Statistical Modeling for Hydrogen Production Using Wind Energy

Md. Shouquat Hossain, Adarsh Kumar Pandey, Mohsin Ali Tunio, Jeyraj A/L Selvaraj, Ali Wad Abbas Al-Fatlawi, and Kazi Enamul Hoque

Abstract—This study contains a statistical model for hydrogen production through water electrolysis using wind energy. This is a modeling with experimental validation for the analysis of polynomial by planting ANOVA (Variables) method to Response Surface Methodology (RSM). The practical data for wind energy and electrical power are collected from the literature for this model. The wind turbine capacity has been taken to be 1kW, 3kW and 5 kW which is the low to high actual value and for output power low to high actual value has been taken as 0.7 to 6.2 kW. The ANOVA method will be utilized to see other statistical proper tools as for actual and predicted values, response between residuals and predicted, 3-D surface and contour analysis plot. The statistical analysis shows that the planned model and the experiment results have a good fit.

Index Terms—Statistical model, wind energy, ANOVA method, hydrogen production.

I. INTRODUCTION

The use of renewable energy and its application in daily life is increasing day by day. The wind energy is one of the important renewable energy amongst others which are freely and abundantly available in the environment ready for use. The wind energy is being explored maximum around the world for e.g. Denmark, India etc. However, an efficient harnessing of wind energy is still a cause of concern. Therefore, researchers around the world are making their efforts to enhance the efficiency by hybridizing the wind energy with other renewable energies such as hydrogen energy. The hydrogen energy offers the opportunity to be used as a fuel to get a reliable power for almost every application that fossil fuel is being used [1].

The concept of hydrogen production by using three variables: time, wind turbine capacity and wind output power

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will be utilized in this investigation. This statistical model will help to determine the necessary steps for the production of hydrogen energy using wind energy. This kind of model is related to the material engineering, which contains kinetics, physical property, mass and energy balance which is processing of a differential algebraic formula for both dynamic and steady state processes [2], [3]. The objective of this work is tantamount to investigate the production of hydrogen using wind energy through the statistical model. Also, to discover the optimum process parameters for hydrogen polymerization in a wind energy using RSM modeling and Central Composite Design (CCD) technique. This novel statistical model will contain all the basic model for producing hydrogen by using any wind turbine panel or hybrid system. So this study will help in predicting the result before doing the experiment also, the actual and predicted value of the results can be compared using the study.

II. EXPERIMENTAL OVERVIEW

This is a 2-D example model for wind energy used water electrolyzer system as showed in Fig. 1. The wind turbine capacity has been taken as 1 kW, 3 kW and 5 kW and the maximum hub height was taken as 20 m. The yearly output power was collected from three different sites
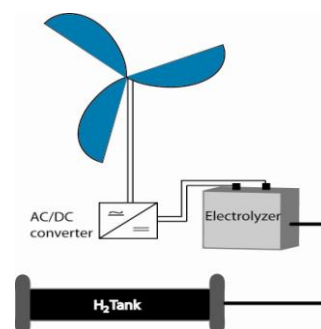

Fig. 1. 2-D basic diagram of wind turbine and electrolyzer system.

Novi Sad, Belgrade and Kopaonik and the average wind velocities of three sites were found to be between 3.16 to 4.76 ms^{-1} [4]. The alkaline electrolyzer HySTAT was chosen for this experiment having maximum hydrogen production rate of 1 Nm^3/ hour and hydrogen gas storage of 100 volumes. The wind turbine average winds velocities can be calculated using the below equation:

$$\frac{U_1}{U_2} = \left(\frac{z_1}{z_2}\right)^{\alpha} \tag{1}$$

where, U_1 and U_2 are wind velocities (ms^{-1}), z_1 and z_2 are

hights from ground (m), α is a power-law exponent for the vertical wind profile having a value of 0.18.

III. DESIGN AND OPTIMIZATION

In this study, the statistical model of wind power water electrolysis will appear results by using Stat-Ease software, where the CCD will help to analyze the interaction among the variables and to highlight the optimum process condition [5]. After calculation the experimental data of total wind power with the design procedures, an idealistic model has been completed according to the RSM methods [6]. In this time, the polynomial function has been adjusted with the statistical data at the initial stage and then the factor values will identify to optimize the real rmirical formula. The exactness of the polynomial model will be determined by the coefficient values R^2 and R^2_{adj} in the equation form as given below [7]:

$$R^2 = 1 - \frac{\sum S^2_{residual}}{\sum S^2_{model} + \sum S^2_{residual}} \qquad (2)$$

$$R^2_{adj} = 1 - \frac{\sum S^2_{residual} \Big/ D_g F_{residual}}{\left(\sum S^2_{model} + \sum S^2_{residual}\right) \Big/ \left(D_g F_{model} + D_g F_{residual}\right)} \qquad (3)$$

Now the composite design of the system has been established by analyzing the response of the normal cubic meters of hydrogen conversion per mass mathematical equation will appear.

$$Y_{Response\ 1} = \beta_\circ + \sum_{i=1}^{k} \beta_i \chi_i + \sum_{i=1}^{k} \beta_{ii} \chi_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} \chi_i \chi_j + \varepsilon \qquad (4)$$

where Y is the total response vector and taking model into the Linier, two-factor and Quadratic interaction effects and ε is the error vector. The ideal preparation condition estimated the three-dimensional plot surface and regression analysis of the independent variables with each dependent variable. These independent variables are level controlled by p-value. At the same time signifies the interaction intensity between all independent variables interface for small p-value where point out the higher level of significance of the related variable. The second-order models has been tested by using ANOVA and the F-value method. The F-value can be formulated in the flowing way:

$$F = \frac{Mn^2_{RG}}{Mn^2_{RD}} \qquad (5)$$

This model error will be represented by coefficients of variation (CV) as given below:

$$CV = \frac{SD}{mean} \times 100 \qquad (6)$$

The CV value should be not more than 10% for any model to be reproducible.

IV. RESULT AND DISCUSSION

Use To assess the compatibility of the system, in this model three variables such as time (A), wind turbine capacity (B) and wind power output (C) has been used. While, the main variables are wind turbine capacity and power output used for water electrolysis during the experiment. Table I shows, the units, type of the experiment (Numeric), low and high actual values and coded values: low (-1) high (+1) for the three factors as discussed above.

The experiment runs about 20 numbers using CCD and the results are shown in Table II. The polynomial method equation has been used for plotting in three dimensional (3-D) and two dimensional (2-D) contours to identify individual factors, their intersection, reaction and response respectively. The mean square error (Mn^2_{er}) for this model is found to be 0.00007 which is very less and shows the model accuracy.

TABLE I: CODED LEVELS FOR EXPERIMENT DESIGN

Factor	Name	Units	Type	Low Actual	High Actual	Low Coded	High Coded
A	time	hrs	Numeric	1.00	365.00	-1.000	1.000
B	wind turbine capacity	kW	Numeric	1.00	5.00	-1.000	1.000
C	wind output power	kW	Numeric	700.00	6200.0	-1.000	1.000

The result of Response 1 showed that the hydrogen production ranged from 70 to 165 Nm^3. The maximum response of 165 has been found with the condition of A is 8760 hours, B is 5 kW and C is 5200 kW. It is very clear the experimental parameters for hydrogen electrolysis system can achieve optimum process condition.

The model fitting analysis by ANOVA method, where the F-value and p-value analysis has been utilized. The Sum of Squares final result model of Linear (A, B, C), 2FI (2 Factor Interaction) (AB, BC, AC) and Quadratic (A^2, B^2, C^2) are 8460.48, 558.56 and 76.67 where the Mean Square results are 2820.16, 186.19 and 25.59. It is observed that the quadratic model is the best for this experimental design. The small p-values of 0.0001, 0.0001 and 0.0170 are less than the F-Values of 66.16, 19.65 and 5.51 (Prob > F) which indicates that the selected model can improve significantly. The proposed model quadratic equation is very important for identifying the independent variations tested to fit. The model accreted value at 0.9949 which is 99.49% valid and 0.41% overall cannot be pure. Another coefficient R^2_{adj} is 0.9904, which shows a relation with the independent variables. The coefficient of variation (CV) in this model is very low (1.95%),

which indicated a high performance and excellent model from the experimental results.

TABLE II: CCD EXPERIMENT RESULTS OF THE RESPONSE SURFACE

Run	Factor A	Factor B	Factor C	Response 1 Hydrogen (Nm³)
1	4392	3.00	2050.00	106
2	2952	3.00	2450.00	110
3	4392	3.00	2850.00	112
4	24	5.00	5100.00	160
5	4392	3.00	2074.93	107
6	4392	3.00	2210.00	113
7	4392	3.00	2150.00	111
8	8760	1.00	780.00	100
9	4392	3.00	2650.00	114
10	8760	5.00	5200.00	165
11	24	1.00	767.00	99
12	4536	3.00	2550.00	111
13	4392	3.00	2420.00	108
14	4392	3.00	1174.93	100
15	4392	5.00	3450.00	130
16	24	1.00	700.00	98
17	4392	3.00	2950.00	115
18	8760	1.00	700.00	97
19	8760	5.00	700.00	70
20	24	5.00	700.00	80

Now polynomial equation will be established with the help of multiple regression and squares method. This is a second order equation. From the study of the variation data, the response hydroden (Y) can be formulated as:

$$\begin{aligned} \text{Response Hydroden}(\%), Y &= (1.57 \times A) + (21.16 \times B) \\ &+ (20.37 \times C) - (2.49 \times A \times B) - (4.08 \times A \times C) \\ &- (32.99 \times B \times C) + (0.33 \times A^2) - (9.34 \times B^2) \\ &+ (1.63 \times C^2) + 118.47 \end{aligned} \qquad (7)$$

It is clear that Y is the response of hydrogen production in Nm³ and A, B, C are independent coded variation.
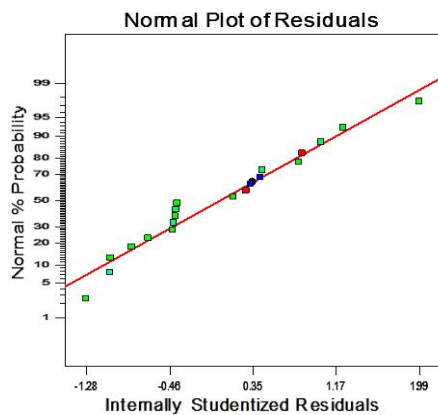
V. IDEOGRAPHIC FOR THE MODEL QUALITY

Fig. 2. Normal plot residuals.

The graphical representation of this model will see more identification of the experimental results. The results came out with the probability of residuals points, actual and predicted value on this statistic experimental model. The normal plot of residuals showed in Fig. 2, which is plotted with respect to the predicted values. However, this drift model

has been used to calculate the prediction results of hydrogen production and compared with the experimental (Actual) consequences as shows in Fig. 3. This model will be more clearly the actual and prediction values and interaction between them. Fig. 4, represent the reaction between residuals vs. predicted data optimization for hydrogen response. From the Fig. 4, two side lines are standard maximum residuals range of ±3.00. The values inside are totally related to the experimental response [8]. It is observed that the fitted model upon the response values created without unknown error. In the experimental time, the outliers are already tested because any time can occur to data arrange or may be severe error [9].
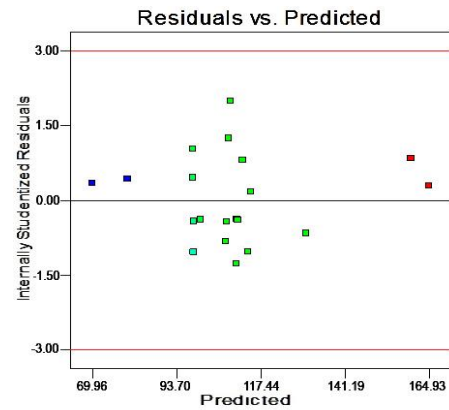

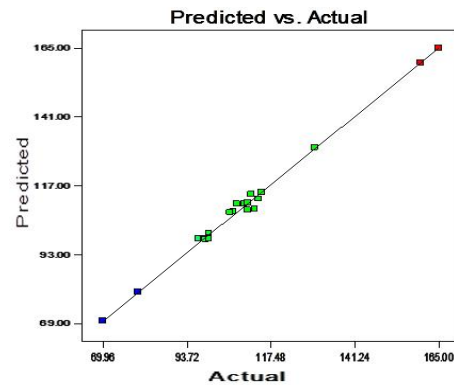Fig. 3. Plotted prediction vs. actual.

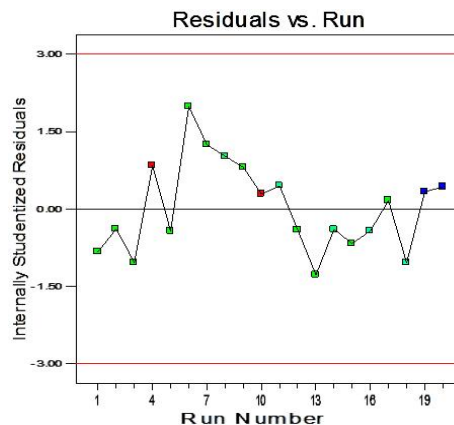

Fig. 4. Plotted residuals vs. predicted.

Fig. 5. Residuals vs. run.

Fig. 5 shows the residual vs run and the amount of hydrogen production run rate in Nm³ shows in Fig. 6. Fig. 6 is the hydrogen production rate with the help of three factors in perturbation plot. It is observed that the slope line is a factor, which is responsibile for the response (Hydrogen) and the flat line shows irresponsible for the response. From the Fig. 6, it is

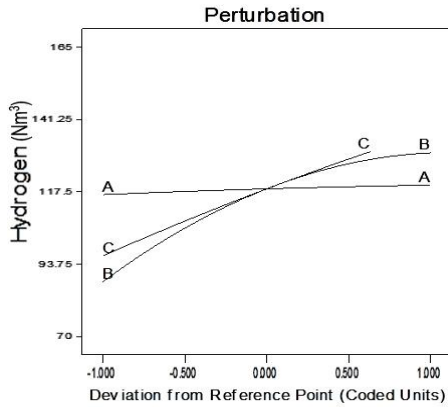clear that the power factor (B) is more effective for the output response.

Fig. 6. Deviation plot for perturbation parameters.
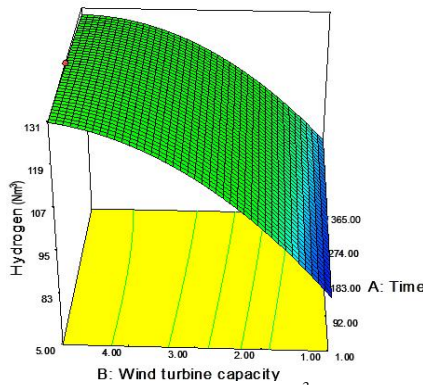
VI. MODEL RESPONSE IN 3-D OUTLOOK ANALYSIS

Fig. 7. 3-D plotted for hydrogen production (Nm^3). Wind turbine capacity vs. time.
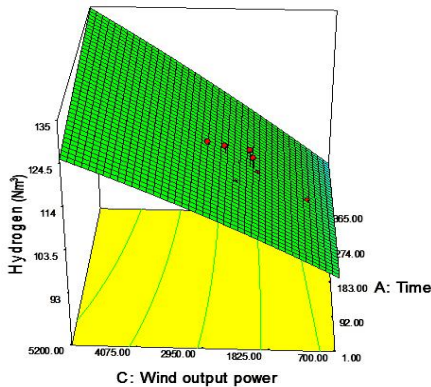

Fig. 8. 3-D plotted for hydrogen production (Nm^3). Wind output power vs. time.

The output result of this model has been involved in 3-D form. The 3-D plot of Fig. 7-Fig. 9, indicates the hydrogen production (Nm^3) with respect to wind turbine capacity (*B*), power (*C*) and time (*A*). It is clear that at the starting point the production was low but when time, turbine capacity and power grows up, the level of the hydrogen production also increased. Fig. 7, shows the variation in time vs turbine capacity, where the hydrogen production rates are expected to be very slow due to the production independency on turbine capacity. Fig. 8, shows the variation in time vs wind power which also shows the inadequate production rates. Fig. 9, shows the variation in turbine capacity vs power which shows

the effective production rate of upto 164 Nm^3. The interaction level between three parameters has been explained by the response surface and further response will be constantly at their middle point.
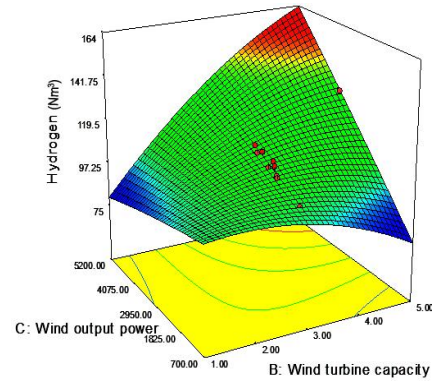

Fig. 9. 3-D plotted for hydrogen production (Nm^3). Wind output vs. wind turbine capacity.

VII. CONCLUSION

The hydrogen production response by using a statistical model is a reliable method as described in the literature. The experimental results were compared with some prediction value and equations from this statistical model using the three different factors (independent variables) A, B and C. These independent variables were identified the most important parameters for hydrogen production. The maximum hydrogen response was considered to be 164 Nm^3, wind turbine capacity of 5 kW, wind output power of 5200 kW and time of 8760 hours. The best part of this model was the comparison of the actual and prediction values which are a justification of a good model.

NOMENCLATURE

$\mathmit{\Sigma}S^2$: sum of squares
$\mathmit{\Sigma}S^2_{model}$: um of squares of model
$\mathmit{\Sigma}S^2_{resideal}$: sum of squares of residual
P: model parameters
N: number of experiments
ANOVA: analysis of variance
CCD: central composite design
Mn^2_{RG}: mean of square regression
Mn^2_{RD}: mean of square residual
Mn^2_{er}: Mean square error
S_{RG}: sum of squares
S_{RD}: sum of residual
D_gF_{model}: degree of freedom of model
$D_gF_{residual}$: degree of freedom of residual
R^2: determination coefficient

R^2_{adj}: adjusted coefficient of determination

CV: coefficients of variation

F-value: model significance

SD: standard deviation

Nm^3/h: Normal Cubic Meters per hour

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