Axis Tracking Analysis of Concentrating Solar Energy Systems: A case study from Cyprus

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***Abstract* — This paper presents the one axis including East-West and North-South tracking and two axis tracking of concentrating solar energy systems. In order to represent valuable information, hourly meteorological data file in TMY2 format taken from the Larnaca Airport has been used for designing a model. This model calculates the tracking and non-tracking system diffuse, beam and global insolation. Valuable tables and graphs for the result of this model are presented in this paper. It is concluded that two axis tracking yields better results.**

***Keywords* — Renewable energy, Concentrated Solar Power, Solar Thermal Energy, Cyprus.**

I. Introduction

Electrical energy demand of Cyprus mainly depends on conventional energy resources at the moment. However Cyprus has high solar potential due to its geographical attributes.

Cyprus Turkish Electricity Authority (KIBTEK) generates, distributes and sells power to the Northern part of Cyprus. KIBTEK has two 60 MW steam plant generators for the base load and six 17.2 MW diesel generators in order to catch up with the peak values [1]. There is another energy company named AKSA which provides 92 MW of capacity to the grid [1]. Moreover, another protocol was signed with KIBTEK and AKSA in order to increase its capacity to 120 MW. Lastly, there is a solar photovoltaic (PV) power plant and its capacity is 1.27 MW. Among all of these resources, fuel oil is the most prominent one and the total capacity is approximately 320 MW.

A comprehensive study has been carried out for evaluating the position of the sun and designing and building a sun-tracking system, which measures direct solar radiation with a pyrheliometer [4]. Another valuable study indicates that for two axes tracking on the solar energy collection the measured collected solar energy on the tracking surface has approximately 40 percent higher efficiency than that of a fixed surface [5].

The rest of this paper is organized as follows: In Section 2, we provide a general background. We detail system modeling in Section 3, and introduce our evaluation and results in Section 4. We conclude our work in Section 5 and discuss the future work in Section 6.

II. Background

Motivation

Solar energy is one of the most abundant resources in Europe. Understanding the global energy problems and its influences to the environment may create a better estimated solution for future generations. Rapid depletion of fossil fuel resources on a worldwide basis brings about an urgent need to look for alternative energy resources. Based on wind speed data, we can present a wind energy harvesting scenario, however wind speed maps around the world do not guarantee any values due to the fact that the wind does not blow consistently. On the other hand solar energy can offer more predictable energy scenarios. Terrestrial solar resources are defined as the solar radiation reaching the earth's surface. There exist one axis concentrating solar systems including East-West (EW) and North-South (NS) tracking, and two axis (2A) tracking systems. Our main objective is to design a computer aided model for the comparison of concentrating solar energy system. In other words, which tracking method has better solar energy absorption for the data set obtained in a specific location in Cyprus.

Beam and Diffuse Solar Radiation

There are two main types of solar radiation, namely beam solar radiation and diffuse solar radiation. Beam solar radiation is the type of solar radiation that comes directly from the sun. On the other hand, diffuse solar radiation is the type of solar radiation that is reflected from surrounding objects.

In this paper, we investigate tracking systems in order to increase solar radiation absorption in order to make more efficient systems.

III. System Modeling

Organic Rankine Cycle:

Following analysis and some of the equations are inspired from [2] and [3]. For this analysis, a nominal thermal efficiency of the Organic Rankine Cycle (ORC) ($\eta_{th,o}$) of 10% is assumed corresponding to hot (Q_H at T_H) and cold (Q_c at T_c) heat transfers at T_H=373 K and T_C=298 K. T_O is the reference temperature and is equal to T_C. As the Carnot efficiency suggests, the actual thermal efficiency of the ORC will vary with the values of T_H and T_C. The actual ORC at METU NCC is designed to operate with T_H = 373 K with an ignorable hit rate, and therefore in this analysis, T_H is assumed as constant at 373 ^oK. However, T_C is related to and therefore will vary with the environmental conditions. Since a wet cooling tower is used, T_C will vary with both the dry bulb temperature (T_{db}) and relative humidity (φ) of the environment, both of which are given in typical meteorological year (TMY2) formatted data sets. However, modeling the impact of both dry bulb and relative humidity on T_C and the resultant variation in thermal efficiency with T_C requires relatively complex modeling which is beyond the scope of our analysis. Therefore, actual thermal efficiency (η_{th}) is assumed to only vary with T_{db} according to the following model in (1), based on Carnot efficiency's variation with T_C.

$$\frac{\eta_{th}}{\eta_{th,o}} = \frac{\eta_{carnot}}{\eta_{carnot,p}} = \frac{\left(1-{}^{T_{db}}/_{T_H}\right)}{\left(1-{}^{T_o}/_{T}\right)} \quad (1)$$

Solving (1) for η_{th} yields as in (2):

$$\eta_{th} = \eta_{th,p}\left(\frac{T_H - T_{db}}{T_H - T_o}\right) \quad (2)$$

As mentioned earlier, $T_o = 298$ K and $T_H = 373$ K. Based on the definition of Carnot efficiency.

$$Q_{orc} = W_{orc} / \eta_{th} \quad (3)$$

(2) and (3) are combined to yield (as in [12]):

$$\dot{W}_{orc} = \max\left[\underbrace{\eta_{th}\dot{Q}_{PTC}}_{\text{Solar Only Mode}}, \underbrace{\dot{W}_{demand,0}}_{\substack{\text{Propane Combined and}\\ \text{Propane Only Mode}}}\right] \quad (4)$$

The rate of heat transfer to the ORC is described as:

$$Q_{orc} = \frac{W_{orc}}{\eta_{th}} \quad (5)$$

Boiler Model:

The boiler for METU NCC system uses propane gas. Propane is used only to meet the minimum electrical energy demand. The rate of heat transfer of the boiler is described in (6).

$$\dot{Q}_{boiler} = \dot{Q}_{ORC} - \dot{Q}_{PTC} \geq 0 \quad (6)$$

The heat transfer per unit mass of propane to the heat transfer fluid (HTF) in the collector loop is assumed equal to propane's heating value (HV). The value of HV is 45982 kJ/kg for liquid propane combustion at 25 °C with water vapor in the products [3]. The rate of heat transfer to the HTF in the boiler becomes:

$$\dot{Q}_{boiler} = \dot{m}_{C_3H_8} HV_{C_3H_8} \quad (7)$$

With (7), the mass flow rate of propane gas is calculated for every hour of the year. Assuming 100% theoretical air and complete combustion and modeling air as 21% O_2 and 79% N_2, the chemical reaction for the combustion of propane described in (8). To quantify the impact on climate change for this system, we also note that three moles of CO_2 are produced for every mole of propane burned in our work.

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.8N_2 \quad (8)$$

Cooling Tower Model:

The interest in modeling the cooling tower is to perform an order-of-magnitude analysis for the water consumed during system operation. For this purpose, a simple model of the cooling tower is sufficient in which all of the low temperature heat transfer from the ORC (Q_c) is used to evaporate water at 25 °C; e.g., only isothermal latent heating and not sensible heating effects are modeled.

$$\dot{Q}_c = \rho_{H_2O}\dot{V}_{H_2O}h_{fg} \quad (9)$$

In (9), ρ_{H2O} represents the density of liquid water, V_{H2O} stands for the volumetric rate of water consumed by the cooling tower and h_{fg} is the enthalpy of evaporation for water. For the base case analysis, we assume ρ_{H2O} as 1.0 kg/liter and h_{fg} is evaluated at 25 °C as 2442 kJ/kg [6].

Parabolic Trough collector Model:

The model results in the heat transfer from the collector to the heat transfer fluid per unit aperture area, (Q_{PTC}/A_a), for each hour of the year. For this analysis, a total collector field aperture area (A_{coll}) of 216 m^2 is assumed and a mean collector operating temperature ($T_{m,op}$) of 120 °C.

$$\frac{Q}{A_a} = \underbrace{F'(\tau\alpha)_{en}K_{\theta b}(\theta)G_b}_{Beam\ insolation} - c_1(t_m - t_a) \quad (10)$$

IV. Results and Evaluation

In this section the results of the model are presented in the form of tables and figures. Consistent with the theory, the amount of carbon dioxide emissions and water consumption increases with ambient temperature, both of which at their peak value in summer months.

Table 1,2 and 3 presents East-West, North-South and 2-Axis tracking system results respectively. Annual results of East-West, North-South and 2-Axis tracking systems are 231.21 kWh/day 219.20 kWh/day and 293.81 kWh/day respectively. To note some of the important aspects of this analysis, it is indicated that 2-Axis system has the best efficiency among all. It is assumed that both EW and NS tracking system has the same initial cost, we are going to prefer EW tracking system in case of more solar absorption.

Although the water consumption is similar for all the systems, the CO_2 emissions are less for 2A systems. fraction values are more for Fresnel collectors. Once economic aspects are investigated, it is also obvious that the PTC systems are highly expensive due to the production of the parabolic shape compared with Fresnel systems.

It is observed that the minimum CO_2 emissions occur in January and the maximums occur in August which can be reasoned by the effect of ambient temperature. Ambient temperature is the factor that reduces the main energy production due to Carnot efficiency. Carnot efficiency depends on the hot and cold temperature values. In the model, collector temperature value is a constant term but the value of T_{cold} relies on the ambient temperature.

Figure 1 presents solar fractions in comparison with one axis (1-A) and 2A tracking systems. It is observed that 2-A tracking system is the best for solar fraction. Almost 30% efficiency can be seen in September. September is the month that ambient temperature is reasonable; therefore, energy generation is high for rankine cycle. 1-A tracking systems have almost the same solar fraction even though EW tracking system has a little bit higher solar absorption.

Table 1: East-West Tracking System

Month	Q_{PTC}	M_{co2}	V_{H2O}	fs
	kWh/day	kg/kWh	lt/kWh	-
Jan	249.69	1.66	11.16	0.18
Feb	145.75	1.81	11.24	0.10
Mar	172.54	1.81	11.44	0.12
Apr	196.59	1.85	11.95	0.13
May	185.52	1.97	12.58	0.12
Jun	211.18	2.03	13.19	0.13
Jul	210.91	2.12	13.77	0.13
Aug	200.77	2.13	13.76	0.12
Sep	374.64	1.82	13.29	0.23
Oct	311.43	1.82	12.74	0.20
Nov	308.19	1.70	11.93	0.20
Dec	207.27	1.75	11.40	0.14
Annual	231.21	1.87	12.37	0.15

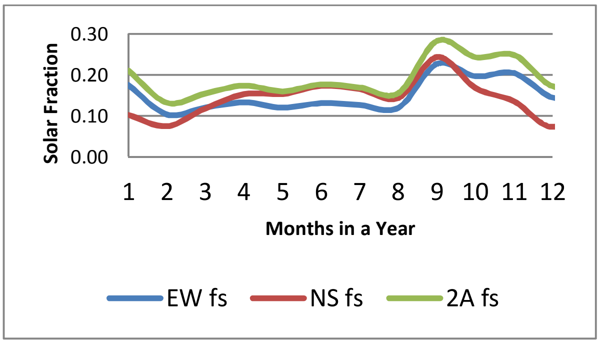

Figure 1: Solar Fraction

Table 2: North-South Tracking System

Month	Q_{PTC}	M_{co2}	V_{H2O}	fs
	kWh/day	kg/kWh	lt/kWh	-
Jan	141.54	1.80	11.15	0.10
Feb	104.45	1.87	11.23	0.08
Mar	167.92	1.81	11.44	0.12
Apr	225.61	1.81	11.95	0.15
May	236.74	1.89	12.58	0.15
Jun	279.66	1.93	13.19	0.17
Jul	276.32	2.02	13.77	0.17
Aug	240.14	2.08	13.76	0.14
Sep	394.98	1.78	13.29	0.24
Oct	261.64	1.88	12.73	0.17
Nov	198.31	1.84	11.92	0.14
Dec	103.13	1.90	11.39	0.07
Annual	219.20	1.88	12.36	0.14

Table 3: 2-Axis Tracking System

Month	Q_{PTC}	M_{co2}	V_{H2O}	fs
	kWh/day	kg/kWh	lt/kWh	-
Jan	301.30	1.59	11.16	0.21
Feb	186.51	1.76	11.24	0.13
Mar	221.79	1.74	11.44	0.16
Apr	257.25	1.76	11.95	0.17
May	247.23	1.88	12.58	0.16
Jun	285.14	1.92	13.19	0.18
Jul	283.52	2.01	13.77	0.17
Aug	260.40	2.05	13.76	0.16
Sep	469.78	1.68	13.30	0.28
Oct	387.10	1.71	12.74	0.24
Nov	377.68	1.60	11.94	0.25
Dec	247.95	1.70	11.40	0.17
Annual	293.81	1.78	12.37	0.19

V. Conclusion

In designing a solar power system, analysis of tracking solar systems play a significant role but analysis of these solar systems are highly dependent on their location and time of use. Analysis of detailed incoming solar radiation data indicates which system has better solar energy absorption. Furthermore, this analysis can save money for the investors by allowing them to compare the efficiency data of the tracking systems between each other. Beam and diffuse solar radiation have a significant role for selecting tracking or non-tracking systems. It is observed that tracking systems have more tolerances in case of higher beam solar radiation. 2-A tracking system has the best solar absorption for Cyprus, it has about 19 % yearly average efficiency.

VI. Future Work

The work we conduct in this paper consists of 1-A and 2-A tracking systems. Further work may be done to carry this over to a more general and detailed range by including cost analysis of each system.

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