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One-year Dynamic Study of the Use of Solar Water Heater for Domestic Consumption in Egypt: An Energy Assessment

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The use of fossil fuels leads to greenhouse gas emissions, global warming, and secondary consequences such as desertification and winds in the Middle East and Africa, including Egypt. The use of renewable energy is the most appropriate solution to prevent the emission of polluting gases. Egypt is one of the best places to use solar water heating systems, located in the solar belt. In this paper, for the first time, the best place to use solar water heater (SWH) systems is examined using TSOL 2018 R(1) software and climate data for residential apartments in 35 stations in Egypt. The results showed that Sharm el sheikh station with supplies 96.8% of its total heat needs is the most suitable station for using solar water heating systems. According to the studies performed, using solar water heaters in the studied stations generated good energy savings annually (production of 134.5 GWh of solar heat). Also, greenhouse gas emissions were significantly reduced (preventing the emission of about 39.2 tons of CO_2 pollutants per year) and as a result, the government should turn to the use of clean and renewable energy.

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NOMENCLATURE

SWH	Solar water heater	G_{diff}	Diffuse solar radiation striking a tilted surface (kJ/m^2)
GDP	Gross domestic Product	G_{dir}	Part of solar radiation striking a tilted surface (kJ/m^2)
DHW	Domestic hot water	k_0, k_q	Heat transfer coeffcient (W/m^2.K)
TSOL	Thermal solar	$Q_{Aux.DHW}$	Auxiliary heating for domestic hot water (kWh)
f_{IAM}	Incidence angle modifer factor	$Q_{CL.DHW}$	Collector loop heating for domestic hot water (kWh)
$f_{IAM.diff}$	Diffuse incidence angle modifier factor	**Greek Symbols**	
$Q_{S.HL}$	Solar heating for heating load (kWh)	ρ	Collector losses (kJ/m^2)
T_A	Air temperature (K)	η_0	Collector's zero-loss efficiency
T_{km}	Average temperature of collector (K)		

INTRODUCTION

People's daily lives depend on energy production and consumption, so supply and demand in human societies are constantly increasing [1]. The rapid growth of global energy consumption, in addition to creating problems in the field of energy supply, has also led to harmful environmental effects [2, 3]. In recent years, a large

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amount of CO_2 from the combustion of fossil fuels has been released in to atmosphere, of which about 72% of greenhouse gases are produced in the Middle East [4]. Therefore, replacing fossil energy with renewable energy, including solar energy, is one of the solutions to deal with energy and environmental crises [5-7].

Applications of solar energy include power plant and non-power plant applications such as solar water heaters, solar baths, and solar cooling and heating, as well as solar water desalination systems, solar dryers, solar stoves, solar ovens, solar houses, etc. [8, 9].

Cooling, heating, and hot water together consume about 60% of the total energy of the building [10-12]. Of this amount, water heating consumes on average about 22% of the total energy consumption in the world's buildings [13].

By using solar water heaters, to a large extent, the energy required for heating can be provided. Using solar energy to supply hot water to homes and industrial centers is one of the most practical and cost-effective ways to use renewable energy in the world today [14]. For this reason, most developed and developing countries are investing heavily in the use of solar systems and clean energy [15]. The largest manufacturers of heating collectors are China, the USA, Japan, and Turkey, respectively [16]. In 2020, The solar heat capacity reached to a new maximum 501 GWth in the world [17].

A research was conducted on the abundant natural resources of sub-Saharan Africa and Egypt and the use of the perspective of four major sources of renewable energy, including water, solar, wind, and biomass, and attention to climate change during the seasons, as well as the energy storage technology. It was found that Egypt has a high potential for renewable energy.

Egypt is a country rich in solar energy and radiation in Egypt has a high intensity that reaches 7.2 kWh/m^2 [18]. It is noteworthy that the tourism industry in Egypt is considered the most significant economic hub of the country, which accounts for about 11.3% of GDP. It was determined that the use of SWH systems is common in hotels, tourist centers and government offices which are important centers such as hospitals and schools and to a lesser extent residential house [19].

A study on the economic evaluation of the potential of solar water heaters in Egypt found that the demand for solar water heater systems in Egypt is limited to high-income people and tourist and recreational places [20]. Due to low electricity prices, people do not go for solar water heating systems because they believe that the cost of initial purchase and maintenance is very high. In this study, strategies to increase demand are considered, which include: improving simplicity, reducing production costs, allowing the use of solar systems during the initial design of the building, and government and private sector support. If these solutions are used, reduction in fossil fuels and the use of solar water heating systems in Egypt could be facilitated.

In 2021, Nasser et al. [21] examined the use of solar energy as a source of renewable energy in comparison with traditional energy for heating greenhouses in winter. In this study, they investigated the effect of two different heating systems, traditional heating (G1) and solar heating (G2) on cucumber growth parameters during the growing period. Temperature and relative humidity were recorded during the growing period and they concluded the use of solar energy heating system does not affect the quality of the product and is also cost-effective.

In 2021, Kotb et al. [22] Presented a conceptual design model for Hybrid Renewable Sustainable Energy System (HRSES). In this model, the feasibility of different HORSES alternatives is examined and a multi-criteria decision model based on fuzzy theory is given to select the energy optimization solution, accurately. In the proposed model, HOMER software was used to perform an energy-environment optimization analysis, which was selected the best design by considering ten performance criteria. They concluded that wind turbines, a 328 kW photovoltaic array, a 100 kW diesel generator, 112 batteries and a 235 kW converter were the optimal system.

In 2016, Sharshir et al. [23] conducted a study on the design of a hybrid washing system using moisture and sunlight. The system consisted of several parts, including a developed hybrid desalination system, hot water, and humidifier. When the solar part was used extensively, a humidification system was used, which was the result of this study being economical and using a lot of sunlight and clean energy.

The use of SWHs in Egyptian residential buildings is another research topic in the field of SWHs [24]. In this study, Egypt is mentioned as a country located on the solar belt, which due to sunlight, the use of solar thermal water heaters is a very economical way. The aim of this study was energy efficiency and electricity supply by the renewable sources by 2020 to meet 20% of the total needs of the country.

In 2010, Fahmy et al. [25] conducted a study on the design of a biogas-fired SWH system in a remote area of central Egypt. The results showed that the best use of this system was especially in the government buildings and hospitals, and remote areas, which could produce much less pollutants.

According to the studies, there is no comprehensive study on finding the potential of all parts of Egypt and finding the optimal stations to use SWH. Given that finding suitable locations is one of the most essential issues in renewable energy projects, in the present work, for the first time, a one-year dynamic evaluation of 35 stations in Egypt is performed using TSOL 2018 R(1) software. Considering the thermal and optical losses has caused the results of the present work to correspond to reality with a very high degree of accuracy.

Solar water heaters

About 20 to 30 percent of the energy consumed in a building is spent on heating sanitary water [16]. Solar hot water systems provide sanitary hot water throughout the year. These systems can also provide part of space heating in winter because building space heating is always needed in winter. In winter, due to the reduction of the day time and the reduction of the angle of the sun's radiation, the absorption of the sun's absorbable energy occurs. Therefore, in order to provide heating for the building space, the level of solar collectors should be increased to the required amount. This can provide up to 30% of energy for space heating of buildings from the sun [26].

Study place

Egypt is a country in the northeast of Africa, with an area of 1,010,408 km^2, is the 28th largest country in the world. As shown in Figure 1 [26], in the north of Egypt, the Mediterranean Sea, and in the east, the Red Sea is located. It borders Sudan to the south and Libya to the west. It is also connected to Palestine from the Sinai Desert.

Egypt is a country with a hot and dry Mediterranean climate. The longitude of the country extends from 24 degrees east to 47 degrees east, about 4% of which is agricultural land. The population of Egypt in the latest census is estimated at 85 million. Egypt is one of the most densely populated countries in the world because of its population of 1120 people per km^2 [27].

Stations under study

According to Table 1, the required information of 35 stations in Egypt has been collected according to TSOL 2018 R(1) climate simulation software, which are extracted from METEONORM 7.3 software, which is installed along with the simulation program and its task is to generate a file of climate.

Software used

TSOL 2018 R(1) software is the software used for simulations in the present work. This software is a professional simulation program for designing and programming solar thermal systems [28]. By providing tools, equipment of solar systems, and components related to these systems (such as hot water source, swimming pool, heating process, etc.), this program has made simulation and calculations for such systems much easier [29]. Using this program, less time and money will be spent on the optimal design of solar heating systems, temperature simulation, and energy performance assessment [30]. Calculations in TSOL 2018 R(1) software are performed based on energy flow balance and final demand-supply using meteorological hourly data [31]. The amount of total radiation to the collector surface is equal to the sum of direct radiation and diffusion radiation [32]. Direct radiation is available in climatic files and calculations are performed to calculate the amount of diffusion radiation on the collector surface with the applied angle and hourly air filtration coefficient. After entering the available climate data, using the simulation start command, a one-year analysis is performed based on Equations (1) to (4) [28-31, 33] and the output is displayed as graphs and tables.

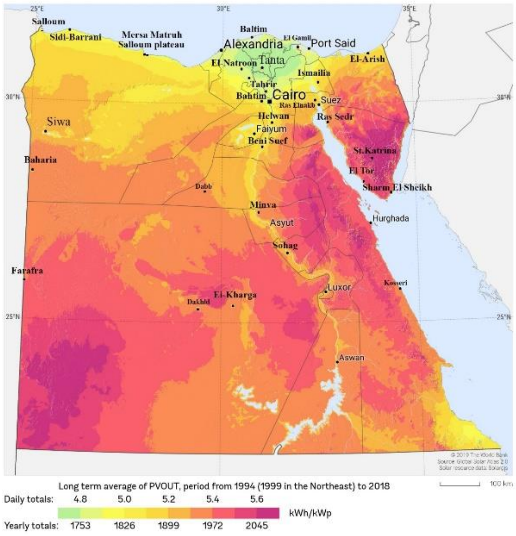

Figure 1. Solar radiation map of Egypt [16]

$$\rho = G_{dir} \cdot \eta_0 \cdot f_{IAM} + G_{diff} \cdot \eta_0 \cdot f_{IAM \cdot diff} - k_0 (T_{km} - T_A) - k_q (T_{km} - T_A)^2 \quad (1)$$

$$Solar\ fraction \cdot total = \frac{Q_{CL \cdot DHW} + Q_{S \cdot HL}}{Q_{CL \cdot DHW} + Q_{S \cdot HL} + Q_{Aux \cdot DHW} + Q_{Aux \cdot HL}} \quad (2)$$

$$SolarfractionDHW = \frac{Q_{CL \cdot DHW}}{Q_{CL \cdot DHW} + Q_{Aux \cdot DHW}} \quad (3)$$

$$Solarfractionheating = \frac{Q_{S \cdot HL}}{Q_{S \cdot HL} + Q_{Aux \cdot HL}} \quad (4)$$

Required simulation data

For the studied stations in Egypt, the average daily consumption of sanitary hot water is equal to 110 liters of water, the temperature of sanitary hot water is 60 ºC and the time period of the hot water required for space heating is considered all days of the year except June to October. Also, the heat load of the used space was 10 kW, the temperature of the used spaces was 21 ºC and the useful area of the residential apartments was 80 m^2. The windows were double glazed and the window area was considered by default. Heat gain was considered from the heating equipment inside the building 5 W/m^2 and the wall material was considered as medium type. The standard type of SWH is a flat plate with an area of 13 m^2 and an azimuth angle of zero degrees [34, 35], and the type of boiler used was gas boiler. The schematic diagram of the studied system is shown in Figure 2.

Table 1. Information of the studied stations

No.	Station	Latitude	Longitude	Total annual irradiation (kWh/m^2)	Cold water temperature (Feb/Aug).ºC	Diffuse radiation percentage (%)
1	Alexndria	31.2	-30	2085.4	19/22.5	35.1
2	Aswan	24	-32.8	2268	24/29.5	33.2
3	Baharia	28.3	-28.9	2308.2	20.5/25.5	32.1
4	Bahtim	30.2	-31.3	1906	19/22.5	42.4
5	Baltim	31.6	-31.1	2004	19.5/22.5	37.1
6	Beni Suef	29.2	-31	2025	20.5/24.5	38.9
7	Cairo	30.1	-31.3	1879.7	20.5/24.5	42.9
8	Dabb	30.9	-28.5	2166.9	19/22	34.4
9	Dakhld	25.5	-29	2242.9	21.5/27	33.4
10	El-suez	29.9	-32.5	1966.1	21/24.5	39.4
11	El-Arish	31.1	-33.8	1996.3	18.5/22	38.2
12	Ei-Kharga	25.5	-30.5	2221.7	22.5/28	33.8
13	El-Natroon	30.4	-30.4	2023.8	21/25	37.5
14	El Tor	28.2	-33.6	2302.6	21.5/25	31.5
15	Farafra	27	-27.5	2389.4	21/26	31
16	Helwan	29.9	-31.3	1898.8	20.5/24.5	42.4
17	Hurguada	27.2	-33.9	2409.4	23.5/27	35.8
18	Ismailia	30.6	-32.2	1985.5	19.5/23.5	39.1
19	Kosseri	26.1	-34.3	2324.8	22.5/26	31.5
20	Luxori	25.7	-32.7	2237.5	22.5/28	33
21	Mersa Matruh	31.3	-27.2	2001.1	18.5/21.5	37.3
22	Minva	28.1	-30.7	2244.6	19.5/24.5	30.3
23	Port Said	31.3	-33.3	2020.4	20.23	37.7
24	El Gamil	31.3	-32.2	2022.1	20/23	36.8
25	Ras Sedr	29.6	-32.7	2111.6	21/25	34.9
26	Ras Elnakb	29.6	-34.8	2278.3	17.5/22.5	35.9
27	Salloum	31.5	-25.2	2033.2	18/21	36.3
28	Salloum plateau	31.6	-25.1	2068.1	17.5/21	35.5
29	Sharm El Sheikh	28	-34.4	2369.1	24/28	31.4
30	Sidi-Barrani	31.6	-25.4	1977.6	17.5/21	38
31	Siwa	29.2	-25.5	2243.6	20/25.5	31.1
32	Sohag	26.6	-31.7	2223.6	20.5/26	32.6
33	St.Katrina	28.7	-34.1	2388.9	16/21.5	40.8
34	Tahrir	30.7	30.7	2049.5	20.5/25	36.1
35	Tanta	30.8	-30.9	2027.4	20.5/24	37

RESULTS

The results obtained from the TSOL 2018 R(1) software are presented in Table 2. As can be seen from this table, Sharm El Sheikh, Kosseri and Hurguada stations are the most suitable stations for using SWH systems with 96.8%, 95.8%, and 91.2% of their total heat needs, respectively. St. Katrina also has the lowest percentage of

Table 2. Results of the studied parameters

Station	Total solar fraction (%)	Solar contribution to heating (kWh)	Heating solar fraction (%)	Solar contribution to DHW (kWh)	DHW solar fraction (%)	CO_2 emissions avoided (kg)	Boiler energy to heating (kWh)	Boiler energy to DHW (kWh)
Alexndria	52.4	1018.14	23.3	2693.11	99.3	1180.16	3,349	18.3
Aswan	79.4	1187.09	55.5	2478.24	100	1167.86	950	0
Baharia	62	1900	40.5	2643.58	100	1348.91	2,788	0
Bahtim	55	769.14	22.2	2571.83	98.4	1089.55	2,697	42
Baltim	54.1	797.30	21.7	2649.43	98.4	1118.46	2,875	44
Beni Suef	58.6	1037.53	28.8	2624.25	99.4	1164.04	2,571	16
Cairo	55.1	779.13	23.1	2508.04	96.7	1072.65	2,598	85
Dabb	54.5	1205.25	26.9	2729.84	99.7	1231.25	3,273	8.8
Dakhld	66	1796.45	44.3	2589.95	100	1313.62	2,261	0
El-suez	67.6	858.77	34.8	2576.67	98.4	1123.24	1,608	41
El-Arish	73.2	1085.09	44.6	2692.53	98.7	1168.23	1,346	35
Ei-Kharga	70.2	1404.15	45.5	2544.64	100	1223.54	1,679	0.32
El-Natroon	62.8	1086.36	33.4	2589.74	99.4	1176.02	2,166	15.9
El Tor	81.5	994.04	54.6	2634.10	100	1180.14	826	0
Farafra	68.3	2247.63	49.9	2623.92	100	1419.55	2,258	0
Helwan	54.8	761.08	22.3	2534.84	97.1	1074.26	2,644	76
Hurguada	91.2	1081.32	75.4	2557.71	100	1182.36	353	0
Ismailia	52	1234.88	25.9	2637.12	98.5	1199.37	3,533	41
Kosseri	95.8	395.58	75.4	2589.82	100	1044.29	129	0
Luxori	69.8	1498.90	46.1	2546.99	100	1247	1,755	0
Mersa Matruh	48.9	1047.14	21.4	2680.90	98.5	1178.18	3,850	40
Minva	58.2	1864.29	36.3	2688.37	100	1346.50	3,272	0
Port Said	59.7	550.79	20.5	2643.01	99.1	1075.21	2,131	24
El Gamil	63.1	674.18	99	2644	99	1104.59	1,914	26
Ras Sedr	66.4	1046.17	36.2	2614.05	99.6	1170.08	1,842	9.4
Ras Elnakb	47.1	2047.24	27.5	2763.35	99.8	1379.34	5,396	4.3
Salloum	46.6	1458.20	23.5	2718.93	98.9	1263.34	4,751	31
Salloum plateau	43.6	1581.38	22.2	2737.36	98.6	1287.76	5,557	39
Sharm El Sheikh	96.8	380.69	79.9	2513.88	100	1012.67	96	0
Sidi-Barrani	40.7	1381.44	18.9	2719.87	98.3	1234.37	5,924	46
Siwa	56.5	1665.97	33.3	2657.48	100	1301	3,334	0
Sohag	57.9	1544.75	33.7	2629.11	99.9	1264.24	3,038	2
St.Katrina	40.6	2084.70	22.5	2827.51	99.8	1390.27	7,178	7
Tahrir	61.8	973.83	30.5	2624.50	99.8	1154.37	2,215	4.5
Tanta	65	952.50	33.3	2630.75	99.3	1157.98	1,906	19.8

solar heat supply among the studied stations, with 40.6% of its heat needs supplied by SWHs. On average, 62.2% of the total heat required in all stations under studied is provided by SWHs. Regarding the heating required for the space, Farafra, St. Katrina, and Ras Elnakb stations generated the most heat with 2247.63, 2084.70, and 2047.24 kWh, respectively.

Of course, in this regard, El Gamil and Sharm El Sheikh stations with 99% and 79.9%, respectively. The obtained data have been able to meet the highest space heating needs by the SWH system. The lowest percentage of space heating with 18.9% is related to Sidi-Barrani station. The average space heating supply for all studied stations is 38% (1211.2 kWh) and in total in the studied stations, about 42.4 GWh of solar heat has been produced for space heating.

St. Katrina with 2827.51 kWh has produced the highest amount of solar heat for the sanitary hot water used. Ras Elnakb and Salloum Plateau stations with 2763.35 and 2737.36 kWh, respectively, were able to use in the next categories of the high production of sanitary hot water. The lowest percentage of hot water supply is 96.7%, which is related to the Cairo station and is due to the production of 2508 kWh of heat by SWH. In terms of meeting the needs of consumer sanitary hot water, almost all 35 stations have been able to meet their needs 100% with the solar water heating system, because the average percentage of sanitary hot water is over 99%. In total, 92.1 GWh of solar heat is produced annually for the sanitary hot water used in the studied stations.

In order to prevent the emission of CO_2 pollutants, Farafra stations, St. Katrina and Ras Elnakb are the most suitable stations with 1419.55, 1390.27, 1379.34 kg/year, respectively. The average prevention of CO_2 emissions in each station is 1189 kg/year, which in total annually prevents the emission of about 39.2 tons of CO_2 pollutants.

In terms of the need for auxiliary gas boilers for space heating and hot water consumption, St Katrina, Sidi Barrani, and Salloum Plateau stations with 7185, 5970 and 5596 kWh/year are the most in need of gas boilers. The lowest need for auxiliary gas boilers, which corresponds to the highest percentage of total solar fraction with a rate of 96 kWh, is related to Sharm El Sheikh station. In total, about 95 GWh of heat generated by the auxiliary gas boiler is required annually for all stations under study

Future work

– In the present work, we have used flat-plate solar collectors. It is suggested to use new generation vacuum tube collectors.

– In the present work, we have not done the financial analysis, and we have only done energy and environmental analyses. For the present work to help energy decision-makers in Egypt as a road map, it is suggested that financial analysis be done in future studies.

– The scale of the present work is an apartment. It is suggested to evaluate other scales such as commercial, administrative, etc., in future works.

– In the continuation of the present work, it is possible to check the use of the solar system with different hot water tanks.

– Hot water supply for the swimming pool in these 35 stations can also be studied.

CONCLUSION

In Egypt, people are encouraged to use SWHs in the domestic and commercial sectors to reduce the consumption of produced electricity from fossil fuels. In the present work, for the first time, the potential measurement of the use of SWHs in Egypt has been carried out to provide a comprehensive map for decision-makers and investors in this area, in addition to finding optimal places for installing SWHs. In the present work, the best place, percentage of heat supply, the amount of pollution prevention, and the amount of auxiliary gas boiler to use SWH systems using TSOL 2018 R(1) software and using climate data to consume an apartment residential surveyed in 35 stations in Egypt. The following results were obtained:

– According to the results, using SWH systems in the field of space heating and sanitary water consumption, about 62% of the total energy of the building is supplied. Of this amount, the supply of sanitary water heating and space heating are on average about 99.3% and 38.1%, respectively.

– Sharm El Sheikh station is the most suitable station for using a SWH system.

– Farafra station has produced the highest amount of solar heat for space heating and El Gamil station has provided the highest percentage of space heating needs by SWH system.

– St. Katrina has produced the highest amount of solar heat for the sanitary jot water used.

– Farafra station is the most suitable station in the field of preventing the emission of CO_2 pollutants.

– The greatest need for an auxiliary gas boiler, there is at St. Katrina.

– In all stations under study, about 42.4 GWh of solar heat is produced annually for space heating and 92.1 GWh of heat is produced for the production of sanitary hot water, which prevents the release of about 39.2 tons of CO_2 pollutants per year.

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CONFLICT OF INTEREST

There is no conflict of interest.

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Persian Abstract

چکیده

استفاده از انرژی‌های فسیلی، انتشار گازهای گلخانه‌ای و بالطبع بروز پدیده‌ی گرمایش جهانی و پیامدهای ثانویه‌ای نظیر گسترش بیابان‌ها و وزش باد در منطقه‌ی خاورمیانه و آفریقا از جمله کشور مصر را به همراه دارد. بهره‌گیری از انرژی‌های تجدیدپذیر مناسب‌ترین راهکار جهت جلوگیری از انتشار گازهای آلاینده می‌باشد. کشور مصر با قرارگیری در کمربند خورشیدی یکی از بهترین مکان‌ها جهت بکارگیری سیستم‌های آبگرمکن خورشیدی است. در مقاله‌ی حاضر برای نخستین بار بهترین مکان جهت استفاده از سیستم‌های آبگرمکن‌های خورشیدی با استفاده از نرم‌افزار شبیه‌سازی اقلیمی TSOL و با بهره‌گیری از داده‌های اقلیمی جهت مصرف آپارتمان‌های مسکونی در ۳۵ ایستگاه کشور مصر مورد بررسی قرار گرفته است. نتایج نشان داد که ایستگاه Sharm el sheikh با تامین ۹۶/۸ ٪ از کل نیازهای حرارتی خود، مناسب‌ترین ایستگاه برای استفاده از سیستم‌های آبگرمکن خورشیدی می‌باشد. همچنین با بررسی‌های انجام شده در صورت استفاده از آبگرمکن‌های خورشیدی در ایستگاه‌های مورد بررسی می‌توان سالیانه صرفه‌جویی مناسبی در انرژی انجام داد (تولید ۱۳۴/۵ GWh حرارت خورشیدی) و کاهش چشمگیر تولید گازهای گلخانه‌ای (جلوگیری از انتشار حدود ۳۹/۲ تن آلاینده CO_2 در سال) و در نتیجه روی آوردن به استفاده از انرژی‌های پاک و تجدیدپذیر داشت.