An-Najah National University

Energy and Environment Engineering Department

Benefits of building thermal insulation on HVAC system sizing and PV penetration

Graduation project (2)

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A Graduation Project Submitted to the Department of Material Engineering in Partial Fulfilment of the Requirements for Bachelor Degree

Date of submission: June 14th, 2020

Acknowledgment

First of all, we would like to thank the administrative committee of our university for organizing the department and choosing the best doctors and courses relevant to energy engineering to get high quality of education.

Our big thank is for Dr. Mohammed Al-Sayed due to teaching us and simplifying the concepts of the earlier courses well which enabled us to do this project and face the challenges during it successfully. In addition to this, he supervised our work on the project step by step throughout the semester.

We hope to be this research beneficial by spreading awareness to people and motivating competent authorities to obligate thermal insulations in Palestinian buildings.

Contents

Table of figures

List of tables

Nomenclature

HVAC: Heating, ventilation and air conditioning.

SPP: Simple payback period.

Q: Heat transfer (W)

U: Overall heat transfer coefficient (W/m^2℃).

V_f: Volumetric flow rate of infiltrated air (m^3/s).

LM: Latitude –Month correction factor.

CLTD: The value of cooling load temperature difference.

$(\mathrm{CLTD})_{corr}$: The correction value of cooling load temperature difference.

CLF: The cooling load factor.

SG: Solar gain rate.

SHG: The solar heat gain rate factor (W/m^2).

SC: The shading coefficient.

W: watt.

m^2: meter squared.

m^3: meter cubic.

℃: Celsius degree.

S: second.

X_{opt}: Optimal thickness.

cm: centimeter

kWh: kilo watt hour.

$: U.S dollar.

T: the average sunlight hour in Palestine and equals 5.4 hours

Nis: Israeli shekel.

Kcal: energy unit.

Pmax: maximum power.

Vo.c: open circuit voltage.

Is.c: short circuit current.

Vm: maximum power.

Im: maximum current.

ρ: The resistivity of copper

L: length of cable.

I: current across the cable.

Vd: voltage drop.

A: cross sectional area of the cable.

Abstract

This report aimed to determine the optimal thickness of two types of thermal insulation; expanded and extruded polystyrene, and choosing the best of them to be added to the construction layers of the external walls and roof of a villa in Jerusalem with a floor area of **241 m^2**. The best type of the thermal insulation was extruded polystyrene with an optimal thickness of **9 cm** for external walls and roof, and an initial cost of **15 223 Nis**. It also studied the saving in HVAC system capacity cost and its yearly operating cost resulted due to that optimal thickness of extruded polystyrene use instead of not using insulation scenario, where; the initial cost of HVAC system was **35 900 Nis** with saving in initial cost due to saving in capacity was **8 975 Nis**, the cost of double glass was **61 852 Nis** and the annual saving in operating cost was **6 411 Nis/year** that led to obtain **8 years** simple payback period. After that, design of a photovoltaic system was required to determine how much the PV system will feed the need of HVAC load according to the available roof area, **110 m^2**. However, the installed PV panels only can feed approximately **50%** of HVAC load in the optimal thickness of insulation case that has a load of **100 kWh/day**, while in without insulation case that has a load of **126.6 kWh/day**, the installed PV panels can feed only **39%** of HVAC load. Because of the penetration level of **50%**, the system was installed on grid not off grid system, because there will be no excess of power to be stored in batteries. The investment of this project included cost of solar panels with installation, inverter, cables as well as annual cleaning and estimated as **27 080 Nis**, and with **11 668 Nis/year** annual saving in operating cost resulted due to reduction of electricity consumption from 23 625 to 11 957 Nis /year, the simple payback obtained was approximately **two years.**

Chapter 1: Introduction

Energy resources all over the world are getting depleted. Over 90 percent of all the energy used in the entire world comes from fossil fuels (coal, oil and gas) that are exhaustible[1]. Millions of years ago, organic matter (the remains of plants and animals) decayed and built up into thick layers.

Currently, the world consumes in one year large amount of fossil fuels. At our present rate of consumption, and assuming no population increase, all the known oil reserves could be exhausted by the middle of this century and natural gas by 2070[1]. Coal supplies will last much longer – for roughly 200 years at current consumption rates[2].

Since the fossil fuels resources are rather limited and environmental problems are caused due to usage, such as global warming, acid rains, dangers posed by leaded fuels, oil spills, gas leaks, explosions, water and air pollution, the development of renewable energy sector is foreseen the most advantageous solution to meet the increasing energy demand and reduce the environmental impacts. So, this was mentioned in energy consultation 2017-2020.[3]

In Palestine, the energy sector still faces major obstacle, the population growth rate is about 3.0% and the average household size is about 5.6 persons[2]. Energy consumption in all sectors is relatively small compared to neighboring Arab countries ,the highest percentage of energy consumption is in the household sector with 46.8%, followed by the transportation sector with 36.4%, and the trade and services sector with 9.9% ,industry and agriculture account for 9.6% of the total energy consumption[2]. Most building loads fall under two parts, air conditioning and lighting ,so, Palestine suffers from the problem of the lack of a compulsory green building code where there is still optional, so there is no awareness to the importance of saving energy inside buildings and how much energy can be saved.[4]

It's well known that most of the Palestinian modern buildings consist of walls constructed from stones, concrete, bricks and plaster with a total thickness exceeding 25 cm[5]. Flat roofs are constructed of concrete, hollow bricks and plaster, while the most types of thermal insulations used are; expanded and extruded polystyrene[5]. Technical papers by Palestinian researchers have shown that the typical values of thermal transmittance of walls range between 1.5 and 1.8 Kcal/hr.m^2.°C compared to values range between 0.1and 0.35 Kcal/hr.m^2.°C.Accordingly, energy loss in winter in local homes exceeds 6 times energy loss in buildings in the USA similar weather conditions.[5]

In terms of the renewable energy, there are multi forms that could be used to reduce the amount of fossil fuel would be consumed, some of them can give heat like; solar water heater, and the other can generate electricity like photovoltaic system and wind turbine[6]. Photovoltaic system is more common and used than wind turbine due to ease of usage for houses[6]. However, there are two methods to design a photovoltaic system to generate electricity for feeding household or industrial load; **on grid system** which is connected to the grid and doesn't use batteries, **and off grid (stand**

alone) system which is not connected to the grid and uses batteries to store the electric power[6], where; selecting one of these design depends on the application and load type will be used for and according to how much the design will feed and cover from the load, where; off grid is used when the power generated by PV is more than the household need and so, it needs to be stored to use it later at cloudy days or night.

The present project is concerned with energy efficiency in buildings and introducing a technique and building method for minimizing heat loss in winter and heat gain in summer by using optimal thickness of thermal insulation in wall and roof exposed to outside. The project will have an impact on lowering energy consumption in buildings and minimize greenhouse gas emissions. In addition to this, a form of renewable energy will be applied to consume less electricity from the grid.

1.1 Problem Statement

In Palestine, most of buildings are built without adding thermal insulation in the building envelop[5]. This is due to lack of studies related to it and its effects on the size of heating, ventilation and air conditioning system (HVAC), its initial and running costs[5]. So, to increase citizen's awareness toward energy management, it was required, in this project, to reduce the thermal loads for a villa to the least possible by using an optimal thickness of best type of thermal insulation in Palestine. This will definitely lead to minimize the HVAC system size significantly, as well as its initial and running cost.

1.2 Objectives of the work

The proposed research aims to:

1- Define the most suitable types of thermal insulation used in Palestine.
2- Determine the optimal thickness of these types of insulation and choose the best type according to financial terms.
3- Determine HVAC size, initial and running cost according to the optimal thickness chosen for the villa.
4- Design a photovoltaic system (PV) for the villa after using the optimum thickness and according to the available area of the roof.

1.3 Scope of work

A villa of one floor, in Jerusalem, is now under construction, including designing and simulation of HVAC system. This study calculates the cooling and heating loads by using ecotect software, while considering the optimum thickness of the best and most insulation type used in Palestine. And according to that, a photovoltaic system would be designed manually according to the available area of the roof.

1.4 Significance of work:

Using energy efficiency measures before choosing the HVAC design help to choose smaller system size and so, less initial cost would be paid than selecting randomly and approximately without calculations. As a result of that, less energy will be consumed due to less power, and so less cost during operating. In addition to that, using the renewable energy to feed some of villa loads will reduce usage of power from utility, and then, reduce the cost of electricity bill.

1.5 Organization of the report

This report includes nine sections. The first talked about constraints and codes that the project is based on, as well as the studied courses which enabled to make this project. The second section, as literature of review, mentioned previous studies and researches that aimed as this project to study the effects of insulations on heating and cooling loads. In addition to that, theories and equations of thermodynamics, which were used for calculations, were also explained. The third section was the methodology that illustrated the steps to calculate the optimum thickness, heating and cooling loads. The next two sections were the results and discussion. These two sections showed in table different thickness of two types of thermal insulations with total cost and simple payback period to select the optimum thickness. In addition to that, the heating and cooling loads in each month, the cost of total construction and the size of system chosen are shown according to the optimum thickness. In terms of the discussion, the money that could be saved due to insulation and number of years needed to recover the capital were debated. The sixth section concluded the solution of oversized design problem and presented some recommendations. The final two sections were the references and attachments**.**

1.6 Case description

The case study investigated is a villa in Jerusalem in Palestine. It has sixteen zones with 241 m^2 floor area, 1513.090 m^2 total area and a volume of 942.260 m^3.The ground floor has three bedrooms, three bathrooms, one kitchen, one living room with one corridor, one guest room and one dining room. While the roof contains two bedrooms, two bathrooms, one kitchen and one living room. The schemes of villa for the both floors are attached in appendix A.

According to The Palestinian meteorology, the maximum temperature in Jerusalem is 32$C°$, and the minimum is 2 °C, while the maximum average of number of hours of solar radiation is 12.4 hours in June and the minimum is 5.4 hours in January, considering the average solar radiation equals 5.4 kW/m^2[7]. The inside temperature would be designed is considered as 20-23$C°$ and the relative humidity is taken as 55%. The latitude of Palestine is 31.9 N and the longitude is 35.2 E[7]. The climate statics of Jerusalem is attached in appendix B.

The construction layers for external and internal walls, ceiling, roof, windows and floor with their thickness are illustrated and attached for the two scenarios in appendix C.

Chapter 2: Constraints, Codes and Earlier course work

This part talks about the constraints that is faced to achieve the project idea in terms of the building itself and the local market, and about the standards and codes regarded for building and designing PV system. It also talks about the earlier courses that have been studied during the Bachelor's study years.

2.1 Constraints

They are related to the HVAC sizes, and the types of the thermal insulation most used and existed in the local market; expanded and extruded polystyrene, with their costs per one cubic meter and their specifications like, thermal conductivity and density, where, choosing one of them with an optimum thickness depends on considering the quality and total cost together. In addition to the previous constraints, designing PV system is considered. It is based on the available area on the villa roof for installing the solar panels (module), which may lead to insufficient system power in case of small roof area.

2.2 Standards and Codes

It's related to selection of the type of construction layers for internal and external walls, ceiling and roof as well as insulations that are committed by what Palestinian codes for green buildings state. In terms of photovoltaic design, the design used is The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) that has special standards for testing the ability of the photovoltaic panels to absorb the beam radiation at noon for determining the efficiency of these solar panels [6].

2.3 Earlier coursework

The beneficial courses which have been studied, promoted and enabled to achieve this project are almost five courses, Thermodynamics and Heat transfer courses that were studied in the second year of the Bachelor, Heating, ventilation and air conditioning (HVAC)and Energy saving and auditing courses that were studied in the third year. While the rest courses; Life cycle assessment and Energy management were studied in the fifth year.

Chapter 3: Literature Review

There is a study done in a department at the faculty of engineering and technology at the University of Jordan in Amman. It aimed to study the effects of adding thermal insulation in walls and double glass for windows on HVAC design. It's a paper existing in Sustainable Cities and Society journal called ' Energy audit, an approach to apply the concept of green building for a building in Jordan' for the authors, and it was published in 27 August 2014[10].

Chapter 4: Theoretical background

This chapter talks about the theories and laws used in calculations. The first part includes the laws used to determine the optimum thickness of the thermal insulation, the second and third parts include the laws used to find heating and cooling loads, while the final part has the theories applied for PV installation.

4.1 Optimum thickness

The following equations used to calculate the optimum thickness [8], [9] :

$$CDH = (1\ year)\sum_{day=1}^{365}(1\ day)\sum_{hour=1}^{24}(To - Tb) \quad (1)$$

$$q = U_{ov}(T_o - T_b) \quad (2)$$

$$E_{AC} = \frac{U_{ov}}{COP}CDH \quad (3)$$

$$U_{un} = \frac{1}{R_i + R_w + R_o} \quad (4)$$

$$U_{ins} = \frac{1}{R_i + R_w + R_{in} + R_o} \quad (5)$$

$$\Delta U = \frac{1}{R_{tw}} - \frac{1}{R_{tw} \mp \frac{x}{k}} = U_{un} - U_{in} \quad (6)$$

$$P_1(N, i, d) = \sum_{j=1}^{N}\frac{(1+i)^{j-1}}{(1+d)^j} = \begin{cases} \frac{1}{d-i}\left[1 - \left(\frac{1+i}{1+d}\right)^N\right], & if\ i \neq d \\ \frac{N}{1+i}, & if\ i = d \end{cases} \quad (7)$$

$$P_2 = 1 + P_1 M_s - R_v(1+d)^{-N} \quad (8)$$

$$C_{ins} = C_i x \quad (9)$$

$$S_c = P_1 E_{AC} - P_2 C_{ins} \quad (10)$$

$$x_{opt} = \left(\frac{P_1\, C_E\, k\, CDH}{P_2 C_i COP}\right)^{1/2} - R_{tw}\, k \quad (11)$$

$$SPP = \begin{cases} \dfrac{ln\left[1 - \frac{P_2\, C_i\, COP\, (R_{tw}\, x + R_{tw}^2\, k)(d-i)}{C_E\, CDH}\right]}{ln(\frac{1+i}{1+d})}, & if\ i \neq d \\ \frac{P_2\, C_i\, COP\, (R_{tw}\, x + R_{tw}^2\, k)(1+i)}{C_E\, CDH}, & if\ i = d. \end{cases} \quad (12)$$

$$C_t = P_1 E_{AC} + P_2 C_{ins} \quad (13)$$

4.2 Heating load calculation

The equations that used for calculation of heating load [9]:

- Heat losses through walls, floor, ceiling, glass of window

$$Q = A * U * (T_i - T_o) \quad \text{...} \quad (14)$$

- Infiltration losses through cracks.

$$Q_{sensible} = V_f * \rho_{air} * C_p * (T_i - T_o) \quad \text{...} \quad (15)$$

Where U is the overall heat transfer coefficient and its values for wall is 1.7 W/m^2 $C°$, for doors is 2.8 W/m^2 $C°$,and for window single glass is 6.7 W/m^2 $C°$.

- $V_f = no\ of\ ACH\ /h *\ Room\ volume$.................................. (16)
- $\rho_{air} = 1/v_o$.. (17)

4.3 Cooling load calculation

The equations that used for calculation of cooling load [9]:

- Heat gains through floor, doors and ceiling

$$Q = U * A * (Tadj - Ti) \quad \text{...} \quad (18)$$

- Heat gain due to solar effects

$$Qs = U * A * (CLTD)corr \quad \text{...} \quad (19)$$

- Heat gain through window

$$Qg = A * (SHG) * (CLF) * (SC) \quad \text{.......................................} \quad (20)$$

- Heat gain due to occupancy

$$Qoc = \left(\frac{Number\ of\ persons * SG}{1000}\right) * (CLF)oc \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(21)}$$

- Heat gain due to lights

$$Qlight = \left(\frac{Insulated\ lamp * A}{1000}\right) * (CLF)light \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(22)}$$

- Heat transmitted due to infiltration

$$Qf = \left(\frac{Vf}{vo}\right) * (ho - hi) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(23)}$$

4.4 Photovoltaic design

To design an on grid photovoltaic system, the daily load, available area of roof, number and area of solar panels must be determined. Anyway, these following equations are used for designing taken from Fundamental and Applications of renewable energy book [6]:

- $daily\ load = \frac{yearly\ load\ (\frac{kWh}{year})}{365\ day} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(24)}$
- $PowerofPV = \frac{yearlyload}{365*T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(25)}$
- $Aestate = 1.3 * Apv \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(26)}$
- $\eta PV = \frac{peakpowerofPVsystem}{standardsolarradiationkW/m^2 * AreaofPV} \ldots\ldots\ldots\ldots\ldots\ldots \text{(27)}$
- $numberofmodules = \frac{totalareaofpanels}{areaofeachpanel} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(28)}$
- $Power\ of\ invertor = 0.75 * rated\ PV \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(29)}$
- $Power\ of\ charge\ controller = Vin * Irated \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(30)}$
- $A = \frac{\rho\ L\ I}{Vd} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(31)}$

Chapter 5: Methodology

To determine the optimum thickness and the best thermal insulation type would be used, steps should be taken; First, determining, by excel software, the initial, operation and total cost and simple payback period (SPP) for the both types (expanded and extruded polystyrene) in different thickness. Second choosing the thickness that has the lowest value of total cost and SPP for the both types. Finally comparing between the two types and selecting the type has lower total cost and SPP.

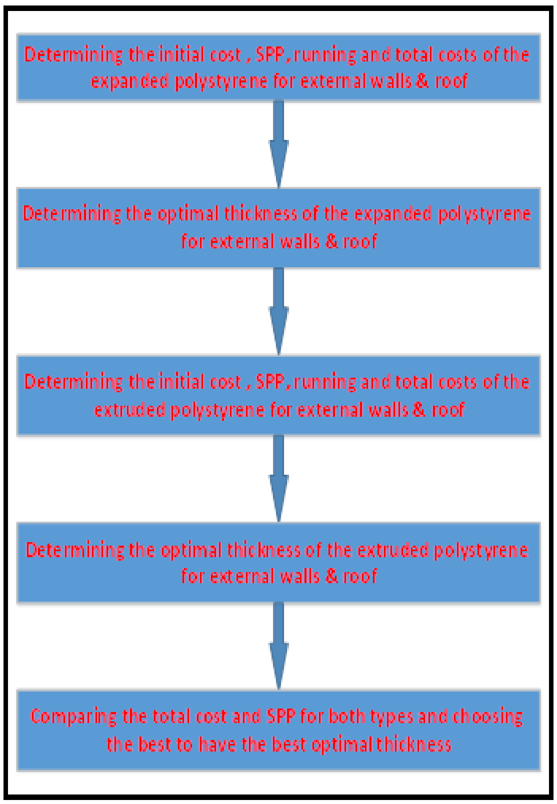

Figure 5.1: Steps of calculating optimal thickness of two insulation types.

After that, steps of heating and cooling loads calculation are followed while considering the best optimum thickness of insulation between the two types and comparing the HVAC design between the two scenarios; without insulation and with insulation. First, determining the overall heat transfer coefficient (Uov) by determining U for each component of walls, windows, floor, roof, ceiling and doors. Second, determining the inside and average outside temperatures in summer and winter. Third, calculating the heating load by finding the heat transmission losses through walls, windows, floor, ceiling and doors, and the infiltration losses through cracks. Fourth, calculating the cooling load by finding; the heat gains though walls, windows, floor, ceiling and doors by conduction, heat gain through windows (glass) by radiation, heat gain from infiltration and heat gains from occupants, lights and appliances. Fifth, system identification market sizing. Sixth, determining the initial and running costs. Seventh, comparing between the two scenarios.

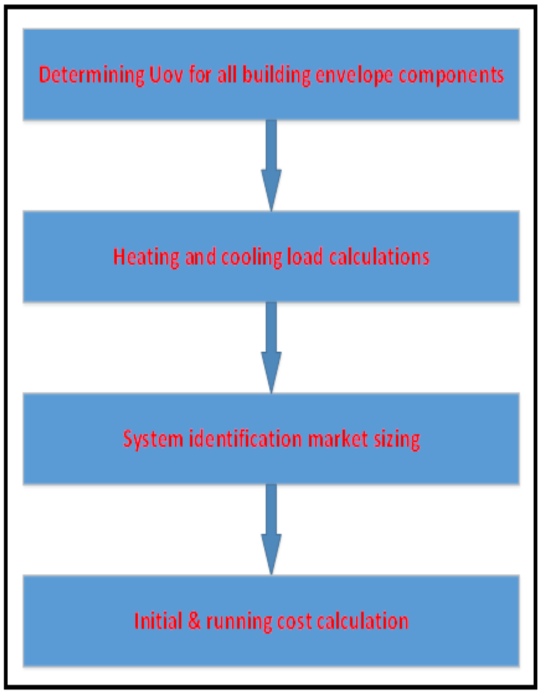

Figure 5.2: Steps of calculating heating and cooling loads.

After designing the HVAC unit according to the optimal thickness of the insulation, steps to design a photovoltaic system (on grid) are taken. Firstly, determining the daily load of heating and cooling the villa. Secondly, determining the power of PV system needed to feed all HVAC load. Thirdly, calculating the area of PV panels required according to the available area of the roof. Fourthly, determining the power of PV system according to the available area and comparing it with the power of PV needed to feed all HVAC load. Fifthly, calculating the number of solar panels required. Sixthly, finding the maximum power of each module. Seventhly, calculating the size of inverter, charge controller and cables. Finally; calculating the simple payback period by estimating the investment and saving.

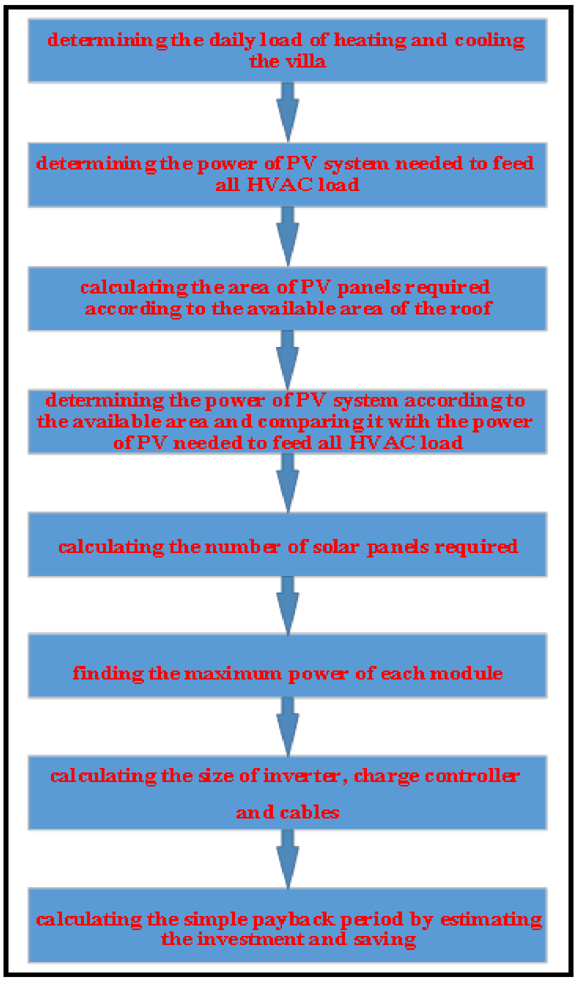

Figure 5.3: steps to design PV system.

Chapter 6: Results and Discussion

There are two types of thermal insulation that are the most used in Palestine; expanded polystyrene and extruded polystyrene. Below, the optimal thickness of each type in the external walls and roof are found and the best of them is chosen to study the effect of it on the yearly HVAC system consumption in terms of the operation costs.

6.1 Expanded polystyrene

6.1 (a) External walls

According to the local market, one cubic meter of expanded polystyrene costs 375 $ or 1346 Nis (considering 1$ = 3.59 Nis). And by applying the previous equations of the optimum thickness mentioned in the literature review on excel software, table (5.1) was obtained. It illustrates the total cost and the simple payback period (SPP) for different thickness of insulation up to 15 cm for external walls, where; the highlighted one (X = 5 cm) is considered the optimum thickness, because it has the lowest total cost of 92 $/cm as it's compared with all thickness, and the lowest simple payback period of 2.3 years as it's compared with those thickness higher than 5 cm. The decrease of the total cost of the optimal thickness occurs because of the reduction of operation cost due to decrease of the heat transfer passing through it. According to ecotect, expanded polystyrene has an overall heat transfer coefficient of 0.035 $W/m^2.K$.

Table 6.1: Optimal thickness for expanded polystyrene in external walls.

Thickness [cm]	***SPP [year]***	***Total cost [$/cm]***
0		237
1	0.91	152
2	1.27	118
3	1.63	103
4	1.99	95
5	2.34	92
6	2.70	92
7	3.06	93
8	3.42	96
9	3.78	99
10	4.13	103
11	4.49	108
12	4.85	113
13	5.21	118
14	5.57	124
15	5.92	129

Table (6.1) can be expressed in curve as shown in figure (5.1), where; x-axis is the thickness of insulation and y-axis is the total cost. It's observed that 5, 6, 7, 8 and 9 cm thickness have approximately the same value of total cost but the 5 cm thickness was chosen due to the lower simple payback period caused by less initial cost (investment).

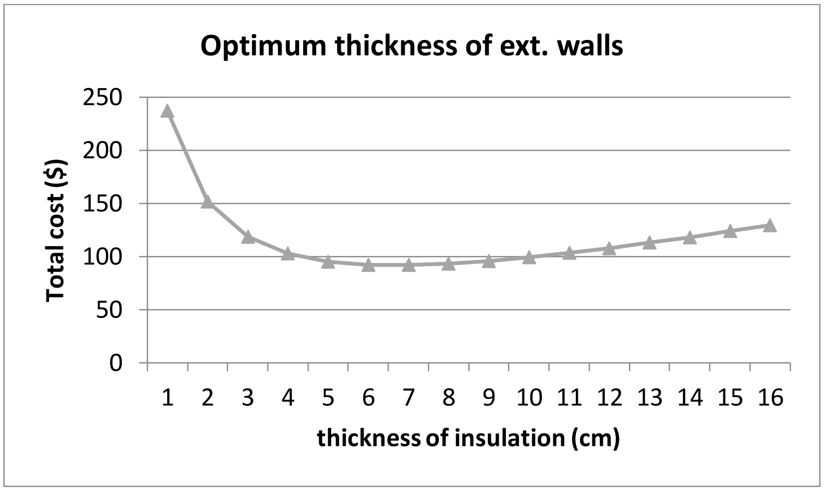

Figure 6.1: Optimal thickness for expanded polystyrene in external walls.

6.1 (b) Roof

Also, by applying the same equations on excel software, table (5.2) was obtained which illustrates the total cost and simple payback period (SPP) for different thickness of insulation up to 15 cm for roof, where; the highlighted one (X = 6 cm) is considered the optimum thickness, because it has the lowest total cost of 94.8 $/cm as it's compared with all thickness, and the lowest simple payback period of 1.82 years as it's compared with those thickness higher than 6 cm. The decrease of the total cost of the optimal thickness occurs because of the reduction of operation cost due to decrease of the heat transfer passing through it.

Table 6.2: Optimal thickness for expanded polystyrene in roof.

Thickness [cm]	***SPP (year)***	***Total cost [$/cm]***
0		330.72
1	0.54	181.86
2	0.80	133
3	1.05	111.32
4	1.31	100.90
5	1.57	96.22
6	1.82	94.86
7	2.08	95.59
8	2.34	97.73
9	2.59	100.86
10	2.85	104.71
11	3.11	109.10
12	3.36	113.91
13	3.62	119.05
14	3.88	124.45
15	4.14	130.07

Table (6.2) can be expressed in curve as shown in figure (5.2), where; x-axis is the thickness of insulation and y-axis is the total cost.

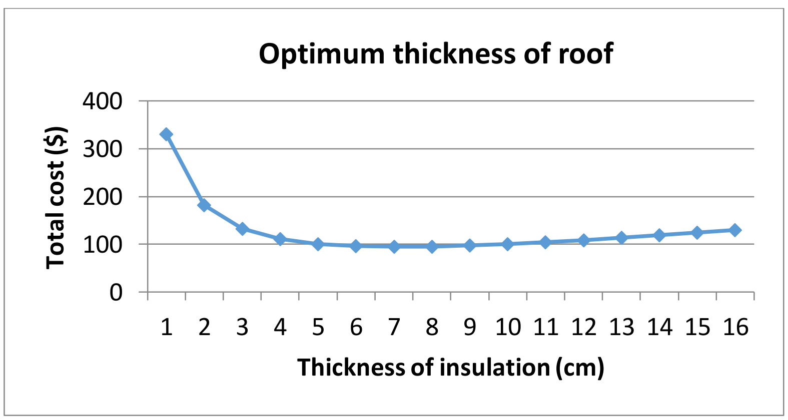

Figure 6.2: Optimal thickness for expanded polystyrene in roof.

6.2 Extruded polystyrene

6.2 (a) External walls

According to the local market, one cubic meter of extruded polystyrene costs 128.5 $ or 461.3 Nis (considering 1$ = 3.59 Nis). And by applying the same equations of optimal thickness in the literature review on excel software, table (5.3) was obtained. It also illustrates the total cost and simple payback period for different thickness of insulation up to 15 cm for external walls, where; the highlighted one (X = 9 cm) is considered the optimum thickness, because it has the lowest total cost of 51 $/cm as it's compared with all thickness and the lowest simple payback period of 1.3 years as it's compared with those thickness higher than 9 cm. The decrease of the total cost of the optimal thickness occurs because of the reduction of operation cost due to decrease of the heat transfer passing through it. According to ecotect, extruded polystyrene has an overall heat transfer coefficient of 0.027 W/m2.K.

Table 6.3: Optimal thickness for extruded polystyrene in external walls.

Thickness [cm]	***SPP [years]***	***Total cost [$/cm]***
0		237
1	0.28	132
2	0.41	94
3	0.54	76
4	0.67	65
5	0.79	59
6	0.92	55
7	1.05	53
8	1.18	52
9	1.31	51
10	1.44	51
11	1.57	52
12	1.70	52
13	1.83	54
14	1.95	55
15	2.08	56

Table (6.3) can be also expressed in curve as shown in figure (5.3), where; x-axis is the thickness of insulation and y-axis is the total cost.

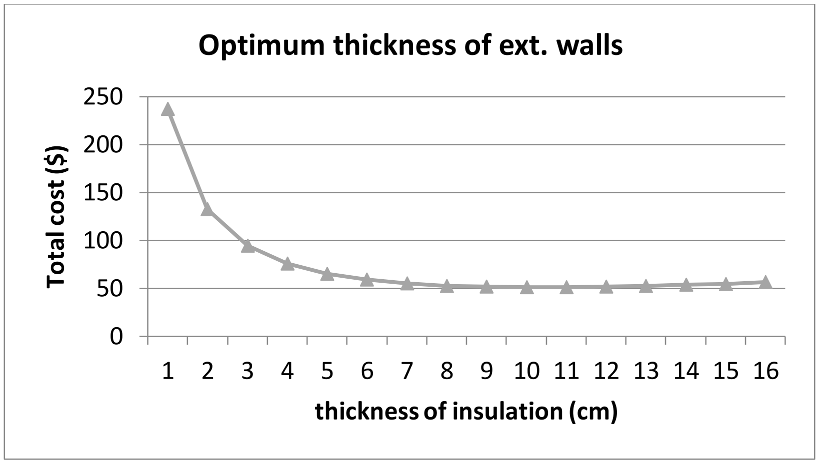

Figure 6.3: Optimal thickness for extruded polystyrene in external walls.

6.2 (b) Roof

Again, by applying the same equations on excel software, table (5.4) was obtained which also illustrates the total cost and simple payback period (SPP) for different thickness of insulation up to 15 cm for roof, where; the highlighted one (X = 9 cm) is considered the optimum thickness, because it has lowest total cost of 52.09 $/cm as it's compared with all thickness, and the lowest simple payback period of 0.91 year as it's compared with those thickness higher than 9 cm. The decrease of the total cost of the optimal thickness occurs because of the reduction of operation cost due to decrease of the heat transfer passing through it.

Table 6.4: Optimal thickness for extruded polystyrene in roof.

Thickness [cm]	***SPP [years]***	***Total cost [$/cm]***
0		330.72
1	0.17	155.86
2	0.26	104.91
3	0.35	81.66
4	0.44	69.02
5	0.54	61.57
6	0.63	57.05
7	0.72	54.32
8	0.81	52.79
9	0.91	52.09
1	1.0	52.0
11	1.09	52.35
12	1.18	53.05
13	1.28	54.02
14	1.37	55.20
15	1.46	56.56

To express table (6.4) in curve, figure (6.4) is obtained, where; x-axis is the thickness of insulation and y-axis is the total cost.

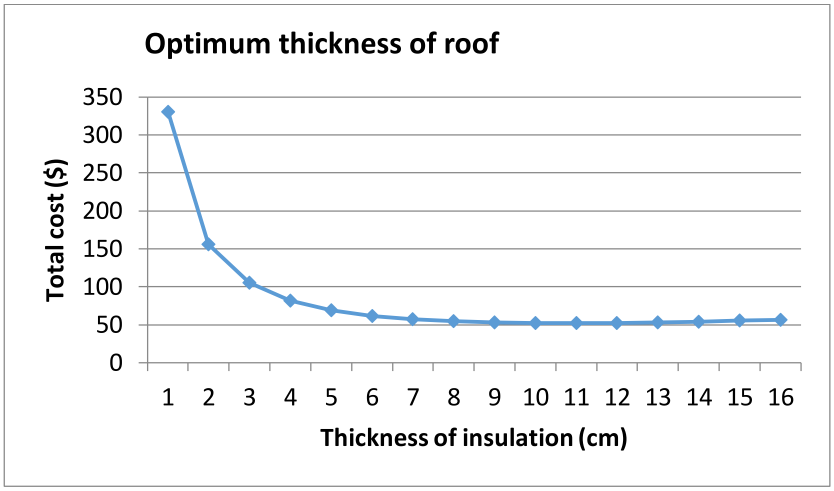

Figure 6.4: Optimal thickness for extruded polystyrene in roof.

6.3 Comparison between expanded and extruded polystyrene.

Table (5.5) and (5.6) summarize the pervious tables for better comparison, where; table (5.5) shows the optimum thickness of insulation in external walls for both types, and table (5.6) shows optimum thickness of insulation in roof for both types. According to these two tables, extruded polystyrene insulation was chosen for external walls and roof, highlighted in red, because it has lower total cost and simple payback period than the expanded polystyrene does have. It's good to indicate that low simple payback period means short period will be taken for recovering the capital of the project (use of thermal insulation).

Table 6.5: The optimum thickness of insulation for external walls with its total coat and SPP.

Choice	*X opt for External wall (cm)*	*Total cost ($/cm)*	*SPP (Year)*
Expanded polystyrene (U = 0.035 W/m2.K)	5	92	2.34
Extruded polystyrene (U = 0.027 W/m2.K)	9	51	1.31

Table 6.6: The optimum thickness of insulation for roof with its total cost and SPP.

Choice	X opt for Roof (cm)	Total cost ($/cm)	SPP (Year)
Expanded polystyrene (U = 0.035 W/m2.K)	*6*	*95*	*1.82*
Extruded polystyrene (U = 0.027 W/m2.K)	*9*	*52.1*	*0.91*

6.4 Heating and cooling load for the optimal thickness of extruded polystyrene insulation

After choosing the type of insulation that will be used for external walls and roof, which is the extruded polystyrene, and after determining its optimal thickness (9 cm), heating and cooling loads for the villa are calculated by ecotect software as shown in the following table (5.7).

Where; $U_{wall} = 0.260\ W/m^2.K$

$U_{roof} = 0.270\ W/m^2.K$

Table 6.7: Heating and cooling loads of the villa, considering extruded polystyrene as a thermal insulation.

Month	Heating (kWh)	Cooling (kWh)	Total (kWh)
Jan	6167.47	0	6167.5
Feb	6300.85	0	6301
Mar	4736.52	0	4736
Apr	2448.40	0	2448
May	0	1115.25	1115.25
Jun	0	1292.35	1292.35
Jul	0	2431.68	2432
Aug	0	2881.19	2881.2
Sep	0	1367.05	1367
Oct	0	1096.37	1096.37
Nov	2285.83	0	2286
Dec	4222.45	0	4222.4
TOTAL	26161.5	10184	36 345.46

It's noted from table (5.7) that maximum heating load is 6 167.47 kWh (50.95 kW) in January, while maximum cooling load is 2881.19 kWh (34.15 kW) in August. And for better comparison with the expanded polystyrene, table (5.8) shows the heating and cooling load in case of using the expanded polystyrene. It's noted that the total load in case of extruded polystyrene is **36345.46kWh** while in the expanded polystyrene, the total load yearly is **83 491 kWh** which is higher than the total load of extruded polystyrene yearly.

Table 6.8: Heating and cooling loads of the villa, considering expanded polystyrene as a thermal insulation.

Month	Heating (kWh)	Cooling (kWh)	TOTAL (kWh)
Jan	13263.6	0	13263.6
Feb	13248	0	13248
Mar	10190.6	0	10190.6
Apr	5304	0	5304
May	0	2962.4	2962.4
Jun	0	3929	3929
Jul	0	6116	6116
Aug	0	6971.4	6971.4
Sep	0	4096.6	4096.6
Oct	0	3305.6	3305.6
Nov	5186	0	5186
Dec	8918	0	8918
TOTAL	56110	27381	83 491

6.5 Running cost of HVAC system according to the optimal thickness of extruded polystyrene insulation

To calculate the electricity cost due to HVAC utilization, the electricity price (Nis/kWh) is multiplied by energy consumption for each month (kWh), where the electricity price according to Jerusalem District Electricity Company equals 0.65 Nis/kWh [11]. Table (5.9) illustrates the calculations of the running cost of HVAC system monthly and yearly, which equals 23 625 Nis/kWh/year.

Table 5.9: Running costs monthly due to HVAC system operation in case of optimal thickness of extruded polystyrene.

Month	HEATING (kWh)	COOLING (kWh)	TOTAL (kWh)	Running cost (Nis/kWh)
Jan	6 167.5	0	6 167.5	4009.0
Feb	6 301.0	0	6 301.0	4095.5
Mar	4 736.5	0	4 736.5	3079.0
Apr	2 448.4	0	2 448.4	1591.5
May	0	1 115.0	1 115.0	725.0
Jun	0	1 292.0	1 292.0	840.0
Jul	0	2 432.0	2 432.0	1580.6
Aug	0	2 881.0	2 881.0	1873.0
Sep	0	1 367.0	1 367.0	888.6
Oct	0	1 096.4	1 096.4	712.6
Nov	2 286.0	0	2 286.0	1486.0
Dec	4 222.4	0	4 222.4	2744.6
TOTAL	26 161.5	1 0184	**36 345.5**	**23 625**

According to the first graduation project, electricity cost, in case of without insulation, was calculated as shown in table (5.10) and equaled 30 036 Nis/kWh/year.

Table 5.10: Running costs monthly and yearly due to HVAC system operation in case of without insulation

MONTH	HEATING (kWh)	COOLING (kWh)	TOTAL (kWh)	Running cost (Nis/month)
Jan	7911.0	0	7911.0	5142
Feb	8041.0	0	8041.0	5226.5
Mar	6042.0	0	6042.0	3927.0
Apr	3138.0	0	3138.0	2039.6
May	0	1365.0	1365.0	887.0
Jun	0	1738.0	1738.0	1129.5
Jul	0	2954.0	2954.0	1920.0
Aug	0	3402.0	3402.0	2211.4
Sep	0	1576.0	1576.0	1024.6
Oct	0	1178.5	1178.5	766.0
Nov	3188.0	0	3188.0	2072.0
Dec	5676.0	0	5676.0	3689.0
TOTAL	33 995	12 214	46 209	**30 036**

The difference of cost between the two scenarios is the saving in operating cost:

$$Saving\ in\ operation\ cost = 30\ 036 - 23\ 625 = 6\ 411\ Nis/Year$$

6.6 HVAC system size and the initial cost according to the optimal thickness of extruded polystyrene.

According to the local market, one ton refrigeration (TR) costs 1000 $, where 1 TR equals 3.517 kW. So, to calculate the size and initial cost of HVAC system considering the maximum cooling load not the average:

$$Size\ of\ HVAC\ system = \frac{34.15\ kW}{3.517\ kW/TR} = 9.7\ \approx 10\ TR$$

$$Initial\ cost\ of\ HVAC\ system = 10\ TR * 1000 \frac{\$}{TR} * 3.59 \frac{Nis}{\$} = 35\ 900\ Nis$$

And according to the first graduation project in case of without insulation, the HVAC size was 12.5 TR for the maximum cooling load of 43.9 kW, and its initial cost was 44 875 Nis. So;

$$The\ saving\ in\ initial\ cost\ for\ HVAC\ purchasing = 44\ 875 - 35\ 900 = 8\ 975\ Nis$$

6.7 Simple payback period of the thermal insulation

To calculate the investment for insulating the building envelope and windows, cost of the extruded polystyrene and double glass used must be calculated and added to the initial cost of HVAC system.

*According to the local market, the extruded polystyrene costs 128.5 $/m^3 (461.31 Nis/m^3), and the volume of it which is used for the all villa is calculated by multiplying the exposed surface area of external walls and roof by the optimal thickness.

$$Exposed\ surface\ area\ of\ external\ walls\ =\ 256.2\ m^2$$

$$Exposed\ surface\ area\ of\ roof\ =\ 109.8\ m^2$$

$$Total\ exposed\ surface\ area\ =\ 366\ m^2$$

$$Volume\ of\ extruded\ polystyrene\ used\ =\ 366\ m^2 * 0.09\ m\ =\ 33\ m^3$$

$$Initial\ cost\ of\ extruded\ polystyrene\ used = 33\ m^3 * 461.31\ \frac{Nis}{m^3} = 15\ 223\ Nis$$

* According to the local, the double glass costs roughly700 Nis/m^2, where, the total area of glass used in the villa can be calculated by multiplying the summation of windows areas by 2, which equals 88.36 m^2. To calculate its cost:

$$Cost\ of\ double\ glass = 88.36\, m^2 * 700 \frac{Nis}{m^2} = 61\,852\, Nis$$

Summation the two costs above of extruded polystyrene and HVAC system produces the investment:

$$Investment = 15\,223\, Nis + \ 35\,900\, Nis = 51\,123\, Nis$$

Finally, the simple payback period can be estimated by dividing the investment over the saving:

$$SPP = \frac{Investment}{Saving} = \frac{51\,123\, Nis}{6\,411\, Nis/year} \approx 8\, years$$

This means that after 8 years, the capital of project, which is use of the optimal thickness of insulation and installing 11 TR HVAC system, will be recovered.

6.8 Photovoltaic system installation

Using the photovoltaic system is an excellent way for feeding the household loads to reduce the costs of consumption of electricity coming from the grid as well as reduce greenhouse gases due to fossil fuel combustion. However, it's considered here that only the HVAC load is required to be fed.

PV installation has few steps that should be taken for correct design:

1- Daily load of heating and cooling the villa.

The yearly load of heating and cooling of the villa is 36 345.5 kWh. And to calculate the daily load, the yearly load is divided to 365 days as following:

$$daily\ load = \frac{36\ 345.5\ kWh}{365\ days} = 100\ kWh/day$$

- ✓ Daily load of heating or cooling the villa is 100 kWh/day in case of optimal thickness of insulation.

Daily load of HVAC system in case of without insulation is calculated as:

$$daily\ load = \frac{46\ 209\ kWh/year}{365\ day/year} = 126.6\ kWh/day.$$

- ✓ Daily load of heating or cooling the villa is 126.6 kWh/day in case of without insulation.

2- Power of PV system needed to feed the HVAC load completely

To estimate the power of PV panels needed to feed the HVAC load completely in case of the optimal thickness of extruded polystyrene, where, the efficiency factor is considered 72%:

$$Power\ of\ PV = \frac{yearly\ load}{365 * T * efficiency\ factor} = \frac{36\ 345.5\ kWh/year}{365 \frac{day}{year} * 5.4\ hr * 0.72} = 25.6\ kW$$

- ✓ In case of the optimal thickness, the power of PV system to feed the HVAC load completely is 25.6 kW.

To estimate the power of PV panels needed to feed the HVAC load completely in case of without insulation:

$$Power\ of\ PV = \frac{46\ 209\ kWh/year}{365 \frac{days}{year} * 5.4\ h * 0.72} = 32.56\ kW$$

- ✓ In case of without insulation, the power of PV system to feed the HVAC load completely is 32.56 kW.

3- Area of PV panels according to the available area of roof

The area of PV panels is calculated according to the available area of the roof, where the available area of roof surface is 110 m^2:

$$Aestate = 1.3 * Apv$$

$$\rightarrow Apv = \frac{Aestate}{1.3} = \frac{110\, m^2}{1.3} = 85m^2$$

✓ <u>This means that the area of solar panels according to the available roof area is 85 m^2.</u>

4- Power of PV system according to the available area

After determining the area of solar panels according to the available roof area, the peak power of this system must be calculated at the standard solar radiation 1 kW/m^2 with considering the efficiency of solar panels to be 15 %

$$\eta PV = \frac{peak\ power\ of\ PV\ system}{standard\ solar\ radiation\ kW/m^2 * \ Area\ of\ PV}$$

$$\rightarrow\ kW - peak\ power\ of\ panels = Area\ of\ PV\ system * solar\ radiation\ kW/m^2 * \eta PV$$

$$Peak\ power\ of\ the\ PV\ system = 85\ m^2 * 1\frac{kW}{m^2} * 0.15 \approx 12.75\ kW$$

This means that not all the HVAC load will be covered by the PV system, only 12.75 kW of 25.6 kW will be covered. As a result of this, on grid system will be designed instead of the off grid system. The feeding ratio (Penetration level) of the PV system is determined as:

$$feeding\ ratio = \frac{12.75\ kW}{25.6\ kW} = 49.8\% \approx 50\%$$

or

$$Penetraion\ level = \frac{daily\ energy\ of\ PV}{daily\ load} = \frac{12.750\ kW * 5.4\ h/day * .72}{100\ kWh/day} = 49.6\% \approx 50\%$$

For without insulation scenario:

$$Feeding\ ratio = \frac{12.75\ kW}{32.56\ kW} = 39\%$$

- ✓ <u>In the both cases, the optimal thickness and without insulation, the peak power of PV according to the available roof area system is 12.75 kW. However, the feeding ratio in case of the optimal thickness is 50%, while in without insulation scenario, the penetration level is 39%.</u>

Considering a PV module with these characteristics:

P max = 250 W
V o.c = 37.5 V   I s.c = 8.87 A
V m = 32 V   I m = 8.32 A
Area of 1 module= 1.6 m^2

5- Number of modules

$$\#Modules = \frac{85\ m^2}{1.6\,\frac{m^2}{module}} = 53\ modules$$

Where, the voltage of all modules (Vsyst) is 192 volts to have more modules in the same series for avoidance of current circulation of modules in parallel.

$$\#\ module\ in\ series\ (Nms) = \frac{Vsyst}{Vmodule} = \frac{96\ V}{32\ V/module} \approx 3\ modules$$

$$\#\ strings\ in\ parallel(Nmp) = \frac{Wpeak\ of\ PV\ system}{Nms * Pmax} = \frac{12\ 750}{3 * 250} = 17\ strings$$

As a result of this, the total number of modules is 51, and they are connected as shown in figure 6.5.

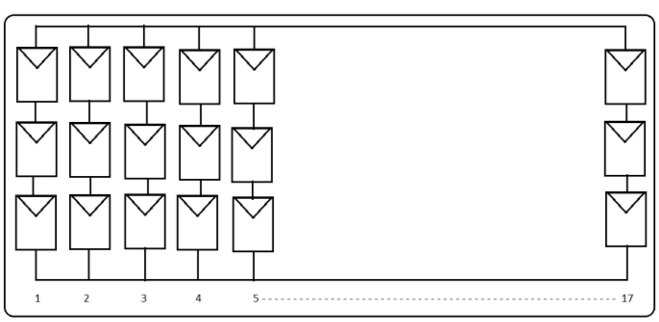

Figure 6.5: connection of moduels in sereis and parallel.

6- Daily energy generated by PV

$$kWh - PV\ generated = (kW - peak\ ) * avg\ sunlight\ hour = 12.75\ kw * 5.4 \frac{hr}{day}$$

$$= 68.85\ kWh/day$$

$$kWh\ of\ PV\ recieved\ by\ load = 12.75\ kW * 5.4 \frac{hr}{day} * 0.72 = 49.6\ kWh/day$$

- ✓ Daily energy produced by PV system is 68.85 kWh/day
- ✓ Daily energy of PV received by load is 49.6 kWh/day due to incidence of alternative (AC) losses.

$$feeding\ ratio = \frac{68.85\ kWh * 0.72}{100\ kWh} = 49.6\ \% \approx 50\%$$

Table (6.11) summarizes all the previous calculations and compares between the both scenarios; optimal thickness of insulation and without insulation in terms of PV design.

Table 6.11 : PV design for optimal thickness and without insulation scenarios.

	Optimal thickness	Without insulation
Load (kWh/day)	100	126.6
PV power to feed the load completely (kW)	25.6	32.56
PV power according to the available roof area (kW)	12.75	12.75
Penetration level %	50%	39%

7- Invertor sizing

It's important to indicate that the size of invertor, and the next appliances don't depend on the load power but the available roof area, this means that the size of inverter, charge controller and cables are the same in the both scenarios; without insulation and optimal thickness. Considering the voltage (Vin) is 48 voltage, the power of invertor is:

$$Power\ of\ invertor = 0.75 * rated\ PV = 0.75 * 12.75 = 9.56\ kW \approx 10\ kW$$

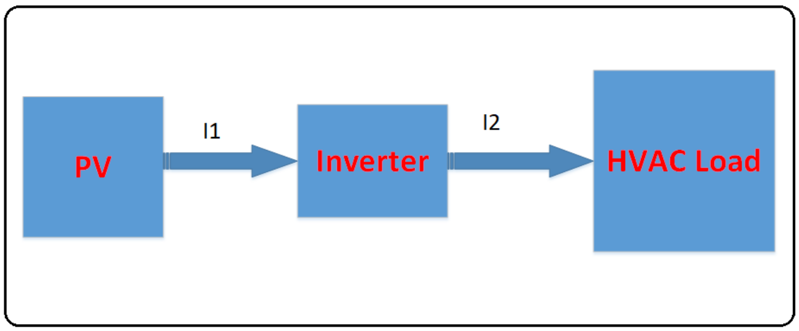

Figure 6.6: Schematic diagram of PV system

8- Cable sizing

Consider the length of cable is 20m from one side, and it's made of copper with a resistivity of $1.724*10^{-8}$ ohm meter, then, the cross sectional area is determined as:

$$A = \frac{\rho L I}{V d}$$

$$Sinv = \frac{Pinv}{pf} = \frac{10\ kW}{0.95} = 10.5\ kVA$$

$$I1 = \frac{Sinv.}{Vsyst.} = \frac{10.5\ kVA}{96\ V} = 109.4\ A$$

$$A1 = \frac{\rho\ L1\ I1}{V} = \frac{1.724 * 10^{-8} * 109.4 * 5}{0.04 * 96} = 2.45 * 10^{-6} m^2$$

$$I2 = \frac{10.5\ kVA}{220} = 47.7\ A$$

$$A2 = \frac{\rho\ L2\ I2}{V} = \frac{1.724 * 10^{-8} * 5 * 47.7}{220 * .04} = 4.67 * 10^{-7} m^2$$

6.9 The simple payback period of PV system

Before using the photovoltaic system, the yearly electricity cost equals 23 625 Nis/year, while after using the photovoltaic system, the yearly electricity cost is determined as multiplying the portion is not fed by PV with the price of 1 kWh.

$$Daily\ energy\ not\ fed\ by\ PV = daily\ load\ of\ HVAC - dialy\ energy\ recieved\ from\ PV$$
$$= 100\ kWh - 49.6\ kWh = 50.4\ kWh$$

$$Electricity\ cost = 50.4\ \frac{kWh}{day} * 365 \frac{days}{year} * 0.65 \frac{Nis}{kWh} = 11\ 957\ Nis/year$$

$$Saving\ in\ electricity\ cost\ yearly = 23\ 625 - 11\ 957 = 11\ 668\ Nis/year$$

The daily energy and yearly energy consumed from the utility, yearly electricity cost and saving are illustrated in table (5.12) for cases of with and without use of PV system.

Table 6.12: Comparing the yearly consumption of electricity before and after PV installation.

	Before installing PV system	After installing PV system
Daily energy consumed from the utility (kWh/day)	100	50.4
Yearly energy consumed from the utility (kWh/year)	36 345.5	18 693
yearly electricity cost (Nis/year)	23 625	11 957
Saving(Nis/year)	0	11 668

* According to the local market, 1 watt of PV costs with installation 0.40 $, the German invertor of 10 kW (kako) costs 6000 Nis, the cables of 40 m for two sides cost 120 Nis and the structure of 12.75 kW costs about 1800 Nis. Therefore, to calculate the investment of PV project, all the previous costs are summed.

$$Cost\ of\ intalling\ PV = 12\ 750\ \mathrm{W} * 0.40 \frac{\$}{W} * \frac{3.59\ Nis}{\$} = 18\ 309\ Nis$$

* The solar panels need annual cleaning estimated as 100 Nis per year. Considering the interest rate is 10% and the project life is 20 years, the net present worth is calculated as:

P = A (P/A, 10%, 20), where the (P/A, 10%, 20) value is found from the economic tables. So;

$$P = 100 * 8.5136 = 851.36\ Nis$$

* Investment of the PV project includes; cost of installing 12.75 kW PV, invertor, charge controller, structure, annual cleaning and cables. So;

$$Investment\ of\ PV\ system = 18\ 309 + 120 + 6000 + 1800 + 851.36 = 27\ 080\ Nis$$

$$SPP = \frac{investment}{saving} = \frac{27\ 080\ Nis}{11\ 668\ Nis/year} = 2\ years$$

Chapter 7: Conclusion

As a conclusion, the optimal thickness of a thermal insulator is the thickness which leads to the maximum heat transfer reduction in winter and summer with the lowest total cost (summation of initial &operating costs), and so, the lowest simple payback period. This means that the HVAC system will operate for less hours and power when the optimal thickness of insulation is used causing lowering of operation costs, increase of saving and so, decrease of the simple payback period.

For a cost-effective feasible way, designing a photovoltaic system according to the available roof area is considered a good choice to feed the need of HVAC load completely or to reduce the consumption of electricity from the grid, remembering that the off grid design has high simple payback period due to the high investment required especially for the batteries. Moreover, to reduce the operating cost of the HVAC central unit system, the ground floor could have an HVAC system which is separated from the roof's system.

Chapter 8: Bibliography

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Chapter 9: Appendices

9.1 Appendix A: AutoCAD scheme of the villa.

9.1 (a) Ground floor scheme

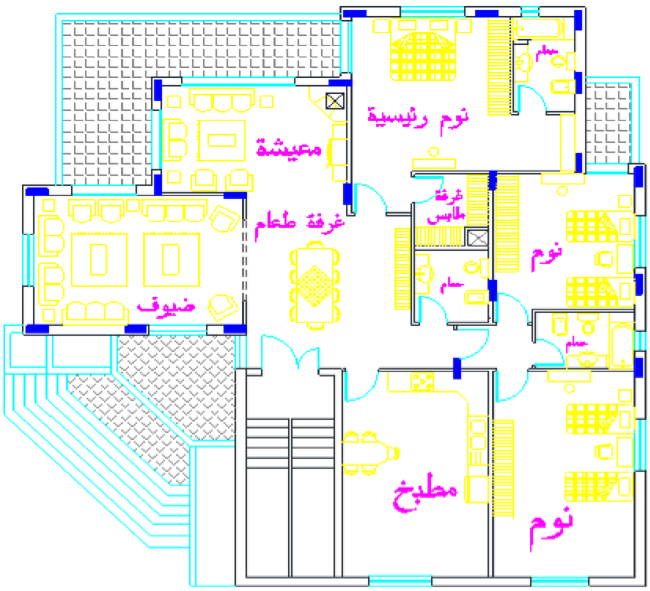

Figure 9.1: Ground floor scheme.

9.1 (b) Roof floor scheme

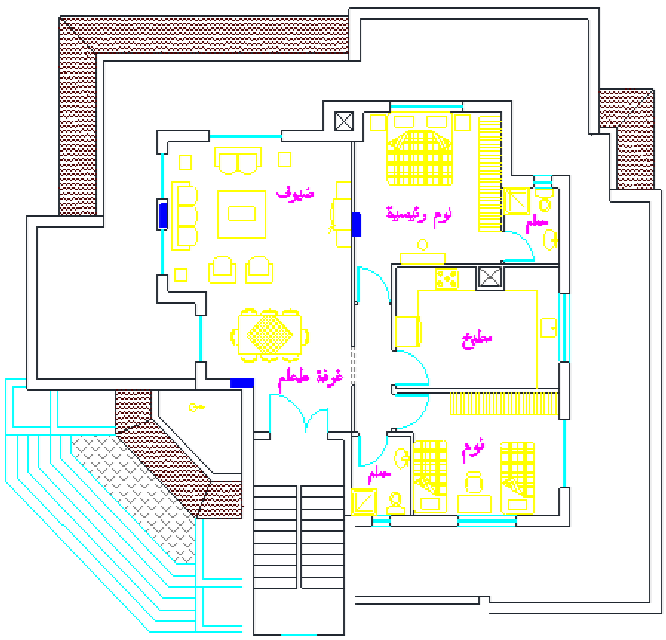

Figure 9.2: roof scheme

9.2 Appendix B: Climate statics of Jerusalem

Table 9.1: Climate statics of Jerusalem. [7]

المحطة: القدس												
العنصر	كانون ثاني	شباط	آذار	نيسان	أيار	حزيران	تموز	آب	أيلول	تشرين أول	تشرين ثاني	كانون أول
المعدل العام لدرجة الحرارة العظمى	11.4	12.9	16	20.9	24.8	27.3	28.4	28.6	27.5	24.5	18.7	18.7
المعدل العام لدرجة الحرارة الصغرى	6.1	6.9	8.7	10.3	15.3	17.7	18.9	19	18.1	16.4	12.3	8
المعدل العام للرطوبة النسبية	67	66	59	50	45	48	53	57	58	56	59	66

Table 9.2: The average of number of hours of solar radiation. [7]

المحطة القدس													
العنصر	كانون ثاني	شباط	اذار	نيسان	ايار	حزيران	تموز	اب	ايلول	تشرين اول	تشرين ثاني	كانون اول	الفترة الزمنية للمعدل
المعدل العام لعدد ساعات سطوع الشمس	5.4	7.1	7.4	9.4	11.4	12.4	12.1	11.8	10.1	7.3	6.5	5.9	1972-1997

9.3 Appendix C: Construction layers

Only the external walls and roof are insulated by polystyrene in the second scenario, while the ceiling and internal walls have the same components in the two scenarios.

9.3 (A) Both scenarios

9.3 (A)-a Components of ceiling (Uov =0.960 W/m2.k)

Figure 9.3: components of ceiling.[5]

9.3 (A)-b Components of floor (Uov = 2.32 W/m2.K)

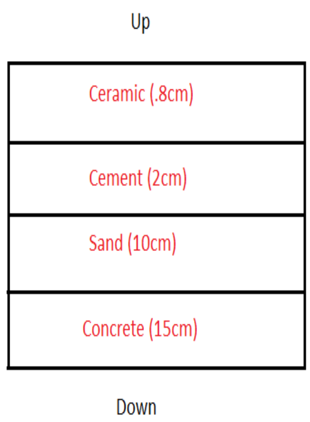

Figure 9.4: Components of floor. [5]

9.3 (A)-c Components of internal walls (Uov = 2.18 W/m2.K)

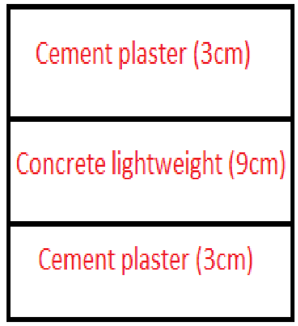

Figure 9.5: Components of internal walls. [5]

9.3 (A)-d Components of internal doors (2.8 W/m^2.K)

Wood pine with thickness of 2.5 cm.

9.3 (A)-e Components of external door (5.54 $W/m^2.K$)

Stainless steel with thickness of 4 cm.

9.3 (B) Before insulation

9.3 (B)-a Components of external wall (Uov =2.24 $W/m^2.K$)

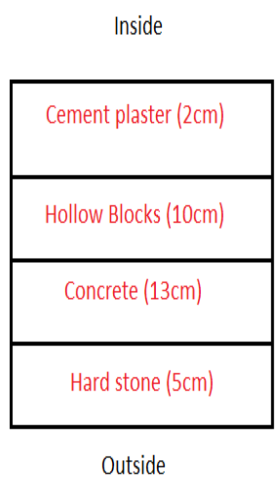

Figure 9.6:Components of external walls before insulation. [5]

9.3 (B)-b Components of roof (Uov = 3.12 W/m^2.K)

Figure 9.7: Components of roof before insulation. [5]

9.3 (B)-c Components of windows (U=5.34 w/m^2.K)

Standard glass with thickness of 1 cm.

9.3 (C) After insulation

9.3 (C)-a Components of external wall (Uov =.960 W/m2.K)

Figure 9.8: Components of external walls after insulation. [5]

9.3 (C)-b Components of roof (Uov = 1.09 W/m^2.K)

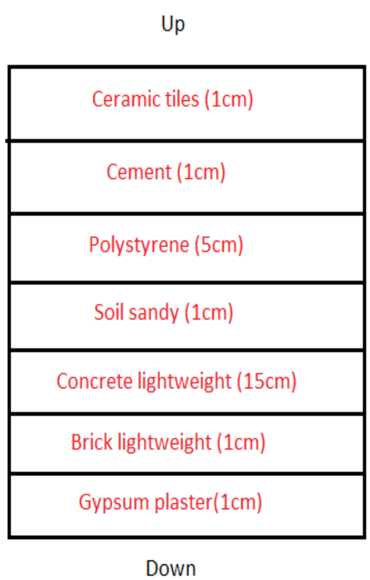

Figure 9.9: Components of roof after insulation. [5]

9.3 (C)-c Components of windows

Figure 9.10: components of windows after insulation. [5]