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A TECHNO-ECONOMIC FEASIBILITY STUDY FOR REDUCING THE ENERGY CONSUMPTION IN A BUILDING: A SOLAR ENERGY CASE STUDY FOR BANDAR ABBAS

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ABSTRACT

In this work, 13 different solutions for the optimization of energy consumption of a building located in the tropical city of Bandar Abbas are studied out via the EnergyPlus and TRNSYS (Transient System Simulation Tool) commercial codes. Then, the suggested solutions are economically studied and the most economically viable ones are proposed. Ultimately, an energy efficient consumption scheme is put forward with the approach of solar energy utilization. Results reveal that 9 out of 13 studied solutions are techno-economically viable; and by implementing these solutions the energy consumption of the building could be decreased by 81% up to 165624.1 kWh as well as preventing 63022.66 kg of CO_2 emission.

Keywords: *Building Energy Conservation, Techno-Economic Study, Solar Energy, EnergyPlus, TRNSYS*

INTRODUCTION

With the energy crisis turning into a global concern, solutions are sought for the energy issues. Increasing energy efficiency as well as renewable energies are seen as potential solutions out of this crisis, so many studies have been carried out to increase energy efficiency in energy sectors [1-8]. With regard to the household sector being a major energy consumer [1], one approach for lowering the total global energy consumption would be to optimize building energy demands and the application of green energies. Therefore, reducing the energy consumption of the building sector will significantly enhance the sustainable and environmental-friendly development, since the larger part of this energy is provided by fossil fuels, emitting greenhouse gases and accelerating the global warming. Various efforts are performed for predicting and modeling the building sector energy consumption. In a review, Zhao and Magoules [9] classified the building energy consumption prediction methods into 5 categories, namely engineering methods, statistical methods, neural networks, support vector machine, and Grey models. They reviewed the advantages and major drawbacks of each method. In another attempt, Balaras et al. [10] investigated the potentials of energy conservations in buildings. They followed the EPIQR methodology and software.

The methods of performing energy conservation are the subject of a vast number of scientific attempts for both the existing buildings and new building constructions. Chwieduk [11] investigated the modern and traditional options for building energy conservation. The traditional attempts include lowering energy needs, final energy demand, and the primary energy demand of the building, whereas modern options mostly include using renewable energies such as solar energy in active and passive modes. Since maintaining the comfort temperature in a building consumes a large part of the total building energy, insulation methods also play a crucial role in reducing the energy conservation of a building. Aditya et al. [12] reviewed the insulation materials for building energy conservation and compared the advantages and drawbacks of each. Recovering low-grade heat as well as heat storage via phase change materials (PCMs) are other useful approaches to energy conservation. Liu et al. [13] investigated the active low-grade energy recovery potential for this purpose. Khudhair and Farid [14], Tyagi and Buddhi [15], and Kenisarin and Kenisarin [16] reviewed the utilization of PCMs for heat storage, including solar energy, in building applications. Also, Sharifi et al. [17] investigated the application of PCMs in gypsum boards for energy conservation purposes. Dabiri et al. [18] investigated thermal analysis of a brick including PCM and ten air cavities using CFD in both the coldest and hottest days of Tehran in 2016. The result showed that in the summer, the latent heat storage constituted about 71 % of the thermal storage. By contrast, in the winter, more than 72% of thermal storage was made up of sensible heat storage.

Also, the amplitude of the internal temperature variation in the summer and winter decreased by 48.5 % and 44 %, respectively. Furthermore, cogeneration could also be utilized in buildings as investigated in [19]. Annad et al.

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[20] was studied the influence of various operating parameters such as COP and flow rate using the concept of energy and exergy in a single-effect absorption system for building application. As a result, such system can easily be applied to the building systems for attaining thermal comfort and achieve passive cooling.

With the technology being developed and cost efficiency being justified, incorporating renewable energies in buildings for energy reduction is becoming vastly popular in the last decade. Among these energies, solar energy is the most popular one due to extensive availability and lower costs. Older attempts mostly includes passive systems [21] or solar water collectors, while newer ones are a combination of both methods in most cases [22]. Chan et al. [23] reviewed the passive solar heating and cooling technologies in buildings. One common passive method is to store solar energy within the walls using special mediums, as the cases presented in [24] and [25]. In another research [26] using innovative Trombe wall with extra glazing in the massive wall for capturing solar radiation in order to cover a part of the heating loads of a building located in Athens, Greece was investigated by means of the commercial software Solidworks Flow Simulation. The result showed that the new Trombe wall is the most appropriate technology, creating warmer indoor profile than the other cases, especially the hours between noon and afternoon. Mehrpooya et al [27] presents an optimal planning model of a hybrid renewable energy system to meet a real load with a combination of photovoltaic panels (PV), diesel generators and batteries using HOMER software. Su et al. [28] comparatively studied different patterns of solar energy utilization for different applications, including residential, official, commercial, and industrial districts. Photovoltaic (PV) systems are the most common patterns used for solar energy utilization in buildings due to ease of maintenance and application. Various attempts are performed in this area within the literature, two of them being presented in [29] and [30] to name a few. Another passive application in this field is utilizing specific windows along with dedicated control devices. In this way, both lighting, heating, and cooling requirements of the building could be enhanced leading to lower total energy consumption, as presented in [31] and [32]. Kuhn [33] also reviewed advanced control devices used in solar buildings. Finally, solar energy could also be utilized in buildings via heat pumps or collector heaters. This application mostly covers heating and cooling needs, although in case of organic Rankine cycles (ORC), power generation could also be considered. Various efforts are performed in this field. Modeling and analyses presented in [34] and [35] could be pointed out as examples.

While technical performance of solar building systems is the first issue to be investigated, the factor that makes them being practical is the price. Economical and feasibility assessments if accompanied by technical analysis, provide a comprehensive guide for integrating solar energy systems in buildings. Several attempts are performed in this field. Poppi et al. [36] presented a techno-economic review of solar heat pump systems utilized in buildings. Also, Quoilin et al. [37] reviewed the ORC systems in buildings from a techno-economic perspective. Jo et al. [38] presented a parametric techno-economic model for analyzing renewable energy integration in residential buildings. Also, Liu et al. [39] analyzed the general indicator for techno-economic assessment of renewable energies. Various attempts are performed in the field of techno-economic analysis of building PV systems. Buonomano et al. [40] present a detailed exergetic and techno-economic analysis of a building integrated photovoltaic thermal system, while Lang et al. [41] performed a techno-economic analysis on rooftop photovoltaic cells for self-consumption in residential and commercial buildings. Also, Liu et al. [42] conducted Techno-economic simulation and optimization of residential grid-connected PV system for the Queensland climate. Finally, Turkay and Telli [43] presented an economic analysis of standalone and grid-connected hybrid energy systems in buildings. According to the literature, there are variety of studies on energy conservation of building, but there are no studies to investigate different solutions including modern technology such as using renewable energy for a specific environment condition such hot and humid climate and present the applicable solutions for this condition. Since hot regions are more intense energy consumers, while they benefit from the higher solar insolation, in this study Bandar Abbas city with hot and humid climate condition is selected for the case study.

Hence, in this study different solutions for energy reduction are investigated for reducing energy consumption of a building in Bandar Abbas city where have a hot and humid climate. Iran is located inside the solar belt, and studies have revealed that solar appliances are suitable for application in the country and capable of supplying for a portion of the nation’s energy demand. The city of Bandar Abbas consumes high energy, particularly during peak solar insolation. Therefore, energy efficiency and application of solar devices in the region can provide a significant reduction in city’s energy consumption.

Hereby, we first techno-economically analyze the energy efficiency solutions for energy efficiency in a nominal building in Bandar Abbas, Iran, including insulating and replacing the windows. Secondly, we study the optimum building equipping with solar energy systems. Ultimately, a suitable economical scheme is proposed which is capable of reducing the energy consumption of the nominal building. The present approach is an effective way to cut a considerable amount of household energy consumption in tropical regions, while being both environmentally benign and effective in curbing the foreseen energy crisis.

THE BUILDING

Cooling and Heating Systems

Due to the hot and humid climate of Bandar Abbas, its buildings requisite cooling, and there is no need for heating in cold seasons, due to the relatively high outdoor temperature. Electric water heaters and natural gas capsules are used for heating domestic water and cooking, respectively. Four split heat pump units, having compression cycles, cool the building, the capacity of which is 24222 Btu/h (7 kW) for one unit and 15222 Btu/h (4.46 kW) for the other three. One or two of them are usually active.

Lighting Systems

Energy saving light bulbs are used as follows: seven 58 watts and eight 42 watts bulbs inside the units, and twelve 22 watts bulbs for the corridors and the parking space.

Building Energy Consumption

The energy carriers used in this building are electricity and natural gas. The energy consumption of the building is shown with details in Table 1. The majority of the consumption is dedicated for cooling purposes.

Table 1. Energy consumption value of all the applications in the building

Application	Consumption value (kWh)
Cooling	172329.14
Heating	21640.69
Domestic Hot Water	2948
Lighting	1231
Electric Devices and Appliances	6289.53
Total Building Energy Consumption	204438.36

SIMULATION OF THE BUILDING IN ENERGYPLUS

In order to model the building in EnergyPlus software, a 3D design of the building structure is developed with Open Studio software at first, which incorporates a graphical user interface and depicted in Figure 1.

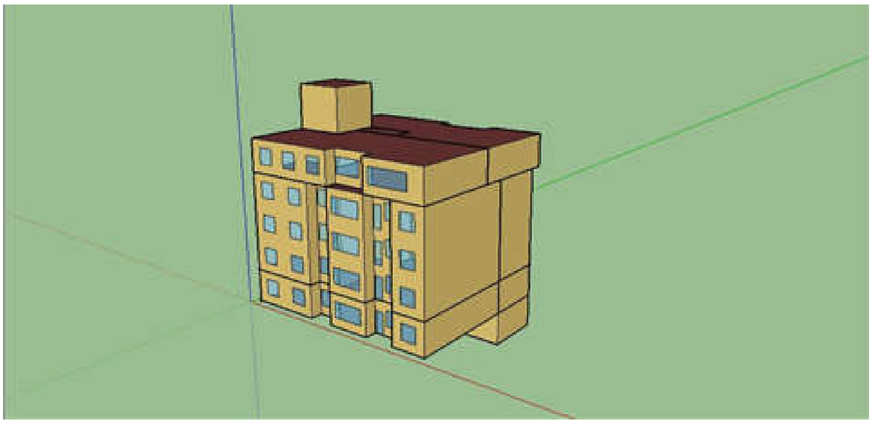


Figure 1. The building model in open studio

The first step in thermal modeling of a building in any energy simulator software is to define the thermal zones of the building. The Proper definition of the thermal zones both makes the results more reliable and decreases the required computational resource. Nine thermal zones were defined for the considered building. The probability of yielding considerable results is used for specifying the zones, e.g., the difference between the top and middle floors, between north and south zones, and between the underground and over-the-ground spaces were recognized to be significant. The thermal zones are considered as follows:

-Parking
-Stairs
-The northern part of the first-floor unit
-The southern part of the first-floor unit
-The northern part of the 2nd to 4th-floor units
-The corridor between the units
-The northern part of the 5th-floor unit
-The southern part of the 5th-floor unit

The thermal zones are illustrated in Figure 2 modeled in an Open Studio environment and specified with different colors.

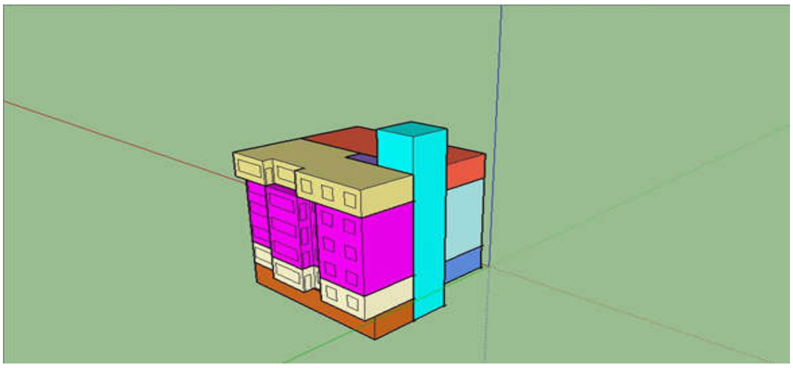


Figure 2. Thermal zones presented with specific colors in open studio modeling environment

The model is then transferred to EnergyPlus software environment, adding other required data including structural layers information, wall properties, installations, lighting systems, and residents' schedule. Moreover, the weather data are extracted from the file reported by the Mehrabad, Tehran, weather station available on EnregyPlus website.

VALIDATION

The best criterion for establishing a comparison between the thermal performance of the modeled and the real studied building is energy consumption. The energy consumption data of the buildings were analyzed as a first step toward establishing the comparison. Electricity can be regarded as the main energy source (fuel) of the building since cooling is conducted with compression refrigeration and the domestic hot water is provided with the electric water heater.

Table 2. Actual and simulated power consumption of the building

Date Range	Simulation (kWh)	Electricity Bill (kWh)
21 Mar – 20 Apr	14834.75	14175
21 Apr – 21 May	21193.77	19694.92
22 May – 21 Jun	28215.60	25474.96
22 Jun – 22 Jul	28087.09	26094.25
23 Jul – 22 Aug	27119.71	26183.43
23 Aug – 22 Sep	28936.45	26200.58
23 Sep – 22 Oct	20078.65	18110.4
23 Oct – 21 Nov	14160.98	16661.4
22 Nov – 21 Dec	6985.43	7585.62
22 Dec – 20 Jan	6000.69	6577.2
21 Jan – 19 Feb	6019.66	8838.2
20 Feb – 20 Mar	7775.13	8842.4

By studying Table 2 and Figure 3, which depict the simulated power consumption of the building, it is observed that the overall discrepancy between the actual and the simulated energy consumption values is 10%, which is due to the fact that the comfort range is defined to be 23-27℃ for software; while the HVAC is assumed to be ON continuously throughout the year. However, the occupants may be out for days, or the room temperature may rise over 27℃ in spite of the presence of the occupants. Therefore, the simulation carried out with EnergyPlus software is considered as an acceptable model of the actual building, and can be used for the forthcoming study of the effectiveness of energy efficiency measures.

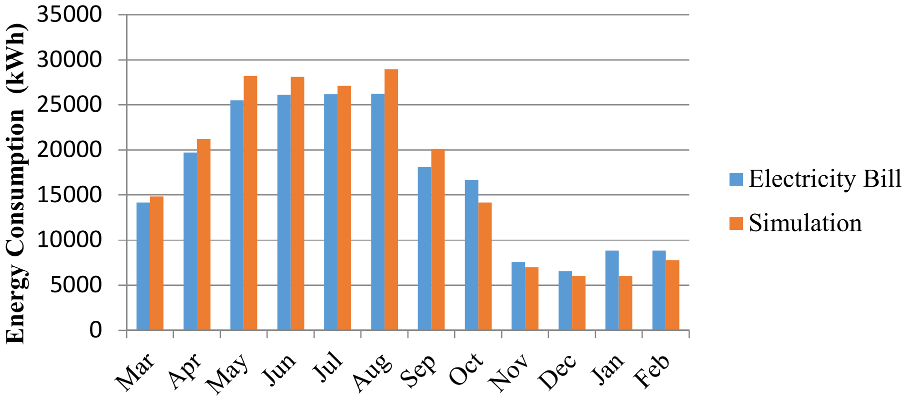


Figure 3. Real and simulated power consumption of the building

ERROR ANALYSIS

For the purpose of conducting a detailed error analysis, the statistical methods consisting the normalized mean absolute error (MAEnorm), and the mean relative error (MRE) methodologies are used for this validation by means of following formula.

$$MAE_{norm} = \frac{1}{y*avg(m_i)}\sum|e_i - m_i| \tag{1}$$

$$MRE = \frac{1}{y}\sum\left|\frac{e_i-m_i}{m_i}\right| \tag{2}$$

where e and m are the theoretical and experimental values, respectively. Also, y is the number of value for comparison. Based on the calculation, the percent value of the MAE norm and MRE are obtained as 9.8% and 10.9 % respectively.

TECHNICAL ANALYSIS OF ENERGY EFFICIENCY SOLUTIONS FOR THE BUILDING

In this section, the simulation is used for analyzing the effectiveness of energy efficiency measures taken in the studied building. In the following, 13 energy conservation solutions are investigated and the value of energy and CO_2 saving is presented.

Thermal insulation of the ceiling:

One of the cost-effective ways for energy saving is insulation which act as a barrier to heat loss. Based on the studies using of glass wool in tropical condition was recommended as insulation [44]; so, 10 cm thick glass wool is applied in the current study. The effect of insulating the ceiling with 10 cm thick glass wool is shown in Table 3. As Table 3 suggests, insulating the ceiling cut 10% of cooling power consumption of the building, equal to 17232.91 kWh. Also, 72%, equal to 15581 kWh of heating power consumption was saved. Thus, an overall 32814.21 kWh is saved annually, which prevents 11154.711 kg of CO_2 emission.

Table 3. Energy consumption with and without ceiling insulation

Energy required for cooling with insulated ceiling (kWh)	155096.23
Energy required for heating with insulated ceiling (kWh)	6059.39
Energy required for cooling in current condition (kWh)	172329.14
Energy required for heating in current condition (kWh)	21640.69

Thermal Insulation of the Walls

Considering the humid climate of Bandar Abbas, two layers of breathable waterproof membranes inside and outside should be considered in addition to the regular 5cm thermal insulator layer. The effect of thermally insulating the walls with polystyrene is investigated here. As is evident in Table 4, an 8% reduction, equal to 13786.33 kWh, was observed in cooling energy demand, and 76%, 16446.92 kWh, the reduction was observed in heating energy demand. A total power saving of 30233.26 kWh is reachable for the building with thermal insulation of the walls, which prevents the emission of 9976 kg of CO_2.

Table 4. Energy consumption with and without wall insulation

Cooling energy consumption with wall insulation (kWh)	158544.8
Heating energy consumption with wall insulation (kWh)	5193.766
Cooling energy consumption without wall insulation (kWh)	172329.14
Heating energy consumption without wall insulation (kWh)	21640.69

Utilizing Low-Emissivity Films

In order to study the effect of UV light blocking on energy consumption, low-emissivity windows are used instead of the current regular windows of the building. This is also achievable with laminating the regular windows with a low-emissivity film. Since the cooling load reduction is a significant goal, the low-emissivity layer is added to the inner surface of the outer glaze of a double-glazed window. The EnergyPlus results revealed that the low-emissivity film is capable of impeding sunlight UV and cutting 1723.292 kWh equal to 1% of the energy required for cooling, as presented in Table 6. However, reducing the energy gain from sunlight causes the heating load to increase by 865.62 kWh (4%). Overall, using low-emissivity windows saves 857.66 kWh annually and prevents 283 kg of CO_2 emission.

Table 5. Specifications of the low-emissivity window (laminated film on the outer glaze)

Thickness (m)	0.005
Solar beam transmittance in perpendicular	0.65
Solar beam reflectance in perpendicular, outer surface	0.22
Solar beam reflectance in perpendicular, inner surface	0.17
Visible light transmittance in perpendicular	0.84
Visible light reflectance in perpendicular, outer surface	0.078
Visible light reflectance in perpendicular, inner surface	0.055
Infrared spectral hemispherical emissivity, outer surface	0.1
Infrared spectral hemispherical emissivity, inner surface	0.84
Conductivity (W/(m.K))	1.05

Table 6. Comparison of cooling and heating energy demand with and without laminating the windows with low-emissivity film

Cooling energy demand with laminated low-e film (kWh)	170605.8
Heating energy demand with laminated low-e film (kWh)	22506.32
Current cooling energy demand	172329.14
Current heating energy demand	21640.69

Installing Horizontal Shades for Windows

Considering the fact that the major energy consumption share of the considered building is dedicated to cooling, our priority was to decrease the cooling load. Thus, installing shades for windows is desirable in a way that effectively prevents direct sunlight of the hot seasons from entering the inner space, while significantly preserving the direct gain of sunlight in cold seasons. Regarding the altitude of the sun, southward windows provide the chance of utilizing horizontal shades in order to fulfill the aforementioned goal. The acquired results revealed that installation of horizontal shades over southward windows decreased the building cooling load by 46528.87 kWh (27%), while the heating load of the cold days is also increased by 5974.118 (95%) which is due to the decreased direct solar heat gain, as shown in Table 7. The cooling load reduction is higher than the heating load increase, which indicates that installing horizontal shades for the windows would be useful, being capable of saving 40554.75 kWh of the building's power consumption as well as preventing 13383.07 kg of CO_2 emitting to the atmosphere.

Table 7. Energy demand with and without the horizontal shades

Cooling load after installing shades (kWh)	125800.2722
Heating load after installing shades (kWh)	12262.66275
Current cooling load (kWh)	172329.14
Current heating load (kWh)	6288.545

Replacing the Lights with LED Light Bulbs as Well as Lowering the Number of Light Bulbs

20 and 10 Watt LED light bulbs are recommended for replacing the existing 85 and 40 Watt compact fluorescent energy saving light bulbs (CFL) of the building, respectively. Numerous 80 and 40 watt light bulbs are currently used in the considered building for several hours a day, the replacement of which with LED light bulbs would significantly decrease building's power demand. As is evident in Table 8, using LED light bulbs annually decreases the overall electricity consumption by 76% equal to 939.8 kWh and prevents 319 kg of CO_2 emission. This economically justifies the use of relatively uncostly LED light bulbs, specifically in the halls.

Table 8. Lighting power demand of the building before and after LED light bulbs replacement

Annual power consumption of LED light bulbs (kWh)	292
Current (CFL) annual power consumption kWh	1231.88

Using Green Walls

Growing adequate greenery over the building's facades is one of the most affordable, economically viable methods of environmental control and energy saving. The method works with preventing the undesirable effects of intense direct sunlight over the structure in summer. The temperature of the green surface is 11 to 25℃ lower than that of the similar surface without the plants' shades. Also, the air temperature is 1 to 5 ℃ lower in the presence of greenery, according to US Environmental Protection Agency (EPA). The southern and northern facades of the building, which inhere the capability of growing plants on, are stone walls with a thermal resistance of 0.52 W/m^2K. With the plantation on the walls, thermal resistance needs to be recalculated. According to the empirical studies on the thermal resistance of still air layer adjacent to the wall [45], the overall thermal resistance of a green façade is 0.64.

As seen from the simulation results, listed in Table 9, it is evident that by covering the building envelope via greenery, the cooling and heating loads could be decreased by 3% equal to 5169.874 kWh and 19% equal to 4111.731 kWh, respectively; which sum up to 9281.605 kWh and prevent 3062.92 kg of CO_2 emission.

Table 9. Cooling and heating loads, before and after using green walls

Current cooling load (kWh)	172329.14
Current heating load (kWh)	21640.69
Cooling load with the green wall (kWh)	167159.2658
Heating load with the green wall (kWh)	17528.9589

Controlling HVAC Using BMS

In order to investigate the energy saving effectiveness of this solution, the presence and absence times of the residents of one unit was studied, and it was found that the residents are usually out for 2 hours a day, and leave the heat pump split unit of 18000 Btu/h working. Therefore, excluding the three cold months, during nine mild and hot months, the heat pump is working to cool the space while the residents are out. Building management system (BMS) allows the residents to switch the cooler about half an hour before returning home, or to remote control the cooler when they are away for days. Assuming the residents are away for five days a year (120 hours) and they are absent for 2 hours daily, this system saves 12% (20679.49 kWh) on the electricity bill, which also prevents the annual release of 6824 kg of CO_2.

Table 10. Power demand before and after BMS installation

Current power demand for cooling (kWh)	172329.14
Power demand for cooling with BMS (kWh)	151649.64

Greenhouse for Heating

In order to investigate the effect of building a greenhouse on the room condition, a greenhouse was added to the model of the building, where there is currently a balcony (attached to the room). The greenhouse walls receive sunlight only from one direction, due to the plan of the balcony. The balcony has a width of 1.5m and a length of 3.5m. Cooling and heating loads are recalculated with the greenhouse in place, and the results are plotted in Figure 4 and Figure 5, for before and after of incorporating the greenhouse, respectively.

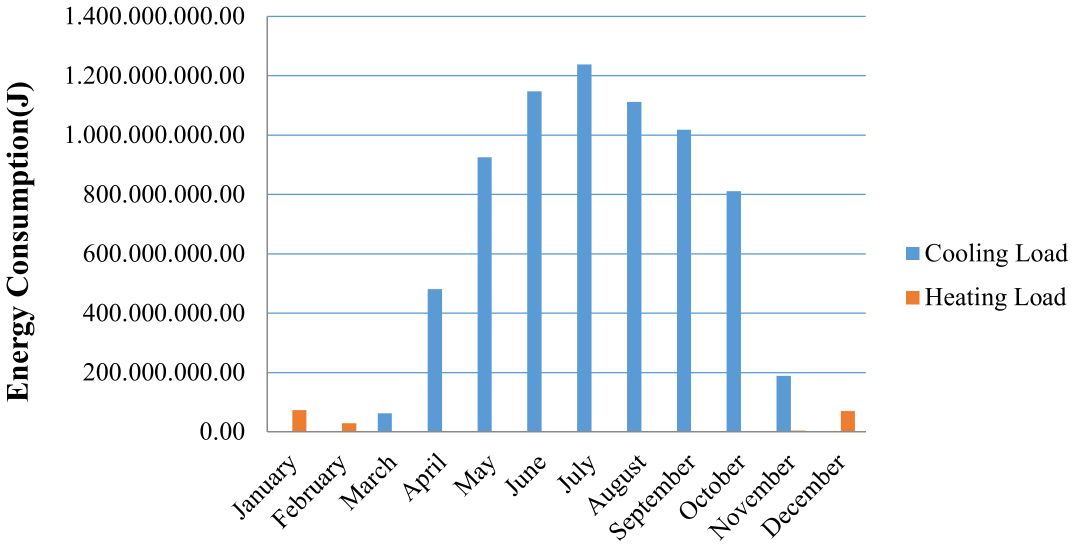


Figure 4. The current cooling and heating loads of the room

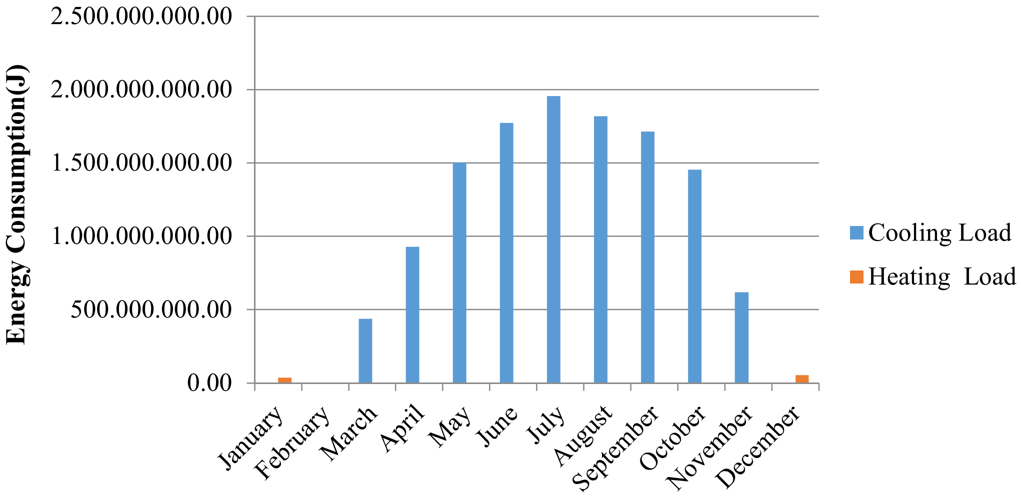


Figure 5. Cooling and heating loads of the room with a greenhouse instead of the balcony

As is evident from Table 11, the greenhouse increases the cooling load of the room by 1448.379 kWh, while decreasing the heating load by 24 kWh. Therefore, considering the massive increase in the cooling load of the hot months, which is incomparable with the decrease in the heating load of the cold months, it is concluded that this type of measure is not suitable for this climate.

Table 11. Energy consumption for the room with and without the greenhouse

Cooling load of the room (kWh)	1939.640
Heating load of the room (kWh)	48.917
Cooling load of the room with a greenhouse (kWh)	3388.020
Heating load of the room with a greenhouse (kWh)	24.310

Integrating Solar Heat Reservoir in the Building Envelope

In climates with major hot or cold days, e.g., tropical and polar climates, utilizing heat mass effect in building envelope might even inflict adverse results. This way, both interior and exterior walls tend to reach the mean daily temperature, which is for sure too warm or too cold and out of the comfort range. Therefore, in a hot and humid climate like that of Bandar Abbas, which demands open building plans to use breezes, masonry with low heat capacity are preferred, and application of heat reservoirs inside the walls is refuted.

Installing Photovoltaic Systems on the Roof

PV SOL commercial software was used in order to investigate the application of a photovoltaic (PV) system on the roof with the aim of supplying the electricity demand of the building. The performed model is depicted in Figure 6. The modules were installed with 37° inclination since Bandar Abbas is located on 27° N of latitude.

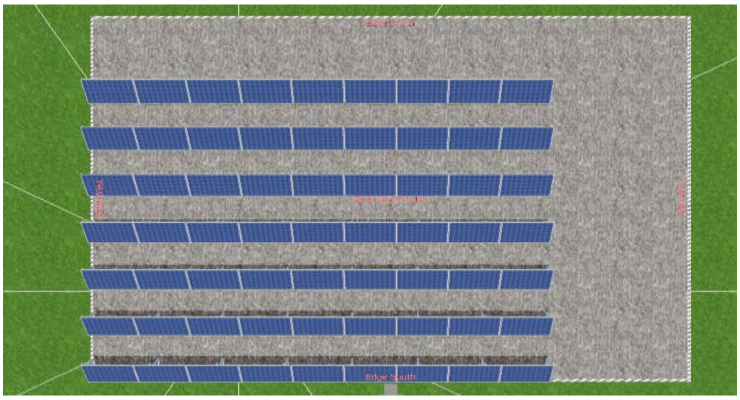


Figure 6. PV module arrangement modeled in PV SOL

The DC voltage (V_{dc}) was chosen to be 48V. In order to find the number of series modules, V_{dc} should be divided by a single module voltage, being 12 V in the present study.

$$N_s = \frac{V_{dc}}{V_m} = \frac{48}{12} = 4 \tag{3}$$

In order to find how many strings should be set up parallel to each other, the peak power demand of the building is divided by the power each string can generate as follows:

$$N_s = \frac{P_{peak}}{P_m \times N_s} = \frac{4.48 \times 1000}{4 \times 80} = 14 \tag{4}$$

With 14 parallel strings, the total number of modules would be 56 modules and the whole area is acquired to be 91.3 m^2, assuming 0.4 m^2 of each module area.

Monthly production of the designed PV system is shown in Table 12 as well as Figure 7. Based on Figure 7, the highest and lowest production are about 2000 and 1600 kWh in May and December, respectively. The power generation output is 13.5 kW and produces 21876 kWh of electricity per year. This case is accounted for 10% of the annual electricity demand of the building, i.e., 209407.9 kWh and prevents 13113 kg of CO_2 emission.

Table 12. PV SOL simulation results

Climate data	Bandar Abbas (1986-2005)
PV Generator Output	13.5 kWp
PV Generator Surface	91.3 m^2
Number of PV modules	56
Number of inverters	1

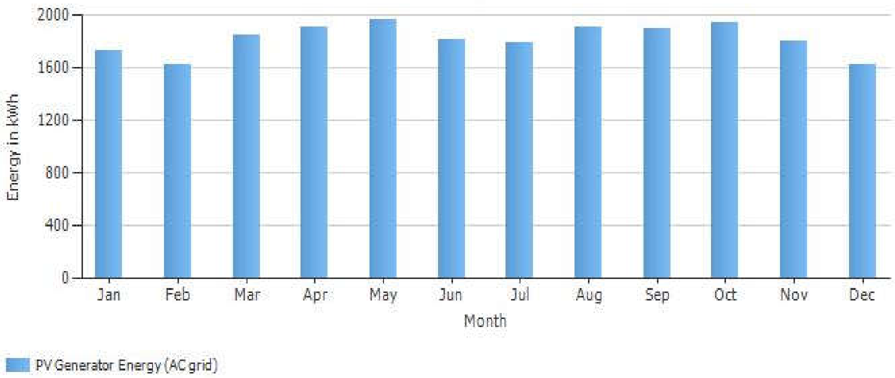


Figure 7. Monthly power generation of the PV system

Installing PV Cells Over the Southern Window Shades

We can further harvest the solar energy potential of the southern façade, in order to compensate for the high electric energy consumption of the building, each unit of which has two heat pump split units activated for several hours a day. It is possible to install PV panels on window shades of the southern façade, which was previously suggested, in order to resource a portion of the heat pumps energy demand. With each window having one module, 20 PV modules assumed over the shades of southern windows were able to produce a considerable amount of electricity, as shown in Figure 8. It is found out from Figure 8 that installing PV panels on the shading of southern windows leads to 6479 kWh electricity production, i.e., preventing 3888 kg CO_2 emission. Also, the highest and lowest electricity production are for May and December, respectively.

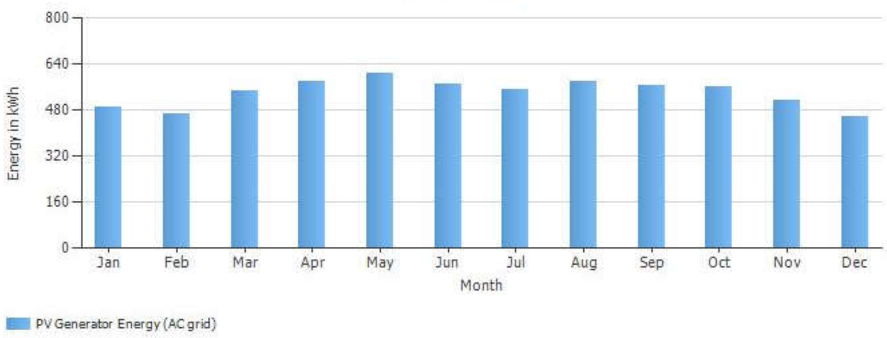


Figure 8. The monthly energy generation of PV modules over the window shades

Utilizing Solar Heating System

TSOL commercial software was used in order to simulate the application of solar water heater. Flat plate solar collectors (FPC) have proven to be more economically viable in tropical regions than evacuated tube solar collectors (ETC) [46]. Therefore, in this simulation, 3 Solar Polar FPCs are used, each having 1.5m^2 of absorber area with 0.96 absorption coefficient. Each unit is assumed to house a household of 5 members. Figure 9 shows a schematic of the solar water heater designed in TSOL. In order to find the optimum inclination of the collectors, the energy generated by the collectors is studied over the year and depicted in Figure 10. The results show that an inclination of 37° provides the highest annual useful energy gain. The efficiency of the solar collector is investigated by the following formula:

$$\eta = \eta_o + a_1 \frac{(T_{in} - T_a)}{G} - a_2 \frac{(T_{in} - T_a)^2}{G} \tag{5}$$

where η is the collector efficiency, and η_o, $a_1$and a_2 are constant coefficients which can be evaluated analytically or experimentally. These are presented by the solar collector manufacturer as the standard performance data. Also, G is the solar irradiance, T_{in} and T_a are the collector inlet temperature and ambient temperature, respectively

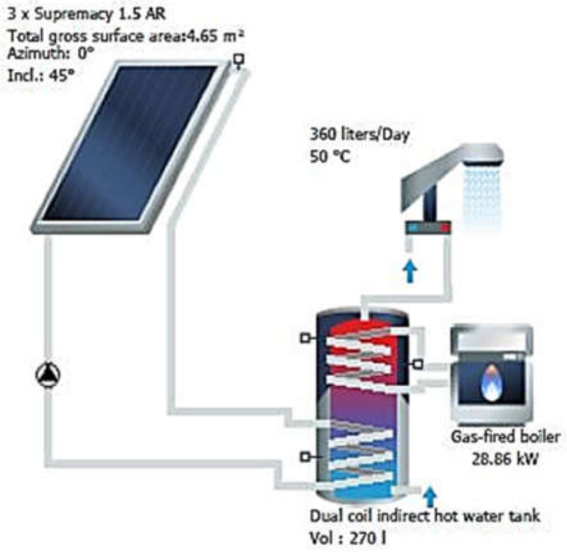


Figure 9. Schematic of the solar water heater designed in TSOL

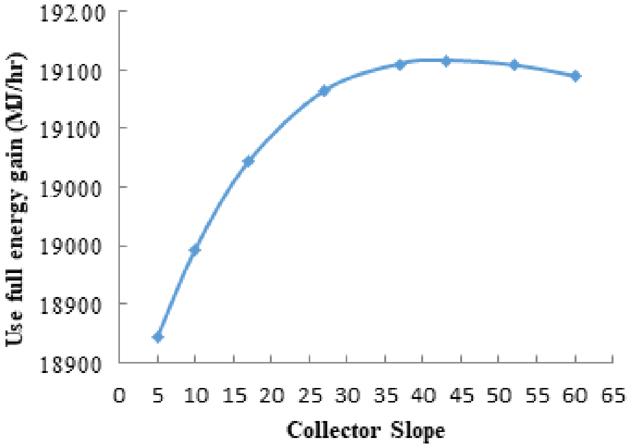
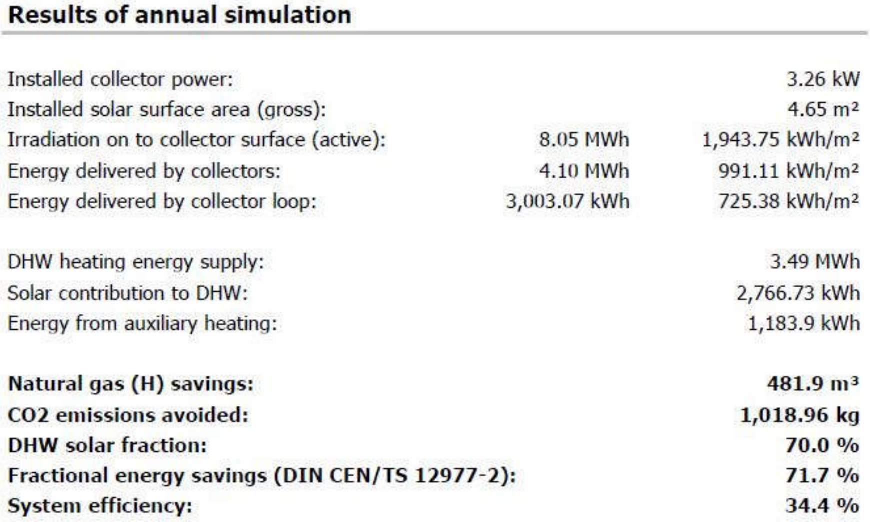


Figure 10. Collector useful energy gain for various collector inclination angles

According to the results of the annual simulation, shown in Figure 11, by means of 4.65 m^2 solar collector, 2766 kWh annual energy consumption is saved, and of 1018.96 kg CO_2 emission is prevented. Based on this figure, the solar fraction is 70%, and the system efficiency is 34.4%.



Results of annual simulation

Installed collector power:		3.26 kW
Installed solar surface area (gross):		4.65 m²
Irradiation on to collector surface (active):	8.05 MWh	1,943.75 kWh/m²
Energy delivered by collectors:	4.10 MWh	991.11 kWh/m²
Energy delivered by collector loop:	3,003.07 kWh	725.38 kWh/m²
DHW heating energy supply:		3.49 MWh
Solar contribution to DHW:		2,766.73 kWh
Energy from auxiliary heating:		1,183.9 kWh
Natural gas (H) savings:		**481.9 m³**
CO2 emissions avoided:		**1,018.96 kg**
DHW solar fraction:		**70.0 %**
Fractional energy savings (DIN CEN/TS 12977-2):		**71.7 %**
System efficiency:		**34.4 %**

Figure 11. Results of annual simulation of the solar water heater

Solar Absorption Cooling System

Major components of an absorption cooling system include absorption chiller, boiler, and cooling tower. In solar absorption cooling systems, solar collectors replace the boiler and generate the required heat of the system. Cooling towers cool the condenser hot water cycle. The cooling process in cooling towers is based on surface evaporation of a portion of the water subject to the air stream. Therefore, the towers are built with extended evaporation surfaces to provide water with more surface in contact with air, which makes cooling towers vast in dimensions. Cooling towers, just as other evaporative devices, perform effectively in hot-arid and hot-semi-arid regions, while are of virtually no use in the humid areas. The monthly and annual average relative humidity of Bandar Abbas from 2010 to 2016 are listed in Table 13.

Table 13. Bandar Abbas's relative humidity over six consecutive years

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
2010	63	67	70	63	66	67	76	79	62	63	72	60	67
2011	67	66	71	68	59	63	73	74	68	66	61	78	68
2012	73	77	80	67	62	65	59	75	77	67	49	62	68
2013	71	67	75	72	61	67	70	74	72	72	67	69	70
2014	74	70	70	63	56	56	71	66	66	64	63	65	65
2015	63	73	63	57	55	63	66	70	72	66	68	48	64
2016	65	66	65	59	67	63	63	65	71	62	54	67	64

As is evident from Table 13, during the six consecutive years, the average relative humidity had always been over 60%, which implies the unsuitability of solar absorption cooling system for this city, which requires evaporative cooling towers.

ECONOMIC STUDY OF THE PROPOSED SOLUTIONS

13 solutions were proposed and technically studied in the previous section with the aim of energy efficiency in the nominal building in Bandar Abbas as a hot and humid region. In this section, these solutions will be studied from economic aspects, and the propositions will get more practical regarding the energy efficiency of the buildings in the hot and humid city of Bandar Abbas. The payback time for each solution is estimated to prioritize and categorize the solutions. For calculating the cost savings provided by each solution, the energy saving (in kWh) of each one is multiplied by the price rate per kWh (0.0238 \$). The payback time is derived from the following equation. Table 14 lists the costs and payback periods of all solutions.

$$Payback\ time = \frac{Innitial\ investment}{net\ annual\ saving} \tag{6}$$

Table 14. Economic estimation of the solutions.

Solutions	Energy Saving/Generation (kWh)	CO2 Emission Reduction (kg)	Capital costs (US$)	Net annual cost savings (US$)	Payback time (yr)
Roof thermal insulation	32814.21	11154.71	65714.28571	7812.907143	8.4
Walls thermal insulation	30233.26	9976	8671.371429	7198.395238	1.2
Low-emissivity film for the windows	857.66	283	15750	204.2047619	77.12
Shading for windows	40554.75	13383.07	45000	9655.892857	4.66
LED light bulbs	939.8	319	6083.333333	223.7619048	27.18
BMS	20679.49	6824	33333.33333	4923.688095	6.76
Green walls	9281.61	3062.92	4761.904762	2209.905952	2.15
Rooftop PV	21876	13113	48214.28571	5208.571429	9
PV on facade	6479	1018.96	14285.71429	1542.619048	9
Solar collector	2766	3888	14047.61905	658.5714286	21
Solar absorption cooling	Considering the humid climate of Bandar Abbas, the evaporative cooling tower will not perform effectively. Hence, an absorption cooling system is not suitable for the region.				
Greenhouse	The greenhouse slightly reduces the heating load, while causing significant cooling load during nine warm months. Therefore, the solution is not suggested.				
Solar heat reservoir	Bandar Abbas's climate is continuously warm, making the solution unsuitable for the region.				

Investigating Table 14, the priorities of the solutions are as follows:

- The highest cut in the electricity demand of the building is incurred by installing shades over the southern windows, with a payback time of 4.66. This measure not only suggests short payback time, but it also brings comfort to the residents as well.
- The second energy saver solution is the implementation of insulation for the walls and roof, with 1.2 and 8.4 years of payback times, respectively. This solution brings comfort to the residents and prevents the humidity infiltration.
- The next appropriate measure is BMS utilization with 6.76 years of payback time. This will save energy along with bringing comfort and ease of mind to the residents since the interior temperature is set to the desired level when the residents return after a while.
- The next proposed solution is building green walls over the façade of the building, which has both aesthetic and cooling/heating energy saving aspects with a payback time of 2.15 years.
- The other solution which significantly shrinks the electricity bills of the building is replacing the lights with LED light bulbs. If applied to all the units of the building, the payback time will be 27 years, which is an ideal length of time, regarding its energy saving and capital cost.
- Utilizing PV systems, rooftop and wall mounted, is suggested as well as using a solar water heater, although with considering their environmental aspects. The payback time for these solutions is 9 and 21 years, respectively.
- Laminating the glazes of the southern windows with the low-emissivity film will cause an 857.66 kWh reduction in energy consumption, having a payback time of 77 years. This solution is not suggested.

Therefore, 9 out of 13 studied solutions are techno-economically viable, and their implementation can reduce the building energy consumption by 81 % to 38814.25 kWh as well as preventing 63022.66 kg of CO_2 emission. Table 15 lists the building energy consumption before and after implementing the suggested solutions.

Table 15. Energy consumption as well as CO_2 emission reduction of the enhanced building

	Energy consumption (kWh)	CO_2 emission reduction (kg)
Typical Building	204438.36	-
Enhanced building	38814.25	63022.66

CONCLUSION

This work techno-economically studied 13 solutions for bringing energy efficiency to a typical building in Bandar Abbas, Iran. As Bandar Abbas receives a high amount of solar insolation, utilization of solar systems for HVAC and power generation is investigated for the building. Beyond the 13 various energy solutions mentioned above, housekeeping solutions that are economically and technically feasible, are presented to reduce the energy consumption of the building. According to the results, installing shades over the southern windows, insulating the walls and the roof, using BMS, green walls, replacing the lights with LED light bulbs, installing rooftop and wall-mounted PV modules, and using a solar water heater are the economically and environmental-friendly solutions. Installing shades over the southern windows, the implementation of insulation for the walls and roof have highest energy saving, which are 40554.750, 32814.210 and 30233.260 kWh, respectively. Due to the hot and humid climate condition, laminating the windows with low-emissivity film, building a greenhouse, solar heat reservoir, and solar absorption chiller are not suggested. The 9 suggested solutions, which are convenient for this climatic condition, can reduce building energy consumption by 81% as well as preventing 63022.66 kg of CO_2 emission. The proposed solutions could be considered as means for managing the energy and environmental crisis of hot and humid regions.

NOMENCLATURE

MAE	Mean Absolute Error
MRE	Mean Relative Error
HVAC	Heating Ventilating and Air-Conditioning
TRNSYS	Transient System Simulation
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
PCM	Phase Change Material
ORC	Organic Rankine Cycle
LED	Light-Emitting Diode
CFL	Compact Fluorescent Lights
EPA	Environmental Protection Agency
BMS	Building Management System
PV	Photovoltaic
FPC	Flat Plate Solar Collectors
ETC	Evacuated Tube Solar Collectors
e	Theoretical
m	Experimental
T	Temperature
G	Solar Radiation in The Collector Plane
a	Loss Coefficient
V	Voltage

Greek symbols

η	Efficiency

Subscripts

norm	Normalized
i	Inlet
a	Ambient
o	Optical
DC	Direct Current
s	String
m	Module

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