A Predictive Numerical Model for Analyzing Performance of Solar Photovoltaic, Geothermal Hybrid System for Electricity Generation and District Heating

Samuel Sami, Jorge Rivera

Research Center for Renewable Energy, Catholic University of Cuenca, Cuenca, Ecuador

Email address:

dr.ssami@transpacenergy.com (S. Sami)

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Abstract: A simulation and analysis of the energy conversion equations describing the behavior of a hybrid system composed of solar photovoltaic PV, and geothermal subsystems for power generation and district heating are presented in this paper. A numerical model based upon the aforementioned energy conversion equations was developed, coded and results were compared to experimental data. The model is intended to be used as an optimization and design tool for such hybrid systems. The model predicted results compared fairly with experimental data under various conditions.

Keywords: Hybrid System, Solar Photovoltaic, Geothermal, Modeling, Simulation, Validation, Experimental Data

1. Introduction

Renewable and nonconventional methods of power generation such as wind, solar, hydraulic, biomass, geothermal, thermal storage and waste heat recovery power generations offer power supply solutions for remote areas that are not accessible by grid power supply [1-6]. Hybrid renewable energy system is an integrated system of two or more renewable energy systems that can complement each other, provide higher quality and reliable power supply independent of the grid [1-8]. Hybrid solar/biomass plants will become an increasingly attractive option as the price of fossil fuel and land continue to rise and the cost of solar thermal technology falls [5, 6]. Although biomass power plants can operate continuously, they can have high initial cost, uncertain supply chain security and require bulk transportation [4].

Mustafa [9] presented and discussed the electrification of rural areas and a review of power standalone system such as; solar and hybrid, solar-wind, solar-hydro hybrid, solar-wind-diesel hybrid, and solar-wind-diesel-hydro/biogas. In addition, reference [9] presented and analyzed the viability and importance of solar energy use in global electrification. Another study was proposed by references [10] for

implementation of hybrid systems in rural area disconnected from the grid. The study discussed two tri-hybridization processes. The tri-hybrid system included hydro-wind and Photovoltaic.

Geothermal energy utilization is generally divided into two categories, i.e., electric energy production and direct uses. Direct utilization of geothermal energy refers to the immediate use of the heat energy rather than to its conversion [11-16]. Geothermal power can be produced by dry steam, flashed-steam, binary and Kalina as well as Organic Rankine Cycle (ORC) plants depending on the temperature and state of the geothermal fluid [13]. Flashed steam (single and double-flash) are most commonly used in geothermal power generation systems with a total share of 61% within the installed capacity in the World, mainly because most geothermal reservoirs are formed by liquid dominated hydrothermal systems [11-16]. Geothermal systems either use steam, which flows through the entire cycle of conventional (dry and flashed-steam) or ground water that drives ORC using organic fluids or refrigerants. Most direct use applications use geothermal fluids in the low-to-moderate temperature range between 50°C and 150°C [17, 18]. This system is considered in the present study. The proposed geothermal system is consisted of a production facility well

to supply the heated water to the surface, a mechanical system including piping, pump, valves, other fittings and controls to deliver the geothermal energy to the buildings. Hot water radiators were bused to heat up the buildings warmer during winter seasons.

Of a particular interest is the electrification of remote areas. A review of power stand-alone system that are suitable for electrification of remote areas such as solar and hybrid, solar-wind, solar-hydro hybrid, solar-wind-diesel hybrid, and solar-wind-diesel-hydro/biogas hybrid systems have been presented and discussed in reference [19-24]. The viability and importance of solar energy as well as other renewable energies used in global electrification also have been presented and analyzed. Another study was proposed by Bhandari [21] for implementation in rural areas disconnected from the grid. The study discussed two tri-hybridization processes. The tri-hybrid system included hydro-wind and Photovoltaic. Furthermore, another PV and hydro-wind system has been suggested to supply uninterrupted power to a remote village in Ethiopia by Bekele and Tedesse [24] and the code HOMER was used to optimize that hybrid system. In addition, other studies were presented on PV-wind-battery hybrid and PV-wind-diesel-battery hybrid intended for rural electrification in Malaysia [25-27]. Furthermore, the energy conversion equations describing the total power generated by a hybrid system of solar photovoltaic, wind turbine and hydraulic turbine were presented by Sami and Icaza [28], and integrated simultaneously. For the purpose of validating this simulation model, the energy conversion equations were coded with MATLAB-V13.2.

This paper is concerned with analysis of the main heat and mass transfer mechanisms in PV thermal behavior and the direct use of geothermal energy for power generation and district heating in buildings. To this end, a numerical simulation model using one dimensional system of equations is presented hereby to describe the geothermal, district heating as well as thermal PV phenomena and related issues.

2. Mathematical Modeling

In the following sections, the energy conversion equations of the geothermal energy and solar radiation into an electrical energy and heat are presented;

2.1. Geothermal Energy

In the following a heat and mass transfer model is presented for the geothermal energy conversion;

The thermal energy required to heat the building can be written as [17-19],

$$Q = Q_o (T_{in} - T_{out}) / (T_{in} - T_{out,0}) \quad (1)$$

Where Q_o represents the design load at design conditions and $T_{out,0}$ is the design outdoor temperature.

And equation (1) can be rewritten as follows;

$$Q = Q_o (\Delta T_{im} / \Delta T_{im,0})^n \quad (2)$$

Where the Logarithmic Mean Temperature Difference (LMTD) between the indoor space and heating water circulating is given by the following relationship;

$$\Delta T_{im} = (T_s - T_r) / \ln[(T_s - T_{in}) / (T_r - T_{in})] \quad (3)$$

The exponent “n” in equation (2) is assumed as 1.3 [16];

$$Q = Q_o (\Delta T_{im} / \Delta T_{im,0})^{1.3} \quad (4)$$

The heat transfer from the radiator heat exchanger to the building as shown in Figure 1-a can be expressed as follows;

$$Q = V c_p \rho (T_{sw} - T_{rw}) \quad (5)$$

Where, V , C_p and ρ are water mass flow rate, specific heat of water and density, respectively.

T_{sw} and T_{rw} are supply and return temperatures of water.

The heat balance at the radiator heat exchanger and the time variation of the heating water delivery temperature T_d can be expressed by the following equation [17-20];

$$dT_d/dt = -(m_w c_p (T_d - T_L)) / (\rho_w c_p V_{HE}) + (m_{geo} \eta_{HE} (T_{well} - T_{rejection})) / (\rho_w c_p V_{HE}) \quad (6)$$

Where;

m_w : Heating water mass flow rate

m_{geo} : Geothermal water mass flow rate

T_d : Heating water temperature delivery to building

T_L : Heating water return temperature from building.

The geothermal efficiency for heating the building can be expressed as follows;

$$\eta_{geothermal} = \frac{Q_{ed}}{Q_{geothermal}} \quad (7)$$

Where,

Q_{ed} : represents the heat load during the district heating application.

$Q_{geothermal}$ is the geothermal energy and is obtained by the following equation;

$$Q_{geothermal} = m_{geo} C_p \eta_{HE} (T_{well} - T_{rejection}) \quad (8)$$

2.2. Solar Photovoltaic

The solar photovoltaic panel is made of modules and each module is consisted of arrays and cells. The dynamic current output can be obtained as follows [17, 20, 22, 26, 27, 30, and 31];

$$I_p = I_L - I_o \left[\exp \left(\frac{q(V + I_p R_s)}{A k T_c} \right) - \left(\frac{(V + I_p R_s)}{R_{sh}} \right) \right] \quad (9)$$

And

$$I_o = B T_c^3 \left[\exp \left(-\frac{E_{go}}{k T_c} \right) \right] \quad (10)$$

$$I_L = P_1 G [1 - P_2 (G - G_r) + P_3 (T_c - T_r)] \quad (11)$$

Where;

The PV cell temperature T_c is influenced by factors such as solar radiation, ambient conditions, and wind speed. This

parameter impacts the PV output current, and its time-variation can be determined from the following [8-10, 17];

$$(m C_{p_{module}}) \frac{dT_c}{dt} = Q_{in} - Q_{conv} - Q_{elect} \quad (12)$$

Where;

$$Q_{in} = \alpha_{abs} G S_p \quad (13)$$

$$Q_{conv} = S_p H (T_c - T_a) \quad (14)$$

$$Q_{elect} = \eta G S_c \quad (15)$$

$$H = 1.2475 (\Delta T \cos \beta)^{\frac{1}{3}} + 2.685u \quad (16)$$

$$\eta = \eta_o [1 - \gamma (T_c - T_r)] \quad (17)$$

Where;

$T_c - T_r$ Represents the difference between the PV cell and reference temperatures, respectively.

2.3. Battery Charging and Discharging Model

The battery stores excess power going through the load charge controller (CF Figure. 1a). The battery keeps voltage within the specified voltage and thus, protects over discharge rates, and prevent overload.

During the charging period, the voltage-current relationship can be described as follows [17, 27];

$$V = V_r + \frac{I \left(\frac{0.189}{(1.142 - soc) + R_i} \right)}{AH} + (soc - 0.9) \ln \left(300 \frac{I}{AH} + 1.0 \right) \quad (18)$$

And;

$$V_r(V) = 2.094 [1.0 - 0.001(T - 25^\circ C)] \quad (19)$$

However, during the discharging process and using equation (19), the current-voltage can be;

$$V = V_r + \frac{I}{AH} \left(\frac{0.189}{soc} + R_i \right) \quad (20)$$

And R_i is given by;

$$R_i(\Omega) = 0.15 [1.0 - 0.02(T - 25^\circ C)] \quad (21)$$

Where,

$V_r(V)$, I : the terminal voltage and current respectively

$R_i(\Omega)$: Internal resistance of the cell and T is the ambient temperature.

AH : Ampere-hour rating of the battery during discharging process

Finally, the power produced by the PV array can be calculated by the following equation,

$$P = V I_p \quad (22)$$

Where I_p is given by equation (9).

2.4. Charge Controller

Generally, the controller power output is given by [17, 28];

$$P_{Cont-dc} = V_{bat} (I_{rect} + I_{PV} + I_{orc}) \quad (23)$$

Where; V_{bat} is multiplication of the nominal voltage DC in the battery for any particular system and I_{rect} , I_{PV} and I_{orc} represent the output current of the rectifier in DC and currents of PV and ORC vapor turbine.

2.5. Inverter

The characteristics of the inverter are given by the ratio of the input power to the inverter P_{inv-ip} and inverter output power P_{inv-op} . The inverter will incur conversion losses and to account for the inverter efficiency losses, η_{inv} is used [28, 30];

$$P_{inv-ip} \cdot \eta_{inv} = P_{inv-op} \quad (24)$$

The AC power of the inverter output $P(t)$ is calculated using the inverter efficiency η_{inv} , output voltage between phases, neutral V_{fn} , and for single-phase current I_o and $\cos \phi$ as follows;

$$P(t) = \sqrt{3} \eta_{inv} V_{fn} I_o \cos \phi \quad (25)$$

Finally, the hybrid system energy conversion efficiency for harnessing energy from solar PV and geothermal is given by;

$$\eta_{hs} = \frac{P(t) + Q_{ed}}{Q_{in} + Q_{igeothermal}} \quad (26)$$

Where $Q_{igeothermal}$ and Q_{in} are the geothermal heat and solar irradiance, and given by equations (10) and (13), respectively. In addition, Q_{ed} is the heating load supplied to building in the district heating application and $P(t)$ is the PV solar electrical output and defined by equation (25).

3. Numerical Procedure

The energy conversion and heat transfer mechanisms taking place during various processes shown in Figures 1a, and 1b, are described in Equations (1) through (26). These equations have been solved as per the logical flow diagram presented in Figures 2a, and 2b, where, the input parameters of geothermal and solar PV conditions as well as other independent parameters are defined. Dependent parameters were calculated and integrated in the system of finite-difference formulations. Iterations were performed until a converged solution is reached with acceptable iteration error.

The numerical procedure starts with using the solar radiation, geothermal well conditions to calculate the mass flow rate of geothermal flow rate circulating in the geothermal loop and water flow to heat the building under specified conditions. The thermodynamic and thermophysical properties of geothermal were employed to calculate the water flow. This follows by using the finite-difference formulations to predict the time variation of the building heat load, supply water temperature to building, and the PV cell temperature, as well as other hybrid system power outputs and efficiencies. Finally, hybrid system efficiency is calculated at each input condition.

Figure 1a. Proposed hybrid system; geothermal subsystem.

Figure 1b. Proposed hybrid system; PV system.

Figure 2a. Flow diagram for geothermal subsystem.

Figure 2b. Flow diagram for PV subsystem.

4. Results and Discussion

In order to solve the aforementioned equations (1) through (26) and taking into account the heat and mass transfer during the geothermal, district heating and PV conversion process, the above mentioned equations were coded with finite-difference formulations. In addition, for the purpose of validation, the predicted simulated results were compared to data under various conditions. In the following sections, we present analysis and discussions of the numerical results predicted as well as validations of the proposed simulation model.

Figures 3 and 4 present a typical ambient and solar isolation profiles at the site for various months of the year 2015 and 2016 at different hours of the day. It is quite apparent that the peak solar irradiation and maximum temperatures occur at midday. However, average solar irradiation and ambient temperatures were used in the modeling and simulation of the Photovoltaic panels.

4.1. Geothermal Simulation

Equations (1) through (9) present the heat and mass energy balance during the geothermal process where geothermal heat absorbed heat from geothermal well is converted to heat up the building. Different geothermal flows of 400 GPM to 650 GPM were considered for this study. In addition, different geothermal well temperatures were also considered in this study varied from 220F to 350 F.

The predicted results of the geothermal simulation at different conditions are presented in Figures 5 through 7. In

particular, Figures 5 and 6 depict geothermal output energy power and geothermal energy conversion as function of geothermal flow rate and well temperatures. It is quite evident that geothermal energy increases at higher well temperatures. Meanwhile, the results show also that the higher the geothermal well temperature the lower is the energy conversion efficiency.

Figures 7 through 9 have been constructed to show the impact of well temperature and return heated water temperature on the geothermal energy conversion efficiency at different geothermal flow rates. The results displayed in these figures show that the higher geothermal flow the lower the geothermal energy conversion efficiency. Furthermore, the results also illustrate that the lower the return heating water temperature from building the higher the energy conversion efficiency. The higher return temperature indicates less building heating load and lower heat required to heat the building. Obviously, this impacts the geothermal energy conversion efficiency. This is consistent with has been discussed previously on the geothermal energy conversion efficiency, heat delivered to the building and reported in the literature [11-16].

On the other hand, Figure 10 is presented to illustrate the impact of the building heating loads on the building heating water flows conditions at well temperature 220 F. It is evident that the higher geothermal flow rate results in higher building flow rate and higher heating loads. Similar behavior has been observed at other geothermal well temperatures and reported in the literature [11-16].

Figure 3. Ambient temperatures (°C) profile 2015-2016.

Figure 4. Solar irradiances (w/m^2) Profile 2015-2016.

Figure 5. Geothermal heat load at different well temperatures.

Figure 6. Geothermal process efficiency at different conditions.

Figure 7. Geothermal process efficiency at different conditions.

Figure 8. Geothermal process efficiency at different conditions.

Figure 9. Geothermal process efficiency at different geothermal flow rates.

Figure 10. Building heating flow rate at different geothermal flows.

Figure 11. Dynamic temperature of building water at different geothermal well flows.

Figure 12. Dynamic temperature of building water at different well flows and well temperature 350 F.

The dynamic behavior of the heat transfer fluid temperature supplied to the building is impacted by the well temperature and geothermal flow rate among other parameters. The time variation of the heat transfer fluid temperature is predicted by equation (6) and is shown in Figures 11 and 12 for various geothermal flow rates and well temperatures. It is quite clear from this figure that the maximum allowable temperature was achieved faster at higher geothermal well temperature as shown in Figure 12.

The same trend was observed with other geothermal well temperatures at different geothermal flows. It is also important to highlight that once the designed supply temperature of the heating water to the building, reaches the geothermal well temperature, heat transfer ceases in the tank heat exchanger due to thermal equilibrium as shown in Figure 1a from geothermal flow. Therefore, it is imperative that the time-variation of the supply temperature should be observed to avoid such a condition to occur.

Figure 13. Time variation-of temperature of building supply water at different well temperatures.

In an attempt to illustrate the effect of the geothermal well temperature on the supply of heating water temperature to the building, Figure 13 was constructed for a geothermal flow of 550 GPM. It is evident from the data depicted in this figure that the higher the geothermal temperature the higher the supply water temperature to the building. It is also worth noting the equilibrium point is achieved when the well temperature is equal to the water supply temperature where there is no heat transfer to the building. Despite that the data depicted in this figure are for 550 GPM, other geothermal flows showed similar behavior.

4.2. PV Simulation

The basic concept of energy conversion from the solar insolation into electrical energy is as shown in Figure 1a. The PV solar as an integral part of the hybrid system is presented and analyzed in the following sections. Figures 14 through 25 illustrate the energy conversion from the solar insolation into electrical energy in terms of volts, amperes and power, and energy conversion efficiencies and time-variation of PV cell temperatures. It is worthwhile noting from these figures that the numerical simulation presented hereby presented the variation of PV cell temperatures from 10°C through 38°C. In general, it is quite clear from the aforementioned figures that higher irradiance will result in higher energy conversion efficiency and output PV power (see Figure 4). Therefore, the

solar panels will be more efficient to operate at sites with higher solar irradiance. Furthermore, in order to demonstrate the characteristics of the solar PV panel, Figures 14 through 18 were constructed to show amperage, voltage, efficiency and power for a particular solar radiation (W/m^2) during daily hours. It is quite clear that the PV characteristics have the same trend as the hourly profile of the solar radiation. In particular, Figure 18 shows the impact of different solar radiations (W/m^2) on the solar PV electric power generated. It is evident that the higher the solar radiation the higher PV power generated. This is in full agreement with other research findings published in the literature [28, 31, and 32].

On the other hand, Figures 19 through 22 present a comparison between the PV power, amperage and efficiency between year 2015 and 2016 plotted at daily hour's bases. Where in particular, Figure. 22 shows the solar PV efficiency of the full year 2015 compared 2016. The simulation results presented in the aforementioned figures are significant for users and designers of solar PV panels since they take into account the hourly variation of PV efficiency according to hourly variation of solar radiation.

Furthermore, another important parameter for users and designers of solar PV panels is the PV cell temperature as calculated by equation (12). In order to study the impact of the initial PV cell temperature on the energy conversion process and its efficiency, Figures 23 and 24 have been

constructed. It is evident from these figures that at a particular solar radiation, the higher the initial cell temperature the higher the PV power produced and the higher the PV solar efficiency. This is significant since normally higher initial cell temperatures are associated with higher solar radiation. Furthermore, Figure 24, in particular, presents the PV solar energy conversion efficiency for different initial PV cell temperatures. The data presented in this figure illustrate that the higher the initial cell temperature the higher the PV efficiency.

Finally, the hybrid system efficiency has been calculated using equation (26) that represents the ratio of output energy produced by PV solar panel and heat supplied to the district heating, to the input energy from the geothermal well and solar radiation. Figure 25 has been constructed to illustrate the impact of geothermal well flow rates on the hybrid system efficiency at different daily hours. It should be noted that only the PV power output varies according to the solar radiation intensity during the hours of the day.

Figure 14. PV Current for different values of daily hours.

Figure 15. PV Voltage at different daily hours.

Figure 16. PV efficiency at different daily hours.

Figure 17. PV Power at different daily hours.

Figure 18. PV Power at different solar radiations.

Figure 19. PV current at different daily hours.

Figure 20. PV power at different daily hours.

Figure 21. PV efficiency at different daily hours.

Figure 22. PV yearly efficiency at different daily hours.

Figure 23. Time variation of PV cell temperature for different solar radiations.

Figure 24. PV efficiency for different values of irradiance- W/m² and Cell temperatures.

Figure 25. Hybrid system; geothermal-Solar PV different daily hours.

In addition, the aforementioned data and PV simulation model clearly illustrates that the energy conversion efficiency is impacted by the thermal efficiency of the geothermal energy source and, PV solar electrical efficiency of the Solar PV as well the ambient conditions

4.3. Validation of Simulation Model

In order to validate our numerical model prediction described in equations (1 through 26), we have constructed Figures 26 and 27 to compare the predicted results with data presented in the literature for solar PV. No site or experimental data were available on geothermal for comparison therefore, only PV solar model's validation is presented hereby. It is quite apparent from comparison

showed in Figure 26 that the model prediction fairly compares with the data of the dynamic PV cell temperature presented by Fagali et al. data [17]. The comparison presented in this figure also showed that the model and data have the same trend, however, some discrepancies exist. It is believed that the discrepancies are due to the fact that the Fagali et al. [17] did not provide full disclosure of the various parameters used in equations (10) through (26) and Reference Rajapakse et al. [31] had to be consulted on the various missing parameters in Fagali et al. [17]. However, taking into account the complexity of the PV cell temperature phenomena and its thermal behavior, we feel that our model fairly predicted the PV cell dynamic profile.

Figure 26. Comparison between present model prediction for cell temperature and Fagali et al. data [17].

Figure 27. Comparison of Current model prediction [28] and Data [32] at 750W/m².

On the other hand, Figure. 27 also showed the solar PV characteristics were fairly predicted by the present model [28] when compared with Ramon et al [32] at solar radiation of 750 w/m².

5. Conclusions

The energy conversion equations describing the total power generated by a hybrid system of solar photovoltaic, and geothermal combined heat and power hybrid system have been solved and presented. The geothermal data illustrates that the higher the geothermal flow rate the higher the efficiency and the lower the well temperature the higher the geothermal efficiency.

Furthermore, the PV simulation study results showed that the higher the solar radiation the accelerated increase in the PV cell temperature. Consequently, it also shows the higher the solar radiation the higher the PV power and PV amperage. It is imperative that the design of the PV panel and its cell temperature take into consideration the solar radiation as well as the ambient temperatures. Finally, the model prediction compared fairly with the PV data at different conditions.

Nomenclature

B : Device and material constant
 C_{pw} : Specific heat of geothermal flow
 E_g : Stefan Boltzmann Coefficient
 E_{go} : Band gap Energy at 0 K
 G : Solar radiation (w/m²)
 G_r : Reference radiation (w/m²)
 H : Convective heat transfer coefficient
 I_p : Output current of PV panel.

I_o : Reverse saturation current and is a function of the cell temperature as per equation (11).

I_L : Load current

$m C_{p_{module}}$: Effective thermal capacity of the PV module

P_1, P_2, P_3 : constants

Q_{in} : Solar energy absorbed by the module

Q_{conv} : Energy loss due to convection

Q_{elect} : Electric power produced

Q_{comb} : Combustion heat added

Q_{rad} : Radiative heat

Q_{conv} : Convective heat

Q_{evap} : Evaporative heat

Sp : Total surface area of PV module

Sc : Total surface area of cells in the module

T_c : The cell temperature (K)

T_r : Reference temperature (K)

ΔT : Temperature difference ($T_c - T_a$)

$(T_c - T_r)$: Difference between reference temperature (298 K) and cell temperature.

T_{well} : Temperature of well supply

$T_{rejectionl}$: Temperature of well rejection

u : Wind speed

V : The output voltage of the PV array and approximately equal to the battery voltage.

V_{tank} : Volume of heat exchanger tank

Greek alphabet

α_{abs} : Overall absorption coefficient

β : Tilt angle

ρ_{air} : Air density.

η_o : Module efficiency at reference temperature (298 K)

η_{inv} : Inverter efficiency

η_{hs} : Hybrid system efficiency

γ : Coefficient for photovoltaic conversion efficiency

Subscripts:

bat – Battery

inv – *ip* - Inverter input
inv – *op* - Inverter output
p – Power
PV – Photo Voltaic
total – Total
3f – Three phase AC

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