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Multiple regression analysis of performance parameters of a binary cycle geothermal power plant

Murat Karadas[a,*], H. Murat Celik[b], Umran Serpen[c], Macit Toksoy[d]

[a] Energy Engineering Programme, İzmir Institute of Technology, 35430 Urla, İzmir, Turkey
[b] Department of City and Regional Planning, Istanbul Technical University, Istanbul, Turkey
[c] NTU Geothermal Consulting Ltd., Karataş, İzmir, Turkey
[d] ENEKO, Research & Development Department, AOSB, 35620 Cigli, İzmir, Turkey

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ABSTRACT

Regression analysis of a 7.35 MW_e existing binary geothermal power plant is conducted using actual plant data to assess the plant performance. The thermo physical properties of geothermal fluid and ambient conditions, which are brine (geothermal water) temperature and flow rate, steam and NCGs (non-condensable gases) flow rates and ambient air temperature, directly affect power generation from a geothermal power plant. Generally, amount of power generated is calculated by deterministic formulations of thermodynamics. However, the data would be probabilistic because inputs may be measured by uncalibrated devices or some parameters may be neglected during the calculation. In these cases, the performance of power plant may be estimated by using regression analysis and then changing of plant performance may be monitored over time. All measured parameters on DORA-1 Geothermal Power Plant from 2006 to 2012 and 49,411 hourly time series data are used in this study.

A review of the available literature indicates this paper is the first study to focus on the prediction of power generation of a geothermal power plant by using multiple linear regression analysis. In this study, annual multiple linear regression models are developed to estimate the performance of a geothermal power plant. These models are tested by using classical assumptions of linear regressions and positive serial autocorrelation is found in all models. Autocorrelations are eliminated by using Orcutt–Cochran method.

Although the performance model trends, from 2006 to 2008, are found to be close, the performance status of the plant is generally variable from year to year. According to annual regression models, since 2009, the plant performance started to decline with 270 kW_e electricity generation capacity. The total degradation of the plant performance reached 760 kW_e capacity by 2012.

1. Introduction

Regression analysis is used in a wide range of the scientific disciplines such as in medicine, biology, econometric, engineering and social sciences (Ghani and Ahmad, 2010). If there is a relationship between two or more variables, which is not explained by any rule, this relation generally falls under the scope of statistics. One or more independent variables may affect a response variable in any case. Multiple linear regression analysis is a method of regression in statistics that is used to analyze the relationship between the single dependent variable with two or more independent variables.

In engineering, most of the regression analysis studies related to energy are about prediction or understanding of energy consumption of buildings (Tso and Yau, 2007; Kaza, 2010; Cho et al., 2004; Katipamula et al., 1994) Also, some studies focus on evaluation and estimation of energy performance of buildings by regression analysis (Chung, 2012; Lee, 2010; Danov et al., 2013; Ghiaus, 2006; Freire et al., 2008). In addition, cooling loads of air conditioning (HVAC) systems are modeled for buildings (Lam et al., 1997; Ben-Nakhi and Mahmoud, 2004; Lam et al., 2010). Besides, regression analysis is often used to predict wind properties such as wind speed and direction (Salcedo-Sanz et al., 2011; Douak et al., 2012; Utsunomiya et al., 1998). Several authors (Carta et al., 2011; Amjady et al., 2011; Liu et al., 2013) studied estimation of power generation of a wind turbine.

Most studies in the relevant literature focus on regression analysis. However, none of them are associated with estimation of

* Corresponding author. Tel.: +90 5419104292.
E-mail address: muratkaradas@iyte.edu.tr (M. Karadas).

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Nomenclature

Symbol	Description
b_i	least square estimator
Cov	covariance
d	Durbin–Watson statistics
$\dot{m}$	mass flow rate, kg s^{-1}
R^2	determination coefficient
S	error sum of squares
T	temperature, °C
Var	variance
VIF	variance inflation vector
$\dot{W}$	work, kW
X	independent variable
Y	dependent variable

Greek letters

β	partial regression coefficient
ε	error term
σ	variance

Subscripts

brine	geothermal fluid
min	minimum
NCG	non-condensable gases
net	net power

electricity generation of a geothermal power plant. The estimation of the potential instantaneous power generation in a geothermal power plant is very important to determine the performance status for plant operation.

Electricity generation of a power plant is determined by deterministic formulation. In literature, there are many studies on performance investigation of a geothermal power plant (Kanoglu and Bolatturk, 2008; Valdimarsson, 2003; Ganjehsarabi et al., 2012). However the data would be probabilistic because it is possible that inputs could be measured by uncalibrated devices or some parameters may be neglected during the computation. Thus, the performance of power plant could be estimated by using regression analysis. An accurate estimate indicates whether the status of plant performance is higher or lower than design conditions.

Air-cooled binary cycle geothermal power plants are generally the most appropriate selections for Turkey's geothermal resources because of water supply shortages. Therefore, performance model of an air-cooled integrated two level binary cycle geothermal power plant is developed in this study. Power generation from a geothermal resource is limited between thermo-physical properties of high temperature heat resource (geothermal reservoir) and low temperature sink source (air). Temperature, pressure, mass flow rate of geothermal fluid and its contents (vapor and non-condensable gases) and ambient temperature directly affect the performance of plant.

Generally, geothermal power plant manufacturers calculate the theoretical correction functions to define off-design conditions for all independent variables such as heat source and sink parameters, thermodynamically. These theoretical correction functions indicate whether the status of the plant performance is over or lower than design conditions for off-design operations. However each theoretical correction functions only indicate the effect of one independent variable and more than one correction factors must be used to calculate total effect of the independent variables on dependent variable. The result of theoretical correction functions does not exactly express the performance of an actual plant. The regression analysis is a useful method for these conditions. If you have annual time series data of a plant, all effects of independent variables may be calculated by a regression function.

This paper, which is the first study to focus on the prediction of power generation of a geothermal power plant according to a review of the available literature, utilizes multiple linear regression analysis of an existing binary geothermal power generation plant located in Aydın, Turkey, using the SPSS Software. This parametric study of the power plant behavior with the ambient air temperature, geothermal fluid (brine) temperature and brine mass flow rate is conducted using the validated power plant performance model.

2. Plant operation

Binary geothermal power plants' operation is based on the Rankine Cycle. Geothermal power plants produce electricity by using heat of geothermal fluid (brine) which comes from underground through the geothermal wells. A small amount of NCGs (non-condensable gases) and steam coming with brine from the geothermal wells are used as additional sources for electricity production. Two phase geothermal fluid is physically separated in the separator; brine, steam and NCGs are sent to the power plant by individual pipelines.

The plant is divided into two Rankine Cycle Levels: Level 1 and Level 2. Although, the working principles of the two cycles are the same, their working pressures are different. The brine first enters the vaporizer of Level 1, heats the working fluid (*n*-pentane). Then, it enters the vaporizer of Level 2 and some heat of brine is transferred to the working fluid in this heat exchanger. Afterwards, the temperature of brine decreases and the brine is divided equally to enter to the preheaters of Levels 1 and 2. In preheaters, the temperature of brine drops a little and finally it leaves the power plant cycle and goes to reinjection wells. The vaporizer of Level 2 has also steam and NCGs tube section where Steam and NCGs pass through. After the steam condenses, the condensate is pumped to the reinjection pipeline by a condense pump. NCGs are released at the end of the vaporizer with some uncondensed steam. They are sent to another company to produce CO_2.

In the vaporizers, the working fluid is heated up to boiling point and it evaporates. Then superheated vapor enters the organic turbine and expands. Thus, this process results in pressure and temperature drop as well as the production of rotational shaft power by transforming kinetic energy gained by expansion of vapor process. The low pressure vapor flows to an air-cooled condenser where the vapor is condensed and then pumped back into the preheaters. Both levels have closed cycle and are independent from each other (Fig. 1).

Electricity generation mainly depends on temperature range of heating and coolant source in a power plant. Therefore, knowledge about design conditions of power plant is one of the most important requirements needed to achieve an efficient performance. Performance of DORA-1, which is the main subject of this study, is expected to generate 7.35 MW_e gross, 6.50 MW_e net power, when power plant works at design conditions. The design parameters of DORA-1 are shown in Table 1.

3. Data

Although a lot of parameters effect the plant performance such as thermal energy conversion efficiency related to heat exchangers surface area, turbine efficiency, working fluid flow rate, etc., the performance of a geothermal power plant (net power) mainly depends on five parameters which are ambient air temperature, brine temperature, brine mass flow rate, NCG and steam mass flow