than the load demand is in winter and so the load during winter is covered mainly by the batteries and only a small part is covered by the PVs. Consequently, the system is being oversized in terms of both generation and storage (PVs and batteries) in order to be able to have an almost 100% load coverage in all seasons and especially during winter time when the energy production by the PVs is the lowest annually. Although, Figure 8.9 shows a randomly selected winter 24h period it should be noted that other days during winter time have much better solar irradiation which charge the batteries adequately so as to supply the system during days of low or no sunshine.

Finally, from the analysis of the results it can be concluded that the possibility of long term energy storage for covering the winter load by using the energy surplus of other seasons is a very important and promising issue to be investigated.

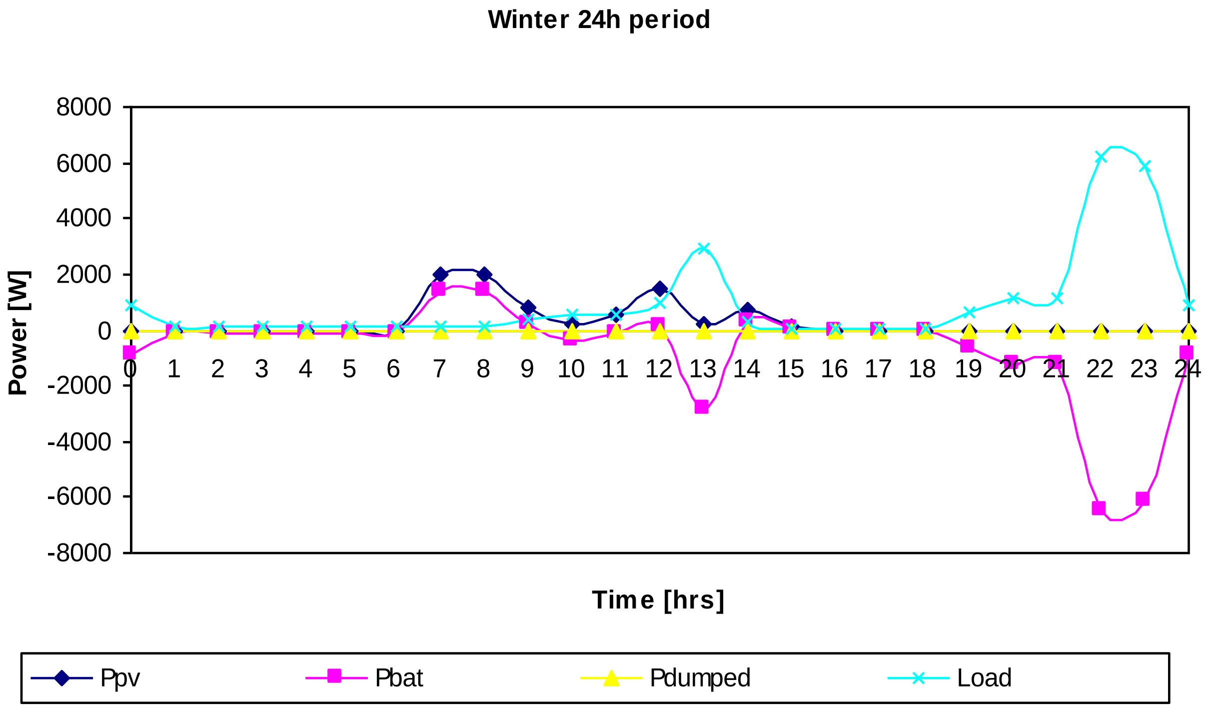

Figure 8.9 Load coverage curves during a randomly selected winter 24h period

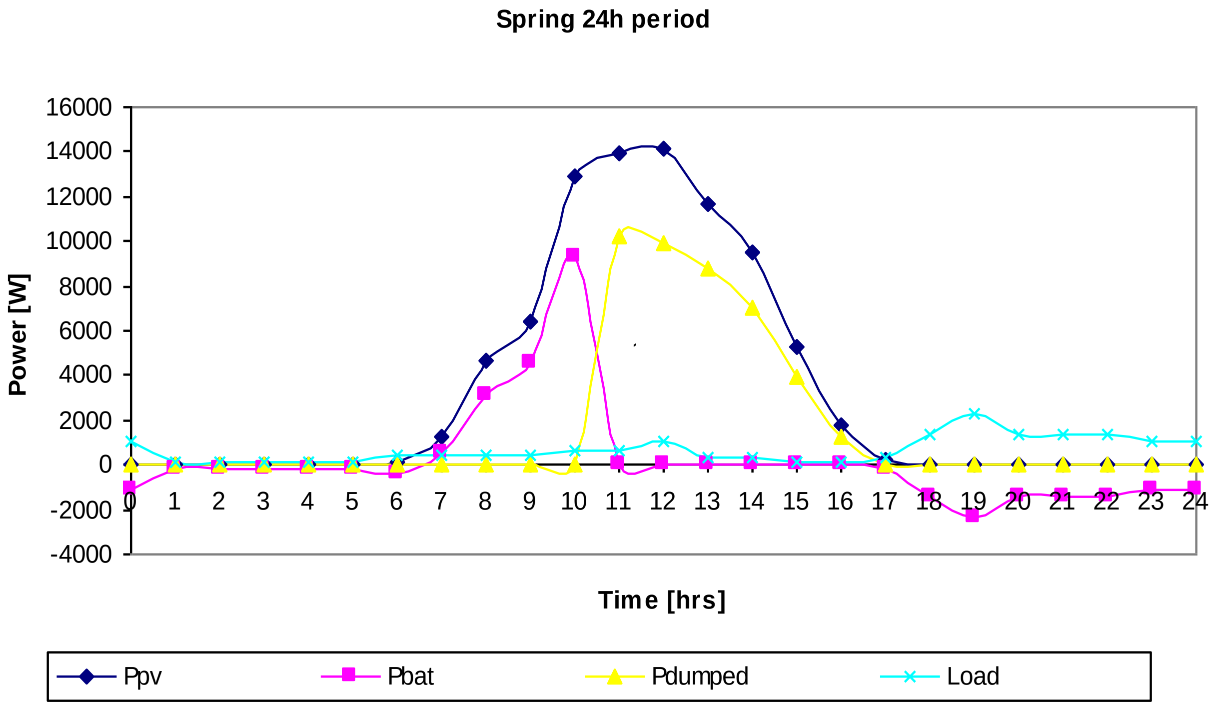

Figure 8.10 Load coverage curves during a randomly selected spring 24h period

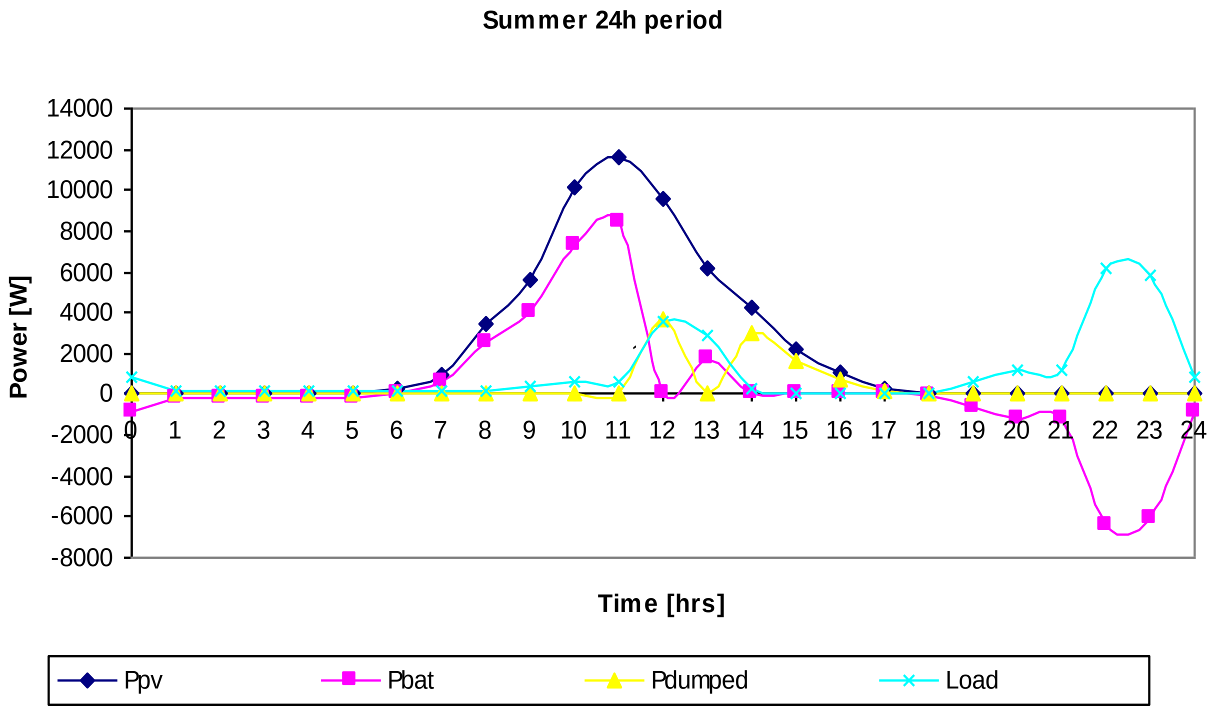

Figure 8.11 Load coverage curves during a randomly selected summer 24h period

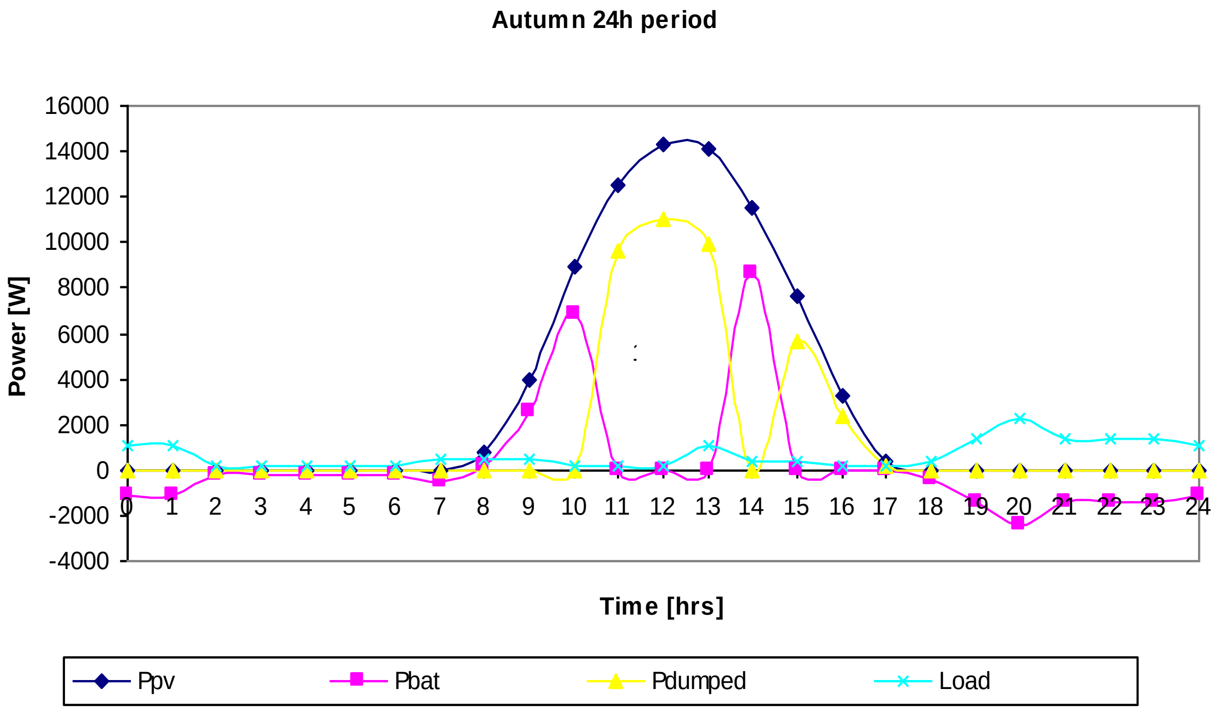

Figure 8.12 Load coverage curves during a randomly selected autumn 24h period

The seasonal and annual results of the simulation are presented in Table 8.9. These results concern the power produced by the PVs, the excess energy and the energy demand by the load. As it can be seen in this table the excess energy has its maximum peak in summer, it reduces gradually from spring to autumn and finally it meets its minimum peak in winter. It can also be observed that the energy produced by the PVs is much higher than the energy demand by the load. This is due to the fact that the system is oversized and also due to the different timing between the production and demand. This difference is causing the energy to be stored in the batteries and then to be fed to the load on demand. Due to these processes energy is subject to the efficiencies of the inverter, the regulator and the batteries and thus losses occur.

Table 8.9 Seasonal and annual simulation results

Season	**P_{pv}**	**P_{dumped}**	**Load**
	[kWh]	**[kWh]**	**[kWh]**
Winter	3,500	220	1,812
Spring	5,358	1,870	1,638
Summer	6,276	2,273	1,958
Autumn	4,926	1,535	1,705
Total	20,060	5,897	7,113

8.5 MODEL DESIGN FOR HYBRID STANDALONE PV-WIND SYSTEM

The model for the hybrid standalone PV-Wind is based on the model for the standalone PV system. The only difference is that in the PV-Wind system a small domestic wind turbine is incorporated into the system model. In this model, as in all hybrid power systems, more than one source of energy is used in order to diversify the sources and to achieve load coverage under various climatic conditions and during the entire 24 hour period. In the hybrid system considered, the power produced by the wind turbine is directly fed to the load through an inverter/power conditioner and the rest of the load is satisfied by the PV subsystem. For the design of this model two wind turbines were considered, 1.5 kW and 2.4 kW. The wind potential in the area investigated is shown in Figure 8.13. It can be seen that more than 86% of the time the wind velocity is between 0-6 m/s and the average velocity is 4 m/s. The characteristics of the two wind turbines considered are presented in Table 8.10 and their characteristic power versus wind velocity curves in Figures 8.14 and 8.15.

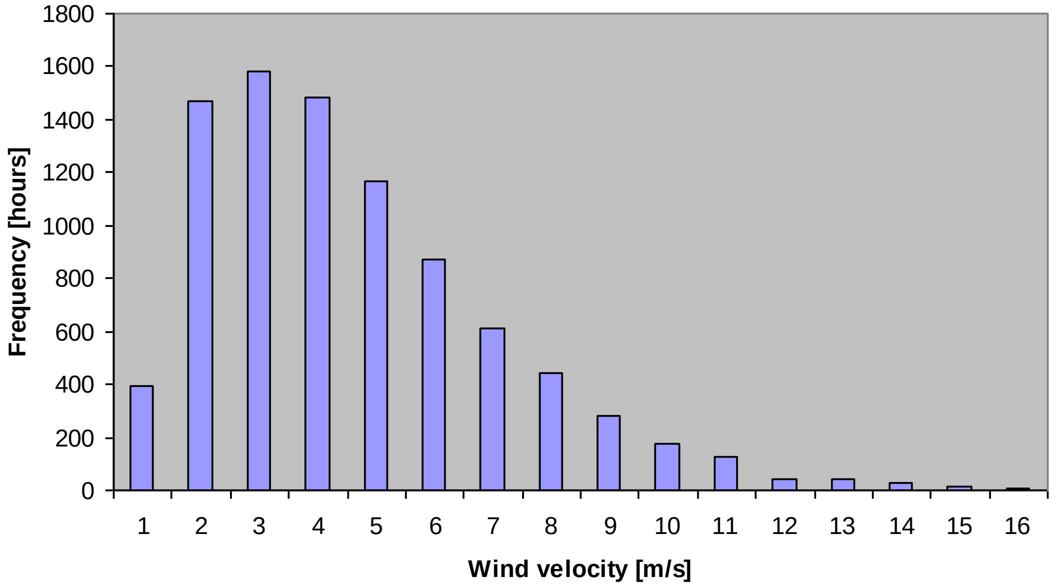

Figure 8.13 The wind profile of the investigated location (Nicosia, Cyprus)

Table 8.10 Wind turbine characteristics for both turbines examined (1.5 and 2.4 kW)

Characteristics of the two wind turbines considered	**Nominal Power (kW)**	
	1.5	**2.4**
Rotor centre height [m]	12	14
Rotor diameter [m]	3	3.72
Turbulence intensity valid for this curve	0.10	0.10
Power curve air density [kg/m^3]	1.225	1.225
Rated power of the turbine [kW]	1.5	2.4

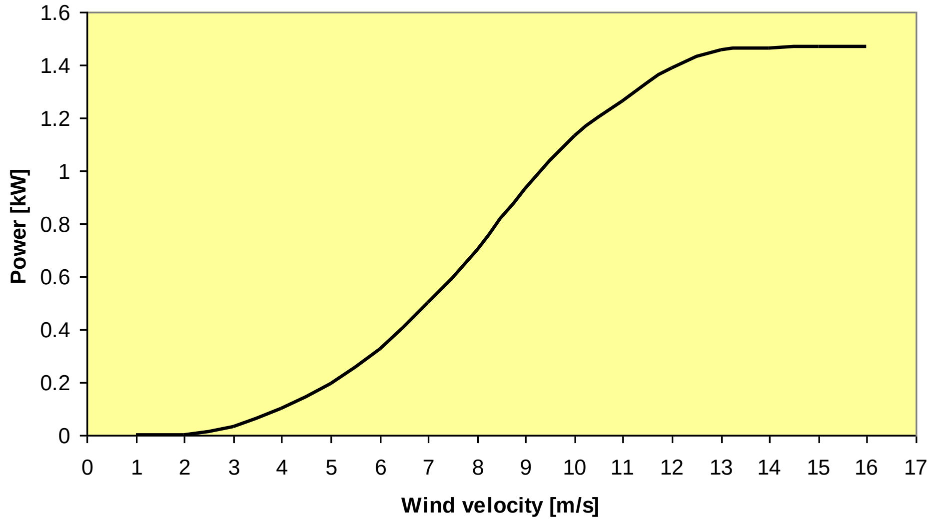

Figure 8.14 Characteristic power curve of the 1.5 kW wind turbine

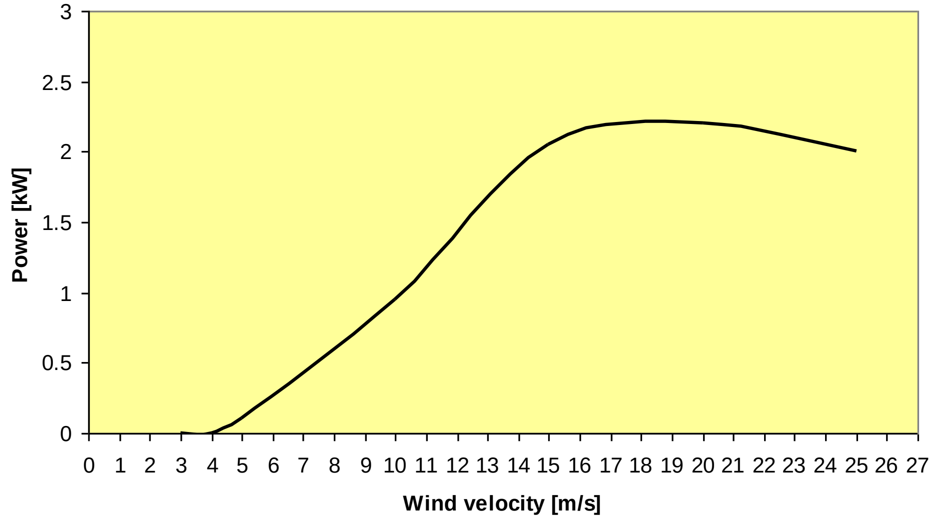

Figure 8.15 Characteristic power curve of the 2.4 kW wind turbine

Using the weather file (TMY2) model and the wind turbine model simulations were carried out to determine the energy that would be generated by the two wind turbines over a year. The results are presented in Table 8.11. It can be seen that the 1.5kW turbine will generate a slightly more energy than the 2.4kW turbine and this was selected for the analysis. The 1.5kW turbine will also have a lower cost.

Table 8.11 Simulation results for both wind turbines examined

Energy Produced [kWh]	**1.5 kW Wind turbine**	**2.4 kW Wind turbine**
Maximum	1.5	2.3
Average	0.146	0.145
TOTAL	1,279	1,271

The additional component of this model is the wind turbine and the model is presented below.

- **Wind turbine – Type 90**

Type 90 is a mathematical model for a Wind Energy Conversion System (WECS). The model calculates the power output of a WECS based on a power versus wind velocity characteristic (provided in a table form in an external file). This information together with the characteristics shown in Table 8.10 are the parameters used for the wind turbine model. The impact of air density change and wind speed increase with height is also modelled. The main equations used in this model are based on the work of Quinlan (2000) and Quinlan *et al.* (1996) and are presented below. In spite of the fact that Type 90 has been used in numerous studies (Bakić *et al.*, 2012; Ulleberg *et al.*, 2010; Samaniego *et al.*, 2008) to model a wind turbine within a RES system it has not been validated experimentally yet.

According to the momentum theory thrust force D can be expressed as follows:

$$D = \rho A_W U_W (U_0 - U_W) \tag{8.2}$$

Where:

ρ = air density,

A_W = area far downstream in the rotor wake,

U_W = velocity far downstream in the rotor wake and

U_0 = velocity in the free stream.

When considering Bernoulli's equation of the pressure difference across the rotor then thrust force can be also expressed as:

$$D = \frac{1}{2}\rho A_R (U_0^2 - U_W^2) \tag{8.3}$$

Where:

A_R = area of the rotor

The power output of a wind turbine can be written as the product of the thrust time rotor velocity.

$$P = DU_R \tag{8.4}$$

Where:

P = power output and

U_R = velocity of the rotor

Equation (8.3) can be substituted into Eq. (8.4) to create an expression for the power output.

$$P = \left(\frac{1}{2}\rho A_R (U_0^2 - U_W^2)\right) U_R \tag{8.5}$$

By substituting $U_R = U_0\ (1 - a)$ and $U_w = U_0\ (1 - 2a)$, where a is defined as the axial induction factor (or the retardation factor) and is a measure of the influence of the rotor on the wind, in Eq. (8.5) then it becomes:

$$P = \frac{1}{2}\rho A_R U_0^3 4a(1-a)^2 \tag{8.6}$$

The power coefficient for a wind turbine, C_P, is defined as the power of the turbine divided by the power in the wind. Thus, the power coefficient can be expressed as a function of the axial induction factor:

$$C_P = 4a(1-a)^2 \tag{8.7}$$

Finally, when power coefficient (C_p) is taken into consideration then Eq. (8.6) becomes:

$$P = \frac{1}{2}\rho A_R U_0^3 C_P \tag{8.8}$$

It should be noted that the maximum power coefficient was first derived by Betz in 1919 and has since been called Betz's limit and it equals to 59.3%.

8.6 EVALUATION AND ECONOMIC ANALYSIS OF STANDALONE PV-WIND SYSTEM

The configuration of the complete model of the PV-Wind system can be seen in Figure 8.16.

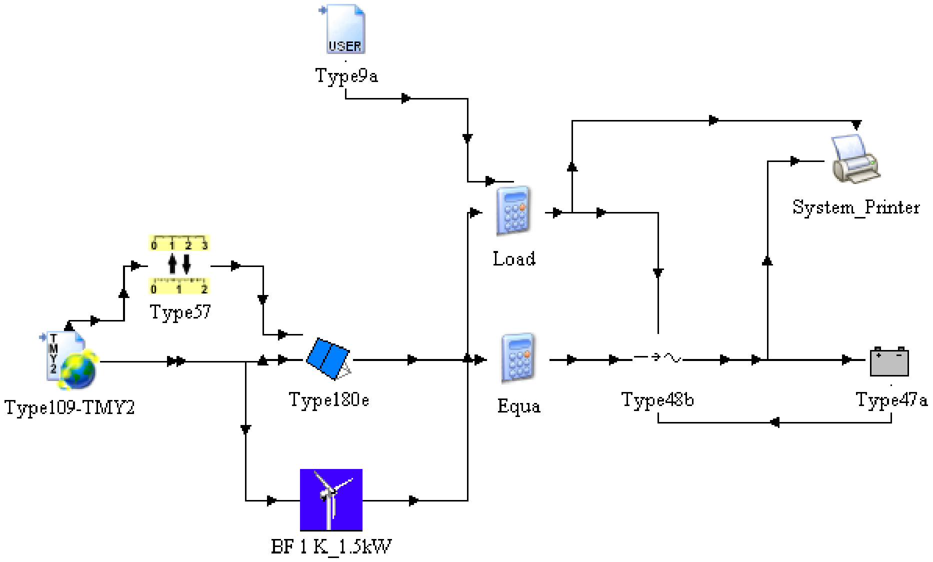

Figure 8.16 Configuration of the complete model for the standalone PV-wind system

The equation component ('Load') has been included to serve as a power conditioning unit and also to determine the load and the energy generated by the turbine. If the energy generated by the turbine is insufficient to cover the load, the balance is provided by the PV system. If the energy generated by the turbine exceeds the load then the excess energy is used to charge the batteries.

The simulation process used for this system is similar to the one carried out for the PV system.

Since the optimum capacity of the batteries to cover the load over a typical year was calculated to be 108 kWh, this capacity should also be the same for the case of the PV-Wind system as the energy provided by the wind turbine is very small. So, by keeping the battery capacity constant and altering the number of PV panels, and thus their power, several simulations were performed to identify the optimum system configuration.

The results of the simulation process were recorded in a data file and processed to evaluate the load coverage achieved by each configuration. The most important of the results are presented in Table 8.12. It can be seen that the system which achieves 100% annual load coverage over a typical year is that of Configuration 6.

Table 8.12 Results of the simulation process for the standalone PV-Wind system

Configuration Nº	Nº of PVs	PV array power	Nº of Batteries	Battery capacity	Annual Energy Deficiency	Annual period of Energy Deficiency
	[-]	[kW]	[-]	[kWh]	[kWh]	[hrs]
1	55	9.90	36	108	24	33
2	57	10.26	36	108	15	22
3	58	10.44	36	108	11	7
4	59	10.62	36	108	7	10
5	60	10.80	36	108	1	10
6	61	10.98	36	108	0	0

The load coverage curves of randomly selected 24h periods for each season for the PV-Wind system are presented in Figures 8.17 to 8.20. In these charts five different curves are plotted as follows:

- Load demand curve (Load),
- Energy generated from the PVs curve (P_{pv}),
- Energy generated from the wind turbine curve (P_{wind}),
- Energy to or from batteries curve (P_{bat}) and
- Excess energy that is either not collected or dumped curve (P_{dumped}).

An observation that could be made concerning the energy produced by the wind turbine is that it is generated during day-time and more specifically between 11:00-16:00. Nevertheless, it is more important to note that the amount of energy generated by the wind turbine is almost insignificant compared with that generated by the PVs. It can also be observed that during night-time the load is entirely covered by the batteries. It is important to note that as mentioned in Section 8.4 from the analysis of the results there is a possibility of long term energy storage to cover the winter load by using the energy surplus of other seasons. This is an area that merits further investigation.

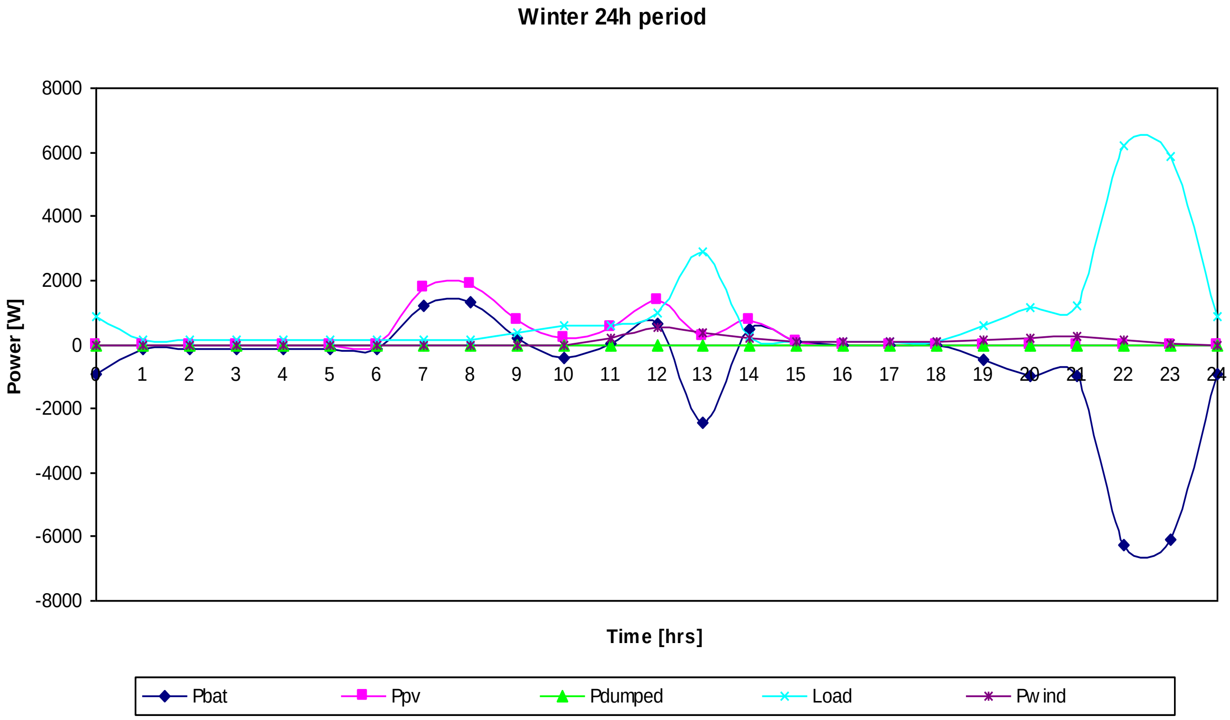

Figure 8.17 Load coverage curves of the PV-Wind system during a typical winter 24h period

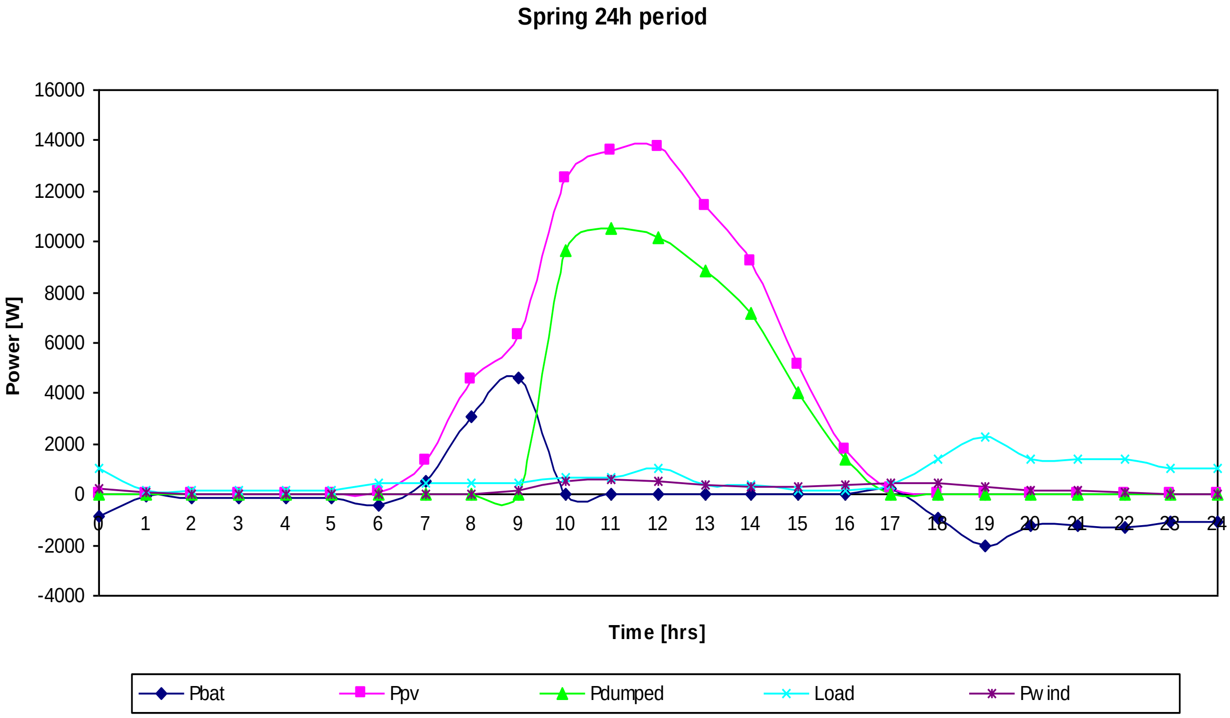

Figure 8.18 Load coverage curves of the PV-Wind system during a typical spring 24h period

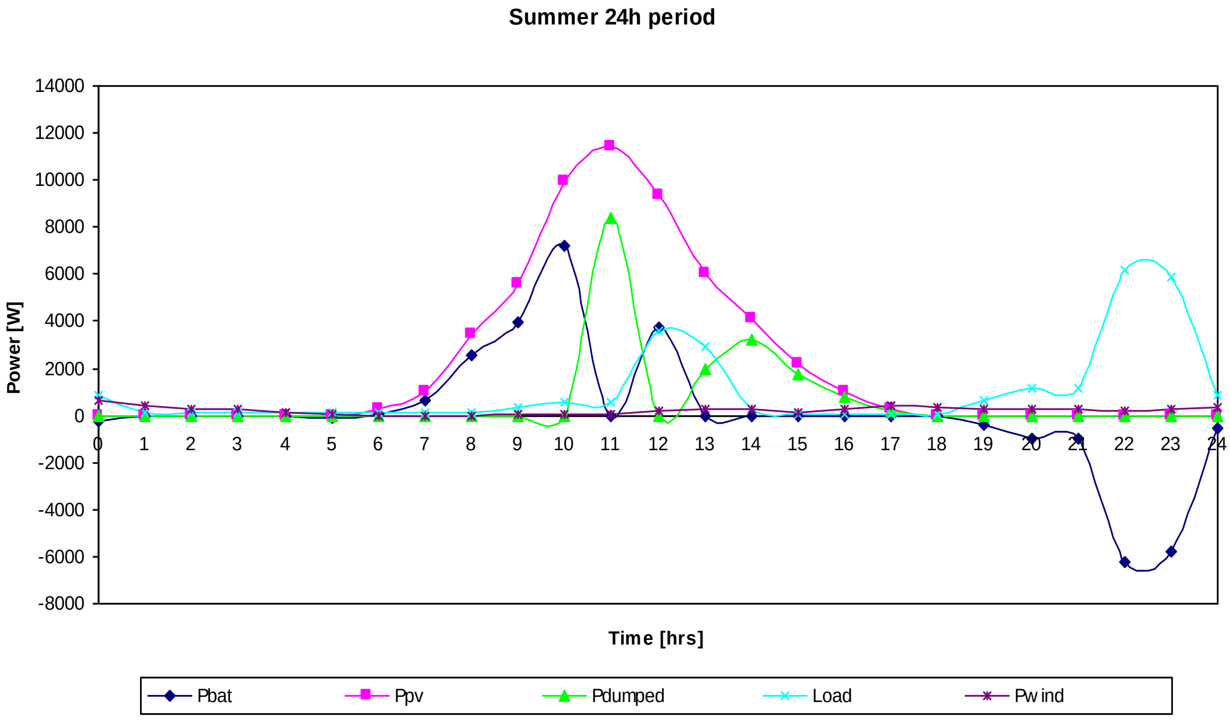

Figure 8.19 Load coverage curves of the PV-Wind system during a typical summer 24h period

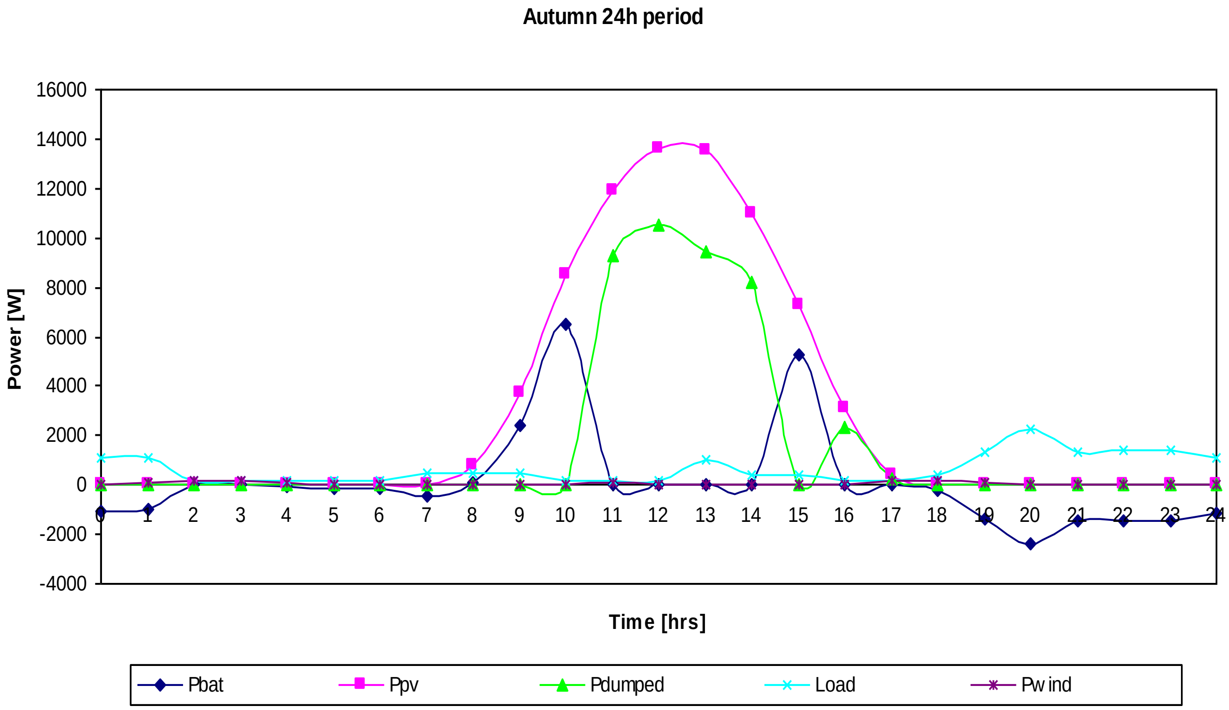

Figure 8.20 Load coverage curves of the PV-Wind system during a typical autumn 24h period

A cost analysis of the optimum configuration is presented in the form of a pie chart in Figure 8.21 where the batteries represent around 50% of the overall cost. The cost of the wind turbine (1.5 kW) is € 1,995 (http://www.eshop.com.gr, accessed on 13/09/10)

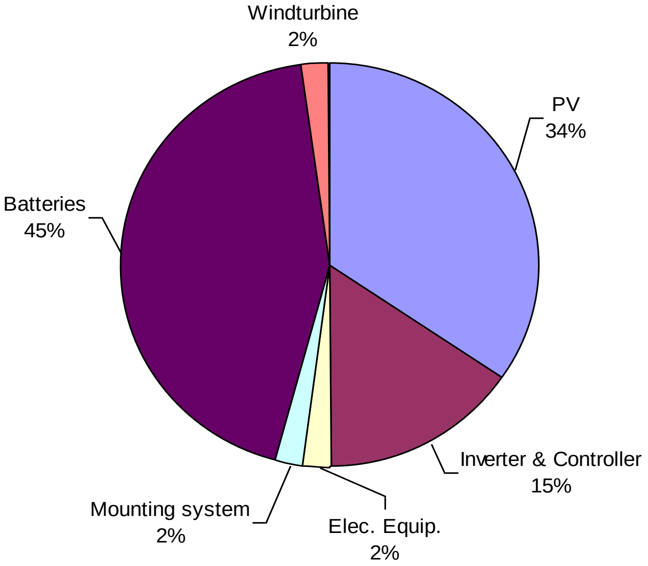

Figure 8.21 Pie chart showing the cost of each component for the optimum system configuration

8.7 COMPARISON AND CONCLUSIONS

The comparison was carried out for a lifetime of 25 years for both systems and the results were recorded in Tables 8.13 and 8.14 respectively.

Table 8.13 Economic analysis results for the PV system

PV system						
	Equipment	**Number**	**Power per component**	**Lifetime**	**Price**	**Price overall**
1	PV	**63**	180 W	25	€ 36,288	€ 36,288
2	Inverter & Controller	**3**	4,500 W	15	€ 7,977	€ 15,954
3	Elec. Equip.	-	-	25	€ 2,381	€ 2,381
4	Mounting system	-	-	25	€ 2,268	€ 2,268
5	Batteries	**36**	1,500 Ah	18	€ 23,040	€ 46,080
					TOTAL	**102,971 €**

Table 8.14 Economic analysis results for the PV-Wind system

PV-Wind system						
	Equipment	**Number**	**Power per component**	**Lifetime**	**Price**	**Price overall**
1	PV	**61**	180 W	25	€ 33,408	€ 35,136
2	Wind turbine	**1**	1,500 W	20	€ 2,250	€ 2,250
3	Inverter & Controller	**3**	4,500 W	15	€ 7,977	€ 15,954
4	Elec. Equip.	-	-	25	€ 2,192	€ 2,192
5	Mounting system	-	-	25	€ 2,088	€ 2,088
6	Batteries	**36**	1,500 Ah	18	€ 23,040	€ 46,080
					TOTAL	**€ 103,700**

From the results of the economic analysis it can be seen that the two systems have the same overall cost with a slight decrease (€ 1,000) in favour of the PV system.

From the results presented above it can be concluded that in spite of the fact that due to their ability to diversify the energy sources, hybrid systems are generally considered to be a better option for standalone applications, in the case of the location examined the PV-only system is a better option. This is due to the fact that the PV system is entirely based on the very high solar potential of Cyprus whereas the PV-Wind system relies on the very low wind potential observed in the area investigated, which is also typical for the whole island.

It should also be noted that by not using the wind turbine in a domestic area several other possible negative aspects are avoided such as noise caused from the operation of the wind turbine, optical pollution and maintenance requirements which are not considered in the above analysis.

8.8 EVALUATION OF A GRID-CONNECTED PV SYSTEM

Since, according to the results presented in the previous section the optimum RES system to be applied in a dwelling in Cyprus, due to the various reasons analysed above, is the solely PV system this is also evaluated for the case where it is grid-connected. In this case the optimum system defined in section 8.4 is modified for grid-connection. Thus, this system consists of 63 PV panels (180Wp nominal power each) resulting to a total installed capacity of 11.3 kW. The only differences in the grid-connected system from the standalone one is that no batteries and charge controller are used and the inverter model is different (Type 48a instead of Type 48b). A suitable TRNSYS model for the configuration is shown in Figure 8.22.

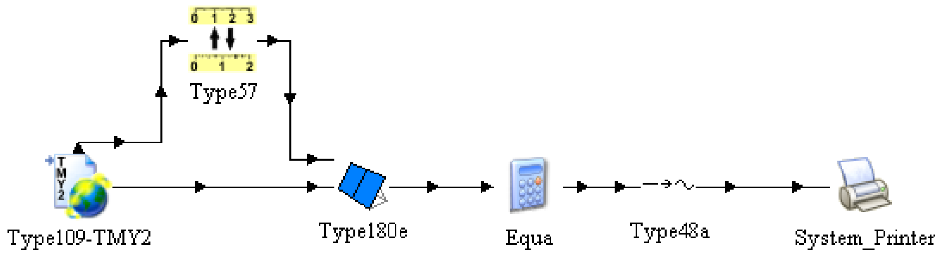

Figure 8.22 Configuration of the complete model for the grid-connected PV system

The results of the economic analysis of the grid-connected system are shown in Table 8.15.

Table 8.15 Economic analysis results for the grid-connected PV system

Cost estimation of the grid-connected PV system						
	Equipment	**Number**	**Power**	**Lifetime**	**Price**	**Price overall**
1	PV	**65**	180	25	€ 37,440	€ 37,440
2	Inverter	**3**	4,000	15	€ 5,577	€ 11,154
3	Elec. Equip.	-	-	25	€ 1,500	€ 1,500
4	Mounting system	-	-	25	€ 2,340	€ 2,340
					TOTAL	**€ 52,425**

Annual electricity produced and sold to the EAC	24,659 kWh
Annual income (0.225 €/kWh, which is the current price for selling RES produced electricity to EAC)	5,548 €
Simple Pay Back Period	9.4 yrs

It can be seen that the cost of a grid-connected system is half the cost of a standalone system. The SPBP of this system is good considering the overall lifetime of the system and also the decreasing prices of the components used (PVs, inverters etc.) will make this kind of systems even more attractive for application in dwellings. Also, by not using batteries several other problems are solved such as their periodic maintenance, their disposal and the space needed for storing them.

8.9 SUMMARY

Two types of standalone systems were modelled and evaluated in this Chapter namely a solely PV system and a hybrid wind-PV system. From the results of the economic analysis both systems have the same lifecycle cost with a slight decrease (€ 1,000) in favour of the PV system.

It is concluded that in spite of the fact that due to their ability to diversify the energy sources, hybrid systems are generally considered to be a better option for standalone applications, in the case of the location examined, as indicated from the results of both simulation and economic analysis processes, the PV-only system is a better option. This is due to the fact that the PV system is entirely based on the very high solar potential of Cyprus whilst the PV-Wind system relies to a certain extent on the very low wind potential observed in the whole island.

It should also be noted that by not using the wind turbine in a domestic area several other possible negative aspects are avoided such as noise caused from the operation of the wind turbine, visual pollution and maintenance requirements which are not considered in the above analysis. By observing the cost analysis of both systems it can be seen that batteries represent over 50% of the overall systems' cost.

Consequently, the optimum standalone system, solely PV system, was evaluated for the case where it is grid-connected. The results indicated that when a RES system is grid-connected and no batteries are used then the cost of the system is reduced by 50%, compared to that of the standalone case. Thus, it is not economically viable or feasible to install a standalone system employing batteries in cases where the dwelling can be connected to the electricity grid. Of course, this changes if there is no electricity grid nearby and the dwelling is isolated.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

It is widely acknowledged that the contribution of dwellings to the final energy consumption is very significant and this has attracted considerable research and development effort over the last twenty years. The main aim of this PhD project was to identify the typical type of domestic dwelling in Cyprus and investigate the most important energy conservation measures (ECM) with the view to identifying the cost-optimal approaches to improve its energy performance.

This thesis investigated the characteristics of dwellings in Cyprus through a sample of 500 dwellings. This resulted in the definition of the typical dwelling of Cyprus. Accordingly, a series of measures were theoretically applied to the typical dwelling in order to improve its energy performance. Specifically, these included commercially available thermal insulation materials, innovative materials such as Phase Change Materials (PCM) and incorporation of Renewable Energy Sources (RES) systems. The work can be detailed as follows:

- Investigation of the characteristics of the dwelling stock of Cyprus using data obtained from 500 questionnaires to define the typical dwelling to be used in the investigations of the effectiveness of thermal insulation and RES systems.

- Review and definition of the commercially available thermal insulation materials in Cyprus along with the most commonly used topologies of their application to domestic dwellings.

- Modelling of the typical dwelling and simulation of the effect of applying the defined thermal insulation material topologies on its energy behaviour and definition of the optimal topologies for application in both new and existing dwellings.

- Theoretical evaluation of the effect of applying Phase Change Materials (PCM) to the building fabric for load shifting and identification of optimal ways for their application.

- Theoretical investigation of the incorporation of RES to the typical dwelling and definition of the optimum type and size of system for dwellings in such weather conditions.

This chapter summarises the findings arising from the research work and provides recommendations for future work.

9.1 CONCLUSIONS

1 A brief review of dwellings in Europe and in Cyprus has been presented in the literature review of this thesis while the European Directives concerning the energy efficiency of dwellings have also been reviewed. Accordingly, some of the main studies concerning the application of ECM in dwellings in countries with similar climatic conditions to those of Cyprus have been reviewed. None of the reviewed studies used a typical dwelling for the country or location for the analysis but rather relied on dwellings selected in an ad-hoc manner. Studies relating to Cyprus were carried some time ago and did not evaluate modern insulation materials. The application of innovative materials such as PCM on the walls of buildings has been researched for different climates, including climates similar to that of Cyprus. However, there are no studies in the literature considering the application of PCM to typical dwelling and commercial buildings in Cyprus. This fact emphasises the relevance of the present study in providing essential data and relevant interpretations in relation to the application of such materials in Cyprus.

2 From the analysis of the results of the sample of 500 dwellings some very interesting conclusions were reached. The total dwelling area and the dwelling area per occupant in Cyprus are much higher than the average European. The majority of the residential building stock of Cyprus was built after 1971 and specifically between 1985 and 2001. The dominant type of dwelling in Cyprus is that of a single dwelling representing 68% of the total residential building stock. A very disappointing fact is that more than 80% of dwellings in Cyprus do not have thermal insulation installed on their envelope. In contrast, 51% of the dwellings have double glazing installed. A very important fact to note is the extensive use of solar thermal systems for the production of domestic hot water (DHW).

3 According to the results of this thesis the typical dwelling in Cyprus is a single floor (ground floor) detached house located in Zone 1 with a total area of 133 m^2. The dwelling does not have thermal insulation installed on its envelope (external walls and roof). It consists of the following

rooms: three bedrooms, kitchen, living room, bathroom, and dining room. A solar water heating system is used for domestic hot water production. The windows of the dwelling are single-glazed with aluminium frame. Finally, the floor consists of marble tiles.

4 The commercially available thermal insulation materials used in Cyprus according to the market survey conducted are extruded polystyrene, expanded polystyrene, stone wool, thermal insulation bricks and thermal insulation plaster. Consequently, the most common wall topologies are external insulation, double wall with insulation in-between without air gap, double wall with insulation in-between with air gap, wall constructed by thermal insulation bricks and the addition of a layer of thermal insulation plaster instead of common plaster. In the case of thermal insulated roofs this is done by adding a layer of thermal insulation material on top of the flat roof.

5 The preliminary analysis of the topology combinations resulted in the definition of 6 combinations; 3 for new dwellings (ND) and 3 for existing dwellings (ED). The criteria for choosing the optimum topology combinations were the highest economic benefit and the highest benefit-cost ratio (BCR). The reason for this was due to the fact that the highest economic benefit defines the most profitable investment and the highest BCR indicates which investment is more efficient in terms of initial cost and total economic benefit. Thus, the optimum topology combinations are the ones presented in Figure 9.1 and Table 9.1.

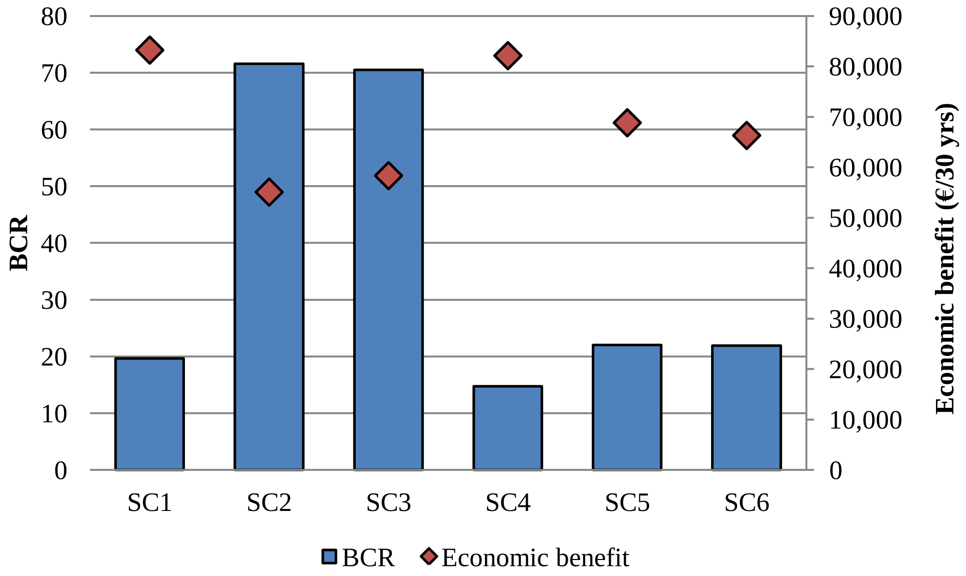

Figure 9.1 Graphical representation of the BCR and the economic benefit of the optimum topology combinations.

Table 9.1 Optimum topology combinations resulted from the preliminary analysis

N^o	Wall Topology	Roof topology	Criterion
New Dwelling			
1	Double wall with insulation in-between with air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.383 W/m^{2}K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^{2}K)*	Double wall with insulation in-between with air gap Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.383 W/m^{2}K)*
2	Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.748 W/m^{2}K)*	Thermal Insulation Plaster 0.025 m *(Uvalue = 0.843 W/m^{2}K)*
3	Thermal Insulation Bricks 0.20 m *(Uvalue = 0.759 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.04 m *(Uvalue = 0.748 W/m^{2}K)*	Thermal Insulation Bricks 0.20 m *(Uvalue = 0.759 W/m^{2}K)*
Existing Dwelling			
4	External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^{2}K)*	ITR & HCITR Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.485 W/m^{2}K)*	External Insulation Extruded polystyrene 0.05 m (0.029 W/mK) *(Uvalue = 0.412 W/m^{2}K)*
5	Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	ITR & HCITR Stone wool 0.05 m *(Uvalue = 0.567 W/m^{2}K)*	Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*
6	Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*	ITR & HCITR Expanded polystyrene 0.05 m *(Uvalue = 0.630 W/m^{2}K)*	Thermal Insulation Plaster 0.035 m *(Uvalue = 0.676 W/m^{2}K)*

6 These topology combinations were further modelled and evaluated in detail. The results showed that for the case of the ND the optimum topologies combination was SC2 followed by SC3. In the case of the ED the optimum topologies combination was SC5 followed by SC6. Their difference relies on the different insulation material used on the roof (stone wool in SC5 and expanded polystyrene in SC6)

A general conclusion is that the use of double wall in ND and external insulation in both ND and ED are not yet economically viable thermal insulation solutions due to their high initial cost compared to the other solutions examined resulting to a low IRR. Additionally, due to their high level of insulation they significantly contribute to the overheating of the dwelling during summer period which is very important especially for predominantly hot environments like Cyprus.

Finally, the optimum way to insulate the external walls of a ND or an ED is by using either a layer of at least 0.025m of thermal insulation plaster or substituting the common bricks with thermal insulation bricks of the same dimensions. The optimum way to insulate the roof of both new and existing dwellings is by adding a layer of either expanded polystyrene or stone wool of at least 0.04m thickness. It can be noted that in order to avoid condensation on the inner side of the roof the insulation is more preferable to be installed on the outer surface of the roof towards the exterior.

7 In this thesis the application of macroencapsulated PCM on the envelope of a test cubicle in Cyprus was also theoretically evaluated. The energy savings achieved by the addition of a PCM layer on the envelope of the test cubicle was 28.6%. The optimum position for the placement of the PCM layer was on the outer side of the brick behind the exterior plaster layer due to the fact that this position is the one where the PCM is most exposed to the outer conditions such as temperature and solar radiation and thus it is more active. Four additional cases were examined for the test cubicle where the optimum PCM case was combined with the optimum topologies of Chapter 5 (2991-SC2 and 2991-SC5) and the insulation only cases (SC2 and SC5). The results showed that the case with the maximum energy savings per year was the one where the PCM was combined with the insulation of SC5 (67.6%). The difference between the insulation only cases and the combined cases ranged between 2.7-6.6%.

In the case were the space was considered to be unconditioned and the air temperature fluctuates freely, the cases containing PCM exhibited a much better behaviour during summer conditions, as expected, while during the winter conditions did not work very well. More specifically, during winter conditions the optimum cases were the insulation ones followed by the combined ones (PCM with insulation). The optimum case was the one where more insulation was used (SC5). On the contrary, during summer time the optimum cases were the combined ones where the mean air temperature was 3-5ºC lower than the base case (PCM-SC2 and PCM-SC5) and the mean temperature fluctuations were much smoother.

These results were extrapolated in order to make an estimation of the energy savings that will occur if the optimum PCM layer is applied on the envelope of the typical dwelling. The results showed that the highest energy and money savings were achieved by the combined case (PCM-SC5) and were 20,567kWh/yr, 3,003€/yr respectively.

The results of the life cycle cost (LCC) analysis showed that the PCM-only case was not considered to be a very attractive solution, in monetary terms, due to the combination of the high initial cost and the annual money saving which resulted in a very long payback time of 14.5 years.

Thus, the application of macroencapsulated PCM on the envelope of dwellings in Cyprus is considered to be a very attractive solution in terms of energy saving and sustainable development while in monetary terms is not yet so attractive due to their currently high initial cost.

8 Two types of standalone systems were modelled and evaluated namely a solely PV system and a hybrid wind-PV system. From the results of the economic analysis both systems have the same lifecycle cost with a slight decrease (€ 1,000) in favour of the PV system.

It is concluded that in spite of the fact that due to their ability to diversify the energy sources, hybrid systems are generally considered to be a better option for standalone applications, in the case of the location examined, as indicated from the results of both simulation and economic analysis processes, the PV-only system is a better option. This is due to the fact that the PV system is entirely based on the very high solar potential of Cyprus whilst the PV-Wind system relies to a certain extent on the very low wind potential observed in the area examined, which is also typical for the whole island.

It should also be noted that by not using the wind turbine in a domestic area several other possible negative aspects are avoided such as noise caused from the operation of the wind turbine, optical pollution and maintenance requirements which are not considered in the above analysis. By observing the cost analysis of both systems it can be seen that batteries represent over 50% of the overall systems' cost.

Consequently, the optimum standalone system, solely PV system, was evaluated for the case where it is grid-connected. The results indicated that when a RES system is grid-connected and no batteries are used, the cost of the system is half that of the standalone case. Thus, it is not economically viable or feasible to install a standalone system employing batteries in cases where the dwelling can be connected to the electricity grid. Of course, this changes if there is no electricity grid nearby and the dwelling is isolated.

9.2 RECOMMENDATIONS FOR FUTURE WORK.

Based on the work conducted as part of this thesis issues that require further investigation include the following;

It would be very interesting if the optimum thermal insulation material and topology for each dwelling type in combination with all possible heating systems used is theoretically defined for the cases of both ND and ED. These results would be very helpful for any individual who is building or renovating their dwelling and also for engineers and policy makers.

Another very interesting perspective is the evaluation of the defined thermal insulation topologies combinations under real conditions by the conduction of outdoor experiments using a properly equipped experimental setup. This would help evaluate the behaviour of these materials and topologies under real weather and operating conditions and would also validate the theoretical results in order to gain confidence in the models used.

The results concerning the application of PCM on the envelope of dwellings in Cyprus are very promising and thus it would be very interesting if they could be validated through the conduction of a series of experiments on an outdoor experimental unit under real conditions. With these experiments the application of additional types of PCM, such as microencapsulated, in dwellings in Cyprus could be evaluated.

During the calculation of the results of this thesis the equipment costs used were the current costs of the time period when the calculations were performed. Thus, since the equipment costs are constantly changing it would be interesting if the calculations are performed again using future costs.

It is widely believed that the ongoing climate change causes an increase of the mean air temperature. Therefore, the investigation of the effect of climate change on the energy behaviour of dwellings and on the optimum topology combinations of insulation materials would be very interesting especially in the Mediterranean region.

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APPENDIX I: FORMULATED QUESTIONNAIRE

Questionnaire for the Characteristics and the Energy Behaviour of Dwellings

(**ATTENTION:** THIS QUESTIONNAIRE CONCERNS ONLY RESIDENTIAL BUILDINGS LOCATED IN CYPRUS)

PLEASE DEFINE THE FOLLOWING DATA FOR YOUR HOUSE:

A_0. Name: ....…………………… Contact Number:..............……………

Annual family income. Define the amount in €………………….. or choose a range

1) 0€ – 9.000 € ☐
2) 9.000€ – 13.000€ ☐
3) 13.000€ – 24.000€ ☐
4) 24.000€ – 36.000€ ☐
5) 36.000€ – 63.000€ ☐
6) 63.000€ – 100.000€ ☐
7) >100.000€ ☐

A_1. Municipality/ Location: ....

A_2. Area of house: .... m^2. **A_3**. Number of occupants: ....

A_4. Mean time of residence daily ……………

A_5. Year of construction: ....

A_6. Type of house:
1) Single house ☐
2) Apartment ☐
3) Other (define): ....(i.e. continuous building)

A_7. Does it have pilotis? a) YES ☐ b) NO ☐

A_8. Does it have sofita? a)YES ☐ b) NO ☐

→ ***Questions A9 to A11 only concern apartments:***

A_9. Number of apartments per floor: ....

A_{10}.Number of floors per building: ....

A_{11}.In which floor is your apartment? ....

→ ***Questions A12 and A14 only concern single house:***

A_{12}. Number of floors per house: .... (Including ground floor)

A_{13}. Does it have a basement? ....

A$_{14}$. The house is in contact with:
1) One building ☐
2) Two buildings ☐
3) Three buildings ☐
4) Detached ☐

A$_{15}$. Define the structure of the house.

Building element	**Structure**	**Thermal Insulation**			
		YES	NO	Material	Width (mm)
External walls					
Foundation walls					
Internal walls					
Floors					
Roof					
Basement					
Pilotis					

If you are not aware of these data is there somebody else who knows? (Name and contact number)
……………………………………………………………………………………………..…………………………………

B$_1$. Define the **heating systems** used as main and secondary:

Main: ...., **Secondary**: .... (Indicate the corresponding number as follows)
1) Boiler using heating oil
2) Boiler using gas
3) Fire place
4) Individual heating units
5) Air conditioning unit
6) Stove
7) Other (define): ....

B$_2$. Is the entire area of the house heated/conditioned?

a) YES ☐ b) NO ☐

B$_3$. If not, which areas are not heated…………………………………………… or a percentage in m^2…………%

B$_4$. Is there a **thermostat** in the house a) YES ☐ b) NO ☐

If **yes**, what is the set point? ....°C

B$_5$. Do you change the set point during **night-time**? ....°C

B$_6$. For how long is the house **heated** daily? (approximately**)** ....hours

B$_7$. Define the equipment used for **cooling** of the house

Air Conditioning units in the house .... , Power (Btu/hr)……….…… Hours of operation daily……………
Power (Btu/hr)……….…… Hours of operation daily……………
Power (Btu/hr)……….…… Hours of operation daily……………
Number of fans in house…………………, Hours of operation daily……………

B$_8$. Domestic Hot Water system:
Solar system ☐
Electric Boiler ☐
Boiler (heating oil) ☐ Other ☐ (................................)

B_9. What is the mean annual consumption of **electricity**? ....kWh

B_{10}. What is the mean annual cost for **heating**? (approximately) .... €
or - if its an apartment the total number of calories consumed ………………………Calories

B_{11}. What is the mean annual cost for **gas**? (approximately) …………………………€

B_{12}. What is the mean annual consumption of **heating oil**? (approximately) ……………. LITRes
(**only if** you buy heating oil separately for your house)

C_1. Maintenance of the heating system:
1) 1 year ☐
2) 3 years ☐
3) Never ☐
4) Not applicable ☐
5) Other: ………………………

C_4. Other equipment:

☐ Electric kitchen
☐ Electric oven
☐ Clothes Dryer

C_2. Is there **double glazing** installed?

a) YES ☐ b) NO ☐

C_3 . Have you made any energy related restorations on your house lately?

1) Addition of thermal insulation, ☐ (where) ……………………………………………………….
2) Change glazing ☐
3) Heating system ☐ ………………………………………………………….
4) Other…………………………………………………………………………………………….