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HYBRID SOLAR SYSTEM (PHOTOVOLTAIC/THERMAL) UTILIZATION FOR HOUSEHOLD APPLICATIONS

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Abstract

The aim of this study is to introduce the possibilities of using a hybrid photovoltaic/thermal solar system, tailored to a city located in southern Iraq - latitude 30.5˚N and longitude 47.8˚E. The reason is: to treat the electricity shortage problem by covering a certain share of the household needs. The study separates the system into two (solar thermal and solar photoelectric) systems, and while using it as a hybrid PV/T system, aims to find out the efficiency and production of both cases by using a water cooling technique. Where installed, the separate systems will cover 100% of hot water, and 39.5% electricity needs, while the hybrid system covers about 63.01% of hot water and about 44.34% electricity needs for the household.

Keywords

Hybrid photovoltaic/thermal system, Photovoltaics, Domestic hot water, Solar radiation.

1. Introduction

The total dependence on the use of fossilised fuels as a main energy source in all applications, the increase of oil prices, and the negative impacts on the environment - all these factors motivated many scientists to invent a system friendly to the environment. This system relies on natural resources, such as: the sun, sea waves, subterranean energy, wind energy, and others. Several analyses were conducted on hybrid PV/T system in theory, as well as the development of cogeneration components, like (PV/ thermal). In recent times, the PV/T solar energy utilization achieved a notable increase, due to the improvement in the performance of PV/T systems [1]. Said improvement consists of a combination of photovoltaic PV cells and solar thermal energy absorbing elements. The power generation is either thermal or electric using solar thermal collectors or PV panels, and there are many types of already advanced PV/T flat-panel collectors. Flat plate PV/T collectors can be split into various categories, according to the nature of the heat transport medium (air or water). [2] And they mainly consist of two systems (flat plate collector and PV system). It produces electricity by the use of solar cells and hot water, and exploits this energy in different house applications. The aim is to heat up the air instead of heating water, drying, or other purposes such as solar cooling, that depends on the sun as a main source to produce thermal energy. This system invaded the field of renewable energy, as it was found that the hybrid PV/T (photovoltaic/thermal) system can provide both electricity and heat at the same time. In order to maintain the electric efficiency of photovoltaic cells at an adequate level, it is necessary for the PV modules to operate at low temperatures. Natural or forced air circulation are simple and low-cost methods for transferring heat from the PV modules [3-4]. Conventional flat plate solar thermal collectors with PV cells that work by absorbing solar radiation, transforming it to the output of both electrical and thermal energy, have also removed the heat from PV cells. This lead to higher electrical efficiency of the photovoltaic part, and the useful thermal energy extracted from one end of the ducts can be exploited. [5] The potential for hybrid system applications is that they can generate both electricity and heat, which can be used to decrease greenhouse hot water usage.

The result of the production of electrical energy from the PV panel increasing is that it also increases the flow rate. This is attributed to the fact that the panel operates at lower temperatures. This indicates that the additional energy required from usefulness to cover the electrical and thermal loads is successive [6]. To take advantage of the hybrid solar collector, in order to maximize the contributions of solar energy to generating electricity and thermal profits, using a hybrid PV/T solar water collector as a single system is both efficient and dependable. This system includes thermal absorption and PV functions [7].

2. Methods

House characteristics

The house in question is located to the south of Iraq (Basrah city), with an area 150 m^2 and flat roof of 120 m^2. There is no shade that can cover the roof, like a tree or high building. And the surface level is not sloped. The roof of the house is made of concrete, the thickness of the roof is about 16 cm, and the wall's thickness is about 31 cm. The surface of this house is covered by pieces of gray cement called (stager), and the house is surrounded by a brick wall with a height of 1.5 m. The number of people living in the house is 4. The total annual electricity consumption in this house is 23 934 kWh and the amount of hot water the house needs 300 litres/day.

Meteorological condition in Basrah city

Basrah city has a semi-desert climate with high temperatures in the summer, where some days reach 56 °C. The mean temperature is 10 °C in the winter, where some days reach -1 °C. The mean temperature peak is 38 °C. The daily average wind speed ranges from 5 m/s to 9 m/s. Max humidity is 94.5% and min humidity 5.14%. [8] The readings taken from the national renewable energy lab (national solar radiation database) show the monthly average solar global horizontal irradiance data depending on the location of Basrah city for each month. The average annual was 5.45 kWh/m^2/day, where the maximum value of solar radiation was in June: 7.613 kWh/m^2/day. But this value will sharply decrease in December: 2.849 kWh/m^2/day [9].

Theory of solar utilization

Solar flat plate collector

This system works by the solar collector absorbing solar radiation, and converting it to heat, and the system taking advantage of said heat for heating water, after which it transfers this heat to a fluid, in order to be used by household applications, which reduces dependence on electric heating. [10] The energy absorbed into the collector comes partly from the radiation affecting the cover, which is absorbed and reflected, whereas the other part affects the glazing material, so not all solar radiation that affects the collector can be taken advantage of. In the end, only a fraction of that radiation is absorbed by the collector. [11] The net rate at which incoming solar energy is absorbed by a collector can be calculated as follows:

$$q_{solar} = G\,A_C\,(\tau\alpha)_e \qquad (1)$$

Where (G) represents all components of solar radiation

$$G = G_{direct} + G_{diffuse} + G_{reflect.} \qquad (2)$$

The net rate at which incoming solar energy is absorbed by a collector can be used to calculate heat loss as follows:

$$Q_{loss} = U_L\,A_C\,(T_b - T_a) \qquad (3)$$

The energy salvaged by a collector can also be determined by measuring the inlet and outlet collector temperatures, and the mass flow rate of the fluid coursing through the collector as follows:

$$Q_u = \dot{m}C_p\,(T_i - T_o) \qquad (4)$$

And the thermal efficiency of the flat plate collector can be calculated by using the following equation:

$$\eta_{th} = Q_u / GA_C \qquad (5)$$

PV Solar system

The recent accelerated growth of this kind of system is mainly due to better performance and the ability to cover either a part of, or all electric energy needs. The ability to convert sunlight into usable energy is affected by several factors, such as cells' temperature, the amount of radiation, and module design. The effective PV temperature (TPV)eff describes how temperature has a significant effect on system operation of PV, where rising heat leads to reduced efficiency of PV system [12]. The effective value (TPV)eff can be calculated by the following formula:

$$(T_{PV})_{eff} = T_{PV} + (T_{PV/T} - T_a) \qquad (6)$$

The conversion efficiency of a PV panel depends on the fluid temperatures – the fluid absorbs the high temperature from cells to keep the stability of conversion efficiency. [2] This can be calculated using the following equation:

$$\eta_{DC} = \eta_{DC0} \; [1+ \beta \, (25 - T_s)] \quad (7)$$

And the efficiency of a solar photovoltaic cell is measured using the following equation:

$$\eta_e = I_m V_m / G \, A_c \quad (8)$$

Hybrid PV/T solar collector

An increase in the PV cell's temperature leads to a drop of electricity conversion efficiency, because more than 80% of the solar radiation falling on the photovoltaic cells doesn't get converted to electricity, but is either reflected or converted to thermal energy. To counter this, usage of the hybrid PV/T system is a method, as it will provide electricity and hot water at the same time, and use the water as a cooler for solar cells. Therefore, it is necessary to operate the PV modules at low temperature to get better efficiency when the system operates [13]. The efficiency of the PV/T system is determined by the equation below.

$$\eta_{pv/t} = \eta_{th} + \eta_e \quad (9)$$

Software used

More than one software program was used for calculations, for each system separately, in order to know the amount of output and efficiency of each system when operating separately, and to find out the results of them working as a single PV/T system. The main calculation for this system consists of three parts. The first part is the calculation of the solar thermal system separately (flat plate collector system) by using the (T*SOL Pro 5.5) software. This software has significant possibilities, it's flexible in calculations, and also provides accurate results. The second part's related to the photovoltaic system - the calculation of this system is done by the (Sunny design 3 software) program. This has possibilities to compute with different choices with different probabilities, modify or change parameters, and presents precise results with graphical interpretations. The third part represents the final calculations for the combined (flat plate collector and PV system), but as a single system (hybrid photovoltaic/thermal solar panels) this software also gave results for hybrid systems with exact values for amounts of hot water and electric production.

All the software that were used were not applicable to usage according to Basrah city, for these were selected for Baghdad city instead of Basrah. At longitude 44.7° E, latitude 33.1˚ N , where Baghdad is, the annual average solar radiation is 5.48 kWh/m²/day and the average temperature is 34 °C. While Basrah city is located at Longitude 47.8° E, Latitude 30.5° N, where the annual average solar radiation is 5.45 kWh/m²/day and the average temperature is 38 °C.

3. Calculations

Results of the calculations for the PT system

Common data for each program

Location: Region: Asia, Country: Iraq, city: Baghdad

Latitude: 33.1˚N, longitude: 44.7˚E, and the altitude above MSL is 33 m

Installation: Orientation: south, azimuth angle: 0˚, and the tilt angle: 23˚

Climate: Annual average solar radiation 5.48 kWh/m²/day, average outside temperature: 34°C,Low outside temperature: 7.8°C.

Part (1) flat plate collector calculations

Hot water consumption: Average daily consumption: 300 litres, and number of people: 4.

Usage of hot water over a year (bathing, cooking, sanitation and washing machine, others).

Collector array: Collector manufacturer: Baymaka. s. Baxi group.

1. Type: advanced XL, description: flat plate collector.
2. Cross surface area: 2.51m².
3. Active solar surface: 2.32 m².
4. Specific heat capacity: 3588 Ws/m²K.
5. Volume flow rate: 3 (l/h) /m² per collector area.
6. Insulation: Rock wool 40 mm.
7. Black plate: 0.8 mm aluminium.
8. Mixing: water-glycol 40% polypropylene glycol.
9. Distance between each collector: 1.09 m.
10. Number of collectors: 12.

Dual coil indirect hot water tank: Manufacture: standard, number of tanks: 1, volume: 1000 litres, Losses: 2.23 kWh/day, thermal loss rate: 2.99 W/K. Insulation of the tank: 100mm.

Boiler auxiliary heating: Manufacturing: standard, Boiler type: electric with nominal power: 2kW.

Table 1. DHW (domestic hot water) consumption, flat plate collector and collector loop

Average annual production	115.7051 m^3	**Total cross surface area**	116.12 m^2
Average daily production	317 litre	**Specific volume flow rate**	2.94 litre/h
Average DHW temperature	65 ^oC	**Specific heat capacity**	5900 Ws/m^2K
Annual energy requirement	6550 kWh	**Simple heat transfer coefficient (heat losses)**	4.36 W/m^2K
DHW heating energy supply (annual)	6217 kWh	**Heat capacity of mixture**	3533 Ws/kg K
Solar contribution to DHW (annual)	5.2 kWh	**Heat transfer medium with water**	40 % polypropylene glycol
Conversion factor	67 %	**The energy delivered by the collector loop (annual)**	5520 kWh

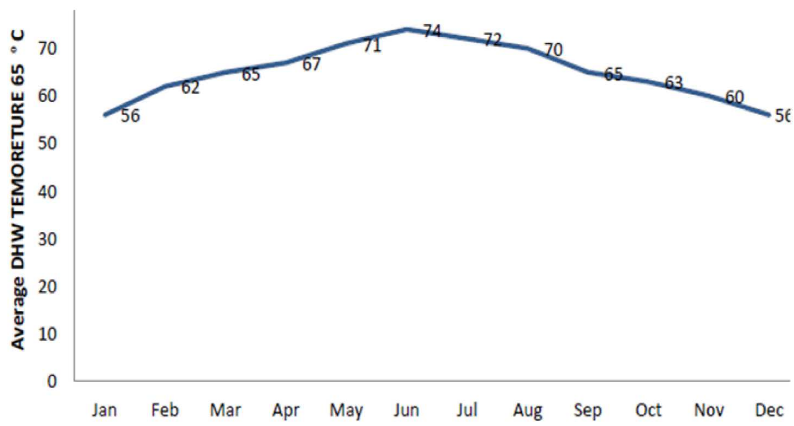

Figure 1. DHW temperature

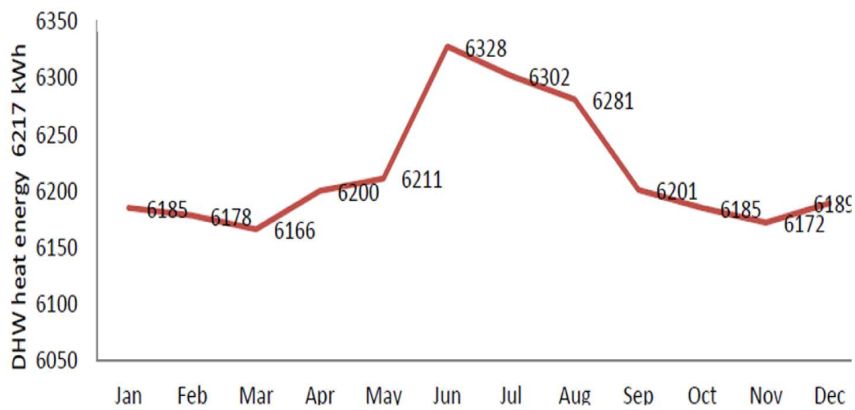

Figure 2. DHW heat energy supply

Table 2. Auxiliary heating and System performance

Auxiliary heating		**System performance**	
Type	Electric heater	**CO_2 Emission avoided**	1817.47 kg
Average Energy Auxiliary heating (annual)	58.4 kWh	**DHW solar fraction**	52.4 %
Efficiency	85 %	**System efficiency**	43.3 %
Energy from auxiliary heating (annual)	1710.8 kWh	**System yields**	5200 kWh
Efficiency based on the higher heating value	77.56 %	**Average annual production**	115.7051 m^3
Efficiency DHW supply	55 %	**With a return temperature of**	33^oC

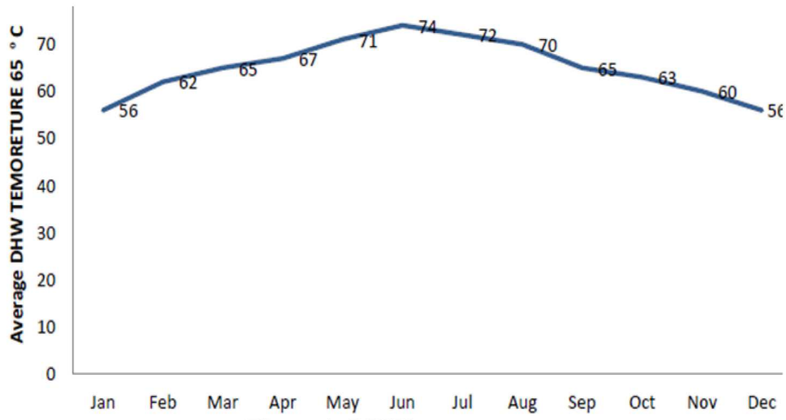

Figure 3. Total solar flat plate collector

Part (2) photovoltaic system calculations

Line losses: D Cand load: All Electric devices + heating +hot water.

Number of PV modules: 12, with manufacturers/ PV module: Shinsung Solar Energy Co. Ltd, PV module: TS-S 430 (UL). Cell Technology: Monocrystallin: it has the best power to size ratio and efficiency, performance in cooler conditions, 18% conversion efficiency, and loss of efficiency is lower at high temperatures, It's good for limited space, PV module efficiency (STC): 16.77%.

Inverter design: 1 x SB 6000TL-21PV system section 1, and Max DC power: 6.28 kW.

Table 3. PV design data

Input A: PV array 1: 8× Shinsung Solar Energy Co. Ltd TS-S 430 (UL), azimuth angle 0 °, tilt angle 23 °
Input B: PV array 2: 4× Shinsung Solar Energy Co. Ltd TS-S 430 (UL), azimuth angle 0 °, tilt angle 23 °

	Input A	Input B
Number of strings	1	1
PV modules per string	8	4
Peak power	3.44 kWh	1.72 kWh
Topical PV voltage	361 V	181 V
Min PV voltage	310 V	155 V
Min DC voltage (grid voltage 220 V)	125 V	125 V
Max PV voltage	525 V	263 V
Mix DC voltage	600 V	600 V
Max current of PV array	8.4 A	8.4 A
Max DC current	15 A	15 A

Table 4. The entire system's data

Photovoltaic design data
Grid voltage: 220V (110V/220V) 50Hz

Total number of PV modules	12	Performance ratio	72.4%
Peak power	5.16kW	Specific energy yield	1833 kWh/kWp
Number of inverters	1	Unbalance load	6.00 KVA
Nominal AC power of the PV inverter	6.00 kW	Max. AC active power (cos ϕ=1)	6.00 kW
AC active power	6.00 kW	Self-consumption	6546.65 kWh
Max. DC power (cos ϕ=1)	6.23 kW	Self-consumption quota	69.2%
Annual energy yield*	9460 kWh	Self-sufficient quota (energy consumption in %	27.4%

Results of the calculations of the PV system

Part (3) Calculation hybrid photovoltaic/thermal solar panel

In this part, the calculations will be conducted for a hybrid system (PV/T) and the software will depend on previous parameters which used it when the systems were evaluated separately, and there are other parameters used with the Polysun software as well, like auxiliary heating: Electric, Storage tank: multi Val CRR 1.25 m, temperature control: class VI-weather compensator, room senior for use modulating heater and pump collector: Small pump.**Results and Conclusions**

According to data that was used in part (flat plate collector) and part (photovoltaic system), and other input data that were used in part three of calculations, the data gained from this part referenced the hybrid system results to a single system (photovoltaic/thermal system), and the results gained from PV/T system were diverse. If we make a comparison between the results of the systems when they were handled separately (FPC+PV system) and the results of the combined PV/T system, looking at the hot water production of the singular system, we get a result of 317 litres/day, and the annual hot water production was 115.7051 m3. The specific volume flow rate was 2.94 l/h, and the average DHW temperature was 65 °C with a 43.3% efficiency for system. As seen in Tables 1 and 2, while hot water production for the hybrid system is 200 litres/day, and the annual production was 73 m^3 and specific volume flow rate was 1.85 l/h, the water temperature output from the hybrid system was 51 °C. The hot water decreased when the system was handled as a single system, because the hot water production came from the absorption of the high temperatures generated by the solar cells, due to direct exposure to solar radiation. Temperatures differed because the piping that carried the water was not directly exposed to solar radiation, and temperatures at the location of piping were below that of the solar cells', so the water worked as s cooling system for solar cell, That is why the amount of hot water production was decreased by 36.91%. When used, the amount of hot water procured from the hybrid system covered about 63.01% of the household's needs, which is considered appropriate for household applications. And in comparison, the electricity produced when the system was a single PV system was 5.16 kWh.

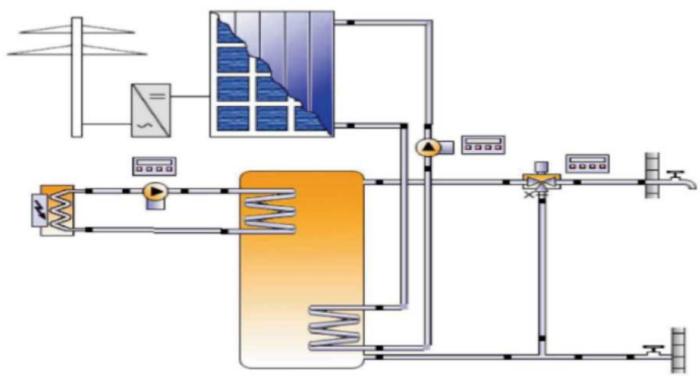

Figure 4. Design of the PV/ T system

Table 5. Production of photovoltaic/thermal hybrid system

Total gross area	116.7 m²	Annual energy production of PV (AC)	10611 kWh
Total annual field yield (solar thermal energy)	5355 kWh	Inverter	SB 6000TL- 21
Collector field yields related to gross area	672.8 kWh/m^2/yr	CO_2 savings	1821.2 kg
Collector field yields related to aperture area	672.8 kWh/m^2/yr	Total solar fraction	52%
Annual solar thermal energy related to the system [Qsol]	446.34 kWh	Performance ratio	76.8%
Average reduction in CO_2 emission	4357.55 kg	Total efficiency	58.6%
Photovoltaic roof plan 1	Monocrystallin	Life span (PV/T system)	25 years
Total nominal power generation field (peak power)	6.42 kWh	Specific energy yield	2343.3k Wh/kWp

Table 6. Results of component systems

Hot water demand		Circuit pressure drop [pump]	0.193 bar
Volume withdrawal/daily consumption	200 litres/day	Electricity energy consumption (annual)	23.5 kWh
Annual hot water consumption	73 m^3	CO_2 savings solar thermal	2561.4 kg
Average temperature of water out of collector	51 °C	Storage tank	
Specific volume flow rate	1.85 l/h	Volume	1000 L
Energy demand [Qdem]	2616.8 kWh	Height	1.25 m
Boiler and Pump collector			
Circuit pressure drop [boiler]	0.34 bars	Thickness of insulation	110 mm
Total efficiency [boiler]	87.2%	Heat loss	278.2 kWh
Auxiliary heater Electric [boiler Power] annual	36 kWh	Connection losses	126.7 kWh

The peak power, and the annual electricity production of the system was 9461 kWh, with a system performance ratio of 72.4%, as seen in Table 4. While used, a hybrid PV/T system gave about 6.42 kWh peak power, and the annual electricity production for the system was 10611 kWh, with performance ratio 76.8% as seen in Table 5. There is an increase in the amount of electricity produced when using the hybrid system - about 1150 kWh, or 10.83%. And the performance ratio increased by 5.73% when using the water as a cooling system for solar cells. The amount of electricity produced from the hybrid system covered about 44.34% from what the household needed. The total efficiency of the hybrid (photovoltaic/thermal) system was 58.6%.

Abbreviations

q_{solar}: rate of energy loss from the collector (kW)
$\dot{m}$: mass flow rate (kg/s)
G: incident total radiation on a collector surface (kWh/m^2)
T_i: inlet temperature °C
A_C: collector absorber area (m^2)
T_o: outlet temperature °C
$(\tau\alpha)e$: effective transmittance-absorption production
T_{PV}: PV module temperature °C
Q loss: heat losses from the collector (kW)
T_a: ambient temperature °C
U_L : overall heat loss coefficient $W/(m^2K)$
η_{DC}: conversion efficiency
η_{DC0}: reference conversion efficiency (cell temperature 25 °C, reference solar radiation $1000W/m^2$)
T_a: air temperature in the vicinity of collector °C
T_s: cell temperature °C
T_p: the average absorber temperature °C
Q_u: the rate of useful energy extracted by the collector (kWh)
β: temperature coefficient of solar cell efficiency (1/K)
I_m,V_m: current and the voltage of the PV module operating at a maximum power (A, W)
$T_{PV/T}$: operating temperature of PV/T module (°C)
T_{PV}(eff): effective PV module temperature °C

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