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Energy Performance and Environmental Impact of an Active Domestic Solar Water Heater in Maghreb Arab Union Countries

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Abstract- In this paper, an active domestic solar water heater is modeled under the climate conditions of five cities of Maghreb Arab Union countries by using Transient System Simulation Software Program. The aim is to evaluate the energy saving, payback period as an economic indicator, and the environmental benefit in reduction of greenhouse gases.
Depending on the climate zone, it is found that the system has the potential to save annually between 3506-4130 kWh with a mean annual solar fraction between 71-100 % and has a payback period of 9.07-27.48 years. Another benefit of using the proposed system is the environmental issue; which results in reducing CO2 emission by an amount between 2-3.8 tCO2. These variations between can be attributed to the energy considerations in each country.

Keywords Domestic solar water heater; Payback Period; Environmental issue.

1. Introduction

Electricity consumption in the residential sector continues to increase worldwide; according to the international energy agency, this sector consumes more than 30.91% of the world's electricity [1]. In the countries of the Maghreb Arab Union which includes Algeria, Libya, Mauritania, Morocco, and Tunisia, the electricity consumption in the residential sector is 35.7 % [1]. The greenhouse gas emissions per capita are 3.6 tCO2 with a total emission of 256.2 Mt of CO2.

Electricity and gas are the dominant energies in water heating using either the electric water heater or the gas water heater in these countries. The use of solar water heaters in this sector will help to reduce the high energy bill in this region, which does not have the same advantages in fossil fuel. While Algeria [2] and Libya are major exporters of oil and gas, other members import the majority of these energy needs from abroad, in the case of Morocco imports 95% of its energy needs [3]. In addition, the solar resources in this region are very important, are estimated between 5-7 kWh/m²/day [4]. This high potential of solar energy can be used in many applications such as solar absorption air conditioning [5-7] and solar drying agriculture products [8].

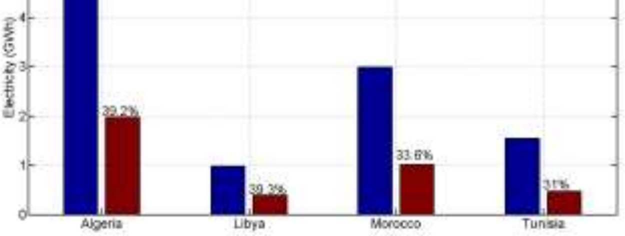

Fig. 1. The final electricity consumption (include all sector) and residential sector electricity consumption in the Maghreb Arab Union countries.

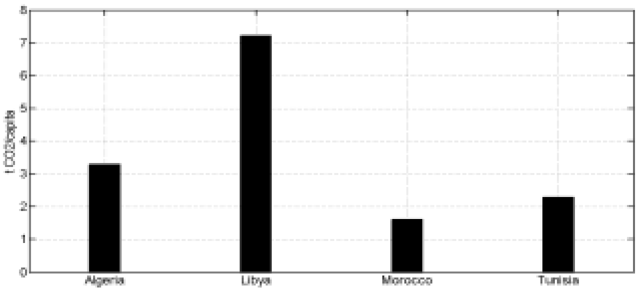

Fig. 2. The gas emissions per capita in the Maghreb Arab Union countries.

For this reason, reducing the high energy bill and exploiting solar resources, the Maghreb countries adopt many programs that encourage the use of solar water heaters. In Morocco, the " PROMASOL " program (Moroccan Program market for solar water heaters) helped to increase the total installed area from 300,000 m^2 to 480,000 m^2 with the ambition to reach 1.7 million m^2 in 2020 and 3 million m^2 in 2030 [9, 10]. In Tunisia, the "PROSOL" program helped increase the installed area from 7,000 m^2 in 2004 to 80,000 m^2 in 2010 [11-13]. In Algeria, the program " ALSOL " started in 2010 with the distribution of 400 individual SDWH (Solar Domestic Water heater) and with an ambition to achieve the installation of 2000 individual SDWH in 2011 [14, 15]. In Libya, there is no a specific name of the program, but there are national plans to promote renewable energies namely wind energy, solar PV (Photovoltaic) and solar thermal for water heating. This plan implemented by Renewable Energy Authority of Libya (REAoL) aims to install 60 MW (Megawatt) of SDWH in the short term (2013 to 2015) in different sites and 250 MW in the medium term (2016-2025) [16]. In Mauritania, according to our best knowledge, there is no program to promote solar water heating systems. The country's effort is focused on the solar PV by constructing the first large-scale grid-connected PV power plant of 15 MWp [17].

In the literature, many researchers are conducting evaluation studies on the SDWH system. In this context, Allouhi et.al. [18] conduct an energy evaluation of SDWH under the climate conditions of six Moroccan cities; they report in their paper that higher solar fraction is obtained by evacuated tube collector rather the flat plate collector. Hazami et.al. [19] conduct a feasibility study on SDHW for FPC (Flat Plate Collector) and ETC (Evacuated Tube collector) technologies in Tunisia, they found that the back period is 8 years for FPC and 10 years for ETC and the GHG (Greenhouse gas) emission mitigated by 27800 tCO2. In these two previous studies, the commercial simulation tools TRNSYS and TRANSOL are used to assess the performance of the SDWH. ZEGHIB and Chaker [20] use a numerical program to evaluate a solar thermal system for domestic heating, they found that the system can save energy consumption by 20%.

In this paper, an active domestic solar water heater will be modeled under the climate conditions of five cities of the Maghreb Arab Union countries by using Transient System Simulation Software Program (TRNSYS) [21] with an objective to evaluate the energy saving, payback period as an economic indicator, and the environmental benefit in reduction of greenhouse gases.

2. Review of the Domestic Hot Water Production Systems

There are many systems based on renewable energy for production of domestic hot water. The aim of this section is to review the most used system.

2.1 Active system or pumped systems

“Fig.3” shows an active solar domestic hot water in this system the heat transfer fluid circulates in the circuit by using a pump. If the fluid is the same in the collector-storage loop and the storage-distribution loop, the system is direct if not the system is indirect system and use a heat exchanger between the two loops. The main components of the active system are a solar thermal collector, hot water tank, electric auxiliary heating, pump, and controller.

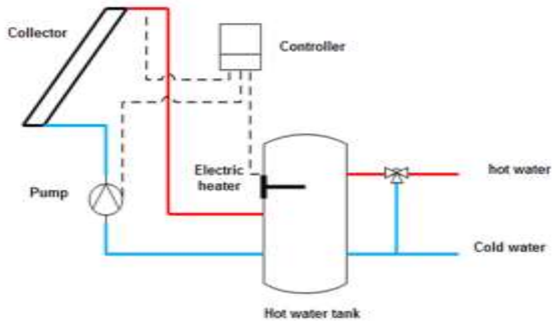

Fig. 3. Schematic illustration of an active solar domestic hot water

2.2 Passive system or thermosyphon system

“Fig.4” shows a passive solar domestic hot water in this system the heat transfer fluid circulates in the circuit by natural convection. The main components of a passive system are a solar thermal collector and hot storage tank. Bamisile et. al. [22] asset the solar water heating in the Cyprus, they found that the thermosyphon SDWH are the commonly used and 8 out of every 10 houses has SDWH systems.

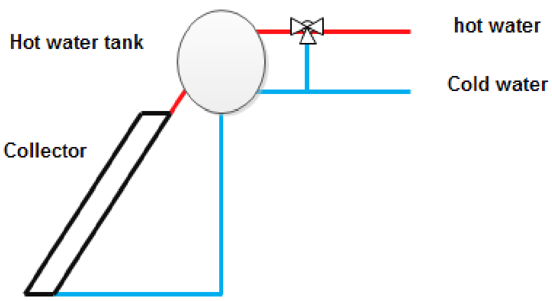

Fig. 4. Schematic illustration of a passive solar domestic hot water

2.3 Heat pump systems

The operating principle is the same as that of the vapor compression machine but the application works in the opposite direction. The evaporator is outside, the condenser raises the temperature of the refrigerant to the condensation temperature, and the condenser is inside the water storage tank which results to the refrigerant to be condensed and the hot water to be produced. The mechanic work of the compressor can be is by solar PV or wind energy as proposed [23, 24].

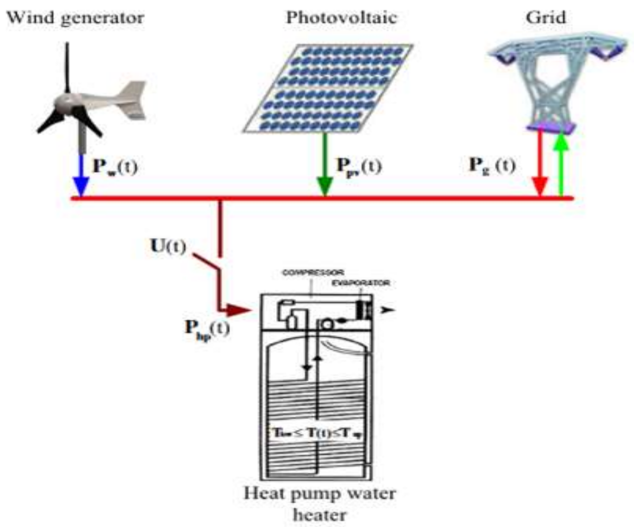

Fig. 5. Wind–PV powered heat pump water heater [23, 24]

2.4 PVT system

The solar PVT (Photovoltaic-Thermal) system provides electricity and domestic solar hot water. Lämmle et.al. [25] asset the electrical and thermal yields of different configurations of PVT system in four European cities, they found that the variations in performance are attributed to a novel parameter which they call characteristic temperature. Simms and Dorville [26] conduct an experimental study on a PVT collector; they found that the performance of PVT was comparable to the SDWH in terms of heating capacity. “Fig.6” shows a PVT system used in an experimental study in the Politecnico di Milano University [27].

Fig. 6. The PVT system located at Test Facility of the Politecnico di Milano[27]

3. SDHW System Modeling

The energy evaluation equations are those of heat transfer in each component of the system like useful energy, solar fraction.

3.1 Solar Fraction

Solar fraction is defined as the ratio of useful energy delivered by the solar collector to the required energy by the load.

$$\mathrm{SF} = 1 - \frac{\mathrm{Q_{aux}}}{\mathrm{Q_{DHW}}} \tag{1}$$

3.2 Useful energy

The useful energy delivered by the solar thermal collector can be determined by the following equation:

$$\mathrm{Q_{col}} = \dot{\mathrm{m}}\mathrm{C_p}(\mathrm{T_o} - \mathrm{T_i}) \tag{2}$$

Where, $\dot{m}$ is the water flow rate in the collector (kg/s), C_p is the specific heat capacity of water (J/Kg.K),T_o is the water temperature at the collector outlet, and $T_i$is the water temperature at the collector inlet.

3.3 Load energy

The load energy is the energy required it can be determined by the following equation:

$$Q_{DHW} = \dot{m}C_p(T_o - T_{DHW}) \tag{3}$$

3.4 Electric heater

The electric heater is used when the storage temperature is less than the desired load temperature. The required auxiliary energy can be determined by the following equation:

$$\mathrm{Q_{aux}} = \dot{\mathrm{m}}_\mathrm{l}\mathrm{C_p}(\mathrm{T_{str}} - \mathrm{T_l}) \tag{4}$$

Where, $\dot{m}_l$is the hot water flow rate drawn to the load (kg/s), C_p is the specific heat capacity of water (J/Kg.K),T_{str} is the water storage temperature, and T_l is the desired load temperature.

3.5 The storage tank loss

$$Q_{str} = U_{str}A_{str}(T_{str} - T_a) \tag{5}$$

Where, U_{str} is the heat loss coefficient (W/m^2.°C), A_{str} the surface area of a storage tank (m^2) and $T_a$is the ambient temperature (°C).

3.6 Collector efficiency

The collector efficiency is defined as the ratio of useful energy delivered by the solar collector to the incident solar radiation.

$$\eta = \frac{Q_{col}}{A_{col}G_t} \tag{6}$$

Where, η is the efficiency of the collector, Q_{col} (W) is the useful energy gain by the collector, A_{col} is the collector area (m^2), and G_t is the global solar irradiance (W/m^2).

4. Methodology

An active SDWH is modelled in TRNSYS software under the climatic condition of five cities of the Maghreb Arab Union countries (Morocco, Algeria, Tunisia, Libya, and Mauritania) “Fig.7”. The hourly global irradiation and the ambient temperature for these cities are given by the Meteonorm database “Fig.9”.

Fig. 7. The countries of The Maghreb Arab Union

During the simulation, the draw water profile was set as TRNSYS default profile with a daily consumption of 200 liters “Fig.8”.

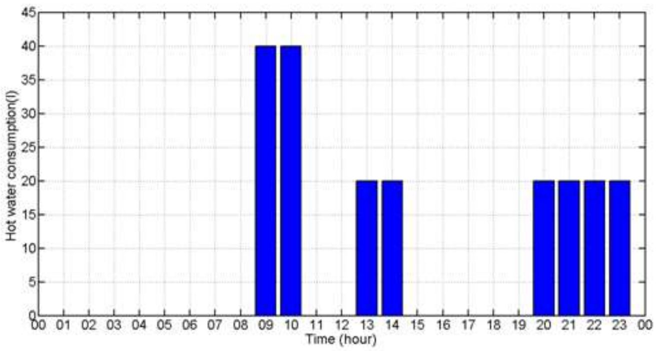

Fig. 8. Daily hot water profile

The solar thermal collectors are flat plate collector their characteristics are giving in “Table 1.”.

The efficiency equation of this type of collectors is:

$$\eta = \eta_0 - a_1\left(\frac{T_m - T_a}{G}\right) - a_2 G\left(\frac{T_m - T_a}{G}\right)^2 \quad (7)$$

Table 1. Parameter of flat plate collector

Parameter	Value	unit
η_0	0.820	-
a_1	4.750	$W/m^2.K$
a_2	0.025	$W/m^2.K2$

Where, η_0 is the zero loss efficiency, a_1 is the first order loss coefficient ($W/m^2.K$), a_2 is the second order loss coefficient ($W/m^2.K^2$), T_m is the mean collector temperature (°c), T_a is the ambient air temperature (°c), and G is the solar irradiance (W/m^2).

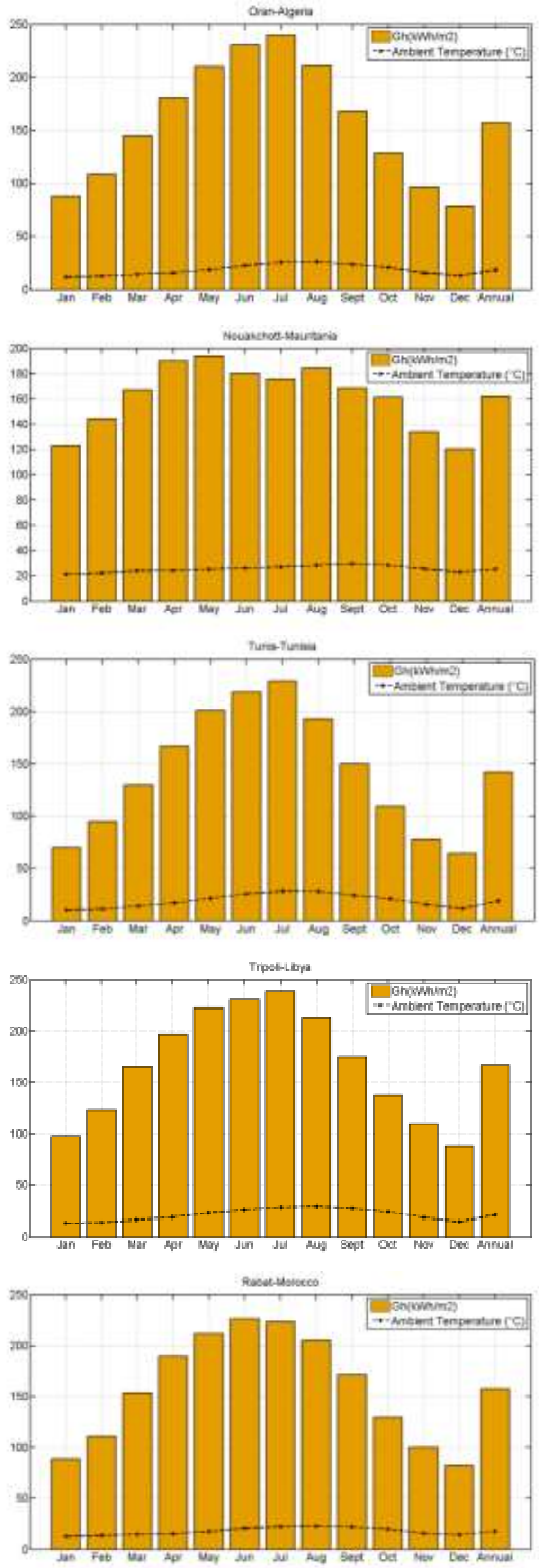

Fig. 9. Global horizontal irradiation and ambient temperature in the five cities of the Maghreb Arab Union countries

The following assumptions are used in this present study:

- The water city inlet temperature is set to 15 °C for all cities.
- The cost of the system is fixed.
- The rate of inflation of electricity is adopted equal to 10%.
- The technical specification of the system is taken fix (area of the collector, the volume of the storage tank).
- No taxes or government subsidies are taken during the study.
- No degradation of performance of the system is taken into account.

Based on the weather data and the aforementioned assumptions a simulation was conducted to study the performance of the system. The results of the simulation are used as input of the economic and environmental evaluations.

5. Energy performance

The monthly energy exchanged by the solar collector, by the auxiliary heater, by heat losses, and energy load is calculated. After calculating monthly energy exchanged, the monthly solar fraction can be estimated.

5.1 Energy performance in Rabat

For a significant analysis, the results of Rabat are taken as an example. "Table 2." summarizes the energy performance of the system.

Table 2. Monthly energy gain by collected, energy demand, auxiliary energy, energy lost and solar fraction in Rabat-Morocco.

	I_{coll} (kWh)	Q_{col} (kWh)	Q_{DHW} (kWh)	Q_{aux} (kWh)	Q_{str} (kWh)	SF (%)
Jan	562.3	251	209	16.9	50.6	92
Feb	611.8	258.9	209	13.5	58.3	94
Mar	737.7	280.09	209	2.56	71.3	99
Apr	792.1	280.8	209	1.55	77	99
May	783.4	285.5	209	1.27	75.2	99
Jun	793.5	291	209	0	79.2	100
Jul	808.6	293.2	209	0	84.1	100
Aug	811.3	297.61	209	0	86	100
Sept	791.3	292.9	209	0	86.2	100
Oct	732.2	285.3	209	0	80	100
Nov	595.7	256.1	209	13.3	60.7	94
Dec	538.8	240.7	209	17.9	52.2	91

"Table 2." shows the results in Rabat-Morocco in terms of the monthly energy gain, the auxiliary energy, the energy demand, the energy loss of the tank, and the solar fraction. As it can be seen, the energy gains are greater than 240 kWh which occurs in December, the maximum occurs in August with a value of 287.6 kWh. The energy demand for domestic hot water is constant and follows the consumption profile "Fig.8". The thermal losses in the tank are greater than 86 kWh which coincide with the same period of high energy gain; this is due to the high storage temperature in the tank, therefore, an important temperature difference which favors the heat transfer by convection with the outdoor "Eq. (5)". Depending on the case of the energy gains by the collectors and the thermal losses in the tank, an auxiliary system will compensate this energy imbalance to satisfy the energy demand. This energy balance is characterized by a factor called solar fraction which indicates the rate of participation of the solar system in satisfaction of the demand. The results in Rabat show that the solar fraction is important; it is between 91-100%.

5.2 Energy saving and solar fraction for the five cities

"Fig.10" and "Fig.11" show the annual energy saving and the solar fraction in the five cities of Maghreb Arab Union, as it can be seen the obtained results are quite similar and are between 3506-4130 kWh in terms of energy saving and are between 71-100% in terms of the solar fraction. This is due as already mentioned in the introduction to that the region has the same potential for solar radiation.

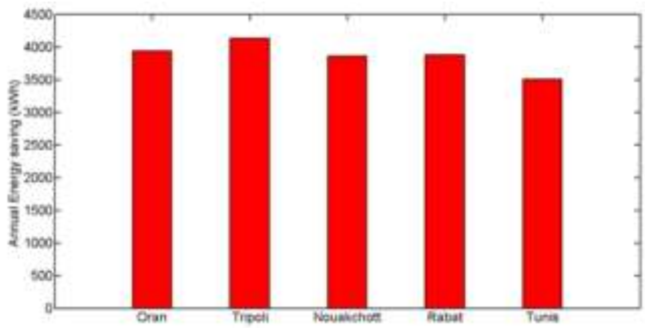

Fig. 10. The collector Energy saving in the Maghreb Arab Union countries

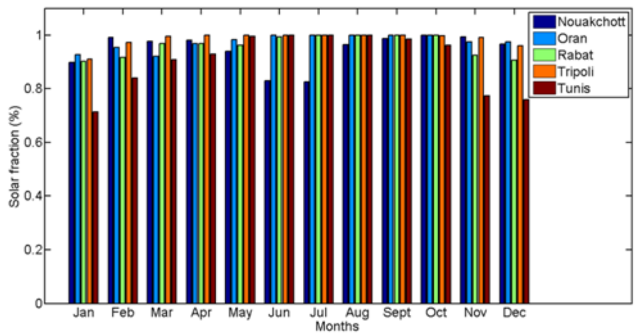

Fig. 11. Solar fraction in the five cities of the Maghreb Arab Union countries

6. Economic Evaluation

In the literature, there are several economic evaluation methods used to assess the renewable energy project. In this work, payback period method is used to assess the SDHW system.

6.1 Payback period

The payback period measures the time needed for energy saving to offset the initial investment [28].

$$PBP = \frac{ln\left(\frac{C_s i_f}{E_s C_f} + 1\right)}{ln(1 + i_f)} \quad (8)$$

Where, C_s is the cost of the system i_f is the fuel inflation rate and C_f is the cost of fuel

6.2 The cost of the system

The cost of the system is expressed as a function of the cost of the components. In this investigation, the costs values are taken from the work of Fraise et.al. [29] in France which is the first trade partner of the Arab Maghreb Union (Morocco, Algeria, Tunisia, Libya, and Mauritania).

$$C_s = C_{misc} + C_{col}A_{col} + C_{str}V_{str} + C_{pipe}L_{pipe} \quad (9)$$

Table 3. Values used in the economic evaluation [29]

Component	Value	unit
Collector	360	€/m^2
Pipe	10	€/m
Tank	4000	€/m^3
Other equipment	575	€
Installation	1600	€

6.3 The tariff of electricity

Electricity tariffs are given by the national companies concerned with the production and the distribution of electricity. The tariffs are progressive in Morocco, in Algeria, and in Tunisia. In the other countries, the tariffs are fixed. “Table 4.” summarizes the tariffs in the countries of MAU (The Maghreb Arab Union).

An average cost of electricity is adopted based on 300 kWh monthly consumption, due to the fact that the tariffs of electricity change and are progressives in some countries. “Fig.12” shows the average cost of electricity in Maghreb Arab Union countries. As it can be seen, the highest cost of the electricity is in Morocco and in Mauritania with 0.0966 € and 0.07 € respectively. The lowest cost of the electricity is in Libya and in Algeria with 0.01 € and 0.0319 € respectively. This difference is due to the fossil resource in these countries, Algeria and Libya are the big producers of oil in the region of Maghreb and in Africa.

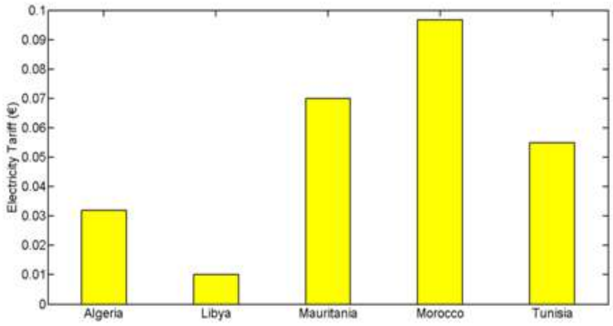

Fig. 12. Electricity Tariff in the Maghreb Arab Union countries

Table 5. Payback period result

City	Cost of electricity (€)	Es (kWh)	PB(Years)
Oran	0.032	3371.77	17.08
Tripoli	0.01	3468.49	27.48
Nouakchott	0.07	3410.82	10.99
Rabat	0.097	3313.51	9.07
Tunis	0.055	3112.32	13.38

Based on the results obtained by simulation and characteristics of the system, the lowest value of the payback period is in Morocco is 9 years and the highest value is in Tripoli is 27.48 years. According to these economic results, the solar water heater is competitive with the electric water heater in Morocco, Mauritania, and Tunisia. For Libya and Algeria, the electric water heater is favored indirectly by the lowest electricity prices in the region

Table 4. Electricity Tariffs (€/kWh) in the Maghreb Arab Union countries

Monthly consumption (KWh)	Algeria [30]	Libya [31]	Mauritania [32]	Morocco [33]	Tunisia [34]
0 - 41.67	0.0133	0.01	0.07	0.08	0.03
41.67-50	0.0311	0.01	0.07	0.08	0.03
50-83.33	0.0311	0.01	0.07	0.08	0.04
83.33-100	0.0358	0.01	0.07	0.08	0.04
101 - 200	0.0358	0.01	0.07	0.1	0.06
201-300	0.0358	0.01	0.07	0.11	0.07
300-333.33	0.0358	0.01	0.07	0.12	0.1
333.33-500	0.0434	0.01	0.07	0.12	0.1
>500	0.0434	0.01	0.07	0.12	0.12

7. Environmental Evaluation

The greenhouse gas emissions mitigation from energy saving due to the using an SDWH system is calculated by the following equation:

$$M_{emission\ mitigated} = CE_{s,an\ nual} \qquad (10)$$

C is the emission factor (Emissions per kWh of electricity generated). The values of this factor for dioxide carbon, and for dioxide of nitrogen are given in the "Table 6." [35]. Because of no availability of the emission factors of Mauritania, the factors of Africa continent are taken in replacement.

Table 6. Emission factor in the Maghreb Arab Union countries [35]

	kgCO2/kWh	kgCH4/kWh	kgN2O/kWh
Algeria	0.66420926	1.2249E-05	1.298E-06
Libya	0.91962905	3.0558E-05	5.6263E-06
Morocco	0.73121146	1.3019E-05	9.4518E-06
Tunisia	0.57216941	1.2093E-05	1.56E-06
Mauritania	0.73576632	1.17363E-05	8.5709E-06

The value of CH4 and N2O are transformed to their equivalent value of CO2 by using the Global Warming Potential (GWP) which equal to 28 times for CH4 and 265 times for N2O. The results obtained are presented in tonnes of equivalent CO2.

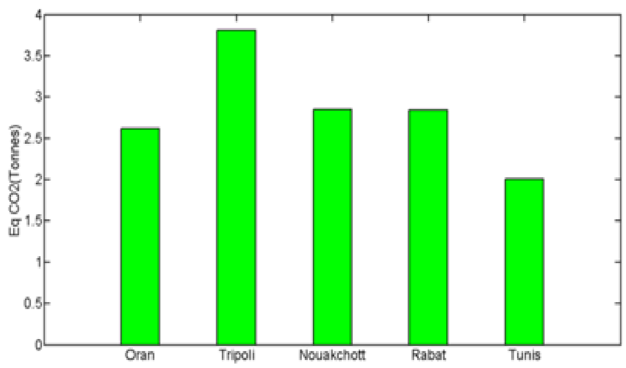

Fig. 13. CO2 mitigation in the Maghreb Arab Union countries

"Fig. 13" shows the annual amount of CO2 avoided when a solar water heater replaces an electric water heater. As can be seen from this figure, the CO2 mitigation is higher than 2 tonnes in Tunisia with a maximum of 3.81 tonnes in Libya. This is due to the difference in electricity-specific emission factors in these countries, which depend on the sources used for generation of electricity. This factor is higher for coal electricity generation than natural gas or nuclear generation, or renewable energies.

8. Conclusion

In this paper, an active solar domestic hot water system was studied; an hourly simulation analysis was conducted to evaluate the energy performance and the environmental impact of the proposed system for five representative cities of the Maghreb Arab Union countries. The results show:

- The proposed system can reduce the energy demand of the building sector. The solar fraction ranges from 71 % to 100 %.
- For almost the same solar potential in these countries, the payback period is different with wide-span 9-27 years, this is due to the energy considerations of each country in terms of resources and applicable tariffs.
- Another benefit of the proposed system is the environmental issue; the use of the proposed system results in reduced CO2 emission.

The carbon market is not considered in this study, in Morocco, an equivalent cost of carbon of 10 €/t ECO2 will be adopted. For the other countries, there is a lack of data about the same initiative.

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