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Simulation of Ground- Coupled Heat Pump with Photovoltaic Thermal Collectors (PVT) in a Desert Climate

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ABSTRACT
This paper presents a challenge study of using geothermal heat pump in desert climate like Kuwait where all cooling and no heating loads. Due to the abundant solar source in these types of climate, using PV is mandatory. PVT collectors have the potential to be a market breakthrough if they could be used to nocturnally cool the borehole thermal energy system. TRNSYS model of Kuwait City house with actual loads was constructed and then connected to a borehole heat exchanger array, PVT collector array, and hot water tank. TRNSYS optimizer used to optimize the number of boreholes, spacing of boreholes, and number of PVT collectors to minimize life-cycle cost. Using hybrid system rather than geothermal heat pump only reduces the number of boreholes from 9 to 6 boreholes. 15 collectors needed for the house with an area of 25m^2. The depth and spacing of boreholes are 75m and 7.5m. The total excess electricity over PV production is 44%. The PV and borehole cost savings are $667/yr and $10,125. The payback period is found to be 7.2 years.

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I. Introduction

Kuwait is a small country in the middle east that is characterized by its long and hot summer period. Kuwait is facing a big challenge in cooling process with less emissions. For example, air conditioning accounts for 75% of the nation's peak power demand and more than 50% of annual energy consumption. Also, 60% of total energy consumption used for residential buildings compared to 25% globally [1]. The demand for electricity is growing at a rate of 10% and is predicted to be more than 20,000 MW in Kuwait by 2020 [2]. Therefore, using different source of energy rather than fossil fuel will not only benefit the economy of Kuwait by increasing the oil exports, but also achieving the sustainability and reducing the harmful effects of global warming.

There are many renewable energy sources that can be used to meet the residential sector demand in Kuwait such as solar, wind, and geothermal. Even though, geothermal energy is not a common source of energy in hot climate countries like Kuwait, primary results of some researches are encouraging for more investigating specially by using hybrid system such as PVT with geothermal boreholes. PV makes sense in these climates obviously due to abundant solar resource. PVT collectors have the potential to be a market breakthrough if they could be used to nocturnally cool the borehole thermal energy system. The PVT system is used to produce both electricity and thermal energy to improve the efficiency of the system, reduce both cost and the space required [3]. It has many applications such as domestic water heating, building applications, and distillation.

On the other hand, in order to maximize the benefit of using hybrid system, is having appropriate design for ground loop heat exchangers. This will reduce the cost of the investment, balance the ground load, and maintains the entering fluid temperature of the GLHE within the required range 35-40℃ [4 & 5].

The scope of this project is to construct TRNSYS model of Kuwait City house with actual loads, connected to a borehole heat exchanger array, PVT collector array, and hot water tank to investigate the performance of a hybrid thermal ground heat exchanger system with photovoltaic thermal collectors in desert climates (Kuwait). Monthly electricity data was collected for 24 months for typical residence house for analysis and validations.

II. Literature review

Jose Bilbao's investigated the performance of unglazed PVT for 24 hours during six months in Sydney, Australia. They found that the 57% of total heat losses are due to radiation while convection and back-edge losses account for 40% and 3%, respectively. Their results showed that the average night radiative cooling of PVT

collectors in Sydney around 750 Wh/m^2 during summer and around 1000 Wh/m^2 during winter. Moreover, they simulated for different climate zone and found the average night radiative cooling throughout the year in Singapore and Tucson, Arizona are 400 and 900 Wh/m^2, respectively. [6].
Similarly, Eicker and Dalibard have done the experiment and took a step further to implement PVT modules in a residential zero energy building in Madrid, Spain. They achieved 60 – 65 W/m^2 of cooling when the PVT collector used to cool a warm storage tank and 40 – 45 W/m^2 of cooling when the energy was directly used to cool a ceiling. In addition to that, the PVT produces 205 kWh/ m^2 of AC electricity in Madrid. [7]

Yi Man in his paper "study on hybrid ground-coupled heat pump system for air-conditioning in hot-weather areas", investigated cooling tower performance as additional heat rejectors for geothermal heat pump system. This is for balancing purposes in cooling dominant buildings. He concluded to the fact that an increase in ground loop heat exchangers temperature can by controlled and eliminated if hybrid geothermal heat pump systems used. Hybrid system has also the advantage of increasing the heat pump performance and significant amount of operating and total cost over 10-year period. [8]

Chiasson in his work "simulation of hybrid solar-geothermal heat pump systems", inspected PVT performance in heating dominant building with use of geothermal heat pump. The use of PVT was for recharging purposes. The result shows that reducing ground loop heat exchangers size by 62% is applicable, if ground was recharged with thermal energy. [9]

Many other authors from various climates have conducted experiments and simulations of PVT or unglazed thermal collectors to provide night cooling. Their findings ranged from 20 to 75 W/m2 per night with negligible differences between PVT and unglazed thermal collectors. For example, the cooling capacity for Iran was from 23-52 W/m2, Spain 60 W/m2, New Zealand 50 W/m2, and Austuralia 75 W/m2.

III. Methodology

TRNSYS optimizer was used to optimize the number of boreholes, spacing of boreholes, and number of PVT collectors to minimize life-cycle cost. PVT type 1011 is a new component that was modeled in TRNSYS due to the lack of PVT specification such as distance between tubes, number of tubes, conductivity from plate to tubes. These data usually are not reported by the manufacturers.

3.1 Simulated model

A residential house in Kuwait can get the benefit from geothermal heat pumps specially in cooling modes since no heating is required in this climate type. The principal is depending on increasing ground boreholes temperature by using heat pumps and maintain high temperature fluids entering heat pumps. In cooling dominant building such as in Kuwait, the relationship between number of ground boreholes and entering fluid temperature is linear. On the other hand, PVT used for many purposes in this climate type such as generate electricity and reduce ground loop fluid temperature. PVT pump play big role in reducing fluid temperature specially at night with both radiation and convection heat transfer with PVT surface.

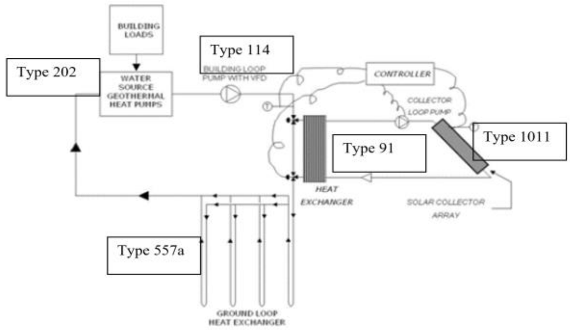

Figure1: Schematic diagram of the hybrid system [9]

The available PVT models in TRNSYS library are called TYPE 50 and TYPE 560. Many researchers reported that TYPE 50 can produce 10 – 60 % of calculation errors due to the assumption of constant collector efficiency factor and not using sky temperature in radiation calculation [10]. In the other hand, TYPE 560 is more reliable but with more details than needed. Also, TYPE 560 applicability is more limited in that it has been optimized for building integrated systems [11]. Therefore, new PVT component has been modeled and added to the TRNSYS library. The new model used the useful thermal energy equation that found in Burch et al [12] which as follow:

$$qu(kW) = F_R A\left[\alpha\ \left(I + \frac{\varepsilon}{\alpha} L\right) - U_L(T_i - T_p)\right]$$

Where:
$F_R = heat\ removal\ effeciency\ factor$
$\alpha = absorpitvity$
$\varepsilon = emissivity$
$U_L = overall\ heat\ coffecient$
$T_i = inlet\ fluid\ temperature$
$T_p = plate\ temperature$
$L = thermal\ radiation = \sigma\ ({T_{sky}}^4 - {T_p}^4)$
$\sigma = Stefan - Boltzmann\ constant$

Also, as stated in Burch et al. modification is needed to recalculate the heat loss coefficient and heat removal factor based on wind speed. The modifications are as the following:

$F_R(\tau\alpha) = a_0 - a_1 \times v$ (Where a_0 = 0.57, a_1 = 0.028 m/s)

$F_R U_L = b_0 + b_1 \times v$ (Where b_0 = 12.08 W/m^2/K, b_1 = 1.842 W.s/m^3/K)

The electrical efficiency of PV collectors defined as a ratio of output power (P) to the incident solar radiation (I) over the collector area (A). The useful energy gain (Q) of thermal collector's equation take in account the energy gain from the sun and the energy loss due conduction, convection, and radiation.

3.2 Building Design and properties

The residential building used in this project is located in Kuwait. It has three floors with a total area of 7272 ft^2. The energy consumption of the house was taken as an average of two years and on monthly basis. Also, eQuest was used to get the average energy consumption over 20 years. The peak heat and cooling loads are 0 and 18kW respectively as the heat load is negligible in desert climate areas such as Kuwait. Figures 2 &3 show electricity and cooling loads for the entire year.

Table1 shows the building loads summary, ground thermal properties and the GHX configuration. The peak cooling load is 18kW where no heating load for the building. The peak design flow rate, heat capacity, and ground thermal conductivity are 3 gpm, 2300 kJ/m^3.k, and 2.1 W/m.K. Ground temperature was calculated based on annual average air temperature to be 27.4 °C. The B/H ratio is around 0.10 that is the borehole spacing to borehole depth. The borehole radius is 0.075. Finally, \$45 per meter was the assumption for the borehole drilling cost. The electrical and thermal characteristic of the simulated PVT is shown in table2. It has an area of 1.65m^2 and cost \$3500/kW [14].

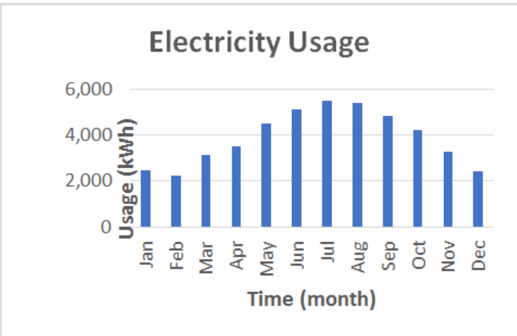

Figure 2: Annual electricity usage of the house

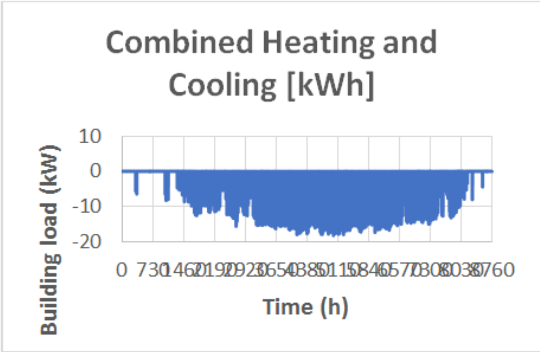

Figure 3: Hourly heating loads (positive) and cooling loads (negative) for the house

Electrical data	
Nominal power (W)	280
Module efficiency	16.87%
Efficiency loss (%/°C)	0.41
NOCT (°C)	45
Referance Temperature (°C)	25
Thermal data	
Optical efficiency a0	55.9%
Heat loss coefficient a1 (W/k.m2)	15.8
Heat loss coefficient a2 (W/k.m2)	0
Testing flow rate (kg/s.m2)	0.018

Table 1 Summary of design data.

Building loads summary	
thermal load peak heating - (kW)	0
thermal load peak cooling - (kW)	18
Vloumitric flow rate of building loop - (kg/h)	3,537
Ground Thermal Properties	
Ground thermal conductivity - (W/m-k)	2.1
Tearth - (°C)	27.4
Ground volumetric heat capacity - (kJ/k-m3)	2300
GHX Design summary	
borehole depth - (m)	75
borehole radius - (m)	0.075
borehole spacing - (m)	7
Grout thermal conductivity - (W/m-k)	2.435

Table 2 PVT electrical and thermal specification.

IV. Result and Discussion

The design started initially with stand-alone geothermal heat pump only and then with PVT as a hybrid system. The results show a 33% less boreholes needed with the hybrid system. The reduction was from 9 to 6 boreholes with the same depth of 75m. The cost savings from reducing the number of boreholes was from \$30,375 to \$20,250. \$676 was saved from installing 15 PVT collectors with an area of 25 m^2. The PVT collectors produces 7.1 MWh electricity throughout the year covering only 9% of the 47 MWh of building usage of electricity while 44% of the PVT electricity production is excess and therefore sold to the grid. (tables 3-6)

The maximum entering fluid temperature is not exceeding 40 ℃ for the simulation period of 20 years for both cases with PV and PVT (figures 4&5). Figure 6 shows the electricity access versus PV output and PV access where figure 7 shows solar cooling gain for each month in the first and 20th year of simulation. The cooling gain increased year by year due to the increase of ground loop temperature which then increased the temperature difference that illustrated in useful energy gain equation above. However, the radiative cooling figure (8) shows that the increasing started from year 8. In addition, the monthly analysis of radiative cooling showed that the collectors have a potential of cooling even during summer nights due to the low sky temperature. Finally, the boreholes cost saving is $10,125, and the simple payback is 7.2 years.

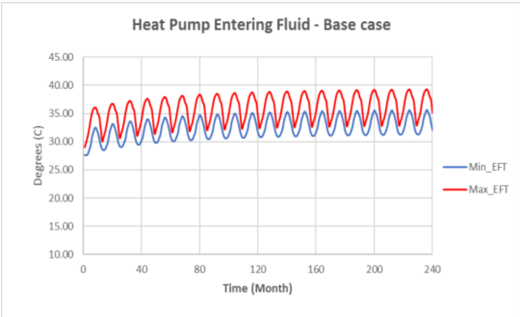

Figure 4 EFT for the base case.

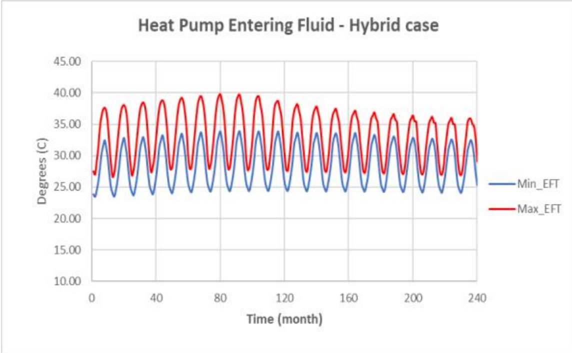

Figure 5: EFT for hybrid case.

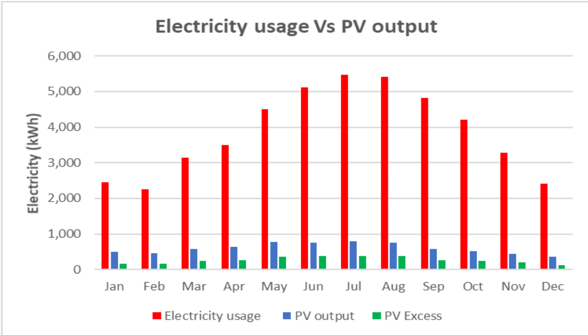

Figure 6: Comparison of electricity usage, PVT electrical output and PVT electrical excess.

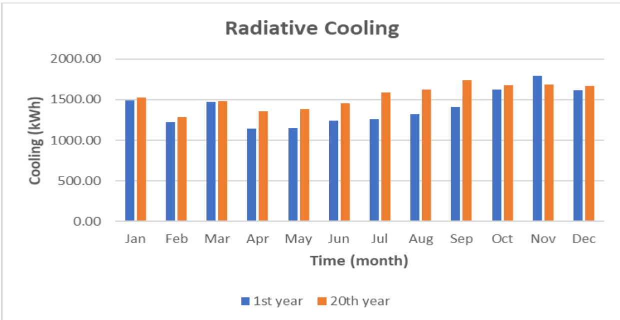

Figure 7: Solar cooling gain for each month in the first and 20th year of simulation.

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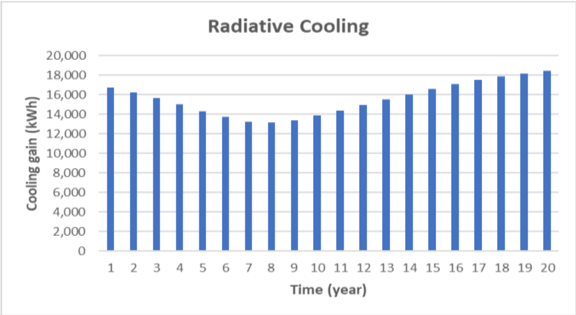

Figure 8: Total solar cooling gain for each year of simulation period.

PVT		
PVT area	1.654	m2
No of collectors	15	-
PVT rated Power	0.285	kWh
Total PV/T Area	25	m2
PVT Cost	3500	$/kWp
Electrecity Purchase cost	0.12	$/kWh
Electrcity sold cost	0.06	$/kWh
Cost	14,963	$
PV Energy	4,005	kWh
PV Energy Excess	3,114	kWh
Electrecity saving	667	$

Gorthermal Boreholes			
Base Case	Number of boreholes	9	boreholes
	Depth	75	
	Cost	30,375	$
	Cost	45	$/m
Hybrid Case	Number of boreholes	6	boreholes
	Depth	75	
	Cost	20,250	$
	Saving	10,125	$
	Boreholes reduction	3	boreholes
		33%	

Economic Analysis		
PVT Cost	14,963	$
PV Saving	667	$/year
Boreholes Cost Saving	10,125	$
Net Cost	4,838	$
Simple payback	7.2	Years

Load met by PV	4,005	9%
Load met by grid	42,574	91%
Total load	46,579	100%
Total PV output	7,119	kWh
Total Excess	3,114	kWh
		44%

Table 3-6: PVT analysis, Geothermal boreholes analysis, Economic analysis, and Total electricity excess from PV

V. Conclusion

In this article, a simulation of ground coupled heat pump with PVT in a desert climate such as Kuwait was investigated using TRNSYS. The simulation was done for the period of 20 years and in monthly and hourly basis. The hybrid system reduces the boreholes by 33% and the cost by $10,125. 15 collectors used to reduce the electricity cost by $667/yr. The total excess over total PV output is 44%. The simple payback period of the hybrid configuration was found to be 7.2 years. Having appropriate design for ground loop heat exchangers will reduce the cost of the investment, balance the ground load, and maintains the entering fluid temperature of the GLHE within the required range. PVT used for many purposes in this climate type such as generate electricity and reduce ground loop fluid temperature. PVT play big role in reducing fluid temperature specially at night with both radiation and convection heat transfer with PVT surface. Thus, it is very important to include sky temperature in radiation calculation.

References

[1]. Ben-Nakhi, A. (2011). The Prospective of District Cooling for Residential Sector in Kuwait. Proceeding of the Kuwait District Submit Cooling, Kuwait.

[2]. Kararty, M., & Hajiah, A. (2011). Analysis of Impact of Daylight Time Savings on Energy Use of Buildings in Kuwait. Energy Policy 39, 2319-2329.

[3]. Aditya Chauhan, V.V. Tyagi, Sanjeev Anand, Futuristic approach for thermal management in solar PV/thermal systems with possible applications, Energy Conversion and Management, Volume 163, 2018, Pages 314-354.

[4]. A.D. Chiasson. Cy Yavuzturk, Assessment of the viability of hybrid geothermal heat pump systems with solar thermal collectors, ASHRAE Transactions, Volume 109, 2003, Pages 487-500.

[5]. Andrew. D Chiasson, Geothermal Heat Pump and Heat Engine Systems: Theory and Practice, John Wiley & Sons, 2016.

[6]. Jose Bilbao, Alistair Sproul, Night Radiative Cooling With Unglazed PVT-Water Collectors: Experimental Results and Estimation of Cooling Potential, Solar World Congress 2015, At Daegu, Korea

[7]. Ursula Eicker, Antoine Dalibard, Photovoltaic–thermal collectors for night radiative cooling of buildings, Solar Energy, Volume 85, Issue 7, 2011, Pages 1322-1335, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2011.03.015.

[8]. Yi Man, Hongxing Yang, Jinggang Wang, Study on hybrid ground-coupled heat pump system for air-conditioning in hot-weather areas like Hong Kong, Applied Energy, Volume 87, Issue 9, 2010, Pages 2826-2833.

[9]. A.D Chiasson, Cy Yavuzturk, Simulation of Hybrid Solar-Geothermal Heat Pump

Systems, Proc. 39th Stanford Geotherm. Work, 2014, Pages 1-8.
[10]. Bilbao, Jose & Sproul, Alistair. (2012). Analysis of Flat Plate Photovoltaic-Thermal (PVT) Models.
[11]. M. Collins, A review of PV, solar thermal, and PV/thermal collector models in TRNSYS, IEA SHC – Task, 35 (2009), p. 78
[12]. Jay Burch, Craig Christensen, Jim Salasovich, Jeff Thornton, Simulation of an unglazed collector system for domestic hot water and space heating and cooling, Solar Energy, Volume 77, Issue 4, 2004, Pages 399-406, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2003.12.014.
[13]. Mohammad Alobaid, Ben Hughes, John Kaiser Calautit, Dominic O'Connor, Andrew Heyes, A review of solar driven absorption cooling with photovoltaic thermal systems, Renewable and Sustainable Energy Reviews, Volume 76, 2017, Pages 728-742.
[14]. UK Department for Business, Energy and Industrial Strategy, Evidence Gathering – Low Carbon Heating Technologies - Hybrid Solar Photovoltaic Thermal Panels, 2016.