FEASIBILITY AND PERFORMANCE ANALYSIS OF USING SOLAR WATER HEATING SYSTEM IN ALGERIA

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In this paper, the comprehensive performance analysis based on technical, economic and environmental aspects of using a solar water heating system in Algeria is carried out. Optimal tilt angle received solar radiation, system yield and efficiency, solar faction, CO_2 emissions are the parameters analyzed. Among the simulated tilt angles from 0° to 90°, the optimal angle is found 30 degrees. The simulation results reveal that the solar irradiation received, system yield, solar fraction and CO_2 emissions are 7149 kWh/year, 3032 kWh/year, 72% and 1659 kg/year, respectively. The solar coverage (%) and CO_2 emission (kg) are (93-1445), (88-1532), (83-1592), (77-1633) and (72-1659) for hot water temperatures of 40°C, 45°C, 50°C, 55°C and 60°C, respectively.

Keywords: Solar water heating, solar fraction, system yield, thermal load management, tilt angle, feasibility, CO_2 saving, Algeria

1. Introduction

At the worldwide level, the fastest increase since 2010 in terms of world primary energy consumption is observed for the year 2018 with a rate of 2.9%, almost double its ten-year average of 1.5%/year. Consequently, global electricity production has also increased by more than 3.7%, as a result, greenhouse gas emissions (GGE) have increased significantly, i.e. 2.0%, which is the fastest growth since seven years with 13864.9 Mtoe, 33890.8 Million tonnes of carbon dioxide [1]. Major electricity consumption (space heating, space cooling, and domestic hot water ...etc) on a global scale is observed in the building sector (domestic, tertiary and industrial), and among all sectors, it is responsible for one third of global GGE emissions [2, 3].

In Algeria, a significant increase in energy needs has been observed in recent years, in response to the results of economic development and living standard improvement of Algerians. In addition, the state policy for the electricity and gas subsidy that has been implemented in Algeria since 1962 makes it possible to increase energy needs, which is found at 55.9 Mtoe in 2014 with an increase of 7.8% compared to 2013 [1]. As is well known, the Algerian economy is highly dependent on hydrocarbon exports where about 90% of electricity is produced mainly from natural gas.

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In all countries of the world, this situation has led governments to re-amend and re-adapt their energy policies through the development of renewable energies (solar, wind, etc.) in order to diversify their energy resources [6]. Like all countries, the Algerian government has launched its first program for renewable energies and energy efficiency developments starting in February 2011, the aim is to diversify energy sources in a sustainable way to reach 12 GW of electricity produced by renewable sources by 2030, which will cover 40% of total national electrical energy consumption [7]. The improvement and use of more efficient appliances, equipment and materials in the different sectors (households, buildings and services) are the measures adopted in terms of energy efficiency.

With Algeria's solar irradiation potential, which is the highest in the world, i.e. about 2560 h/year is the average sunshine duration for coastal regions, 3000 h/year for highlands regions and 3500 h/year for desert regions. Based on this data, it is really necessary to use this technology through the development of different solar energy applications depending on the capture, conversion and distribution modes, such as electricity generation in grid-connected and/or isolated PV systems, solar cooking, solar water pumping and heating systems [4, 8, 9]. Thanks to their simple and inexpensive technology with a fast recovery period, solar water heaters are one of the important applications of renewable energy used as a means to improve energy efficiency, especially in buildings [9]. Algeria has also adopted this technology through a program called "ALSOL" to promote solar water heating systems SWHs by encouraging and creating new industrial operators in this field [10].

Despite this enormous potential of solar energy, the use of solar water heating, among other solar applications, is still very limited in Algeria and has not yet been sufficiently promoted [4]. According to [8], 74.6% of Algerian houses are of traditional or individual type, which makes it possible to use individual solar water heaters perfectly. The total distribution of installed surfaces is shown in Fig 1, which clearly indicates that the country's capital has the highest number of solar water heaters.

As its name indicates, a solar water heater which is usually installed facing the sunlight on the building roof for example is a device that uses solar energy to provide hot water, which is heat the water and store it in an insulated storage tank for immediate or later use for various purposes such as bathing, washing, cleaning, etc.

However, to ensure the maximum benefits of SWH, particularly for domestic use, the appropriate design of SWH systems is an important and required step. Such design, which is based on several parameters such as local weather conditions, water consumption habits, and also the availability of auxiliary resources (electricity, gas, etc.) [11].

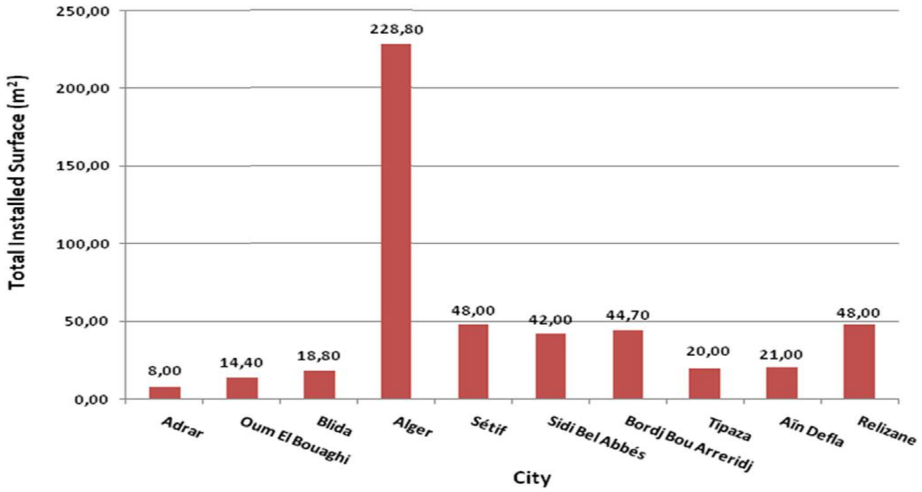


Fig 1. Installed surfaces of SWH system per city in Algeria country.

The use of solar water heaters (SWHs) for domestic applications is widely discussed in many areas of the world, and as well as the advantages and enormous potential of their integration in economic and environmental terms are proven and addressed. Several software programs are used to simulate solar water heating systems such as TRNSYS, EnergyPlus and others online simulation software [3, 12-19]. However, in our country, Algeria, to our best knowledge and based on the literature, to date there is no published work on the SWH system design and sizing, i.e. there is no comprehensive analysis and study of the most influenced parameters on SWH systems operation performance.

As the new Algerian energy policy is based on the development of renewable energy and energy efficiency, this research paper is entered in this context and aims to: firstly, provide an analysis of all the parameters that influence the SWH system operating and design optimization. Some of these parameters includes collector type, tilt angle, solar radiation and user water temperature. Secondly, to assess the technical, economic and environmental feasibility of integrating solar water heater systems as a means and component of residential thermal load management, a typical Algerian house with evacuated tube collector technology (ETC) under the weather conditions of the capital location is selected as a case study and simulated. Annual simulations for the assessment of solar water heater system contribution in terms of energy savings, customer electricity bill cost, GHG emissions reduction are carried out. Solar water heaters system as a tool of thermal load management is discussed in the following section.

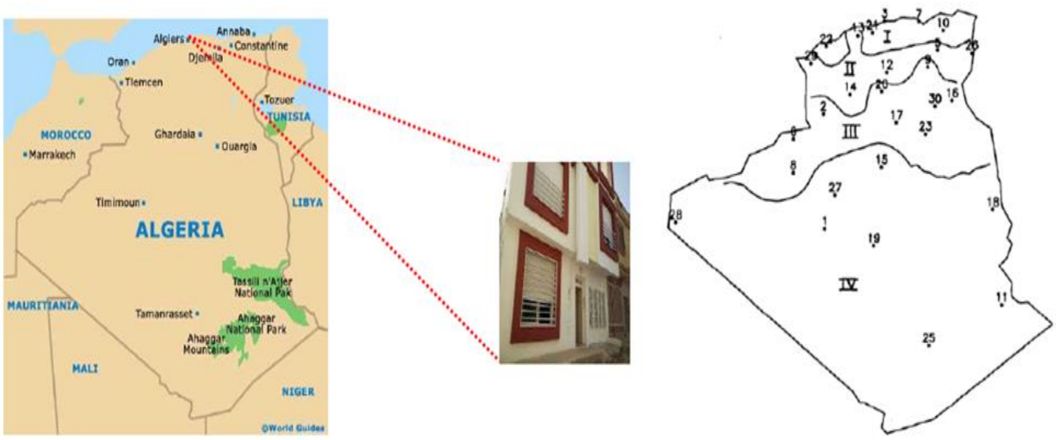
2. Electric and thermal load management

Firstly, the term load management or demand side management DSM, which first appeared in the USA (Electric Power Research Institute), defined as the modification of the customer's energy consumption curve in terms of time and/or quantity in order to promote better efficiency and operation of electrical energy systems. DSM is generally associated with electrical power consumption and generation, and have six strategies which are peak clipping, strategic conservation, valley filling, strategic load growth, load shifting and flexible load shape. Secondly, the term of thermal load management with denomination TLM used in this paper is closely related to the demand side management concept DSM, except that it is intended to optimize the use of thermal energy [19, 20].

As given in the literature, the two concepts TLM and DSM have several positive impacts in technical, economic and even environmental terms, such as increasing the electricity networks and installations efficiency, reducing energy consumption, decreasing electricity bills cost, helping to integrate renewable energies, consequently, reduce CO_2 emissions [21–25]. That's why we have considered solar water heaters as a means (tool) for thermal load management, because all these discussed benefits are available in solar water heating (SWH) technology that reduces both energy consumption and costs, saves fossil fuels and also reduces greenhouse gas emissions.

3. Case study and methodology

A residential building for a typical Algerian family with 4-5 persons is selected as a case study for this study to show the benefits of using SWH. As shown in Fig 2(a), the selected residential building is located in the capital (Algiers), situated in the north of the country (Lat. 36,8 ˚ N, Long. 3,1˚ E and Altitude of 25 m), within the second climate zone in Algeria map, as shown Fig 2(b).



(a) (b)

Fig. 2. Location of studied house in Algeria maps (a), Algerian climatic regions classification (b) [26].

The methodology adopted to conduct this research paper is presented in the flowchart of Fig. 3.

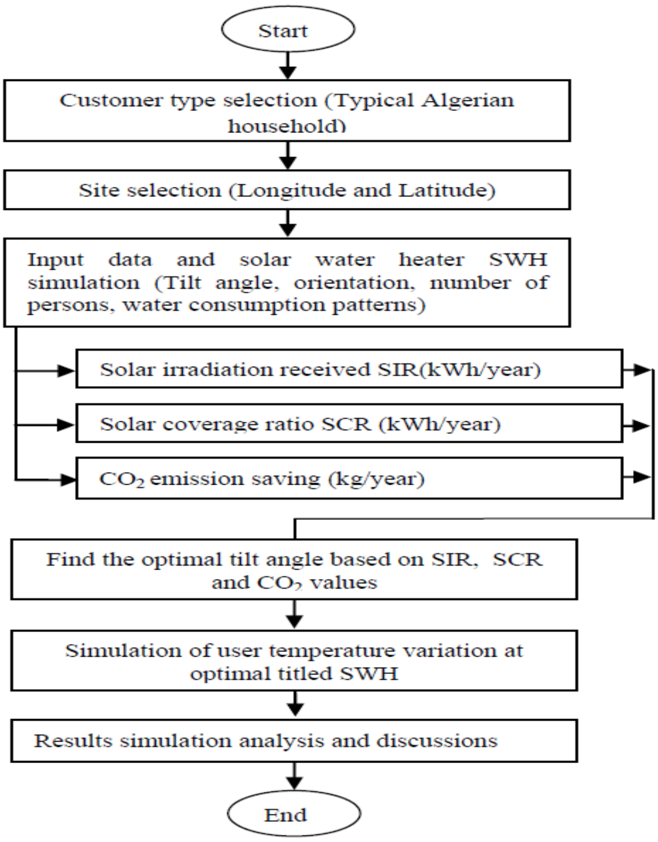


Fig 3. Methodology and research steps adopted in this paper.

3.1 Data collection

The study and design of any energy system depends on several factors that must be taken into consideration. Location, number of persons living in the house, electrical and thermal energy consumption patterns, devices used and others are taken into account in this study. Data collection in terms of energy consumption, electricity and thermal load, is based on the results of a survey conducted with a few small family houses in this region. Her, the electrical energy is used for the most common applications such as lighting, fans, mobile phone charger, television, washing machine and refrigerator. The total electrical energy requirement is estimated at 11.78 kWh/day.

The water heater used in the house to provide hot water for bathing, washing and cleaning is powered by gas and electricity. As we know, hot water needs vary from one person to another which is dependent on several factors such as geography, religion and personal habits. For the Algerian scenario, to date, there is no study that has presented an estimation of the average daily hot water requirements of single-family homes. The estimation of family hot water requirements is given in the literature for several regions, namely the Maghrebian countries, which have similar characteristics to those of Algeria (Geographic location, religions and cultural) such as in Tunisia and Morocco countries [16, 27]. The information details used in this study (Location, electricity and gas network connections, electric load, number of persons etc), are summarized in Table 1.

Table 1

Information details of household and location site

Parameter	Name and/or value
Location name	Algiers, Algeria country
Latitude	36,8° N
Longitude	3,1° E
Elevation	25 m
STC Temperature	25°C
Gas network connection	Yes
Electric load	11.78 kWh/day
Tilt angles of SWH system	From 0° to 90° with steps of 10°
Household details	
Size of the family	Typical Algerian family
Number of person	4-5
Water consumption estimation (Liter)	
Description	Water/person/day
Bathing	40
Wash Basin	10
Kitchen Wash	15
Clothes Wash	20
Others	10

A simple formula is used to calculate the hot water requirements which is the sum of the water consumed by each person in all activities in the house [28].

$$W_{r\_site} = [(W_{task_1} * n_1) + (W_{task_2} * n_2) + (W_{task_3} * n_3) + ...(W_{task_n} * n_n)] \quad (1)$$

Where $W_{r,site}$ in (Liter) is the amount of hot water used, n_1, n_2, n_3 ...n_n are the number of persons in the residential house and W_{task1}, W_{task2}, W_{task3},.... W_{taskn} are the different activities in which hot water is used.

4. SWH system design and components modeling

The principle of solar water heating (SWH) is the conversion of solar light into heat by one of the mechanisms of energy transfer which are convection, radiation and conduction to heat the water [29]. The design and complexity of the solar water heater system depends on its components and others several factors, i.e. hot water consumption, type of collectors, storage tank and auxiliary water heater. There are two different technologies for solar water heating that have been widely used worldwide: evacuated tube collector (ETC) technology and flat plate collector (FPC) technology. Regardless the type of solar water heater, it is composed of the following elements as shown in Fig 4.

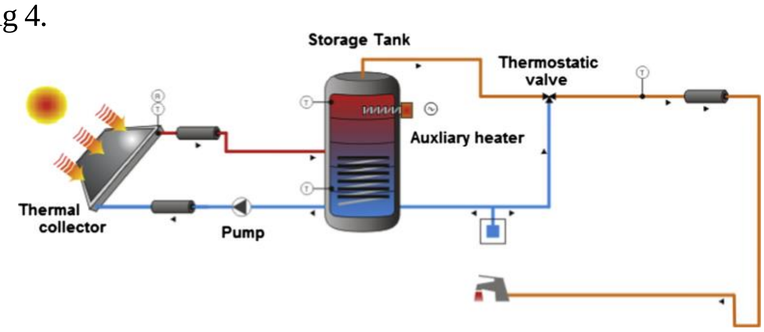


Fig 4. Solar water heating system SWH schema.

Thermal collectors: which is responsible for capturing solar radiation and converting it into heat, which is then transmitted to a heat transfer fluid. have two form such as flat collectors and vacuum tube collectors. Expression 1 gives the mathematical model of thermal collectors which is based on the standard second-order equation of collectors' performance as follows [30].

$$\eta = \eta_0 - a_1 \frac{T_m - T_a}{G} - a_2 \frac{(T_m - T_a)^2}{G} \quad (2)$$

Where η_0 indicates the optical efficiency of the sensor, a_1 and a_2 are the heat loss parameters. G is the solar radiation, T_m and T_a are the average solar collector temperature and the ambient temperature, respectively.

Storage tank: The storage tank system is used to store the hot water that is heated by the solar water heater for instant or later use.

Auxiliary water heaters: which are used to meet the hot water needs of users, there are type of auxiliary water heaters coupled to a solar water heater, electric auxiliary solar water heating system and natural gas solar water heating system, more details can be found in the literature [30]. In this paper, the first type is considered, i.e. electricity as an auxiliary energy source is used to heat water in parallel with solar energy in order to improve water heating system performance.

5. Energy performance analysis

The feasibility and performance analysis of solar water heating in this study is based on several parameters such as tilt angle, received solar energy, solar fraction and CO_2 emissions. Details of these factors are provided in the following sub-sections.

5.1 Tilt angle influence

As is known, there are two forms of conversion of solar energy, conversion to electricity via photovoltaic cells, and to thermal energy via a solar collector to heat water for example (solar water heating). Optimizing the tilt angle of a solar collector is an important step in order to capture the maximum amount of solar radiation. from the literature, the angle at which solar radiation reaches the collector surface perpendicularly is the optimal tilt angle [31]. In this paper, the effect of the tilt angle on the solar heating performance is evaluated, SWH system is simulated under various tilt angles between 0 and 90 degrees with a step of 10 degree. The amount of solar radiation received on a collector (kWh/year) depends on several factors such as site location (site latitude and longitude), the day of the year, tilt angle and azimuth. There are three types of irradiation that are direct radiation, diffuse radiation and reflected radiation, the sum of direct, diffuse and reflected radiation is called global radiation.

5.3 System yield and solar fraction

It is the total energy production generated by the solar water heating system (kWh/year) that depends on the temperature and radiation received, the type of collector and the surface area. The solar fraction (SF) is a factor used to evaluate the performance of the solar water heater system, defined as the percentage of useful solar energy to the total energy requirements to heat the water. Solar fraction is expressed by Eq. (5) [32].

$$SF = \frac{Q_s}{Q_s + Q_{aux}} \tag{3}$$

Where Q_s and Q_{aux} are the solar yield and the auxiliary heating requirement, respectively. The solar yield Qs can be calculated by Eq. (4).

$$Q_s = Q_c - \sum Q_{losses} \tag{4}$$

Where Q_c and Q_{losses} is the energy captured by the thermal collector and the energy lost in the primary and distribution loop and in the solar reservoir, respectively.

5.4 Emissions of CO_2

Since the development of renewable energies aims to reduce CO_2 emissions in all countries around the world. This very important parameter is taken into account in this paper, and the amount of greenhouse gases reduced per solar water heater is evaluated for a meaningful quantitative and qualitative study. The environmental as well as the economic analysis is performed on the basis of the required metrological and economic data. In addition, the effect of the variation in hot water temperature on the solar fraction and emissions is also discussed. The intensity of emissions from heating loads is measured by applying an emission factor to the electricity consumed for heating, and the global warming potential can be calculated by equivalence with CO_2. The mitigated carbon dioxide CO_2 that could be reduced with the proposed SWH system can be calculated by Eq. (5) [33].

$$CO_2 \text{ mitigation} = Annual\ energy * Emission\ factor \tag{5}$$

Where CO_2 mitigation is represented in kg CO_2/kWh, the annual energy generation is the amount energy produced by the SWH (kWh), and the emission factor is the mitigated CO_2 for each kilowatt-hour kWh. Based on the most recent statistics, the specific emission factor of electricity for Algeria is 0.50848 kgCO_2eq.kWh^{-1} [34].

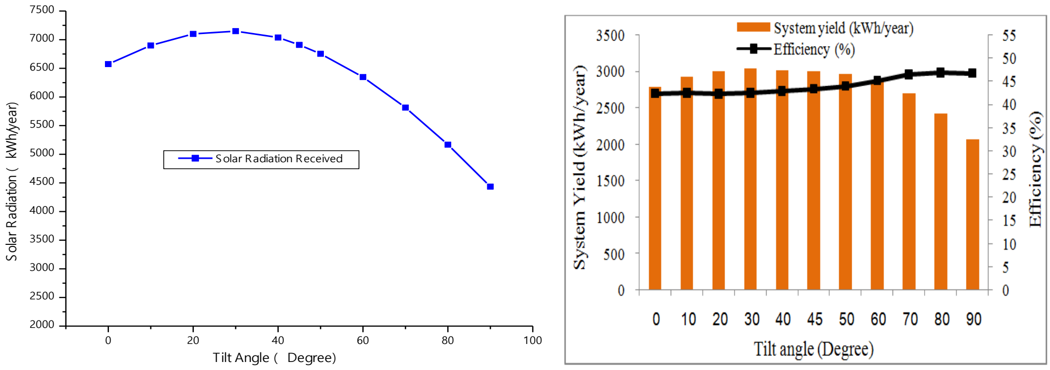
Finally, the economic feasibility study is also performed in this paper, the economic scenario used concerns the costs of the solar system that are paid at the beginning of the installation, as well as the savings that represent the money that the owner will save by using solar water heaters rather than purchasing and/or using electricity/fuel to meet their hot water requirements. For this, the customer's electricity bill is calculated in both cases with and without solar water heater. For the economic analysis, the system lifetime is generally fixed at 20 years. The installation costs of the FPC and ETC systems and the maintenance cost are respectively 5000$ and 5600$, and 1% of the initial investment. The savings are constant over the year depending on the cost per kWh of electricity for each country (3.34 US cents/kWh).

6. Results and discussions

The simulation results of a proposed SWH are presented and analyzed in this section. The system with a storage tank of 200 L, and a water temperature of 60°C is simulated under several tilt angles ranging from (0 to 90 degrees) and oriented 0°/south. On an annual basis, four principal parameters were evaluated, which are received solar irradiation, system yield, solar fraction and reduced CO_2 emissions.

6.1 Received solar irradiation in SWH

The meteorological parameters of the site are one of the influencing factors on the solar water heating system's performance, but also the tilt angle in which the thermal collectors are tilted. The variation in annual solar radiation received on the collector plane in (kW h/year) as a function of the tilt angle is shown in Fig 5(a).



(a) (b)

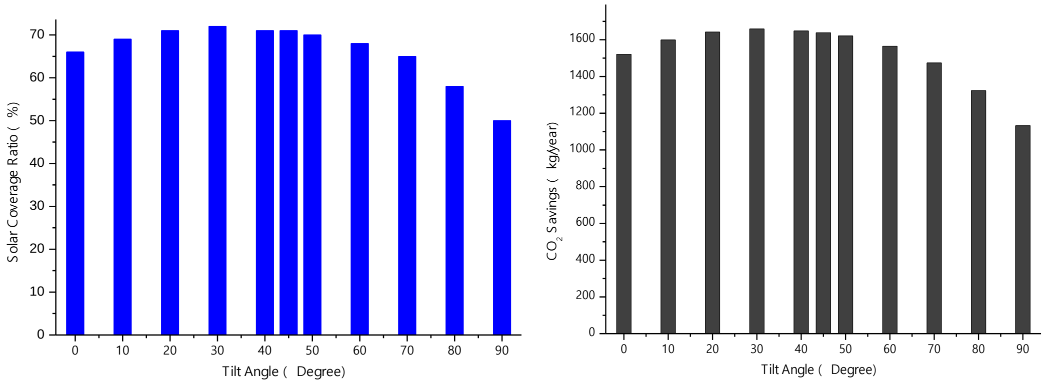
Fig 5. Tilt angle effect on the received solar irradiation (a), annual system yield and efficiency performance (b).

From the results, it is very clear that the annual solar energy received in the plane of the solar water heater collector depends considerably on the tilt angle and varies with its variation. The annual solar radiation received varies between a minimum of 4435 kWh/year for a tilt angle of 90 degree and a maximum of 7149 kWh/year for 30°, i.e. 30 degree is seen as the optimal tilt angle for this location.

6.2 System energy yield and solar energy coverage

The solar water heater system is also evaluated in terms of energy productivity, system yield (kWh/year) and annual system efficiency (%) as a function of the tilt angle variation are shown in Fig 5(b). The system yield and system efficiency are varied with the variation in tilt angles, the maximum energy output of the system is recorded for a tilt angle of 30 degree, i.e. 3032 kWh, and the minimum of 2069 kWh is observed for an angle of 90 degree. We note that system energy yield is increased for tilt angles from 0 to 30 degrees, then it is decreased with the increase of the tilt angle to 90 degrees. The tilt angle that gives the best results in terms of energy yield is observed 30 degrees. However, the system has a maximum efficiency for a tilt angle of 80 degrees with 46,78% and a minimum of 42,28% when the solar water heater is inclined at 0°.

This section concerns the results of the solar fraction, which is defined as a measure of fractional energy savings in comparison to that used for a traditional system (electricity, gas, etc.). The variation of the annual solar contribution with respect to the tilt angle variation is illustrated in Fig 6(a).



(a) (b)

Fig 6. Annual solar energy fraction vs. tilt angle (a), annual reduced greenhouse gas emissions (CO_2) (b).

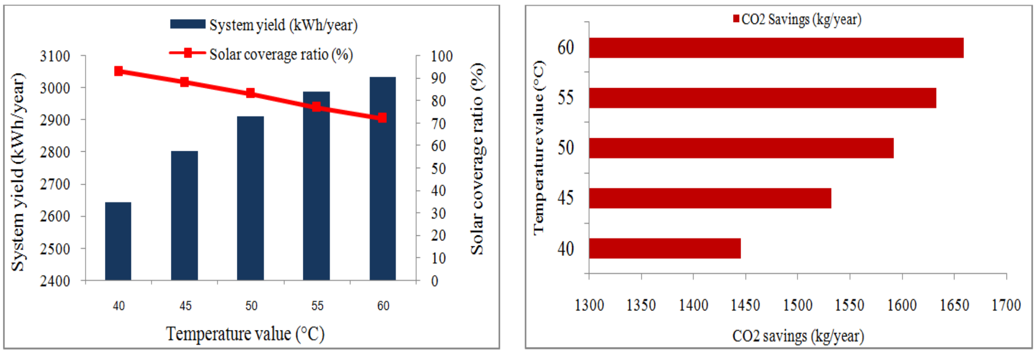
From Fig 6(a), the values of annual solar energy fraction varies according to the tilt angle variation, increases when tilt angle changes from 0° to 30° degree and decreases when tilt angle moves from 30° to 90°. The maximum and minimum annual solar fraction for this case study is about 72% and 50% observed for the tilt angles of 30 and 90 degrees, respectively.

One of the objectives of using solar water heaters is to reduce greenhouse gas emissions resulting either from the use of fossil fuels to produce electricity or from the use of natural gas to supply conventional water heaters. So, it is certain that the use of solar energy makes it possible to reduce or avoid these emissions, and this is discussed in this section. As seen in the previous results, the tilt angle also influences the amount of reduced emissions, because CO_2 emissions are related to the system's yield and the solar fraction i.e. emissions are low when the solar system produces more, and this last one depends considerably on tilt angle parameter Fig 6(a).

The annual GHG emissions results of solar water heater are varied when the tilt angle is changed, the reduced emissions are increased when the tilt angle varies from 0 to 30 degrees and the maximum of 1659 kg/year is given for the angle of 30°, this is explained by the high amount of solar energy collected and the solar fraction values. The amount of reduced emissions decreases as the tilt angle increases, the minimum reduced emissions, i.e. 1132 kg/year is observed for 90 degrees.

6.4 Influence of user temperature variation

To understand the influence of hot water temperature, in the rest of this paper, the solar water heating system is simulated for an optimal tilt angle of 30 degrees under four different hot water temperatures, i.e. 45°, 50°C, 55°C and 60°C. The influence of hot water temperature variation on the SWH system performance in terms of energy yield and solar fraction is shown in Fig 7(a). Similarly, the effect of temperature variation on emissions levels is analyzed in this paper, and the CO_2 emission as a function of the hot water temperature is shown in Fig 7(b).



(a) (b)

Fig 7. SWH system performance under user temperatures variation (a), saving in CO_2 emissions at different temperature values (b).

In term of solar energy coverage SF which is decreases with the increase in hot water temperature, i.e. 93%, 88%, 83%, 77% and 72% for the following temperatures 40°C, 45°C, 50°C, 55 and 60°C, respectively. However, in terms of system efficiency, it is the opposite compared to the solar fraction, the system yield of solar water heating increases with the increase in hot water temperature. The high system yield is obtained at a temperature of 60°C, i. e. 3032 kWh/year followed by 55°C, 50°C, 45°C and 40°C with 2986 kWh/year, 2910 kWh/year, 2801 kWh/year and 2642 kWh/year, respectively. From Fig 7(b), we note that each time the hot water temperature increases, the CO_2 emission savings increase as well, i.e. 1445 kg/year for 40°C, 1532 kg/year (45°C), 1592 kg/year (50°C), 1633 kg/year (55°C) and finally 1659 kg/year (60°C). As a summary, a considerable amount of CO_2 emissions is reduced at a single consumer level estimated in kg, which means millions of tonnes to be reduced if the number of solar water heater installations increases at the national level. In terms of electricity bill for thermal use which is dependent on the amount of energy consumed from the electrical power grid, i.e. depends on the contribution of the solar water heater to cover hot water needs. Before using solar water heater, the calculation formula for the consumption bill of thermal use is given in Eq. (6) when the source used is electricity and in Eq. (7) if natural gas is used.

$$CB_{without\ SWH}\left(\$\right)=EC\left(kWh\right)*Pe\left(\$/kWh\right) \tag{6}$$

$$CB_{without\ SWH}\left(\$\right)=GC\left(m^{3}\right)*Pg\left(\$/m^{3}\right) \tag{7}$$

Where CB (%) is the cost of electricity bill, EC is the electricity consumption and Pe is the cost of one kilowatt-hours, GC is the natural gas consumption and Pg is the cost of 1 m^3 of gas. After using solar water heating, the two formulas are changed to Eq. (8) and Eq. (9), respectively.

$$CB_{with\ SWH}\left(\$\right)=\left(EC_{back-up\ unit}\right)\left(kWh\right)*Pe\left(\$/kWh\right) \tag{8}$$

$$CB_{with\ SWH}\ (\$) = \left(GC_{back-up\ unit}\right)\left(m^3\right) * Pg\ \left(\$/m^3\right) \quad (9)$$

Where $EC_{back\text{-}up\ unit}$ is the energy supplied by the auxiliary source, i.e. the difference between the total energy demand required for the thermal load of the house and the energy covered by the solar water heater presented by the solar fraction. Fig 8 shows the contribution of solar water heating and the conventional eclectic grid as a function of hot water temperature.

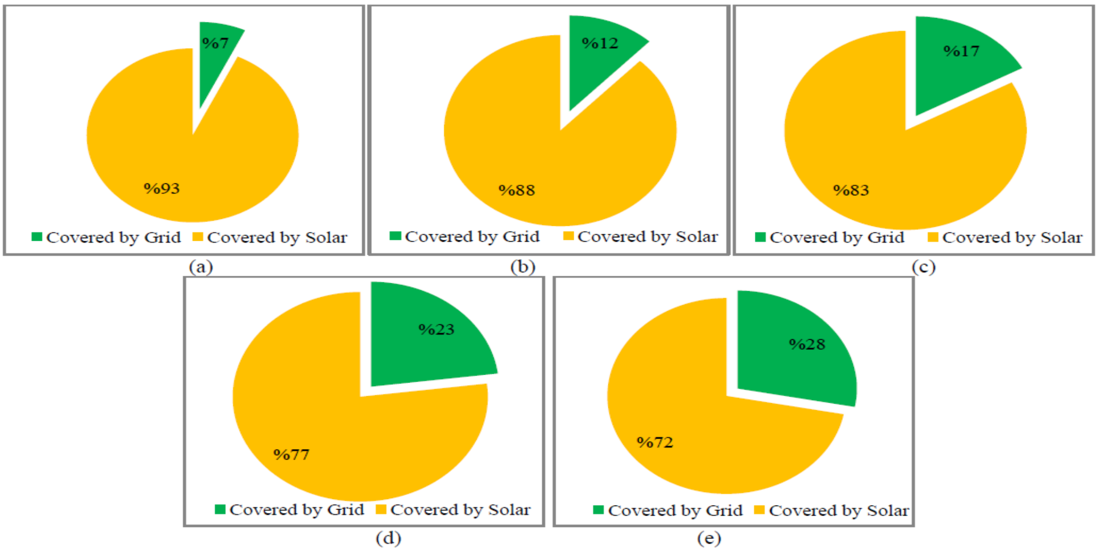


Fig 8. Solar and gird contribution for each hot water temperature values 40, 45, 50, 55 and 60, respectively.

As in Fig 8, the energy covered by the solar water heater depends on the hot water temperature. The energy covered grid takes the values 7%, 12%, 17%, 23% and 28 for hot water temperatures 40°C, 45°C, 50°C, 55°C and 60°C, respectively, the rest are covered by the electricity grid. Which also means that the consumption bill will be reduced by 93%, 88%, 83%, 77% and 72% for the same order of temperature values.

7. Conclusions

In Algeria, solar energy is one of the main sources of renewable energy, unfortunately little used. The technical and economic feasibility analysis of the use of solar water heating SWH for domestic thermal load management is carried out in this paper. The Algiers site is chosen to study the design and analysis performance of solar water heater system in technical, economic and environmental terms, i.e. the optimal tilt angle, energy yield, solar fraction, electricity bill cost and reduced emissions.

Finally, the solar water heater SWH system is seen as a means used for thermal load management and is technically, economically and environmentally feasible for the following reasons: First of all, it is easy to install solar water heaters in the region that have considerable solar potential. Secondly, the solar water heater is an economical solution as it covers and saves about 72% of hot water needs and kWh of electricity per year, and therefore reduces the electricity bill that is consumed to heat the hot water requirement by up to 72% when using 60°C as hot water temperature. Thirdly, from an environmental point of view, and thanks to the use of solar water heating, annual CO_2 emissions are reduced by more than 1659 kg. In addition, the rapid return on investment is achieved by reducing electricity bill costs as well as the cost of reduced emissions. While it is not very significant savings at the customer level. But to ensure a clean, sustainable and eco-friendly energy transition, the economic aspect must be considered as a secondary concern. Finally, the use of solar water heating by individual consumers will save millions of kWh, millions of tonnes of CO_2 emissions and an economy of millions of dollars on a national level by reducing bills costs and emission penalties. The future research aims to perform a comprehensive performance analysis of using solar water heating in terms of energy, economics and environment (3E) for different weather conditions in Algeria (East, West, North, South). In addition to the comparison between the two technologies of solar water heaters that are the flat plate collectors (FPCs) and the evacuated tube collectors (ETCs). It is also recommended that further research focus on the feasibility analysis of the integration of these systems in other sectors such as the industrial sector as well as on a large scale.

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