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Investing in PV Systems utilizing Savings from Building Envelop Replacement by Sustainable Local Material: A Case Study in Lebanese Inland Region

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ABSTRACT: In this work, we propose to reduce the initial building construction cost by using local low-embodied energy materials and use savings to offset the cost of renewable energy installations. A typical house in the desert climate of inland Lebanon is modeled using commercial software for a conventional construction case and when using local construction materials. The savings from envelop replacement were used to invest in installing a solar water heater (SWH), and a photovoltaic (PV) system as well as double glazed windows. This resulted in net energy savings up to 97% and 59% for single and double glazed windows, respectively. When further investment in the PV system is evaluated and optimized based on life cycle cost, the savings from covering the electrical load and selling to the grid decreased respectively to 27% and 75% in the case of single glazing and to 28% and 76% in the case of double glazing.

Keywords: Local construction material; Initial construction cost; PV system design and optimization; Renewable Energy
JEL Classifications: C61; C63; L94; Q20; Q28

Nomenclature

A	=	Area (m^2)
C	=	capital cost ($)
E	=	grid electrical energy (kWh)
LCC	=	life cycle cost ($)
N	=	lifetime (years)
NPC	=	net present cost ($)
P	=	power (kW)
PV	=	photovoltaic
Sav_E	=	total savings in envelop material
U-Value	=	thermal transmittance ($W/m^2 \cdot K$)
Greek		
η	=	efficiency (%)
Subscripts		
dc	=	Direct Current
I	=	inverter
O&M	=	operation and maintenance
PV	=	photovoltaic
SWH	=	solar water heater

1. Introduction

Challenges to the electricity sector faced in several countries in the Middle East are increasing rapidly due to the increase in energy consumption, lack of new projects to cover this increase, and the rapid increase of fossil fuel prices. Since the energy sector has a significant role in the overall development of countries, other alternatives should be sought for clean power generation and decrease in energy consumption particularly in non-productive sectors such as residential sector. Buildings are responsible for approximately 42% of the world's total annual energy consumption (EIA, 2007). Efficient building design has proven to be the first step in decreasing the energy consumption (Da Graça et al., 2012; Murphy et al., 2011; Steijger et al. 2013). In addition, the integration of renewable energy systems in building design and construction is another possible solution for reducing dependence on fossil fuels (Miller et al., 2009; Romano and Scandurra 2011; Maklad[a], 2014; Bekhet and Ivy-Yap, 2013; Agarwal et al., 2012). However, renewable power generation is still an expensive alternative for home owners and developers due to its capital initial cost (Tibi et al., 2012).

One approach to overcome high capital was proposed by Tibi et al. (2012) where savings in capital are generated by using local material at lower cost than conventional material to decrease the first cost of the building. The use of local material will not only decrease the first cost but also the embodied energy. Building materials and their embodied energy constitute an integral part of any sustainable construction. The term initial Embodied Energy is used to refer to the energy consumed in manufacturing, processing and transporting the building construction materials to the construction site (Thormark, 2006; Huberman and Pearlmutter, 2008). The embodied energy constitutes approximately 5% to 15% of the total energy consumption of a residential building throughout its lifetime (Thormak, 2006). So the higher the reduction in the amount of embodied energy in buildings, the lower the environmental impact of the construction is (Morel et al. 2001). One way of achieving reduction in embodied energy is by using local construction material such as rammed earth and straw as Morel et al. (2001) concluded in their study that resulted in an energy consumption reduction of 215% in a small residential unit in southern France. This significance of using local material such as hemp is also verified by Awwad et al. (2010) who surveyed the major coarse aggregate resources in Lebanon and found that the Bekaa area has a supply of this local material that exceeded its demand. Most of the studies were directed towards life cycle assessments considering both the embodied and operational energy of the building from cradle to grave. The literature studies were mainly targeting carbon emissions; however lowering the embodied energy could also lower the first cost of the building which can be beneficial for financing renewable energy systems.

The selection of local material and the selection and design of the proper renewable system are specific to the building and its geographic location (Yassine et al., 2012, 2014). For countries with good solar insolation, renewable energy systems such as photovoltaic (PV) and solar water heating (SWH) systems are the most attractive. Da Graça et al. (2012) studied the feasibility of implementing solar net zero energy building systems for a typical house in the mild southern European climate zone. They sized the solar thermal and PV systems to meet all annual needs, and it was found that having such system in this climate is feasible but with an increase in the initial cost that can reach 22%. Soufi et al. (2013) studied also the feasibility of having a stand-alone photovoltaic system in remote livestock shelters located in a village in Algeria. To cover the daily electric load of 5.5 kWh, it was reported that they need a system composed of a 4 kW PV modules, 6 batteries (200 Ah and 12 V), and a 5-kW inverter (Soufi et al., 2013). Al-Hasan et al. (2004) evaluated the usage of grid connected PV systems to cover part of the electric load in Kuwait. They found that the daily peak load and the maximum solar radiation are attained at the time; this increased the role of the PV system in minimizing the electric load demand (Al-Hasan et al., 2004). Rehman et al. (2007) evaluated the energy production of a 5 MW grid connected PV system power plant in different sites in Saudi Arabia. The best site was shown according to the economic indicators they got such as the net present cost, payback period and the internal rate of return. These systems have relatively high initial cost that restrains house owners from adopting them. But savings from initial construction cost can offset the PV and SWH cost and make them more desirable.

Although the use of PV systems is still minimal in some countries such as Lebanon, the use of SWH is increasing (Houri and Korfali, 2005). This is mainly due to the special financing facilities supported by banks which are encouraging more reliance on the solar water heating systems (UNDP, 2012). These same reasons can encourage home owners to invest in PV if they can afford to. For the investment in PV system to succeed, its components should be chosen and sized accurately. The PV system requires PV modules, inverter, controller, batteries, and mounting structure (Sharma et al. 1995). PV modules power rating is based on Standard Testing Conditions (STC) of 1 kW/m² of sunlight and a PV cell temperature of 25 °C (RetScreen®, 2004).

Predicting accurate output of renewable energy sources is not attainable due to these sources random behavior. Optimization and tradeoffs between the system cost and its reliability level are the best procedure to design such systems while minimizing the possibility of both over sizing and under sizing the system (Bajpai and Dash 2012). According to da Graca (2012), low energy needs efficient energy systems, properly sized renewable energy systems, and exchange prepared electrical grid can lead us to net zero energy house. The low energy needs depend on the optimal building design of the house; from using as much as possible natural lighting and ventilation to the best heating and cooling. Oversizing or under-sizing renewable energy systems can have negative effect on the overall outcome. An equipped grid ready to exchange energy is another important requirement for successful investments in such systems.

Optimization of renewable energy systems design has been studied by many researches so far (Murphy et al., 2011; Bekele and Palm, 2010; Steijger et al., 2013; Maklad[b], 2014; Pempetzoglou, 2014). Minimizing the net present cost (NPC) or levelized cost of electricity (LCE) without losing reliability is the essential of reaching the optimum design (Bernal-Agustín and Dufo-López, 2009). Feasibility and optimization studies have been done extensively in the last 10 years for many applications all over the world. Building houses with cheap local material while enhancing the house energy performance and then presenting a case study that shows how construction savings can be used to invest in an accurately selected and designed PV system, without increasing the house initial cost, is the main contribution of the study.

Since the residential sector accounts for a high percentage of the energy consumption, for instance it reached 47% in Lebanon, any possible consumption savings in this sector would result in improvement in the environmental conditions (Ghaddar and Bsat, 1998). In this study, we aim to replace conventional envelope material of a typical Lebanese house by local construction material to assess reduction in the initial cost of the building and investigate the soundness of investing the savings in a renewable energy system such as photovoltaic (PV) for power generation and solar water heating (SWH), thus decreasing the energy consumption while maintaining initial cost at its conventional level.

2. Methodology

In this study, cheap local construction materials are used as a method to decrease the initial construction cost of a typical house (Tibi et al., 2012). The typical house design reported by Tibi et al. (2012) will serve as a base case model to which the integration of PV system and SWH will be examined. As presented in Figure 1, the PV system is assumed grid connected. The three main components that home owners are concerned with include the decrease in the initial capital cost, the increase of the lifetime benefits, and the minimization of the payback period.

Figure 2 presents a flow chart of the followed methodology in this study. The typical house envelope design is selected such that it meets the thermal standard guidelines to which local material is applied to replace conventional material and reduce initial construction cost. Having the house physical characteristics and occupancy schedule, eQUEST software (2014) is used to simulate the house thermal and electrical load to get the average energy consumption, the daily load profile for all months of the year, and the peak power demand. The SWH size is calculated based on the water consumption of a typical family. Applicable different PV sizes with the inverter sizes are estimated based on the chosen type of PV modules to be installed, the percentage of roof area available for installation of the PV modules, and the maximum electric load. Solar data, results of eQUEST, PV modules sizes, and inverter sizes are then used as input to HOMER software (2014) to study and optimize the best PV system design and operation based on life cycle assessment. Energy savings, initial cost, and payback period reduction are the main indicators to evaluate the studied system.

This methodology is followed to evaluate two scenarios; the first scenario is concerned with designing a system constrained by investing only the savings attained from decreasing the initial cost of envelope construction material and based on lifecycle assessment. The second scenario is concerned with designing and selecting the best PV system size based on life cycle assessment. Both scenarios have to cover the needed electric energy demand.

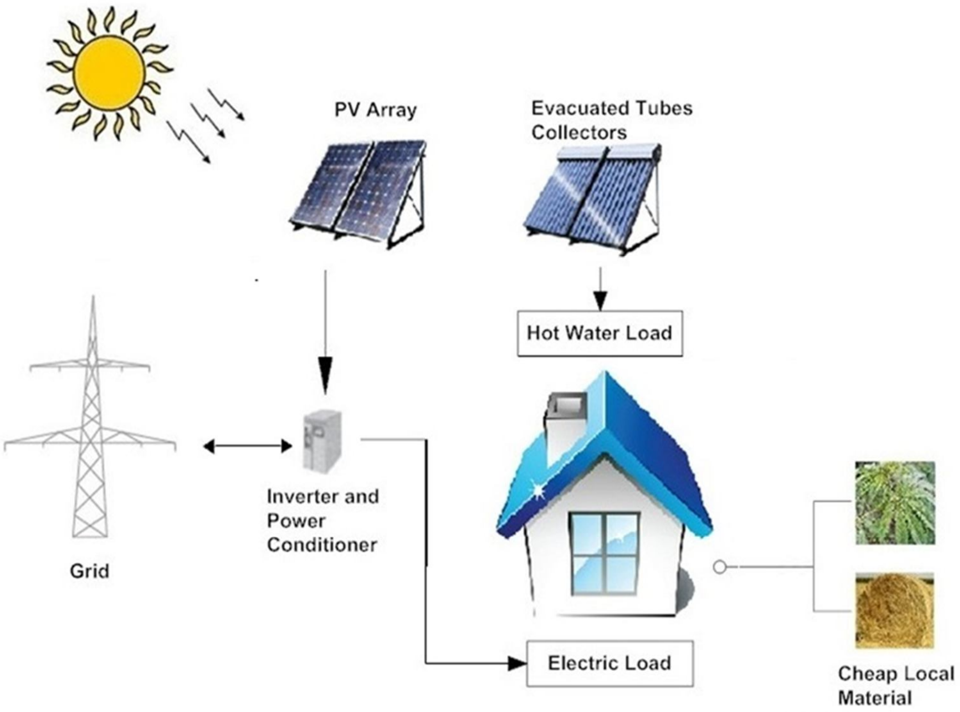

Fig. 1: System Schematic

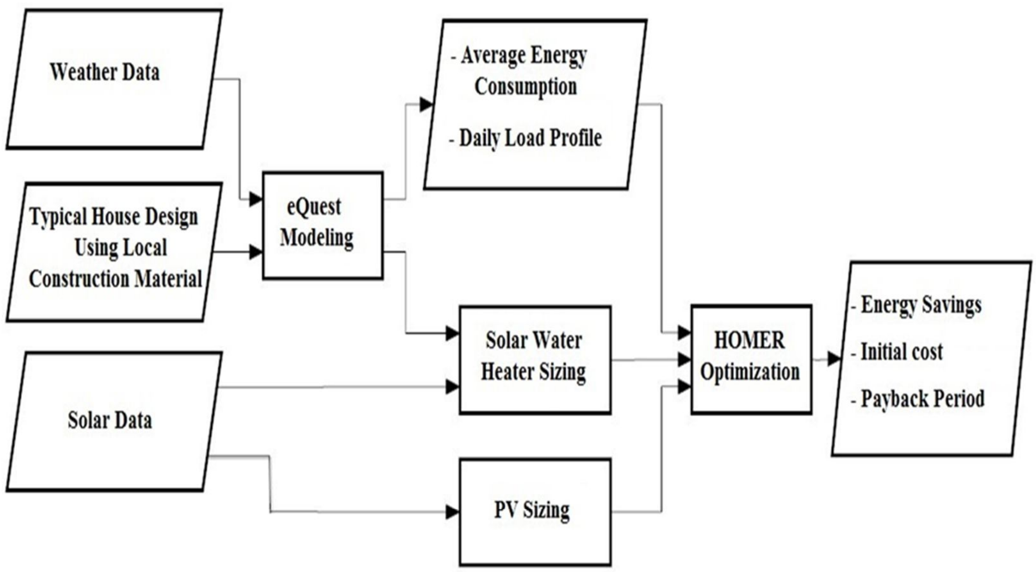

Fig. 2: Methodology Flow Chart

2.1 Typical house envelope description, resulted savings, and energy consumption

The above-mentioned methodology is applied to the typical single-family duplex house located in the Lebanese inland region, Bekaa area. The house has rectangular floor plans with a footprint of 120 m^2, and a total built area of 240 m^2. The number of family members is 7.

Such typical houses usually use conventional building materials such as hollow blocks, steel reinforced concrete, and single glazed windows which have an overall envelope U-value that exceeds the Lebanese thermal standard (UNDP, 2005). The overall envelope U-value for our case study using such material is equal to 3.31 $W/m^2{\cdot}K$ which is much higher than the maximum allowed as set by the standard for the inland regions. The external walls are usually composed of 1.0 cm plaster, 12 cm Hollow block, and 1.0 cm plaster. Slabs are made of steel reinforced concrete without insulation, and so is the flat roof while windows are made of aluminum frames with 6 mm single glass panes (Chedid et al., 2001). In order to decrease this U-value to meet the standard, insulation material such polystyrene is used (Ibrahim et al., 2012). This insulation material has a high embodied energy. The embodied energy of the conventional envelope material without insulation is found to constitute 6% of its lifetime estimated operational energy; however it increased to 50% when insulation is used (Tibi et al., 2012). He reported that using this insulation material caused the overall cost of the initial construction to increase by around \$127/m^2 as compared to the conventional non-insulating envelope according to market prices. The initial cost of the building construction materials needed for the construction of the conventional case model without insulation is estimated to be \$230/m^2 according to the local Lebanese market rates (Tibi et al., 2012).

However, the standard and its recommended overall envelope U-value can also be met by local materials with low embodied energy and relatively high thermal storage capacity such as rammed earth, straw, and natural stone envelop. The rammed earth construction is a method of building walls using a balanced mixture of clay, sand and aggregate. This method has a promising potential for future construction for it is abundant, recyclable and has a minimal environmental impact (Nowamooz and Chazallon, 2011); also, the use of natural fibers such as Hemp to enhance the tensile strength of rammed earth construction proved to be effective (Li et al., 2006). Simulating different materials for the roof, walls, and slabs demonstrated that using straw boards is the best to insulate the steel reinforced concrete roof and slabs. Also, straw boards along with 30 cm hemp-reinforced rammed earth blocks and cement board is the best wall material in terms of reducing space loads.

In our proposed envelope replacement case; the roof and slabs are made up of steel reinforced concrete of 15 cm thickness that is insulated using straw boards of 5 cm thickness decreasing the U-value to 0.82 $W/m^2.K$. The walls are made of hemp-reinforced rammed earth blocks of 20 cm thickness on the interior, insulated using straw boards of 5 cm thickness sealed with cement board on the exterior making the U-value reach 0.51 $W/m^2.K$. The windows are double glazed with a low-e film and aluminum frame decreasing the U-Value to 5.41 $W/m^2.K$. The windows facing south have operable horizontal shading elements to be used during summer. The overall U-value for this replacement envelope is 0.99 $W/m^2.K$ which complies with the Lebanese standard guideline for the inland regions.

Comparing the conventional material envelope case with the local material replacement envelope case, it was reported that the annual embodied energy was equal to 62.1 kWh/m^2 for the conventional case while this embodied energy decreased to 12.4 kWh/m^2 for the optimized case using local material for insulation (Tibi et al., 2012). In order to meet the thermal standard, the conventional case increased the envelope construction cost by 127 \$/m^2 whereas the used local material case increased this cost by only 69 \$/m^2. However, if double glazing is to be used instead of single glazing then the cost will increase to 86 \$/m^2 (Tibi et al., 2012).

Since using local material for the house envelope construction enabled us to have savings of around 59 \$/m^2 if single glazing is used, then we can use the savings to invest SWH and PV. If double glazing is used, the available savings is 41\$/m^2 which is still substantial for investing in PV and SWH. A total of around \$14,000 in the case single glazing and around \$9,900 in the case double glazing are available for investment in renewable energy systems. These values are used as the constraints to determine the selected size of the PV system in both scenarios.

The eQUEST (2014) software was used to get the hourly energy consumption of the typical house. All data was entered for the building envelope, HVAC systems, lighting, and equipment. By using

ASHRAE IWEC2 Weather Files for International Locations and EnergyPlus Energy Simulation Software weather data, the weather files for Damascus were obtained since the weather for Bekaa area (inland of Lebanon) is the same as that for Damascus (ASHRAE, 2012). After simulating the house with both single glazing and double glazing options, the total energy consumption per month is predicted as shown in Figure 3. In addition, the daily electrical load profile through the year peaked early in the morning and at around 6 p.m. The peak demand reached 7.1 kW and 6.6 kW for single and double glazing cases respectively during summer season due to the cooling load. The daily average consumption reached 35 kWh and 32 kWh, and the total energy consumption for one year was found to be equal to 12,629 kWh and 11,826 kWh for single glazing and double glazing respectively.

The domestic hot water system used in this study is considered to use gas. It was found that around 4500 kWh is consumed yearly to heat the water. Based on 40 L/day/occupant (Kalogirou 2013), the average daily usage of hot water was estimated to be around 280 L. This value will be used to size the solar hot water system to replace the gas heaters whenever possible.

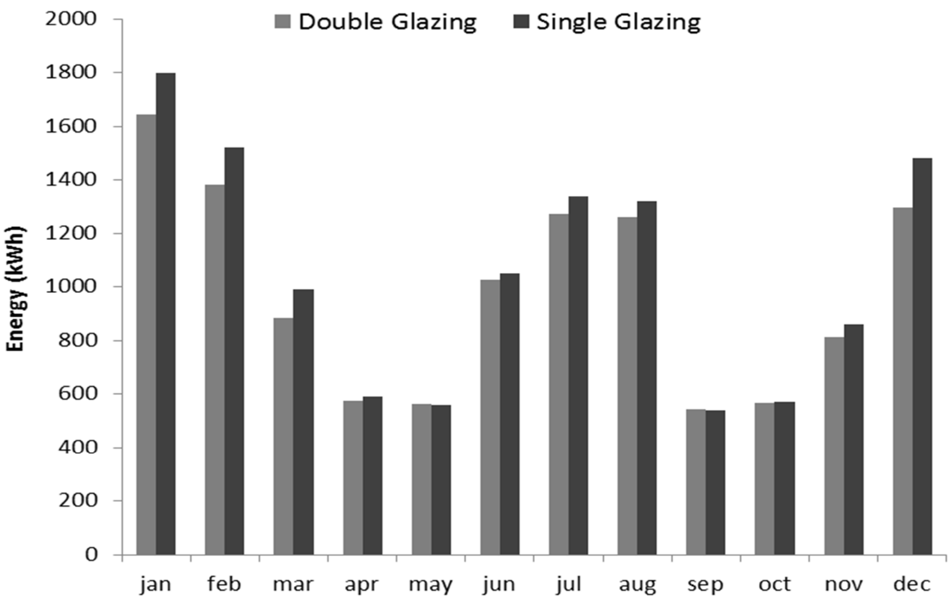

Fig. 3: Energy Consumption for each month when single glazing and double glazing are used

2.2 Sizing the alternative system

2.2.1 *Domestic Hot water Sizing:* The SWH sizing depends on the solar radiation available at the site, the type and efficiency of the collectors, the house hot water demand or the number of occupants, and the desired hot water temperature (DeKay, 1998). RETScreen (2012) software is used to size the SHW. By using the number of occupant of 7 with an average of 65% occupancy rate, RETsreen estimated the average daily usage of around 273 L which in accordance of the estimated value in eQUEST with an error of only 2.5%. The base case was modeled as per the results of eQUEST, and the proposed case consisted of two SWH collectors of 2.8kW capacity with a total storage capacity of 400 L at a cost of 2000$ as per current market prices. The area required to install these solar collectors is around 7 m^2. The proposed system resulted in savings of 80% and the financial analysis estimated around 6.5 years to payback the invested amount in the SWH system. This was based on the current market rate of 1.2 $/Kg of propane gas (Nazerian 2014) which is usually used in gas heaters.

2.2.2 *PV Sizing:* To predict the maximum size of PV modules that can be used to cover the available roof area, the following equation is used:

$$P_{dc} = A * \eta_{PVCells} * \frac{1kW}{m^2} \text{ of insolation} \quad (1)$$

where P_{dc} is the DC rating power of the PV modules, A is the total area of these modules, and 1.0 kW/m^2 is the maximum solar insolation that can be reached at the peak sun hours.

We assume that one third of the roof area is partially occupied with cooling and electrical and systems and SWHs. The remaining roof area can be used for the PV modules and it is equal to 80 m^2. Since the efficiency of the PV cells available in the market ranges between 7 to 18% as mentioned earlier, a 15% efficient module under standard test conditions (STC) is considered for this study. Due to the fact that PV efficiency drops by 0.5% for each one degree Celsius increase above STC temperature of 25 °C (Bergene and Lovvik 1995), this considered 15% efficiency will slightly decrease during summer time, in July and August specifically, where it might decrease to around 14.5% if considering an average temperature of 30^0C during this period of the year. According to Wakim (1981), the PV efficiency in Kuwait decreased by 17% due to sand and dust after 6 days, but this is not a problem in the Lebanon where inland area of Bekaa does not face sand storms as in desert areas of Kuwait. This does not cancel the fact that regular cleaning of the modules is necessary to remove all dust and thus preserve the same efficiency. Thus, the maximum possible size of the PV modules to be considered is 12 kW. However, to reach the best optimized system, a range of PV sizes from 0 kW to 12kW is considered. The selected size will depend on the initial construction cost savings in scenario 1 and on DG elimination for Scenario 2.

Inverter is also needed for the PV system. To size the inverter, the total power of all appliances operating at the same times should be considered. For safety, the inverter should be considered at least of 30% bigger size (Sharma et al. 1995). Since our peak demand reaches 7.1 kW, the maximum inverter size needed is predicted to be around 8.5 kW. However, to have the best optimized system for both scenarios, a range of inverter sizes from 0 to 10 kW is considered.

2.3. PV system selection model

To study the feasibility of installing a PV system in a typical house, HOMER (2014) software was used. Its sensitivity and optimization analysis algorithms help in evaluating the economic and technical feasibility of different technology options while accounting for variations in technology costs and energy resource availability. HOMER's optimization algorithm is an enhanced grid search; it is the most robust since the problem is very non-linear and non-convex. It enables the user to optimize a simulation rather than an analytic function and gives him plenty of flexibility about the decision variables. It is enhanced relative to a simple grid search in that it disregards systems that are smaller than any system it has already found to be infeasible and it re-uses results when possible. Since it was validated by Bekle and Palm (2010), Bludszuweit et al. (2006), Jamil et al. (2012), Shaahid and Elhadidy (2007), and many others as a good tool to access and analyze the importance of using different renewable energy sources, HOMER was used in this study to access the importance of PV.

By using the hourly solar radiation data for the whole year, hourly load profile as resulted in eQUEST, PV, converter, and grid, the model for the gird connected PV system for the house is as shown in Figure 4. The optimization parameters are the PV size and the converter size. The used size range for PV was 0 to 12 kW PV and for converter was from 0 to 10 kW. All component costs adopted in the model were based on current market prices. PV module prices are dramatically going down as per Swanson (2006) who predicted that the module price will reach \$1.44/W in 2013 which is in accordance with what we see currently in the market (http://www.solarserver.com, accessed May 20, 2014). Thus, the cost of 1kW of PV is assumed to be \$1500.

The different configurations were simulated in Homer software while scaling them according to their total lifetime installation and operational cost which is also known as net present cost (NPC). First it was determined if the proposed system can serve the electrical load, then the system's NPC was estimated. The simulations were performed over one operational year based on an hourly time-step. The full year hourly load data obtained from eQUEST served as the input to HOMER. One of the main hourly outputs of the software is the generated PV power which was compared to the required electrical load. If this supply satisfied the load, the excess will be sold to the grid. If the supply did not satisfy the load, the shortage was covered by the grid.

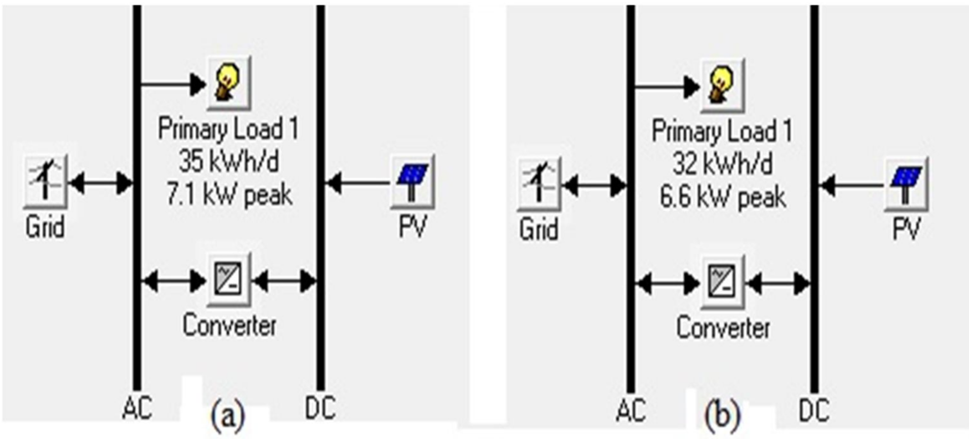

Fig. 4: HOMER Model: (a) if single glazing is used, (b) if double glazing is used

The NPC used to represent the Life cycle cost of the system will be calculated according to equations 2, 3, and 4 (Dalton et al., 2008) as follows:

$$NPC = \frac{TAC}{CRF} \tag{2}$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

$$Salvage(\$) = C_{rep}\frac{R_{rem}}{R_{comp}} \tag{4}$$

The total annualized cost (*TAC*) is the sum of the annualized costs of PV modules, batteries, grid… The capital recovery factor (*CRF*) depends on the lifetime of the project (N) the annual real interest rate (i). The lifetime of the project is considered to be 50 years with an interest rate of 6%. The value that remains from any component at the end of the project lifetime is the salvage value that will also be calculated in *NPC*. The parameters C_{rep}, R_{rep}, and R_{comp} are replacement cost, remaining lifetime, and component lifetime respectively. The two scenarios studied are summarized as follows:

Scenario 1; Initial cost constraint: The first scenario uses only the savings attained from decreasing the initial cost of envelope construction material to optimize the selection of the PV, SWH and double glazing alternatives. The cost function is represented by

$$C_{PV,capital} + C_{b,capital} + C_{I,capital} = Sav_E - C_{SWH,capital} \tag{5}$$

where $C_{PV,capital}$, $C_{b,capital}$, $C_{I,capital}$, $C_{SWH,capital}$ are the PV, batteries, invertor, and SWH, capital cost respectively. The parameter Sav_E is the total savings in envelope material which varies depending on the glazing material used.

So the most feasible combination between the PV and converter for scenario 1 is constrained by the initial cost. The best optimized case should have a capital cost not exceeding the savings of building material (\$14,000 or \$9,900) minus the cost of the SWH system (2000\$). This capital cost should not be much less than the constraint to benefit as much as possible from the savings attained. So, the initial capital cost should be less than or equal to \$14,000 but not less than or equal to \$11,400. After meeting the initial cost constraint, the best optimized case should also cover the needed electric consumption at the lower possible NPC. This would be based on life cycle assessment; that is decreasing the total life cycle cost of the system components. The cost functions are represented by equations 6 to 9 as follows:

$$LCC = C_{PV} + C_I + C_{grid} \tag{6}$$

$$C_{PV} = C_{PV,capital} + C_{O\&M} + C_{PV,rep} \tag{7}$$

$$C_I = C_{I,capital} + C_{I,O\&M} + C_{I,rep} \tag{8}$$

$$C_{grid} = E_{purchased} * C_{1kWh,purchasing} - E_{sold} * C_{1kWh,sold} \quad (9)$$

where $C_{PV,capital}$, $C_{I,capital}$, $C_{SWH,capital}$ are the PV, invertor, and SWH capital cost respectively. $C_{PV,O\&M}$ and $C_{I,O\&M}$ are the operational and maintenance cost for the PV and invertor. $C_{I,rep}$, and $C_{PV,rep}$ are the replacement cost for invertor, and PV respectively. The $E_{purshaces}$ and E_{sold} are the electric energy grid purchases and sales respectively. $C_{1kWh,\ purchasing}$ and $C_{1kWh,sold}$ are the cost of each 1 kWh being purchased from the grid and sold to the grid respectively which are equal to 0.1$.

Scenario 2; Lowest life cycle cost system: The second scenario will evaluate and optimize further investment in the PV system based on life cycle assessment instead of initial cost only and the main objective is to decrease the total life cycle cost. Equations (6) to (9) are also applicable for Scenario 2. The most feasible combination between size of the PV and converter for Scenario 2 should have the lowest NPC and cover the needed electric load.

Grid parity conditions enables house owners to produce electricity from PV that they can consume or sell back to the utility at no additional cost (Cai et al., 2013). Electricity rates must increase as demand decreases so that utilities can recover fixed costs. And these rate increases can result in even more incentives to adopt technologies that reduce consumption from the grid. Therefore, adoption of PV leads to a positive feedback cycle via increasing electricity rates (Burns and Kang, 2012; Cai et al., 2013; Makled[b], 2014). In the two adopted scenarios of this study, the optimization considers two cases where in the first case there is no limit on grid sales even if it exceeds the house rated electrical load while in the second case the house owner cannot sell the excess power to the grid (Baldock, 2008; Burns and Kang, 2012; Cai et al., 2013; Kazar and Kazar, 2014).

3. Results and Discussion

Around 60,000 simulations were performed on HOMER to arrive at optimal designs for the different configurations and scenarios to determine optimal system within budgetary and physical constraints. For Scenario 1, the best optimized system meeting the cost constraint consisted of a 7 kW PV modules plus a 9 kW converter if single glazed windows are used in addition to the grid and the SWH. However, the PV modules size was decreased to 4kW if part of the savings is invested in double glazing. For Scenario 2, the best optimized case and since it is not constrained by the initial investment cost, it consisted of the maximum allowed size of PV modules; that is of 12kW modules in addition to the 9kW converter and the SWH. This result is only valid if the grid sales are allowed to exceed grid purchases; that is home owner will receive payment from the government in return to the additional kWh being sold to the grid. The same result applies to both the single glazed and double glazed conditions. Figure 5 presents the electric load covered by the grid and PV system and the grid sales for the base case, Scenario 1, and Scenario 2 if single glazed windows or double glazed windows were used.

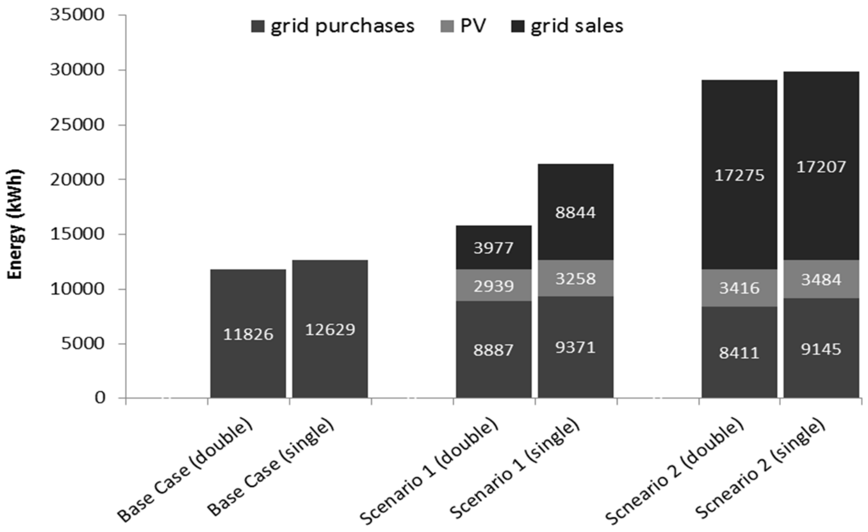

Fig. 5: Plot of grid purchases, electric load covered by the PV system, and grid sales for the Base case, Scenario 1, and Scenario 2 if single glazed or double glazed is used (no grid sales constraint).

Using only the savings in construction cost with single glazing, the resulting PV system could cover up to 26% of the electric load and around 71% of grid sales. However, these percentages increased in Scenario 2 to 28% of the electric load and 137% of grid sales. It is clear from these percentages that increasing the size of the system will not affect much the electric load covered by the PV system but it almost doubled the grid sales. This is due to the fact that during the peak PV production, the house electric load is minimal and was 100% covered by the PV system in Scenario 1. Therefore, increasing the size of this system will only increase the grid sales.

If double glazed windows were used in Scenario 1, the resulting PV system could cover up to 25% of the electric load and around 34% of grid sales. However, these percentages increased in Scenario 2 to 29% of the electric load and 147% of grid sales. Obviously, the load covered by the PV system in Scenario 2 did not show much increase over scenario 1 for the reasons stated previously. Even if the size of the PV system is tripled, the grid sales will be significantly affected by an increase of more than 100% as compared to Scenario 1.

When the grid sales are not allowed to exceed grid purchases, which is an adopted policy in several countries (Burns and Kang; 2012; Cai et al.; 2013), Scenario 2 with the lowest NPC resulted in reduced sizes of PV modules and convertors. The best optimized PV system decreased to 10 kW PV modules and 4 kW converter in the case of single glazing and to 7 kW PV modules and 5.5 kW converter in the case of double glazing. This reduction in the system size is due to the fact that the extra electric production will be lost and will not have any additional benefit to the home owner. The savings from covering the electric load and from selling to the grid decreased respectively to 27% and 75% in the case of single glazing and to 28% and 76% in the case of double glazing.

Figure 6 presents the results for the case of grid sales constraint. During the PV production hours, between 10 a.m. and 4 p.m., and when the AC load is less than this production, the excess in energy is sold to the grid. The maximum attained PV power reached 6.95 kW and in Scenario 1, single glazing during March but with very close values for the other months. For the case of double glazing, the maximum PV power reached 3.97 kW during March as well. The daily PV output profile for the four seasons does not differ much, thus the reliability of the PV system in Lebanon can be considered similar all year round.

In Scenario 2, most of the PV energy output is sold to the grid where these sales reached 83% of the PV output during the peak hours, if not constrained by selling limit, due to the fact that during this time the house load is minimal. The grid sales are not only important to home owners but also to the grid itself where it will be able to cover more of the needed load for other houses or non-residential sector. For instance; the grid is also supplying companies that have their peak load mainly between 10 a.m. and 4 p.m., so the excess in energy generated by the house with the PV can be used to assist the grid in covering the peak load for this company. If more houses invest is this system, they will make the grid stronger and increase its ability to cover higher demand during peak hours of the day.

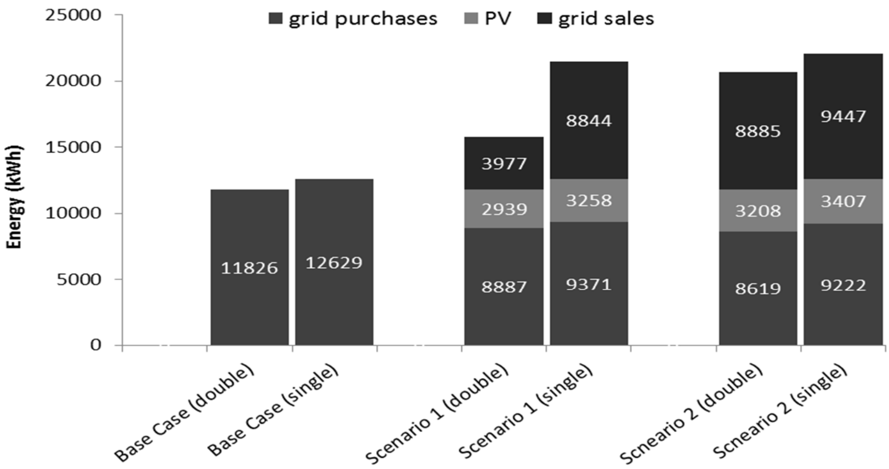

Fig. 6: Plot of grid purchases, electric load covered by the PV system, and grid sales for the Base case, Scenario 1, and Scenario 2 if single glazed or double glazed is used (grid sales constraint).

A comparison is performed with the base case of grid alone to check how profitable it to invest in envelope replacement and us the savings to install a PV system. The base case of grid alone levelized cost of electricity (COE) reflects the unit cost of electricity generation over the life of the project, is 0.1 $/kWh.

To clarify how the PV system can be considered a feasible investment; the economic indicators are presented for all considered cases in Table 1 including the levelized COE, the annual savings, the return on investment, and the payback period. In Scenario 1, the annual savings reached $692 when double glazing is used and $1210 when single glazing is used. However, these savings are equal when both double and single glazing cases are used reaching $2,069 for Scenario 2 with no constraint on grid sales. If there is a limit on how much to sell to grid, these savings will decrease to $1,186 and $1,263 for single and double glazing cases respectively.

Table 1. Scenarios 1 & 2 Economic indicators Results

	Scenario 1		Scenario 2 (area constraint)		Scenario 2 (sales constraint)	
Window type (glazing)	Double	Single	Double	Single	Double	Single
Levelized COE ($/kWh)	0.064	0.04	0.013	0.016	0.035	0.045
Annual Savings ($)	692	1210	2069	2069	1186	1263
Return on investment (%)	8.65	9.74	10.4	10.4	10.3	7.96
Simple payback (years)	10.7	9.83	9.38	9.38	9.47	12.3

By having these savings over the base case, the home owner will be able to payback the initial investment resulted from construction cost savings in around 9.83 years if single glazing is used and in around 10.7 years if part of the construction cost savings were also invested in double glazed windows. It is worth mentioning here, that by decreasing the cost of envelope construction, the home owner will not only have enough money to invest in renewable energy systems, but he will also have this amount of money available again in around 10 years.

For Scenario 2, even though the cost of the system increased as compared to Scenario 1, this investment will also be reimbursed in less than 10 years. This is mainly due to that the higher system allowed for more grid sales thus generated more savings that resulted in such payback period. The increase of payback period to 12 years in case the grid sales are not allowed to exceed grid purchases is because some excess in PV production will be lost decreasing the profit the home owner can make if allowed to sell more. This will decrease the savings thus increasing the payback period.

4. Conclusion

In the view of the above, it is clear that integrating a PV system and a SWH heater in houses will generate not only direct profit to house owners but also to the energy sector. By using savings attained from integrating cheap local material for a typical house design of $58/m^2 to invest in these renewable systems, PV and SWH, will result in further savings that can reach up to $1587 each year from both covering part of the electric load, hot water, and selling to the grid. Investing part of the savings in double glazing though it decreased the electric load by 6% did not have a significant effect as compared to investing this amount to increase the size of the PV system.

However, if increasing the size of the PV system to cover the house roof without being constrained by the construction savings and by any grid sales limit, the total savings can reach around $2466 for each year. This presents clear incentive for home owners to adopt PV technology.

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