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Buildings Optimal Insulation Thickness Effects on Air Conditioning Capacity and PV Self-Consumption Share Level

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Abstract – *Energy conservation projects and renewable energy power generation are the future of sustainable energy supply. Combining both is very effective and maximizes benefits. PTs building sector is the highest consumer, constitute 48.6% of the total Palestinian energy balance. Until now, there is no specific Palestinian engineering building code. As a result, building insulation is still mandatory. There are few performed studies about optimal building insulation thickness economic and environmental benefits. Regarding renewable energy national share increase, the PA developed many ambitious plans, most of which concentrated on increasing PV systems installed capacity due to its high potential. PTs enjoy 3000 sunshine hours per year, 5.4 kWh/m^2/day average solar radiation. Few studies are targeting Palestinian building's renewable energy share increase through the principle of self-consumption. This research presents a novel approach in investigating the economic feasibility of installing optimal insulation thickness in buildings. Practically, insulation layers are assumed to be installed during the building phase, before mechanical building systems. However, the insulation effect will reduce AC required capacity as a result of reducing summer CL, thus, reduce initial investment. For that reason, the P_1-P_2 method has been used to generalize the optimal insulation thickness approach for the West Bank area considering different T_b values. It has been found that at T_b=18 °C, optimal thickness values, total cost, energy saved, and Np values are 10-11 cm, 18 \$/m^2, 175-375 \$/m^2, and 5-14 years, respectively. Then, a commercial building in Ramallah city was taken as a case study; it has a 1,700m^2 roof area for PV installation. PVsyst software is used to design a 173 kWp system. It is estimated to generate 320MWh per year for building self-consumption. The insulation effect raised renewable energy share from 62.6% to 64.1%, and reduced AC rated capacity by 20 refrigeration ton (saved \$20,000 as an initial investment).* ***Copyright © 2021 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Life Cycle Costing, Optimal Insulation Thickness, Buildings Cooling Loads, Photovoltaic, Renewable Energy, CO_2-eq*

Nomenclature

A	Building component surface area [m^2]
AC	Air conditioning
A_{PV}	Area of the PV modules
app	Appliances
BE	Building envelope
C_t	Total cooling cost [\$]
CDD	Cooling Degree Days
CDH	Cooling Degree Hours [°C hour]
C_E	Electricity cost [\$/kWh]
C_i	Initial cost of insulation material [\$/m^3]
CL	Cooling Load
CLF	Cooling Load Factor
$CLTD$	Cooling Load Temperature Difference
CO_2eq	Estimated saved CO_2 equivalent emissions [kg/year]
COP	Coefficient of Performance
$corr$	Corrected
d	Energy escalation rate [%/year]
DDM	Degree day method [°C day]
E_{ac}	Normalized building seasonal AC energy consumption [W/m^2]
f	Attic or roof fan factor
f_{man}	Derating-factor for manufacture tolerance
f_{dirt}	Derating-factor for dirt
f_{temp}	Derating-factor for temperature
GCR	Ground Coverage Ratio
h_i	Inside convection heat transfer coefficient [W/m^2 °C]
h_o	Outside convection heat transfer coefficient [W/m^2 °C]
i	interest rate [%/year]
I	Global annual solar radiation on a horizontal surface in the hourly interval
I_b	Beam annual solar radiation on a horizontal surface in the hourly interval
$I\rho_g$	The diffuse reflectance of the total solar radiation
I_T	Total solar radiation on the tilted surface
inf	Infiltration
k	Thermal conductivity [W/m °C]

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k_{color}	Color adjustment factor
LCC	Life Cycle Cost
LM	Latitude month correction factor
Lt	Lighting
M_s	Annual maintenance and operational costs
N	Total project estimated lifetime [years]
Np	Discounted payback period [years]
NDC	Nationally Determined Contributions
NEEAP	National Energy Efficiency Action Plan
occ	Occupants
P_1	Present worth factor of a series of N future payments
P_2	Ratio of the life cycle additional costs due to insulation capital investment
PA	Palestinian Authority
PENRA	Palestinian Energy & Natural Resources Authority
PCBS	Palestinian central bureau of statistics
PTs	Palestinian territories
$\dot{Q}$	Heat transfer rate [W/m^2]
Rf	Roof
R_i	Inside air film thermal resistance [m^2 °C/W]
R_{in}	Insulation layer thermal resistance [m^2 °C/W]
R_o	Outside air film thermal resistance [m^2 °C/W]
R^2 *adj*	The adjusted coefficient of determination [%]
$R_{t,w}$	Wall total thermal resistance [m^2 °C/W]
R_v	Ratio of resale value to the first cost
R_w	Wall composite construction layers thermal resistance [m^2 °C/W]
Sc	Net normalized energy saving over a lifetime [\$/m^2]
SC	Shading Coefficient
SHG	Solar Heat Gain factor [W/m^2]
T_b	Base temperature [°C]
Ti	Daily mean inside air temperature [°C]
T_o	Daily mean outdoor air temperature [°C]
$T_{o,m}$	The operative mean temperature in [°C]
TOE	A tonne of oil equivalent
T_o	Building outside temperature in [°C]
Uov	Overall heat transfer coefficient [m^2 °C/W]
ven	Ventilation
WT	Wall type
x_{opt}	Optimum insulation thickness [m].
β	Tilt angle of the PV system
γ	Power temperature coefficient
δ	Declination-angle
ω	Hour-angle
∅	Latitude-angle
η_{PV}	PV module efficiency
η_{PV-inv}	Efficiency of the sub-system between the PV array and the inverter
η_{inv}	Efficiency of the inverter
η_{inv_sub}	Efficiency of the sub-system between the inverter and switchboard

I. Introduction

Energy conservation has received great attention in recent times. Following global trends, the Palestinian government is trying to reduce energy consumption to secure resources and protect the environment. Palestinian buildings sector has the largest share of energy consumption. According to the most recent Palestinian Central Bureau of Statistics (PCBS), it consumed 162×10^3 and 179×10^3 TOE of renewable energy and oil products, respectively. And 4,832 GWh of electricity [1].

In 2018, buildings' energy consumption constitutes 48.6% of the total Palestinian energy balance [2]. Palestinian Territories (PTs) depend almost completely on imported energy. The published data of the PCBS regarding energy performance indicators stated that the dependency rate reached 86% in 2018 [3]. Palestinian Authority (PA) aims to reduce its energy consumption.

For that reason, PA developed the National Energy Efficiency Action Plan (NEEAP). It intends to conserve around 385 GWh between 2012 and 2020; around 95% of the total target, approximately 360 GWh should be in the buildings sector [4]. Unfortunately, PA efforts towards developing specific Palestinian buildings and construction codes and standards are still not completed. In 2013, the Palestine engineers association issued the Palestinian Green Buildings Guidelines; it adopted the international energy conservation codes 502.4, 503.2, 504, and 505 to determine the maximum allowable values for heat transfer coefficients [5]. The developed guidelines mentioned general technical specifications for insulation materials. However, it is still elective, and so, buildings insulation is not mandatory. Hopefully, the situation will not be the same soon as Palestinian Energy and Natural Resources Authority (PENRA) prepared a special law draft to penalize industrial and commercial facilities in 2015: it states that if the upper predetermined environmental emissions threshold were exceeded (represented by carbon dioxide equivalent CO_2-eq), business owners will be forced to consider energy conservation practices. Otherwise, they will pay extra taxes as a penalty. The law has not been activated yet due to many reasons. Including Palestinian-Israeli complicated political situation and the Palestinians internal clashes that caused absence of the Palestinian Legislative Council, both reasons have been considered with more priority from PA point of view. Until law activation, the most effective approach to convince citizens to reduce energy consumption will be proving its economic feasibility. So, buildings insulation cost analysis is necessary, and Life Cycle Costing (LCC) minimization is the best method to be considered. In the 2015 Paris Agreement, countries across the globe committed to create an international climate agreement at the United Nations Framework Convention on Climate Change Conference. Through which the state of Palestine defined two political scenarios targets for its Nationally Determined Contributions (NDC):

- Independence scenario: assumes ending the conflict with Israel; therefore, PA will be able to exercise full control over its resources;
- Status quo scenario: assumes a continuation of the conflict with Israel.

The state of Palestine's target is to reduce 510 $ktCO_2eq$ from the building sector by improving building energy consumption efficiency considering the independence scenario. For the status quo scenario, the target becomes zero emissions. For electric generation: independence scenario aims to reduce 2,900 $ktCO_2eq$ by generating electricity from Photovoltaic (PV) power generators, while this target becomes 635 $ktCO_2eq$ under status quo scenario [6]. It is important to note that PTs have Mediterranean weather which is hot and humid in summer. Meaning that buildings' electric consumption increases significantly during the summer season, which happens due to excessive Air Conditioning (AC) systems usage. Interestingly, PTs are considered with high solar radiation potential equals to an average of 5.4 kWh/m^2 day (3,000 annual sunshine hours) [7]. It means that PV has very good potential. Despite this similarity in summer peaking, it is not technically feasible to assume that AC systems electric demand can be fulfilled with complete dependence on PV due to building's roof area constraints and the high price of lands in Palestine.

Therefore, on-grid PV systems can reduce imported power, increase national independence, help in achieving NDC targets by fulfilling significant buildings' electric load, and reduce the effect of summer electric load peak. In other words, PV penetration level increase is a national benefit for PTs concerning all sustainable development pillars: technically, economically, and environmentally.

In the same context, thermal insulation is considered an effective, low investment, and low-risk alternative when it comes to building energy consumption reduction.

Especially when taking into account that the average Palestinian energy prices are among the highest compared to local average individual income [8], it is expected that buildings insulation will be feasible and helpful in achieving the Palestinian national strategic energy conservation targets. This paper presents a new design approach for reducing AC equipment installed capacity, AC summer cooling loads, and increase PV penetration level. The main concept of the design is to prove the extended positive effects of installing optimal insulation thickness in buildings' external walls.

The remaining parts of the paper are divided as follows. Section II explains previous work and the proposed research contribution, Section III describes the adopted methodology, Section IV presents local weather conditions, buildings wall types, and the considered case study description. Then, Section V is dedicated to present results and discussion, while Section VI presents the conclusion and recommendations.

II. Literature Review

Previous researches contain many contributions regarding building insulation thickness optimization, AC system sizing, and renewable energy penetration level increase. One of the key success factors in investigating energy consumption in buildings is to build suitable models with reasonable accuracy, in this context, [9] developed a simplified low order model using thermal networks depending on thermal resistances and capacitances. A stochastic particle swarm optimization algorithm was used to determine the model parameters values. The developed model accuracy was then evaluated based on extensive simulations and validated using a real case study. When it comes to optimal insulation thickness contributions, most of it is based on the Degree Day Method (DDM). For Palestine, [10] used the LCC approach to define optimal insulation thickness for year-round heating and cooling applications for eight Palestinian governorates. Polystyrene and Polyurethane insulations were considered. Results showed that polyurethane is superior considering the thickness and total cost. [11] studied the effect of different wall and fuel types in determining the optimal insulation thickness for heating purposes for four climate zones in Turkey.

Optimal thickness varied between 2 to 17 cm, and the payback period extended to 4.5 years in the coldest zone.

Other researchers applied the LCC method to define optimal insulation thickness for building roofs. [12] determining optimal insulation thickness for external walls and roof considering four cities in Turkey. Results indicated that optimal thickness varied between 3.3 and 8 cm for external walls, and between 2 and 6.5 cm for the roof. Moreover, it included a regression analysis between several degree days as a regressor and optimal thickness as a response and the coefficient of determination (R) values were >0.98. [13] investigated the energy and economic results of using external walls thermal insulation in office buildings in Italy. Simulations using DesignBuilder software were performed considering 10, 20, and 30 W/m^2 internal loads power density. Then, the optimal insulation thickness was determined using the cost-optimal methodology. Other researchers adopted the P_1-P_2 approach. [14] defined optimal summer and winter insulation thicknesses for four main cities in China. Different wall orientations, surface colors, and five insulation materials were considered in the analysis. For all different insulation types, results indicated that optimum thicknesses varied from 5.3 to 23.6 cm, and the Simple Payback Period (SPP) values were from 1.9 to 4.7 years over a lifetime of 20 years. Similarly, [15] calculated the required optimal thickness assuming five different insulation types for four climate zones in Turkey. The analysis included summer cooling and winter heating loads. Results indicated that optimal thicknesses are between 2 and 22 cm, and SPP varied between 0.89 and 2.6 years. Other optimal insulation thickness studies were made assuming steady-state conditions. For example, [16] considered a case study in Tunisia. Complex finite Fourier transform analysis was used for estimating yearly cooling transmission loads considering two types of insulation materials and two typical wall structures. Achieved results were compared to the DDM approach. It revealed that using complex finite Fourier transform yields thicker optimal insulation values, longer payback period, and less life cycle energy savings. However, differences between the two methods did not exceed approximately 20% at most. The authors claimed that their approach leads to 5.7 cm optimal insulation thickness and 3.11 years payback period. The explicit finite-difference method under steady periodic conditions was used by [17] to calculate the yearly cooling transmission loads. The study considered wall orientations and the percentage of radiation blocked for the case of Cameroon, which has a tropical wet and hot climate. A lifetime of 22 years was assumed. It was found that the lowest optimum thickness is 9 cm, and energy savings are approximately 79.80% for the south-oriented wall, while the highest SPP value is 4.73 years on the same face compared to other orientations. Another similar contribution done by [18] focused on the economic performance of external walls optimum insulation thickness. It took three different provinces in Iran and presented a design approach for using composite prefabricated wall block and applying DDM with LCC calculations. A combination of polystyrene, polyurethane, and air-gap was investigated. And the results showed that the optimum thickness relates proportionally with atmospheric conditions severity, which leads to an increase in cost-saving and shortens the SPP. [19] considered bio-based materials for buildings thermal insulation and compared it with conventional insulating materials. Menkes city in Morocco has been taken as a case study and hemp wool and air gap layers were considered for insulation. LCC, energy savings and SPP are calculated over an estimated 20 years life cycle.

One dimensional heat equation was analyzed to determine the optimum insulation thickness for different wall orientations. Results indicated that the highest achieved optimum thickness is for east and west orientations, with about 5cm, followed by southern and northern, with 4cm and 3cm, respectively. Moreover, an environmental assessment was conducted as GHG emissions, and it was found that 71% reduction can be achieved when using optimum insulation thickness of hemp wool and air cavity. Due to the relatively large number of previous contributions, several reviews made in this field contained informative and comparable results, for instance, [20] performed a comparative review included the economic models (P_1-P_2 and LCC), geographic place of investigation, resulted in optimum insulation thickness, considered insulation types, reduced emissions, and fuel type. Moreover, it included a case study of 10 years of life span for determining the optimal insulation thickness for the city of Iskenderun, Turkey.

Other researchers investigated weather parameters on the optimal insulation thickness. [21] studied the influence of hot-humid climate in hot summer and cold winter zones of three representative cities in China. The analysis was made by applying a coupled heat and moisture transfer model. It claimed that moisture transfer and accumulation within exterior walls will affect the cooling and heating transmission loads, and so, exert an influence on the required insulation thickness value. The economic model P_1–P_2 was used. Results showed that optimum thickness varied between 5.3 and 10.5 cm, while SPP values were from 1.89 to 2.56 years. Some researchers combined the LCC method with different analytical approaches. [22] performed exergetic life cycle assessment analysis to determine the optimal insulation thickness in building walls. Rockwool and Glass wool as insulation types were assumed. When targeting environmental impact minimization, optimal thicknesses are 21.9 and 9.8 cm for glass wool and Rockwool, respectively. However, when targeting optimal exergetic life cycle cost analysis, optimal thicknesses are 1.8 and 1.2 cm for glass wool and Rockwool, respectively.

Moreover, sensitivity analysis revealed that the total exergetic environmental impact is affected by the temperature of the fuel entering the combustion chamber, the temperature of stack gasses, and combustion temperature. [23] performed a quantitative comparison between various buildings' thermal insulation materials.

Material manufacturing and installation phase’s carbon footprint were compared to energy savings made up of building thermal load reduction. [24] implemented an integrated decision support method to evaluate 23 configurations that included different insulation and wall structures. The analysis took into consideration the Mediterranean area. Thermal comfort was evaluated using the Predicted mean vote / Predicted percent of dissatisfied people index. [25] investigated the relation between building insulation thickness and the anti-insulation effect. It happens in the special case of internal gain dominated buildings. In such cases, thicker building insulation may prevent heat loss through the walls. So, it results in higher energy consumption by equipment that aims to remove this thermal load. Detailed energetic simulations were performed for different locations around the world. Many other contributions focused their efforts on calculating environmental harmful emissions reduction as a result of installing thermal insulation in buildings. [26] studied the environmental impact of winter heating optimum insulation thickness in external walls for a case in Denizli, Turkey. Coal fuel and expanded polystyrene insulation were considered. It was claimed that energy consumption and emissions (CO_2 and SO_2) can be reduced up to 46.6% and 41.53%, respectively. Similarly, [27] considered six different insulation materials and calculated potential savings and emission reductions in the Maldives. The study considered 2, 4, and 6 cm air gaps in the wall. Optimum thickness is based on the cost to benefit ratio of each insulation material over its lifetime. Obtained results claimed that introducing air gaps can reduce energy consumption and emissions by 65-77%, in comparison to a wall without insulation or air gaps. [28] investigated the economic and environmental behavior of using aerogel super insulation material for office building insulation. The proposed insulation type was compared with four typical building insulation materials, specifically, expanded polystyrene, extruded polystyrene, foamed polyurethane, and glass fiber. Results revealed that aerogel enabled the minimum optimum thickness, 3.7cm, and it can lead to lower GHG emissions.

Similarly, [29] considered energy, economic, and environment comparative approach for determining optimum insulation thickness of office building, where the cost of producing insulation materials was also taken into account. Achieved results showed that polyurethane, expanded polyurethane, and Rockwool optimum thickness are 8 cm, 20 cm, and 7 cm, respectively. The main purpose of buildings is to protect occupants from external conditions, thus, ensure their comforts. This issue is a field of investigation for a large number of researchers. For example, [30] performed a state of the art review targeted buildings energy management systems and internal comfort issues, specifically, thermal, lighting, air quality, and relative humidity parameters were considered as indicators for thermal comfort. It considered and compared the advantages and disadvantages of three model types; grey, black, and white box. Another building insulation interesting contribution was proposed by [31]. It provided an overview analysis considering conventional insulation materials, and different comparative criteria; thermal resistance, moisture, and fire resistance. To optimize the thickness of the studied materials energy analyses using the COMcheck program have been performed based on two globally known energy conservation codes. A high rise building in New York City was chosen as a case study. On the other hand, when it comes to buildings integrated grid-connected PV systems, two main concepts should be considered. Systems working under feed-in conditions and buildings self-consumption conditions. [32] and [33] defined the concept of electricity self-consumption as renewable energy that is produced from energy sources such as PV and consumed by the building owner, not injected into the local electric grid. [32] said also that to date, the highest potential share technology for self-consumption is PV. One major challenge to this configuration in residential buildings is that the daytime of PV peak generation is during noon where most residents are empty. So, energy storage and/or demand peak shifting become necessary when PV production exceeds demand, otherwise, feeding extra energy to the local grid is technically and economically possible, and sometimes necessary. However, commercial buildings can generally overcome this constraint and achieve higher shares of self-consumption.

This is because the peak load of such buildings is normally matching with PV peak generation. Previous literature is rich in contributions working on this field trying to increase the share of PV production. [33] worked on utilizing a practical technical option for self-consumption by the rescheduling of programmable appliances, such as washing machines, clothes dryers, and dishwashers. The contribution highlighted the potential to increase PV self-consumption. A case study of 200 single-family buildings in Sweden was considered. It was found that load shifting can potentially increase PV self-consuming by an average of 200 kWh.

Another demand shifting contribution was performed by [34], where an advanced airflow, energy, and humidity modeling tool was used to evaluate the potential for residential AC loads to be shifted away from the electric peak demand period. The study included simulations of homes in 12 different United States climate zones. Results showed that all of the applied strategies caused shifting at least 50% of the on-peak cooling loads away. Other contributions included energy storage components, [35] performed experimental and theoretical modeling study to investigate the effect of two control strategies on a grid-connected PV coupled with energy storage system supporting heating, ventilation, and AC system. The control strategies are increasing PV self-consumption and grid-peak shaving.

Results revealed that self-consumption rate reaches 30% without energy storage system, but the proposed control strategies can raise it to 50%, depending on the storage capacity and PV nominal power. From another side, [36] reviewed and introduced the modern advances of the buildings integrated PV systems and their properties along with international guidelines and testing standards. It considered PV systems for rooftops, façades and windows. Systems sustainability was assessed based on examining energy payback time and CO_2eq emissions.

Due to this field of research importance and a relatively large number of contributions, many previous manuscripts are dedicated to reviewing issues. [33] reviewed PV self-consumption and its improvement options. The contribution included two options for increasing self-consumption share, energy storage, and load management, also called demand-side management.

Results revealed that it is possible to increase PV self-consumption share by 13-24%, and between 2% and 15% by applying battery storage and demand-side management, respectively. Another review was performed by [37], where buildings integrated PV and building integrated PV/thermal systems were considered.

It took into consideration energy generation, systems nominal power, efficiency, type, and performance assessment methods. It was observed that two research areas are considered in the reviewed articles, which are improvements of system efficiency by modifying the ventilation system and lowering the panel temperature, so, increasing PV system share. And new thin-film technologies that are well suited for building integration.

It can be noticed that all previous contributions focused on the direct benefits of installing insulation in buildings' external walls. Direct benefits included heating and/or cooling systems energy savings due to overall load reduction and it resulted in environmentally harmful emissions reduction. On the other side, many contributions focused on buildings' self-consuming PV produced energy, it considered load shifting and AC temperature setting to increase PV share in the overall building electric bill. There are no previous studies that combined both fields' potential benefits through investigating the effect of buildings external walls optimal insulation thickness on AC equipment capacity, its corresponding initial investment, and/or PV share level. This study aims to bridge this gap and investigate the positive economic and environmental effects of installing optimal insulation thickness in external building walls on AC required rated capacity and self-consuming PV energy share. For that purpose, the study will determine the optimal insulation thickness for different wall structures used in PTs and will consider a commercial building case study to investigate the effect on AC system rated capacity and self-consuming PV share level.

III. Methodology

This section describes the calculation procedure and research implementation steps.

III.1. P_1-P_2 method

Optimal building external wall thickness can be achieved using the procedure presented in [38]. First of all, DDM is based on the principle of thermal equilibrium between a building's internal space and its surrounding outside temperature. The total number of seasonal Cooling Degree-Hours (CDH) is calculated using Eq. (1). Then, Eq. (2) is used to calculate normalized energy consumption (W/m^2) in the summer season due to building envelope external walls interaction with the outside environment:

$$CDH = (1\text{ year}) \sum_{day=1}^{365} (1\text{ day}) \sum_{hour=1}^{24} (T_o - T_b)^+ \quad (1)$$

$$E_{ac} = \frac{U_{ov}}{COP} CDH \quad (2)$$

COP is the coefficient of performance and U_{ov} is the overall heat transfer coefficient. Eqs. (3) and (4) are used to calculate U_{ov} for insulation and no-insulation scenarios, respectively:

$$U_{un} = \frac{1}{R_i + R_w + R_o} \quad (3)$$

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

R_i and R_o are the inside and outside air film thermal resistance, respectively. R_w is the composite wall (construction material) thermal resistance, and R_{in} is the insulation thermal resistance. However, for different insulation thicknesses, R_{in} is calculated using Eq. (5):

$$R_{in} = \frac{x}{k} \quad (5)$$

where x and k are the thickness and thermal conductivity of the insulation material, respectively. Considering $R_{t,w}$ is the wall total thermal resistance without considering the insulation layer, then, the difference in overall heat transfer coefficient is calculated using Eq. (6):

$$\Delta U = \frac{1}{R_{t,w}} - \frac{1}{R_{t,w} + \frac{x}{k}} = U_{un} - U_{in} \quad (6)$$

P_1 represents the present worth factor of a series of N future payments, with i interest rate per year representing the time value of money and d energy escalation rate. Eq. (7) was used to calculate P_1:

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

P_2 represents the ratio of the life cycle additional costs due to insulation capital investment. This is calculated using Eq. (8):

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

where M_s and R_v are the annual maintenance and operational cost to the original first cost, and the ratio of resale value to the first cost, respectively. Since insulation in buildings require no maintenance and has no resale value, P_2 can be assumed 1. At this point, it is necessary to calculate insulation layer initial investment cost using Eq. (9):

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

C_i is the insulation material cost in \$/m^3. The net energy savings (S_c) for cooling over the lifetime per unit area is calculated using Eq. (10):

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

Finally, optimal insulation thickness x_{opt} can be determined mathematically by deriving Eq. (10) and finding its root. This derivative result is presented in Eq. (11), and the discounted Payback Period (Np) in years was calculated using Eq. (12), and finally, total cost C_t was calculated using Eq. (13):

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

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

$$C_t = P_1\, E_{AC} + P_2\, C_{ins} \tag{13}$$

III.2. Cooling Load Calculation

Buildings Cooling Load (CL) correlates with the temperature difference between inside and outside conditions in a proportional way. The correlation level depends on the building envelope performance.

Therefore, walls, windows, roof, floor, and external doors all have an effect. CL calculation depends mainly on Eqs. (14)-(23):

$$\begin{aligned}\dot{Q}_{CL} &= \dot{Q}_{sensible-CL} + \dot{Q}_{latent-CL} = \\ &= \dot{Q}_{BE} + \dot{Q}_{inf} + \dot{Q}_{ven} + \dot{Q}_{occ} + \dot{Q}_{Lt} + \dot{Q}_{app}\end{aligned} \tag{14}$$

where $\dot{Q}$, *BE, inf, ven, occ, Lt,* and *app* represent heat transfer rate in W/m^2, building envelope, infiltration, ventilation, occupants, lighting, and appliances, respectively. For the BE heat transfer rate, Eq. (15) can be used:

$$\dot{Q}_{BE} = \dot{Q}_{wall} + \dot{Q}_{window} + \dot{Q}_{roof} + \dot{Q}_{floor} + \dot{Q}_{door} \tag{15}$$

For every term presented on the right-hand side of Eq. (15), Eq. (16) describes the calculation procedure:

$$Q = UA(T_o - T_i) \tag{16}$$

T_o and T_i are the building outside and inside temperatures in °C, respectively, A is the building component surface area in m^2. Additionally, the solar effect for any building component can be calculated using Eqs. (17) and (18). LM is the latitude month correction factor, $T_{o,m}$ is the operative mean temperature in °C, CLTD is the cooling load temperature difference, k_{color} is the color adjustment factor, f is the attic or roof fan factor, and *corr* represents the term corrected:

$$Q_{solar} = UA(CLTD)_{corr} \tag{17}$$

$$\begin{aligned}CLTD_{corr} &= (CLTD + LM)k_{color} + \\ &+ (25.5 - T_i) + \left(T_{o,m} - 29.4\right)f\end{aligned} \tag{18}$$

Glass window has an extrasolar gain effect which is measured using Eq. (19):

$$Q_{glass} = A(SHG)(CLF)(SC) \tag{19}$$

SHG, CLF, and *SC* are the solar heat gain factor in W/m^2, the cooling load factor, and the shading coefficient, respectively. Infiltration and/or ventilation CL are calculated using Eq. (20), while CL due to occupants and lighting system are calculated using Eqs. (21) and (22), respectively. h_o and h_i represent the outside and inside convection heat transfer coefficients in W/m^2 °C, respectively:

$$\dot{Q}_{inf} \text{ or } \dot{Q}_{vent} = \frac{\dot{V}}{v_o}(h_o - h_i) \tag{20}$$

$$\dot{Q}_{occ} = (\#\, of\, occ\, (SG)/1000)CLF_{occ} \tag{21}$$

$$\dot{Q}_{Lt} = \left(\left(\left(\text{average } \frac{\text{W}}{\text{m}^2}\right)(\text{Building area})\right)/1000\right)CLF_{Lt} \tag{22}$$

From the above equations, before and after building envelope modifications, CL can be calculated. Based on that, estimated electric energy cost savings are calculated as shown in Eq. (23). CE is the cost of electric kWh in USD, removing it from equation (23) results in estimated energy saving in kWh/year:

$$Cost_{Savings} = \frac{\left(\dot{Q}_{before} - \dot{Q}_{after}\right) \times (number\ of\ operating\ hours\ per\ season)C_E}{COP} \tag{23}$$

III.3. PV Design and Simulation

The grid connected solar PV mode is designed to function in parallel and side by side with the electric grid.

Fig. 1 shows the grid connected PV generator main components. The most important element in this mode is the inverter which transforms the DC power produced by the PV system into AC power. The quality of the power signal generated by the PV system should be consistent with that of the electric-grid. Normally special types of inverters are used for this purpose. The grid-connected mode assures a double flow of power between the PV system and the electric-grid. It permits the PV system to provide local load or feed electric-grid when PV power output is larger than local load demand. Geometric factor R_b, total solar radiation on the tilted surface I_T and annual electric energy (E_{grid}) generated by the PV system and injected to the grid are estimated using Eqs. (24)-(26), respectively:

$$R_b = \frac{\cos(\emptyset - \beta)\cos\delta\cos\omega + \sin(\emptyset - \beta)\sin\delta}{\cos\emptyset\cos\delta\cos\omega + \sin\emptyset\sin\delta} \tag{24}$$

$$I_T = I_b R_b + I_d \frac{1 + \cos\beta}{2} + I\rho_g \frac{1 - \cos\beta}{2} \tag{25}$$

$$E_{grid} = \sum_{0}^{8760} \begin{pmatrix} (I_T)(A_{PV})(\eta_{PV})(f_{man}) \times \\ \times (f_{dirt})(f_{temp})(\eta_{pv-inv}) \times \\ \times (\eta_{inv})(\eta_{inv_{sub}}) \end{pmatrix} \tag{26}$$

where ω is the hour-angle, $\emptyset$ is latitude-angle, δ is the declination-angle [39]. I and I_b are the global and beam annual solar radiation on a horizontal surface in the hourly interval, respectively [40]. β is tilt angle of the PV system, and $I\rho_g$ is the diffuse reflectance of the total solar radiation [39].

I_T is the total solar radiation on the tilted surface, η_{PV} is the efficiency of the PV module. f_{man} is a derating-factor for manufacture tolerance.

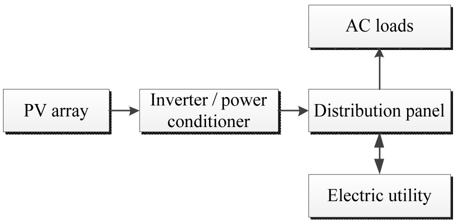

Fig. 1. Main components of the grid-connected PV generator

Normally, a value of 95% is acceptable if the data is not available [41]. f_{dirt} is derating-factor for dirt, f_{temp} is derating-factor for temperature, it is estimated based on a relation depends on value of power temperature coefficient (γ), average daily cell temperature, and cell temperature at standard test conditions. η_{PV-inv} is the efficiency of the sub-system between the PV array and the inverter. η_{inv} is the efficiency of the inverter. η_{inv_sub} is the efficiency of the sub-system between the inverter and switchboard. A_{PV} is the area of the PV modules and it is found after determining the ratio of the PV system area to the total building area, called Ground Coverage Ratio (GCR) [42]. In this research, GCR is assumed to be 0.80.

III.4. Calculation Procedure

To achieve research objectives, the following calculation procedure had been implemented:

- Data collection: including local weather conditions, buildings external walls construction types, insulation material techno-economic parameters, and case study building required information;
- Baseline scenario simulation, AC and PV calculations: the considered building data had been simulated using back-of-the-envelope calculator (available at: https://www.ashrae.org/technical-resources/free-resources/software), simulation provided building estimated AC running load costs under many real operational considered conditions. AC required capacity and PV installed power on available roof area had been calculated using Eqs. presented in Sections III.2 and III.3, respectivelyv
- Insulation material scenario simulation, AC and PV calculations: all construction wall types' optimal insulation thickness had been calculated under different weather conditions using Eqs. presented in Section III.1. After that, considered building optimal insulation thickness was determined, and then, simulated using back-of-the-envelope calculator to investigate effects on AC equipment capacity and annual operational cost;
- Results analysis and discussion: the researchers performed detailed economic and environmental comparison between base line and insulation material scenarios to estimate potential benefits of using the insulation material. These calculation steps and its sequential illustration are shown in the flowchart presented in Fig. 2.

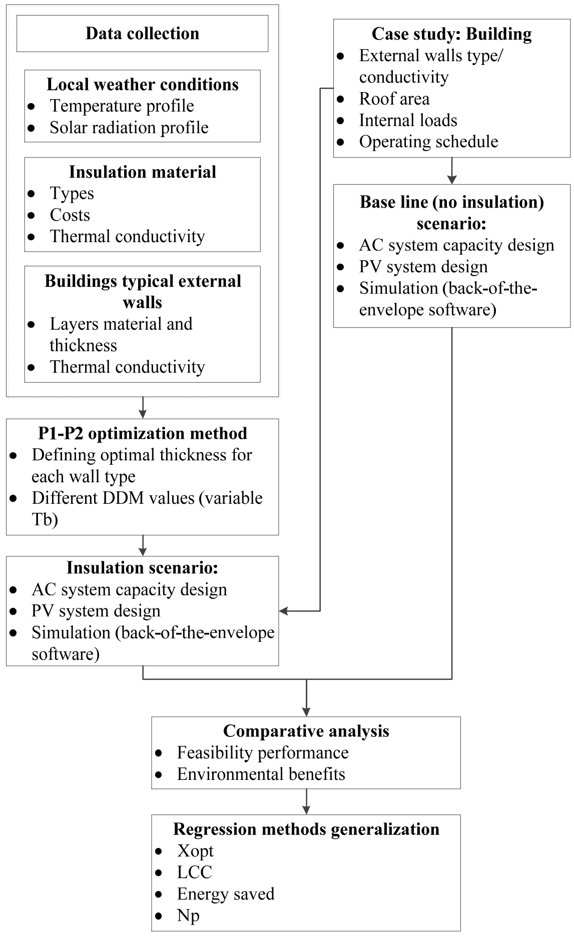

Fig. 2. Calculation procedure flowchart

IV. Local Weather, Wall Types, and Case Study Description

IV.1. Local Weather

According to the Oslo accord, PA is responsible for the West Bank and Gaza strip area called PT's. Its total area is about 6,022 km^2. And so, weather conditions are almost similar in all of its governorates. Fig. 3 presents the average monthly temperature in °C for selected PTs governorates located in the West Bank [42]. Ambient temperature has a direct effect on AC summer electric consumption. To estimate buildings electric consumption due to external walls heat loss, CDH values should be considered. Fig. 4 presents West Bank considered governorates CDH calculated based on different T_b values, CDH is calculated using Eq. (1). The main reason behind considering variable T_b values that constant baseline (T_b=18 °C) value could lead to overestimating of summer CL. In this research, a commercial building located in Ramallah governorate had been considered as a case study. Ramallah is located in the middle region of the West Bank: 31.89 latitude and 35.2 longitude. It is considered the Palestinians economic capital, contains all ministries and the president office, and has the fastest-growing infrastructure rate.

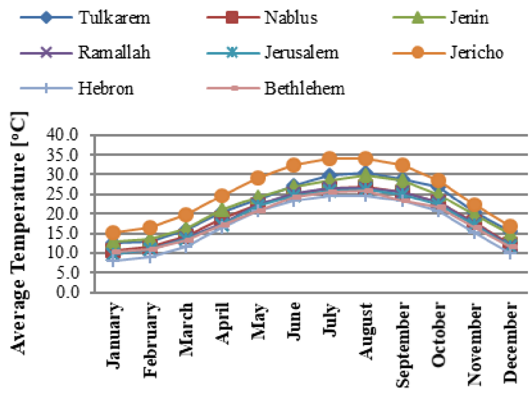

Fig. 3. Average monthly temperature in °C for selected West Bank governorates

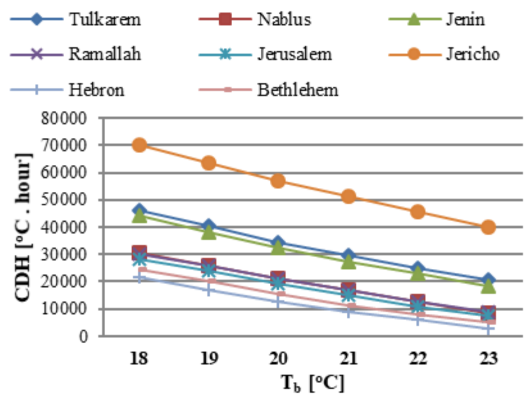

Fig. 4. CDH values for West Bank governorates considering different T_b

Ramallah governorate average solar radiation equals to 5.39 kWh/m^2/day. Fig. 5 presents Ramallah hourly temperature profile in °C.

IV.2. *The Building, Mechanical System, and Local Market*

The considered building in the case study is a commercial mall. It consists of seven floors, each with an area of 2.200 m^2. Three floors are reserved for offices, which are scheduled to work for 9 hours per day, 5 days per week.

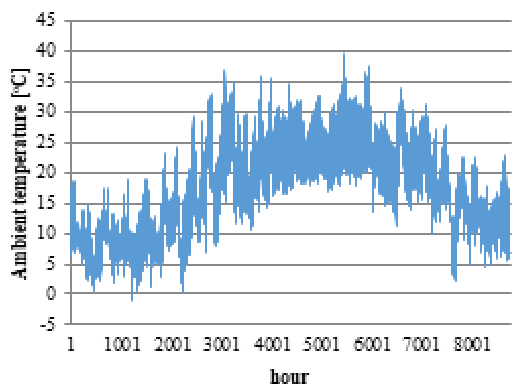

Fig. 5. Ramallah annual temperature profile

The remaining floors are reserved for commercial shops, restaurants, and showrooms that are scheduled for working 16 hours per day, six to seven days per week.

The building will be equipped with a central HVAC system for summer cooling purposes. Palestinians building structure is quite simple, Table I illustrates external walls construction, thermal resistance ($R_{t,w}$), and thermal conductivity (k). WT is used to symbolize wall type and *Rf* for the roof. It is obvious that insulation layers were excluded from the description provided in Table I. The reason is that until now there is no Palestinian building structure engineering code. Thus, using insulation for external walls is mandatory and depends on local community awareness.

IV.3. *Case Study Description*

The studied building envelope, annual energy consumption, mechanical HVAC system, and local required economic indicators are presented in Table II.

Building energy performance is simulated using these parameters and operating conditions.

V. Results and Discussion

V.1. *Optimal Insulation Thickness for Ramallah City*

Using building insulation material is relatively a new energy conservation procedure in Palestine.

TABLE I
TYPICAL EXTERNAL WALL STRUCTURE AND THERMAL PERFORMANCE INDICATORS

Type	Composite layers (cm)	k (W/m °C)	$R_{t,w}$ (m^2 °C/W)
WT_I	Stone (7)/Concrete (20)/Plaster (3)	1.70/1.75/1.20	0.361
WT_{II}	External Plaster (2)/Concrete (20)/Internal Plaster (3)	1.20/1.70/1.20	0.336
WT_{III}	External Plaster (2)/Hollow brick (20)/Internal Plaster (3)	1.20/0.90/1.20	0.444
WT_{IV}	Stone (7)/Concrete (20)/Hollow brick (7)/Plaster (3)	1.70/1.75/0.90 /1.20	0.438
WT_V	Stone (7) / Concrete (20) / Air gap (5) / Brick (7) / Plaster (3)	1.70/1.75/0.28 /0.90/1.20	0.617
Rf	Asphalt (2)/Concrete (5)/Reinforced concrete (6)/Cement brick (20)/Plaster (2)	0.71/1.75/1.76 /0.90/1.20	0.330

TABLE II
CASE STUDY BUILDING ENVELOPE AND OPERATING CONDITIONS

Building location	Ramallah, West Bank.
Description	Commercial
Floor area	2,200 m^2
Available roof area for PV installation	1,400 m^2
Number of floors	7
External wall type	WT_{IV}
Roof type	Rf
Average weekly working hours	74
First floor description	On-grade
Building envelope window to wall ratio	20%
Infiltration (air change per hour)	1.5
Ventilation	8-12 L/s/person
Lighting system intensity	10 W/m^2
Cooling system COP	3.5
Cooling system capital investment	$ 1000 per refrigeration ton capacity
Market discount rate	10% per year
Electricity escalation rate	2.5% per year
Electric energy price	0.17 $/kWh

Among many alternatives, polyurethane rigid foam (k=0.019 W/m K) has the largest market share, and it seems that it will keep growing shortly. It costs around 170 $/m^3, including installation cost. Applying equations presented in Section III.1 on Ramallah city as a case study, Table III presents the x_{opt} for all wall types considering different T_b values. It can be noticed that wall type did not make a significant difference in the required insulation thickness, in contrast, CDD did. When dealing with summer cooling systems, considering T_b equals to 18 °C might lead to overestimation of the required insulation thickness. Besides, considering higher T_b values might be more representative of buildings' occupant behavior, where they usually turn AC on if ambient temperature exceeds 25 °C generally. Knowing that T_b is always lower than ambient temperature with about 1.8 to 2 °C, considering it equals to ≥22 °C will provide more realistic estimates of the expected savings.

In the same context, Fig. 6 shows the total life span cost, including both initial investment and energy running costs. It can be noticed that although the optimal thickness is around 11 cm, all thicknesses above 6 cm provide almost a constant total cost. This is interesting since using 11 cm thickness might not be practical or even acceptable by buildings owners due to area constraints, this issue can be solved by introducing to the market new types of insulation materials with higher thermal conductivity properties, which will result in thinner required x_{opt} values. Until that, installing thinner thickness ($<x_{opt}$) using the market available insulation types will compromise the expected benefits slightly, but save significant area at the same time. This can also be proved from the results presented in Fig. 7. It can be noticed that total energy cost savings over the project lifetime will almost be the same for insulation thickness equals to 6 cm or above. From both figures, it can be noticed that achieved benefits by making the insulation layer much thicker reach a limit, and adding extra insulation will not necessarily result in additional energy and cost savings. Oppositely, going beyond this limit range will adversely affect the economic feasibility of the insulation due to the additional unnecessary initial investment.

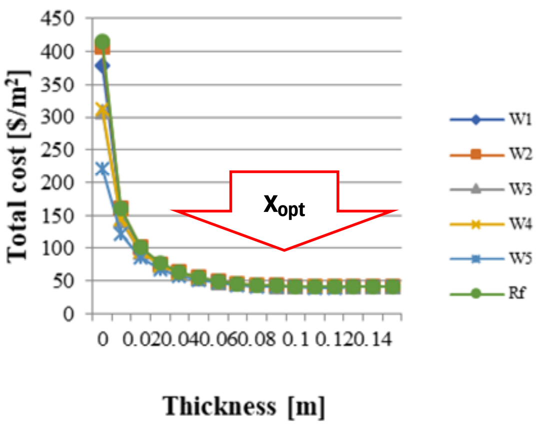

Fig. 6. Total cost over 20 year lifetime variation with insulation thickness

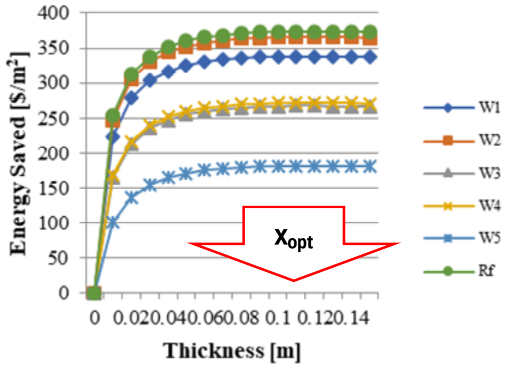

Fig. 7. Total saved energy cost over 20-year lifetime variation with insulation thickness

TABLE III
OPTIMAL INSULATION THICKNESS X_{OPT} IN cm FOR RAMALLAH CITY

T_b (CDD) Wall	18 °C (1258)	19 °C (1074)	20 °C (890)	21 °C (706)	22 °C (522)	23 °C (362)
W5	11.2	10.3	9.2	8.1	6.8	5.5
W3	11.5	10.6	9.6	8.4	7.1	5.8
W4	11.5	10.6	9.6	8.4	7.1	5.8
W1	11.7	10.7	9.7	8.6	7.3	5.9
W2	11.7	10.8	9.8	8.6	7.3	6.0
Rf	11.7	10.8	9.8	8.6	7.3	6.0

One of the most important economic parameters is the discounted payback period (*Np*), it differs from the simple payback period because it includes the required minimum market discount rate, which is important for investors in comparing their investment alternatives and taking low-risk decisions. ***Np*** provides the decision taker with a clear estimation about the time required for an investment to recover itself through savings and/or revenues. Assuming the same case, Fig. 8 shows the Np value for all considered wall types considering T_b equals to 18 °C in Ramallah city, where i and d values are 10% and 3%, respectively. It can be noticed that Np varies between 6 to 14 years at optimal value, this range becomes between 4 and 8 years at 6 cm insulation thickness. All of these results show that installing insulation for buildings' external walls is a promising solution. But when considering the PTs local market, Np is relatively long and might not be convincing for many people, especially if the x_{opt} will be adopted. This shows that PA should develop a suitable building structure code with a mandatory insulation requirement item.

Otherwise, the switching process to building insulation using might continue to be slow. However, there is a need for results generalization for the whole West Bank area. Interestingly, the West Bank is relatively a small area with some minor variability in weather conditions.

V.2. Optimal Insulation Thickness Results in Generalization

West Bank local weather had been described in Section IV.1, it can be noticed that there is no large deviation between cities, the main reason is that the West Bank is relatively a small area, about 5,640 km^2 with almost similar topology.

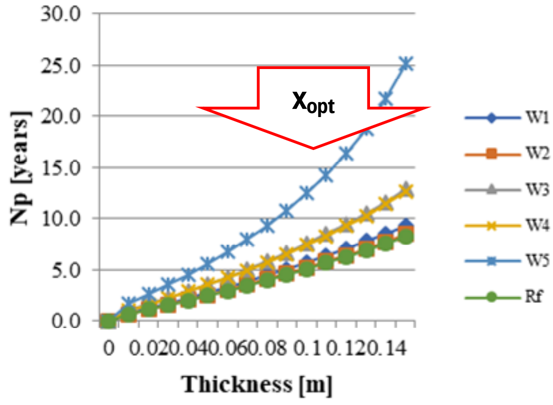

Fig. 8. Discounted payback period (Np) in year's variation with insulation thickness

Therefore, results can be generalized by considering different CDD values representing the cities. Fig. 9 presents x_{opt} variation with U_{ov} and CDD, it can be noticed that CDD has a more significant effect on x_{opt} value compared to U_{ov}. A slight difference can be noticed in the optimal thickness value corresponding to U_{ov} (representing both $R_{t,w}$ and R_{in}) variation, but when CDD value varies (or T_b), x_{opt} value will noticeably differ. This can be justified by noticing Eq. (11), where all used terms have relatively small mathematical values except CDH, which is in tens of thousands as shown in Table IV. A similar conclusion can be reached regarding the total cost in $/m^2 as shown in Fig. 10. CDD is the dominant factor affecting the total cost value. Total cost value includes initial investment and running cost over the project considered lifetime, 20 years in this research. So, although increasing U_{ov} value by adding more insulation will save more energy, the total cost will remain with no significant difference because thicker insulation means more initial investment that will almost compensate for the achieved cost reduction due to energy savings. In contrast, both U_{ov} and CDD have significant effects on energy saved in $/m^2 and Np, Fig. 11 and Fig. 12 show these effects. As expected, increasing the value of U_{ov} for walls by installing insulation will lead to more total energy saved over the project lifetime.

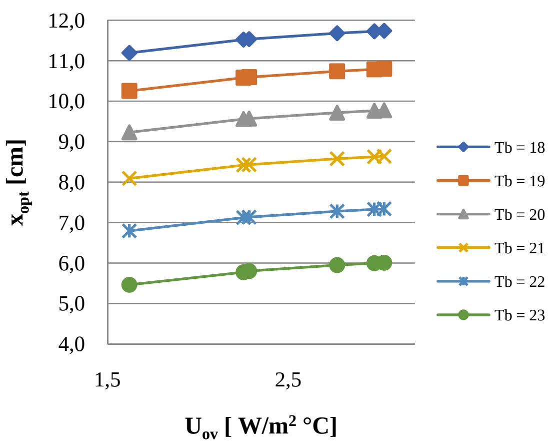

Fig. 9. x_{opt} variation with different U_{ov} and T_b values

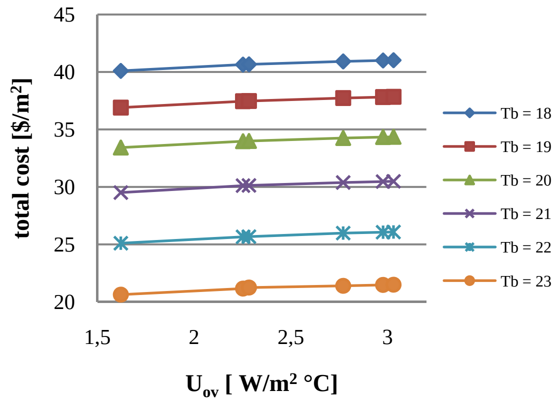

Fig. 10. Total cost variation with different U_{ov} and T_b values

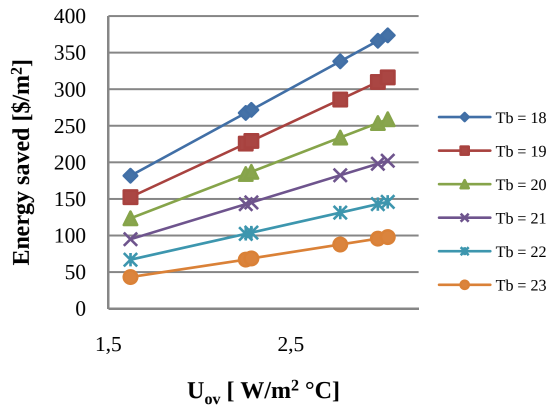

Fig. 11. Energy saved variation with different U_{ov} and T_b values

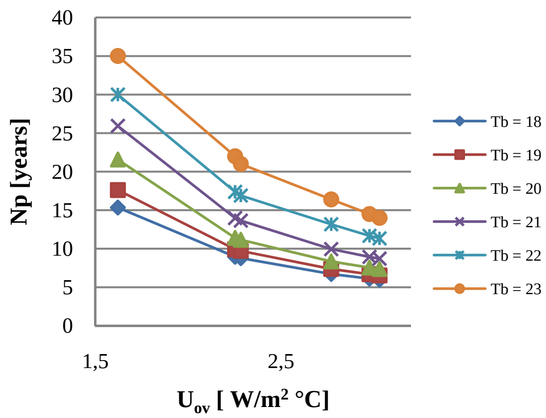

Fig. 12. Np variation with different U_{ov} and T_b values

This is reasonable since calculating energy consumption using Eq. (2) shows that it depends on AC COP, external wall U_{ov}, and CDH only. The values of CDH are way higher than U_{ov} and COP, thus, it is the dominant term in defining energy consumption. This is the reason behind achieving a more significant effect by varying T_b (means different CDH) compared to using different U_{ov} value. For Np variation, Fig. 12 should be explained carefully. It might look like that increasing insulation thickness will lower Np value, and so, the higher the thickness, the more economic feasibility can be achieved. However, this is not true since installing insulation thicker than optimal value will lead to an exponential increase in *Np*, as shown in Fig. 8. In Fig. 12, the wall type with a higher U_{ov} value (before insulation installation), will result in a lower *Np* value when installing the optimal thickness x_{opt}. Since the West Bank area and wall types are limited, results in generalization should be simple and useful for local engineers.

For this purpose, the least-squares multiple linear regression method is very effective and simple to use. Table IV and Eqs. (27)-(30) present generalized formulas achieved through multiple linear regression analysis. Results were achieved using Microsoft Excel 2010 data analysis capabilities. To do so, simulated results following the methodology described in section (3) were used. Resulted in high values of coefficients of determination (R^2 adjusted) prove the usefulness of such generalized formulas. As long as the analysis considered input parameters kept the same, these formulas will continue to be accurate. Changing one or more of the parameters (insulation material type, insulation cost, electricity cost, COP…etc.) means the necessity of repeating the above procedure and develop updated formulas. For that reason, checking and updating these generalized formulas every few years should be accomplished to ensure their accuracy in reflecting the real conditions. From data achieved in Table IV, engineers can quickly apply the following Eqs. (27)-(30) to estimate x_{opt}, total lifetime cost and energy saved, and discounted rate of return:

$$x_{opt} = 2.86 + 0.37(U_{ov}) + 0.006(CDD) \quad (27)$$

$$Total\ cost = 12.7 + 0.64(U_{ov}) + 0.022(CDD) \quad (28)$$

$$Energy\ saved = -230 + 86.6(U_{ov}) + 0.25(CDD) \quad (29)$$

$$N_p = 49.1 - 10.2(U_{ov}) - 0.013(CDD) \quad (30)$$

Similarly, for calculating saved CO_2eq emissions per kWh of electricity saved. [43] shows that Israel electric generation sector burdens the environment with 0.767 kg CO_2eq per kWh of electric energy. West Bank area depends almost completely on importing electricity from Israel. So, CO_2eq saving can be calculated using Eq. (31):

$$CO_2eq\ saved = (Saved\ Energy_{kWh})(0.767) \quad (31)$$

TABLE IV
MULTIPLE LINEAR REGRESSION ANALYSIS RESULTS GENERALIZATION

Dependent variable	Intercept	Independent variables coefficients U_{ov}	Independent variables coefficients CDD	R^2 adj
x_{opt} [cm]	2.855	0.373	0.006	0.992
Total cost [\$/m^2]	12.668	0.640	0.022	0.992
Energy saved [\$/m^2]	-229.870	86.607	0.249	0.964
Np [years]	49.125	-10.159	-0.013	0.889

V.3. PV Design and Simulation

As shown in Table II, the area of the building under investigation equals 2,200 m^2. However, the available roof area for PV installation equals 1,400 m^2. It is free from shadowing objects. This gives a great opportunity to utilize this area for generating electricity using PV technology. As the building is located within a zone covered by the national grid, it is recommended to use grid-connected solar PV mode. PVsyst software has been used to design and simulate the PV system. For the selected site weather conditions, the software used real measured data. In this context, the hourly average air temperature data and (I and I_b) for Palestinian governorates are shown in Figs. 13-15. All can indicate that using PV systems is technically feasible.

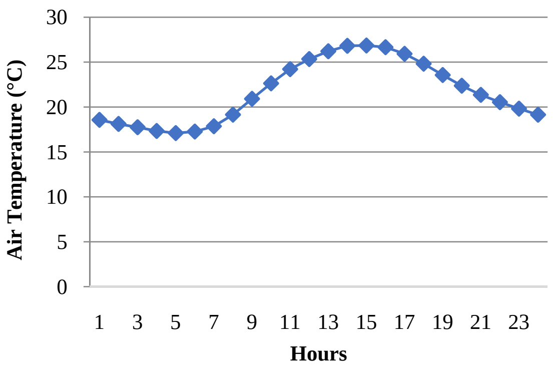

Fig. 13. Annual hourly average air temperature

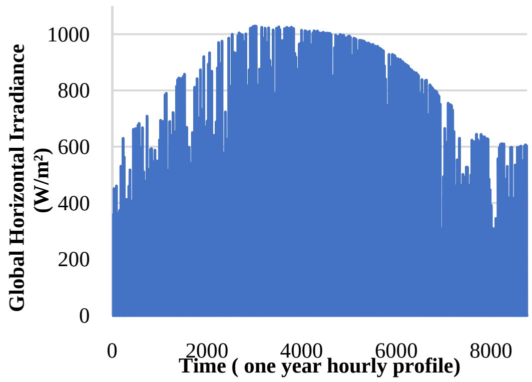

Fig. 14. Annual global solar radiation on a horizontal surface in hourly interval

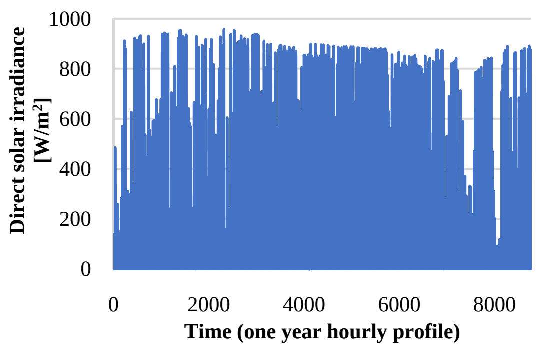

Fig. 15. Annual direct normal irradiance in hourly interval

The software estimates annual diffuse solar radiation on a horizontal surface (I_d) after subtracting I_b from I.

After running the simulation, the output results are summarized in Table V. The intended analysis needs to estimate the monthly output of electricity from the PV system. For that reason, Fig. 16 presents monthly electric production in MWh's. As expected, PV system output peaks during summer, which makes it very suitable for covering AC summer CL partially. Total annual generated electricity equals 320 MWh. The specific production is 1858 kWh/kWp/year, and the performance ratio is 84.6%.

V.4. Building Energy Performance Simulation

This subsection is dedicated to showing the estimated effect of installing optimal insulation thickness on building energy consumption. To do so, the back-of-the-envelope calculator has been used. Table VI presents the baseline (no insulation) simulation results. Peak electric demand and peak cooling demands are 345 kW and 210 ton, respectively. Since external walls and roof insulation will only affect $\dot{Q}_{wall}$ and $\dot{Q}_{roof}$ components as shown in Eq. (15), slight simulation differences will occur regarding building overall electric consumption. But, when it comes to peak electric demand and peak cooling demand, after optimal insulation thickness consideration, estimated values become 325 kW and 192 ton, respectively. It means that 20 kW peak electric demand and 18 ton peak cooling load were saved. This will have an additional direct economic benefit if Palestinian local electric utilities charge customers for peak power demand, which is not applied yet. Thus, economic benefits due to peak power demand reduction have been ignored in this research.

TABLE V
PVSYST DESIGN RESULTS

Collector Plane Orientation	30° (azimuth 0°)
PV module	Si-Poly model HSL 72 P6-PC-1-320 (HanWha solar)
Number of modules	18 in series, 30 in parallel
Array global power	173 kWp (nominal), 155 kWp (at 50°C)
Total area	1056 m^2

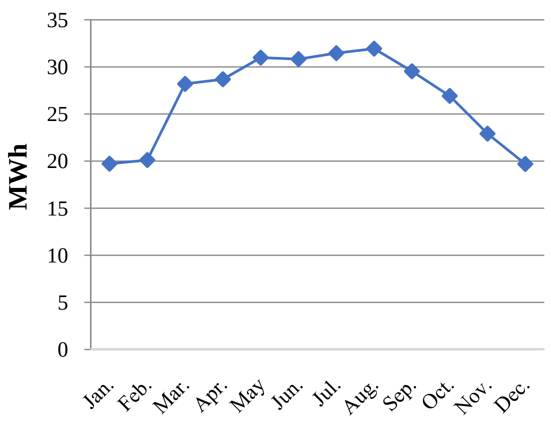

Fig. 16. The energy injected to the grid per month

TABLE VI
BASELINE SCENARIO BUILDING SIMULATION RESULTS

	Baseline scenario (no insulation)
Annual electricity cost [$]	102,270
Annual electric consumption [kWh]	511,350
Cooling cost [$]	36,000
Cooling electric consumption [kWh]	180,000
Peak electric demand [kW]	345
Peak cooling demand [ton]	210
Annual CO_2eq emissions [ton]	392

Knowing that the considered PV system is 173 kWp at its best, and the peak electric demand for the baseline scenario equals 345 kW, all generated electricity can be consumed by the building demand. Especially when remembering that peak building load will happen during the summer AC peak season, which will be also the PV system peak generation period. And so, there is no necessity for injecting extra generated electricity into the grid. The same is expected to happen when considering building optimal insulation thickness installation, where the peak electric demand will become 325 kW, still way higher than the peak PV generation, 173 kWp. Regarding extra insulation economic benefits, peak AC cooling demand will go down from 210 to 192 refrigeration tons.

For design consideration and practical market available systems, can be considered 190 ton. As a result, saving 20 refrigeration ton capacity is estimated to save an extra $20,000 immediately. This saving will reduce the insulation *Np* to become less than three years, making it a very competitive and feasible project. Regarding the share level, insulation resulted in saved energy has increased the PV generation share level from 62.6% to 64.1%.

VI. Conclusion

West Bank area is limited which is about 5,640 km^2, and so, weather conditions differ slightly between governorates. As a result, optimal insulation thickness is almost the same for all governorates. Between 10 to 11 cm of polyurethane insulation thickness is required for all Palestinian wall types; this thickness is almost similar to many other countries, especially the ones similar in weather conditions. The proposed x_{opt} by this research can be reduced to 6cm without compromising the insulation benefits. It means that near-optimal total cost and energy saved can be achieved at this value. However, *Np* varies between 4 to 8 years at this near-optimal value. It is more convincing for the local community in the absence of a mandatory Palestinian building code to enforce insulation.

Due to weather conditions stability, multiple linear regression has been used to develop x_{opt}, total cost, total energy saved, *Np*, and CO_2eq generalized formulas. It can be considered accurate since adjusted R^2 values are all 89% or above. These developed formulas will require a periodic check every few years especially if some input parameters changed such as electricity cost, insulation type, and cost, AC average COP, and/or wall types.

The number of installed grid-connected PV systems continue to grow in an accelerated manner. However, the principle of self-consumption buildings needs more attention since it will help in avoiding electric grid-related technical challenges that come as a result of injecting extra generated electricity. In this context, matching PV generation with AC summer load is quite interesting. Moreover, insulation extended benefits will lead to immediate savings in investment due to AC rated capacity size reduction. The *Np* will reduce significantly and increase renewable energy share from the building total demand. The implemented x_{opt} calculation approach is well known for estimating the economic benefits of external wall insulation. However, it should be kept in mind that since it depends on DDM, it considered assumptions that might cause deviation from reality, therefore, should be clear to results potential users.

Herein, calculating CDH assumes year-round analysis. In other words, it considers the 8,760 hours per year, and so, it assumes the AC is operating 24/7, year-round when required. This might not be the case in a large proportion of buildings; even it does not reflect the situation of the considered case study completely. Future researches should consider developing the DDM and CDH calculation by considering building a daily schedule.

Although this might be exhaustive data collection activity, it deserves investigation to check the amount of deviation that will happen.

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