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Building Energy Optimization Using Sequential Search Approach for Different Climates in Iran

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Abstract- In the current paper, the sequential search optimization method applied to a 430 m^2 three story residential building to find optimal building envelope and solar technology options in order to have a zero energy building design. Five different climates of Iran including: Tehran, Tabriz, Esfahan, Bandar Abbas and Shiraz, which are almost the perfect representatives of the country's climate, are included in the study case. Optimal design options for each climate suggested for different design cases including minimum energy related costs and maximum energy saving design options. It is shown that a proper combination of envelope and solar options can lead to a sustainable design in terms of energy use and environmental effects with an affordable cost. Optimization results showed that at a minimal cost design option, it is possible to reduce the energy costs for up to 23% while increasing the energy savings as much as 15% depending on the considered climate. Maximum energy savings of up to 49% is reported while energy costs rose to 25% in comparison to a reference building. Depending on each climate, different envelope and solar options are suggested which can be used as a practical guideline for energy management companies and architects in early design stages of a building envelope. Investigating on the optimization results toward a zero energy building design revealed that before using solar technologies to produce energy for a house, it is more cost-effective to first reduce the energy consumption of a building by using sustainable envelope parameters which can result in a less expensive PV or solar heat water (SHW) system.

Keywords—Building envelope, Energy saving, Sequential search optimization method, Solar technology.

1. Introduction

Energy consumption in the building industry is increasing with a noticeable pace in conjunction with rising population and living standards in developing counties which has become crucial as none-renewable energy resources are depleting. As a result of the recent advances in building envelope technology the annular energy consumption has descended for more than 40% which is a great achievement. Designing an efficient building envelope is a challenging and complex procedure. Number of drastic parameters on energy characteristics of a building is significant which requires special techniques and methods in order to select the best combinations to achieve an efficient design in terms of energy savings and operation costs.

To have a sustainable and cost efficient building design, it is important to have enough knowledge about building energy performance in early stages of the design process by considering simple but effective measures such as insulation, construction wall material, shading devices, etc. Further energy reductions and better environmental effects are achieved by implementing innovative energy saving measures and renewable energy sources.

A great deal of researches have been done in the recent years to develop technologies and methodologies for sustainable building designs that are focusing on different fields of envelope design such as construction, shape, configuration , control of building systems, and renewable energy resources applications. Amongst all envelope design parameters, a lot of researchers are dealing with construction variables such as material, insulation and glazing. A review of computational optimisation methods applied to sustainable building design by Ralph [1]. It presented a comprehensive review of all significant research applying computational optimisation to sustainable building design problems. A summary of common heuristic optimisation algorithms is given, covering direct search, evolutionary methods and other bio-inspired algorithms.

Chavatal et al. [2] presented a simulation methodology for estimating the impact of the building envelope insulations upon its global thermal performance and annual energy consumption. Daniel et al. [3] developed a simulation–optimization tool which couples a genetic algorithm (MATLAB) to a building energy simulation engine (DOE-2) to select optimal values of a comprehensive list of parameters associated with the envelope to minimize energy use for residential buildings.

Christina [4] reported a parametrical study on the effect of different building envelop strategies on operational energy of a commercial building model in which annual heating and cooling energy demands and artificial lighting and thermal comfort distribution were taken into consideration. Vesna et al [5] performed a parametric analysis on the variation of the glazing-to-wall area ratio from 0% to 80% for six different exterior wall elements with different thermal properties and studied the impact of the mentioned variable parameters on the energy demand for heating and cooling. Sahu et al [6] used admittance method to minimizing energy use in an air-conditioned building in a tropical climate by varying construction materials. Minimization of life cycle cost (LCC) for a single family detached house using combined simulation and optimization is the subject of the work done by Hasan et al. [7]. They coupled IDA ICE 3.0 building performance simulation program with the GenOpt generic optimization program to find optimized values of five selected design variables including three continuous variables (insulation thickness of the external wall, roof and floor) and two discrete variables (U-value of the windows and type of heat recovery). They reported a reduction of 23% to 49% in space heating energy in an optimized house.

Fesanghary et al. [8] developed a novel method to minimize the life cycle cost (LCC) and carbon dioxide equivalent (CO_2-eq) emissions of the building by introducing a multi-objective optimization model based on harmony search algorithm (HS). Several building envelope parameters were considered in their model and it was tested on a typical single family house. In a recent article by Omer et al. [9] a building energy simulation program, e.g. EnergyPlus is coupled with GenOpt genetic optimization tool to find isolation thickness of external walls and roof and fenestration type. They showed a decrease of about 34% in annular total site energy consumption with the initial baseline case and 28.7% life cycle cost reduction over a life span of 25 years.

The other important field in designing a net zero energy building is the application of solar technologies to absorb the solar energy and transform it to heat in solar heat water (SHW) or produce energy using Photo Voltaic (PV) cells. Design and optimization of solar technologies are still developing topics in the building sector and many researches can be found in literature focusing on performance improvement and cost optimization of solar devices. Keshavarz et al [10] provided an atlas to determine maximum solar energy gain and optimum slope angle of solar collectors for Iran's climate. They determined the daily, monthly, seasonally and yearly optimum slope and azimuth angles of solar collectors for 30 cities.

Optimizing the size of grid-connected photovoltaic (PV) system for a residential building is the topic of paper presented by Ren et al [11]. In their work simple linear programing was developed in order to minimize the annual energy costs of a given customer, including PV investment, maintenance, utility and electricity costs, subtracting the revenue from selling the excess electricity to the grid. Chaiwiwatworakul et al [12] studied the energy saving potential from daylighting through external multiple-slat shaded window in the tropics and presented results of an experimental and simulation study on the use of such device with windows. Christian et al [13] developed a model based on linear programming for the optimal sizing of 100% renewable supply systems in terms of the overall system costs. They applied the model in a case study for a so called Net Zero Energy Building in Denmark with three technology options.

Among all design parameters of a residential building, such as building orientation, window-to-wall ratio, type of glazing, shading, thermal mass and insulation, the fundamental robust design solution is required to be examined carefully at the early design stage of a building design process. The accurate combination of these design variables with well-established solar technology e.g. solar heat water and PV, can lead to a robust and efficient building energy design which is the main contribute of the current study. To this aim, five different climes of Iran's large cities including Tehran, Tabriz, Esfahan, Bandar Abbas and Shiraz were studied by using the sequential search optimization approach, moreover different design options were investigated in terms of energy saving and annual energy related costs. Effects of different combinations of wall material with different insulation characteristics, ceiling and roof materials, window to wall ration, passive shading devise, windows type, PV-systems and solar water heating devices are examined and best options are suggested which can be used as a practical guide line for engineers and architects in early stages of a building design.

2. Building Optimization Method

For the work presented in this paper BEopt version 2.2.0.1[14] was used which is an optimization-simulation tool developed by NREL. A quick review of this simulation tool is presented here which is based on two articles by Horowitz et al [15] and Polly et al [16]. BEopt uses Energy Plus, a well-established simulation engine, which is coupled to a sequential search technique to automate process of identifying optimal building designs along the path to Zero Net Energy [14]. The sequential search approach searches all discrete design options (e.g. wall type, ceiling type, window glass type, and solar parameters) for the most cost-effective combination at each sequential point along the path to ZNE. During the optimization process, the marginal cost of saved energy is calculated and compared with the cost of PV energy. From the point where further improvement in the building envelope or equipment has a higher marginal cost, the building design is held constant, and PV capacity is increased to reach ZNE [14]. More detailed description of the sequential optimization method can be found in BEopt documentation [14], Horowitz et al [15] and Polly et al [16]. BEopt users are able to find not only the optimum design but all near-optimal alternative designs along the path of interest (i.e., minimum-cost building designs at different target energy savings levels). This allows for substitution of essentially equivalent solutions based on builder or contractor preferences. Appropriate weather data files for Tehran, Tabriz, Esfahan, Shiraz, and Bandar Abbas, available at NREL website, are used in this study. Economy parameters in BEopt are modified based on available data from Central Bank of Iran which include many parameters for example inflation rate, utility rates, mortgage interest rate, etc.

Figure 1. Building model geometry

2.1. Reference Building Characteristics

For this study a typical three story residential apartment is considered which is shown in figure 1. It is 430 m^2 with two garages. Total Window area of the reference building is 15% of exterior wall. Windows are of double-pane type with air-filled metal frame. Heat transfer coefficient (U-value) and Solar Heat Gain Coefficient (SHGC) are assumed 0.76 $BTU/h\,ft^2$°F and 0.67 respectively. No overhang is considered in reference building. Building orientation is toward North and left and right walls are attached to neighbours with the same geometry. Heating and cooling set-points are different for each city but no demand response schedule is considered. A Concrete Masonry Unit (CMU) of 6-inch-hollow type is used in construction. For interzonal walls fibre glass-based material is used (R-13 Fiberglass Batt), also galvanized steel is used as roof material. Space conditioning is performed using central air conditioner with uninsulated ducts with 15% leakage. A tankless water heater with copper distribution system is considered. Major appliances include fluorescent lightning, three 18 ft^3 refrigerators, and standard cooking devises. No PV system or solar water heater assumed in reference building model. All related costs of materials and devices have been modified based on Iran market and quotes from manufacturers. A 30-year life time is considered for building and its major equipment's.

2.2 Design Parameters and Objective Function

A combination of envelope parameters and solar parameter are considered as design parameters. Tables 1 to 6 list the optimization variables, their related cost and thermal parameters. Cost of each parameter is normalized with respect to the reference model option. Different performance objectives can be used during design optimization. For instance, performance target can be set to minimize the monthly combined mortgage plus energy bill costs. Another objective is to reach a net zero energy building based on the site or source energy [14]. In this article last objective is examined for five cities of Iran.

Table 1. Wall physical properties

walls (CMU)	R value $h\,ft^2\,R/Btu$	Cost per ft^2exterior wall
6-in Hollow	4.20	1.00
6-in Hollow, R-10	11.80	1.28
6-in Hollow, R-12	13.20	1.25
6-in Hollow, R-13	13.90	1.28
6-in Hollow, R-19	19.80	1.13

Table 2. Celling and roof physical properties

Celling	R value h ft^2 R/Btu	Cost per ft^2exterior wall
Ceiling R-30 Fiberglass,	31.60	1.00
Ceiling R-38 Fiberglass,	39.60	1.25
Ceiling R-44 Fiberglass,	45.60	1.43
Ceiling R-49 Fiberglass,	50.60	1.59
Ceiling R-60 Fiberglass,	61.60	1.93

Roof Material	absorptivity	emissivity	Cost
Tile, light	0.60	0.93	2.37
Galvanized Steel	0.70	0.88	1.00

Table 3. Window areas

Window Areas	windows area ft^2
12.0% F25 B25	44,44
15.0% F25 B26	55,55
18.0% F25 B27	66,66
20.0% F25 B28	77,77

Table 4. Windows type

U value h ft^2 R/Btu	SHGC	Cost
Double-Pane, Clear, Metal Frame, Air Fill		
0.73	0.67	1.00
Double-Pane, Clear, Non-metal Frame, Air Fill		
0.49	0.56	1.01
Double-Pane, Medium-Gain Low-E, Non-metal Frame, Air Fill		
0.38	0.44	1.06
Double-Pane, High-Gain Low-E, Insulated Frame, Air Fill		
0.32	0.56	1.19
Double-Pane, Low-Gain Low-E, Insulated Frame, Air Fill		
0.29	0.31	1.30

Table 5. Solar water heating

Solar water heating	Cost
None	NA
40 sqft cloosed loop	1.00
64 sqft cloosed loop	1.05

Table 6. PV system

PV System	cost (Normalized)
None	NA
2 kW	1.00
4.5 kW	2.01

3. Results

Analysis results for considered climates i.e. Tehran, Tabriz, Esfahan, Bandar Abbas and Shiraz are presented in this section. Iran is a vast county with a wide verity of different climates. In order to overcome this problem each city is chosen in different climate. In table 7, elevation and latitude of these cities are tabulated. Annual dry bulb temperature and annual global horizontal radiation of considered climates are shown in figure 2. Tabriz is the coldest city its lowest annual-average daily temperature is about 6 °C, but Bandar Abbas has the hottest climate with a maximum temperature of 33 °C. Tehran, Esfahan, and Shiraz have moderate climates with almost the same annual dry bulb temperature. Tehran has the highest pick of global radiation of about 800 Wh/m^2 which shows a good potential of using solar technology in this city. The lowest amount of global radiation belongs to Tabriz with a pick of about 500Wh/m^2. These differences in climate conditions require different design considerations along the path to Net Zero Energy Building design which is the focus of the current work.

In figure 3, annul source energy consumption for reference building for each city is shown. It includes energy use for hot water, heating and cooling, HVAC fan/pump, etc. Tehran and Shiraz have almost a same annul heating load of about 70 MMBTU/yr. Tabriz is the coldest city consequently it has the highest heating load equals, equivalent to 183 MMBTU/yr and the lowest cooling load of about 17 MMBTU/yr.

Table 7. Sea level and latitude of considered climates

City	sea level (m)	Latitude
Tabriz	4500	38
Tehran	4000	35
Esfahan	5200	33
Shiraz	5000	30
Bandar Abbas	30	27

The highest cooling load belongs to Bandar Abbas it can reach a staggering value of 150 $MMBTU/yr$ which is almost three times the cooling load of other cities. In figure 4 optimal and near optimal points along the path to ZEB is shown for the modelled building in Tabriz. The percentage of the source energy saving versus annual energy related costs is plotted for a reference building. Annualized energy related costs, are calculated by annualizing the energy related cash flows over the analysed period [14]. Cash flow consists of mortgage/loan payments, replacement costs, utility bill payments, mortgage tax deductions (for new construction), and residual values.

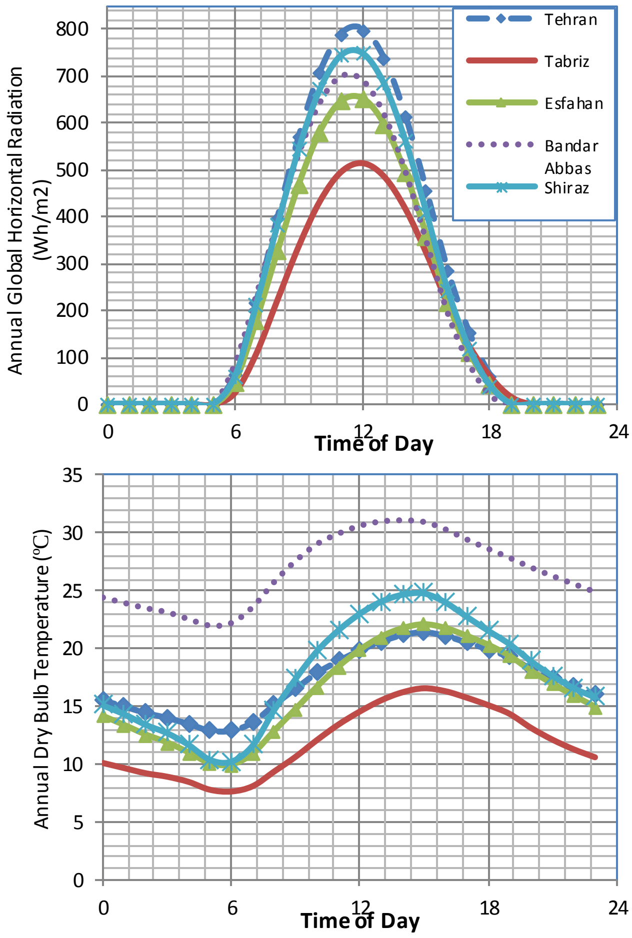

Figure 2. Annual dry bulb temperatures and annual global horizontal radiation

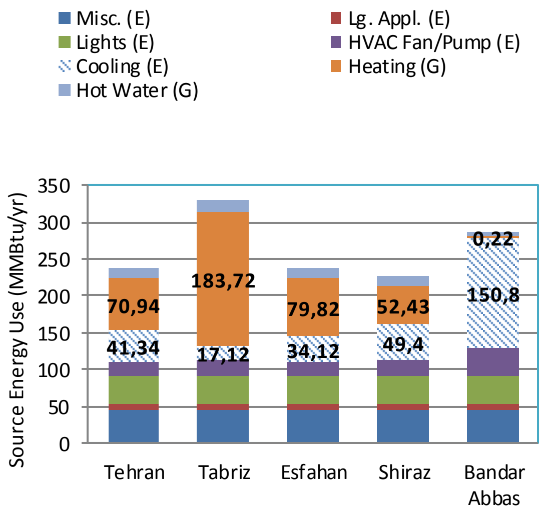

Figure 3. Source energy use for reference building

All costs (except mortgage/loan payments), are inflated based on the time they occur in the analysis period [14]. Each point in this figure shows a different combination of equipment and envelope options for the building. Points with the lowest energy costs are connected with a black line which is referred to as least cost curve or LCC for abbreviation. There are five important points along the path of LCC, reference point, min-cost point, PV-start point, PV-end point, and max saving point. The reference point is the case from which evaluating energy efficiency measures begins. The percent energy savings equals to zero at this point. Min cost point represents the lowest energy related cost option. PV-start point shows the design option in which PV added to the design after the maximum energy saving along with the minimum energy cost is achieved. After PV_end point, no more PV added to the options and efficiency increase vie envelope options. The envelope and solar options of these points for each city will be discussed in more details.

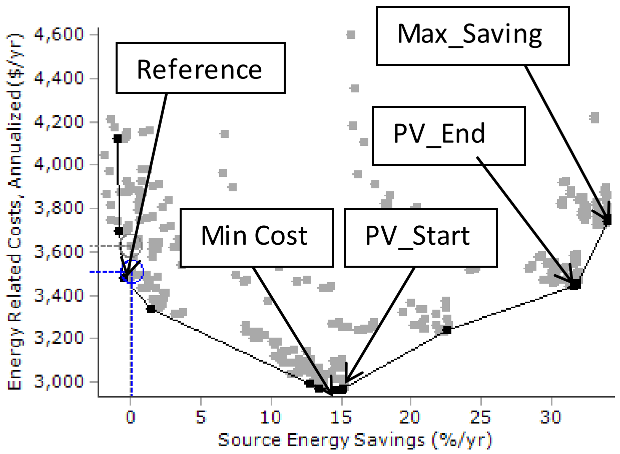

Figure 4. Optimization results for a three story building in Tabriz

LCC for Tehran, Tabriz, Esfahan, Bandar Abbas, and Shiraz is plotted in figure 5. This is the most important result of this work. PV start point is usually very close to Min-cost point therefore it is not clearly visible in figure 5. At the reference point, i.e. zero saving energy case, Shiraz, Tehran and Esfahan had lower energy costs compared to Tabriz and Bandar Abbas with a value of about 2700 $\$/yr$. At this point, Bandar Abbas climate requires 3320 $\$/yr$ and Tabriz requires 3629 $\$/yr$ which is the highest energy cost value. High value of energy cost for Tabriz and Bandar Abbas is due to the huge heating and cooling loads of these two cities which are coldest and hottest respectively.

At min-cost case, Tehran, Shiraz, and Esfahan climates reached the saving energy of about 11% while the energy costs decreased to 10.8, 13.8 and 22.15% respectively. Tabriz and Bandar Abbas min-cost option reached 15 and 17% respectively; meanwhile their cost reduction is equivalent to 22 and 19% respectively. Energy use reduction for Bandar Abbas climate is the highest because at min-cost option a 29% reduction in cooling load is achieved which consequently reduced the energy cost by 19%. This load reduction is obtained via selecting proper windows with minimum area and very low SHGF (solar heat gain coefficient). In Bandar Abbas case, windows area reduced from 15% to 12%, which is a common option for all other climates, but a double-Pane, Low-Gain, Insulated Frame window type is selected during optimization which has the lowest SHGC of 0.31.

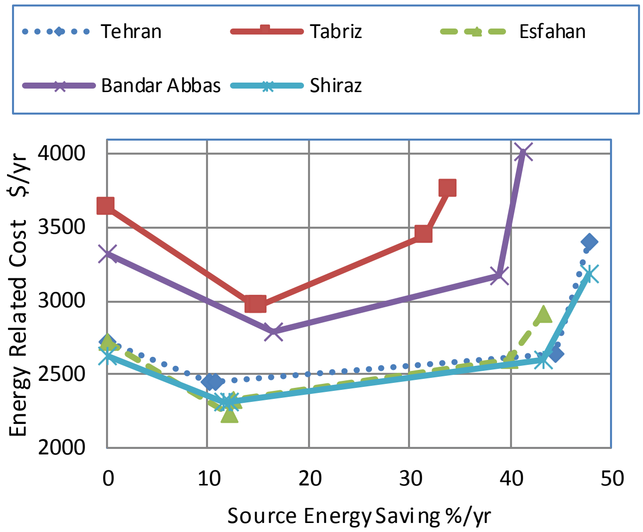

Figure 5. LCC for Tehran, Tabriz, Esfahan, Bandar Abbas, and Esfahan

At PV-end point case for Tehran and Shiraz and Esfahan climates, energy saving rose to 45, 43 and 40% respectively with annualized energy cost equivalent to about 2600 $/yr which is slightly lower than the reference case design. This is an interesting result which shows the importance of optimization of envelope and solar design options in building energy sector which can lead to noticeable energy saving with minimal costs. For Bandar Abbas climate energy saving increased from 16.48% at PV-start to 38.82% at PV_end design case. Tabriz climate has the lowest energy saving of up to 30% which is due to the fact that Tabriz is located at Northwest Iran (Latitude 38) and consequently has very low solar energy gain (figure 2). To address this behaviour, total site energy use and energy produced by PV system is shown for the case of PV_end option in figure 6. It can be seen that for Tabriz climate the total energy use is 286 $MMBTU/yr$ but only 56 $MMBTU/yr$ can be supplied by PV systems which is also the lowest value in comparison with other climates. Tehran climate possess highest PV energy production and consequently has the highest energy saving at PV_end design option.

Envelope options selected by optimization algorithm at min-cost case are similar to those at PV-end design option. The chosen option for wall construction for all climates is 6-inches Hollow, R-19 Fiberglass Batt which has the highest thermal resistance. Ceiling material R-30 Fiberglass is selected for Tehran, Esfahan and Shiraz but for Tabriz and Esfahan Ceiling R-38 Fiberglass material is picked. Windows area of 12% is the case for all climates at PV-end design point.

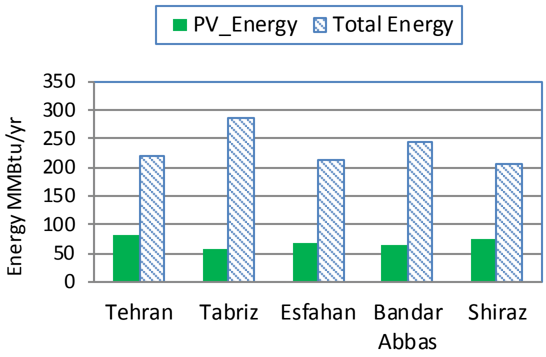

Figure 6. Total energy consumption and energy production by PV system

BEopt Selection for windows type for Tehran, Tabriz and Esfahan are of double-Pane, High-Gain Low-E, Insulated Frame and Air Fill. For Bandar Abbas and Shiraz, which are located in south of Iran, windows with low SHGF of 0.31 and 0.44 is chosen via optimization process to reduce the cooling load imposed by solar radiation through the windows. Solar water heaters were not considered for all climates at PV-end case. A 4.5 Kw PV with a tilt angle of 30 degrees was selected for all cities except Bandar Abbas which had a tilt angle of 20 degrees.

Optimization results at max-saving option along the path of zero energy building for Tehran and Shiraz were very similar with the maximum source energy saving of 47% for both climates as a result about 23% increase in annual energy related costs relative to their reference cases been achieved. The maximum energy saving that can be reached for a three story building in Esfahan is 43% with 6.8% rise in energy costs. In Bandar Abbas climate, max-saving option resulted in 41% energy consumption reduction with 21% increase in energy costs. Tabriz climate had the lowest energy saving which is 34% however this happened with a slight increase in energy costs of about 3.5%. Different envelope and solar options for max-saving designs are shown in table 8 for all considered climates.

At max-saving case, wall material type is 6-in Hollow, R-19 Fibreglass Batt, which has the highest thermal resistance. This is the case for ceiling material too, where R-60 Fibreglass ceiling is selected. Roof material for all climates is galvanized steel except in Tabriz climate where tile with higher absorptivity is picked. Windows area option is exactly the same as in the PV-end design with minimum area. Double-Pane, High-Gain Low-E, Insulated Frame, Air Filled window type is chosen for all climates whereas in Bandar Abbas city a lower SHGC is selected. A 2 feet overhang for all windows is selected just for Bandar Abbas climate which shows the importance of shadow effect in hot climates such Bandar Abbas where solar imposed load to be calculated accurately.

In all climates, a 65 ft^2 closed-loop Solar Water Heating (SWH) system is selected at max-saving design except in the case of Bandar Abbas climate where a 40 ft^2 SWH system is the option which is due to the lower demand for heat water in Bandar Abbas's hot climate. SWH system is to be installed on left floor as the optimization algorithm suggests for all climates. Tilt angle for this system is different for each climate. Like the case of PV-end design, a 4.5 Kw PV system is picked for all cities with azimuth angle as installed on back roof. Tilt angle for all climates equals 30 degrees but for Bandar Abbas climate is 20 degrees.

4. Conclusion

In this work the sequential search optimization method was applied to a 430 m^2 three story residential building to find the optimal envelope and solar technology options along the path of a zero energy building design. Five different city including Tehran, Tabriz, Esfahan, Bandar Abbas and Shiraz, which are almost good representative of Iran's climate were considered and optimal design options for each climate suggested for different design cases including min-cost, PV-end, and max saving options. Optimization results showed that at the min-cost design option, it is possible to achieve energy cost reduction ranging from 10% to 23% with energy saving increase up to 15% depending on the climate. At PV-end design option, energy saving of about 31% to 45% is obtained while there is still annualized cost reduction for all climates. Max-saving option, suggested by BEopt, indicates that energy reduction values can reach from 33% to 49% as energy cost rises up to 3.5% to 25%.

Tehran and Shiraz climates were shown to have a good potential for energy reduction using good combination of envelope and solar parameters. For cold climates like Tabriz, it seems that solar options have less effect on buildings energy effectiveness in comparison with envelope options such as wall material, insulation, and window's area. In the case of Bandar Abbas climate, results showed the importance of considering solar technologies such as PV and SWH systems. For this climate envelope options were considered to decrease the cooling load imposed by solar radiation through windows which is done by optimization algorithm including minimum window's area and windows with fewer SHGC.

Optimization results shows that the sequential search method proposed by BEopt enables architect and construction companies to accurately predict the near optimal design in terms of energy saving and cost effectiveness of different envelope and solar technology options. It is important to note that, the results from the analysis are subject to the assumptions used during the study and the data accuracy available for each climate. More filed data requires to validate the suggested design option for each climate however these results could be used as a good guide line for constructing new buildings in Iran.

Table 8. Envelope and solar options for max-saving design

Tehran	Tabriz	Esfahan	Bandar Abbas	Shiraz
walls (CMU)				
6-in Hollow, R-19	6-in Hollow, R-19	6-in Hollow, R-19	6-in Hollow, R-19	6-in Hollow, R-19
Ceiling				

Ceiling R-60 Fibreglass,	Ceiling R-60 Fibreglass,	Ceiling R-60 Fibreglass,	Ceiling R-60 Fibreglass,	Ceiling R-60 Fibreglass,
Roof Martial				
Tile, light	Galvanized Steel	Galvanized Steel	Tile, light	Tile, light
Window Areas				
12.0% F25 B25	12.0% F25 B25	12.0% F25 B25	12.0% F25 B25	12.0% F25 B25
Window Type				
Double-Pane, High-Gain	Double-Pane, High-Gain	Double-Pane, High-Gain	Double-Pane, Low-Gain	Double-Pane, High-Gain
Solar water heating				
64 sqft closed loop	64 sqft closed loop	64 sqft closed loop	40 sqft closed loop	64 sqft closed loop
Solar water heating Tilt Angel				
50	20	10	50	10
PV System				
4.5 kw	4.5 kw	4.5 kw	4.5 kw	4.5 kw
PV System Azimuth				
back roof	back roof	back roof	back roof	back roof
PV System Tilt Angel				
30	30	30	20	30

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