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MODELLING ELECTRICITY GENERATION FROM BIOGAS

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ABSTRACT: *This study focused on the energy generation from the anaerobic treatment of the sewage sludge. The biogas yield obtained were used to power a micro gas turbine in order to determine electrical energy output from the system, a process that have now been commercialized for economic benefits. Equation 3.24 was derived and its consequent solution, equation 3.27 was used for that purpose. Figure 4.6 shows the energy output for experimental reactor 1. The result obtained shows a close fit between the turbine output and the model output. Precisely, a CORR value of 0.96 was obtained with a small error of estimate of 2.34 and 8.00 respectively for MAPE and RMSE. Similarly, figure 4.7 shows energy output for experimental reactor 2. In this, the coefficient of correlation was found to be 0.94 with MAPE and RMSE being 2.15 and 3.55 respectively. Figure 4.8 and 4.9 shows the energy output for model reactors 1 and 2 respectively. The CORR, MAPE and RMSE were 0.95, 3.78 and 5.51 respectively for model reactor 1 while a similar value of 0.97, 1.73 and 5.02 were recorded for model reactor 2 respectively. In all, a very good correlation values were obtained to show that energy generation from treatment plant can be modelled given the biogas yield data. It should be noted that turbine plant operational mechanism may vary slightly depending on their capacities; consequently, an updated recalibration of the model would be necessary.*

KEYWORDS: Biogas, Generation, Electricity, Modeling.

INTRODUCTION

There are three modeled renewable energy sources in the program. First in biogas from plant waste, Energy potential of the other two (Solar and wind) are determined by the solar radiation and wind speed respectively. The annual average radiation of the site per unit area of horizontal surface is 5.52KWh/m^2/day. Solar energy Data are given in fig. 2.6.1, where clearness index, shown, is the measure of the clearness of the atmosphere. The plant site average wind speed, shown on fig 6 is 4.75m/s.

Micro gas turbines are small gas turbine belonging to the group of turbo machines up to an electric power output of 300KW. In order to raise the electrical output micro gas turbines are equipped with a heat exchanger. They are also equipped with a regular heat exchanger in order to use the waste heat from the exhaust gases. Micro-turbine will be used for producing power from heat exhaust of the fuel cell forming what is called FC – MT hybrid model. This hybrid system offers a solution to two important problems, the low efficiency and relatively high emissions of small gas turbines, and the high cost of small fuel cell power plants.

Micro-turbine has a smaller volume and weight but also a lower efficiency and larger emissions than a normal gas turbine. Therefore, a MT working as a stand – alone device generates not so much benefit. A fuel cell is a clean energy generator and has a considerably higher and constant efficiency even at different operating temperatures, but its volume is still extremely large. The integration of FC – MT hybrid model can be done by two methods, atmospheric pressure system and pressurized system. The main advantage of atmospheric pressure system that it allows is the selection of the MGTR pressure independently of the cell pressure. Mean while some basic studies have concluded that a pressured system may have higher system efficiency over an ambient pressure system from a thermodynamic point of view if equivalent design parameters are assumed. In the pressurized system, used in the design, the fuel cell operates at an elevated pressure with the micro-turbine.

Under steady state, the micro-turbine compressor is used to pressurize the air entering the fuel cell. Chemical reactions take place in the fuel cell producing both electricity and heat. With both fuels, compressed by a fuel pump and the air by the compressor, the hot pressurized exhaust leaves the SOFC and goes directly to the compressor and the generator. The exhaust from the turbine is used through heat exchanger to heat air and fuel prior to entering the fuel cell.

The output of the fuel cell to be directed to the micro-turbine expander is 117KW (42/M/hr) which approximately equals input power required to run a 26KW micro-turbine used in the model. As a result, the SOFC – MT system will deliver 140KW from the fuel cell and 20KW from the micro-turbine. This yield overall electrical power output of 166KW and 32.7KW of useful thermal power leaving heat exchanger.

Combined-Heat-and-Power (”CHP”) is a technology that in a single constellation integrates the simultaneous production of both thermal and mechanical power. By being a specific form of distributed generation of energy, the CHP technology is a more efficient and customized form of energy production compared to central station generation (EPA, 2008). When serving to generate power or supply the heating or cooling needs of the consumer, the CHP technology is advantageous due to its ability to recover the waste heat that is simultaneously produced. The CHP technology utilizes the heat and therefore requires less fuel than traditional systems that have separate constellations for thermal and mechanical power generation. (Shipley et al., 2008).

The CHP system consists mainly of four parts; a prime mover, generator, heat recovery and electrical interconnection. However, when characterizing the most common types of CHP systems, there are two distinct systems. Firstly, there is the CHP system that works with a gas turbine or a reciprocating engine with a heat recovery unit. It is displayed in Figure 4 with all its interconnecting parts. Water and the chosen fuel, most often natural gas or biogas, is the input for the system, and it can be seen that the fuel goes straight into being burned in the engine. The heat recovery unit captures heat from the exhaust stream of the combustion process. With the addition of a generator, transforming the power to electricity parallel with the steam from the heat recovery unit being transported for cooling or heating. The output of power can be distributed to the grid or to the actual site where the system is in use. (EPA, 2013)

The second CHP system commonly in use utilizes a steam boiler with a steam turbine. The scenario is somewhat turned around, showing that the electricity generation is the byproduct of the generation, whereas the previous illustration showed heat as the byproduct of the production of electricity. Fuel and water are inserted into a boiler and

the initial step of this process occurs solely in the steam turbine. Both this and the previous systems are widely used, however, the constellation of the first system can be applied in many ways depending on which engine that is used in the prime mover. (EPA, 2008)

The prime mover is the most central component of the system and works as the heat engine for the generation of power. There are various sorts of heat engines in use for CHP, and certain advantages and characteristics will depend on which type of prime mover that is in use. (EPA, 2008) Next section of this chapter will elaborate which different types of engines that can be in use in a CHP system.

A significant quality of CHP is its ability to work with a wide array of fuels. The prime mover can burn natural gas, coal, oil or a number of more alternative fuels. Combining a CHP system with a renewable source of energy makes the technology superior in its ability to work without in a sustainable and environmentally friendly way. (EPA, 2008) When placing a CHP site close to industrial or agricultural processes, the biomass extraction can enable the CHP engine to run on alternative sources of fuels, called opportunity fuels. Opportunity fuels include black liquor that is a by-product from pulping processes, biomass that is collected in the form of wood waste, sawdust and other agricultural wastes. In addition to these fuels, there is also the possibility to produce biogas from residential and municipal organic food waste and sewage waste. By breaking down the organic matter, as described in section 2.4.1, biogas can be produced and this raw biogas can subsequently be used in the CHP engine. (EPA, 2013)

Since CHP belongs to the technologies collectively called distributed generation, it has the ability to be regarded as separate units that can be transported and placed in the location most suitable for its consumer. However, the CHP system can at the initially be defined by four types of systems; i) packaged CHP which is a complete package of the system, serving to be placed close to the client’s electrical and heating systems;(ii) Micro-CHP has the function of being a replacement to a site’s small commercial scale boilers; iii) Custom-built CHP is the system that can more easily be designed completely after the site’s specific conditions; and iv) Renewables

CHP that is the alternative when only using opportunity fuels for the prime mover of the CHP system. (Department of Energy and Climate Change, 2013)

Due to the conditions of this report’s set out objectives, the last type of the CHP systems will be the one relevant for observation. If the model of the chosen energy system for this report is to function, then the choice of CHP system is required to be able to run on biogas in addition to be properly scalable in dimensions for the use in the eco-city. When examining CHP technologies, the choice of engines in the prime mover is mainly the determinant of how the technology works. Therefore, the following two prime movers will be presented, due to their ability to burn or boil raw biogas; the reciprocating engine and the gas turbine.

The reciprocating engines with internal combustion are amongst the most frequently used technologies in use for CHP systems. The engine gains popularity due to both its scalability, it is used both for small-to-medium installations as well as on large-scale industrial sites as well as its capability to handle several different fuel sources. The engine is equipped with either a spark-ignition that generates power outputs of up to 5 MW or a compression-ignition that can generate as much as 15 MW of power (Shipley et al., 2008). The firstly-mentioned version only uses gaseous fuels for combustion, whereas the second option burns oil or oil-gas-mixtures. (DECC, 2013)

The reciprocating engine in the CHP-system generally burns natural gas, yet the use of landfill gas, propane or biogas is possible. Using a reciprocating engine in a CHP system, the sparkignition is the version used for burning and with the use of a renewable gas such as biogas; the system can produce up to 5 MW of power while at the same time as keeping the process sustainable. (Shipley et al., 2008)

When compared to conventional power generation, CHP is predominantly more efficient. Separate heat-and-power production ("SHP") is less efficient due to its inability to use wasted thermal energy in a way to minimize the losses in production. When producing electricity and thermal power separately, the losses from each production are then put together, negatively affecting the efficiency level of the overall system. When combining the heat-and-power production as with CHP, the effective usage of waste heat from production enables the system to produce more electricity or useful thermal energy without increasing the initial fuel needed. The losses are smaller than for SHP and the system is more energy efficient from an overall energy system perspective. (Combined Heat and Power Partnership, 2011)

When defining efficiency levels for different CHP systems, the most common processes are to calculate the CHP efficiency with either the total system efficiency methodology, or the effective electricity efficiency methodology. For this report, the focus will be on presenting the relevant metrics and calculations necessary for the CHP system that will be used in the model. Therefore, this section will only highlight the informative version of CHP efficiency calculations, and section 3.7.3 will further present the calculations in use for the model of this report.

The initial and most straightforward algorithm in how to calculate a system's efficiency is simply to divide the sum of the thermal and electricity outputs with the input of fuel used. The total system efficiency methodology requires one to establish the quota between the outputs and the inputs, and it will show how efficient the system is in transforming and recovering fuel and energy in the system to generate useful thermal energy and electricity as outputs. The incorporated parameters are total fuel energy input Q_{FUEL}, net useful power output W_{E}, and net useful thermal output ΣQ_{TH}. This way the overall CHP system efficiency η_{CHP}can be calculated as follows. (Combined Heat and Power Partnership, 2011)

$$\eta_{CHP} = \frac{(W_E + \sum Q_{TH})}{Q_{FUEL}} \qquad Eq.\ 1$$

The total fuel energy input means the total fuel used by the system multiplied with the heating value of the fuel of choice. Heating value will in Equation 2 be named ht. The equation for the total fuel energy input is the following:

$$Q_{FUEL} = \sum Q_{FUEL} * ht$$

Eq. 2

The heating value varies between fuels, and this can be displayed via a given set of examples; Natural gas has a heating value of 1020 Btu per cubic foot, coal has a heating value of 10 157 Btus per pound, and diesel fuel comprises a heating value of 138 000 Btu per gallon. (Combined Heat and Power Partnership, 2011) Btu stands for British Thermal unit and is defined as the thermal energy required to increase the temperature of 0,454 kg of water from 3,8C! to 4,4 C!. (Wikipedia, 2013) For the objectives of this report, the fuel of interest for the CHP system is biogas, where the input of raw biogas from the anaerobic digestion process will be used as fuel. The heating value ht!"#$%&of raw biogas can be calculated based on the parameter of methane content in the gas, and is presented in Equation 3. (Astals & Mata, 2011)

$$ht_{BIOGAS} = \frac{35800}{\%CH_4} * 100 \qquad Btu$$

Eq. 3

Calculating the effective electricity efficiency εEEis slightly different from the total system efficiency equation presented for the CHP efficiency, however a small addition of one parameter is necessary. As can be seen in Equation 4, $\alpha$is added, and it stands for the efficiency of the traditional technology with which the useful thermal energy output would be produced as if the CHP system did not exist. (Combined Heat and Power Partnership, 2011)

$$\varepsilon_{EE} = \frac{W_E}{Q_{FUEL} - \sum(Q_{TH}/\alpha)}$$

Eq. 4

When exemplifying typical values for effective electricity efficiencies the combustion turbinebased CHP systems and the reciprocating engine-based CHP systems can be given. The firstly mentioned ranges from 51 to 60 percent efficiency while the second system has a significantly higher efficiency of 69 to 84 percent. The parameter $\alpha$is typically fixed depending on which system is of use, and it is mainly 0,8 when the CHP system includes a boiler that burns natural gas, 0,83 for a coal-fired boiler and 0,75 for the boiler burning biogas. (Combined Heat and Power Partnership, 2011)

As a conclusion, CHP systems can be customized in several manners and with different integrated technologies, and depending on parameters such as choice of CHP system, prime mover, fuel type and heating value of fuel type, the efficiency of the systems may differ between them. The two methodologies presented are both useful, however under slightly different circumstances. The total system efficiency is valuable when a comparison of a CHP system and a traditional SHP system is performed. When the performance of a CHP system is compared to conventional power production technology, the effective electricity efficiency proves to be more useful.

When finally stating an example of realistic efficiency levels for a CHP system, the thermal efficiency will also be considered. In many CHP systems the assumption is often that the thermal efficiency is roughly double the electricity efficiency. (Malmqvist, 2013)

The importance and relevance of using the CHP technology in different energy systems, infrastructures and sites is today significantly apparent. It is a widespread technology with many usage areas and it is fairly adaptable, due to its ability to be used on smaller sites as well as in industrial environments. It is however important for the objective of this report to make a difference between the CHP technology that suits small and medium-scale projects, to that of the large-scale biogas conversion plants with CHP. This section is therefore discussing the properties and features of large-scale CHP with biogas and its output in the form of electricity and thermal energy.

MATERIALS AND METHOD

Review of Experimental Procedure

A gas turbine is a rotating engine that extracts energy from a flow of combustion gases that result from the ignition of compressed air and a fuel (either a gas or liquid, most commonly natural gas). It has an upstream compressor module coupled to a downstream turbine module, and a combustion chamber(s) module (with igniter[s]) in between. Energy is added to the gas stream in the combustor, where air is mixed with fuel and ignited. Combustion increases the temperature, velocity, and volume of the gas flow. This is directed through a nozzle over the turbine’s blades, spinning the turbine and powering the compressor. Energy is extracted in the form of shaft power, compressed air, and thrust, in any combination, and used to power aircraft, trains, ships, generators, and even tanks.

Electric Power Generation Per Day of Gas Yield from Reactors

A micro gas turbine generator set was employed for determination of the electrical energy output from which a model was developed for prediction purpose. An equal amount of gas yield per day was fed into the turbine in order to determine the equivalent amount of energy output. In the end, analysis was drawn between the model results for each reactor and the turbine output for each day of gas yield.

MODELING ELECTRICITY GENERATION DERIVATION

Producing electricity from biogas is still relatively rare in most developing countries; however, conversion of biogas to electricity has become a standard technology. The conversion of biogas to electric power by a generator set is much more practical. In contrast to natural gas, biogas is characterised by a high knock resistance and hence can be used in combustion motors with high compression rates. The following model was used to describe the process effectively.

$$\frac{d^2I}{dv^2} - 3\frac{dI}{dv} + 2I = v^2 \qquad (3.24)$$

Where

I = Amount of electricity generated (in kwh)

V = volume of methane gas (i.e. V_{CH4})

The plant mechanism shows that at V = 0, I = 0.75kwh and $\frac{dI}{dv}$ = 2.5.

The solution to equation (4.24) follow thus;

Complementary function (C.F) is given as; $m^2 - 2m + 2 = 0$

$$:. \quad (m-1)(m-2) = 0, \quad m = 1 \text{ or } 2$$

$$\Rightarrow \quad I = Ae^{v} + Be^{2v}$$

Particular integral (P.I) is given as

$$I = CV^2 + DV + E$$

$$:. \quad \frac{dI}{dv} = 2CV + D \text{ and } \frac{d^2I}{dv^2} = 2C$$

$$2C - 3(2CV + D) + 2(CV^2 + DV + E) = V^2$$

$$2CV^2 + (2D - 6C)V + (2C - 3D + 2E) = V^2$$

$$2C = 1, \qquad C = ½$$

$$2D - 6C = 0 \;:.\; D = 3C = \tfrac{3}{2}$$

$$2C - 3D + 2E = 0$$

$$:. \quad 2E = 3D - 2C = \tfrac{9}{2} - 1 = \tfrac{7}{2} \qquad :.E = \tfrac{7}{4}$$

$$:. \quad \text{P.I is } I = \frac{V^2}{2} + \frac{3V}{2} + \tfrac{7}{4} = \tfrac{1}{4}\left(2V^2 + 6V + 7\right)$$

General solution:

$$I = Ae^{V} + Be^{2V} + \tfrac{1}{4}\left(2V^{2} + 6V + 7\right) \qquad (3.25)$$

Substituting the conditions;

V = 0, I = 0.75 in eqn. (4.25), yields

$$0.75 = A + B + \tfrac{7}{4}$$

$$\Rightarrow \quad A + B = -1 \qquad (i)$$

by differentiating equation (4.25), we obtain:

$$\frac{dI}{dV} = Ae^{V} + 2Be^{2V} + \tfrac{1}{2}\left(2V^{2} + 3\right) \qquad (3.26)$$

again, at V = 0, $\frac{dI}{dV} = 2.5$, substitute in equation (3.26)

$$2.5 = A + 2B + \tfrac{3}{2}$$

$$:. \quad A + 2B = 1 \qquad (ii)$$

Solving equations (i) and (ii) simultaneously gives:

A = -3 and B = 2

Substitute these values in eqn. (4.25) to give;

$$I = 2e^{2V} - 3e^{V} + 0.25(2V^{2} + 6V + 7) \qquad (3.27)$$

Equation (4.27) is the general solution of the model.

RESULT AND DISCUSSION

Electric Power Generation Per Day of Gas Yield from Reactors

Table 4.7 - 4.10 shows electrical energy generated from daily gas yield by reactors.

Table 4.7: Electrical Energy Generated from Daily Gas Yield from Experimental Reactor 1

Experimental Reactor 1			
Day	**Gas Yield (ML/gVS)**	**Turbine Output (kwh)**	**Model Output (kwh)**
1	256	1.65	1.63
2	256	1.65	1.63
3	281	1.78	1.75
4	281	1.78	1.75
5	290	1.82	1.79
6	295	1.84	1.81
7	325	1.97	1.97
8	314	1.83	1.92
9	285	1.77	1.77
10	304	1.87	1.86
11	295	1.81	1.81
12	322	1.99	1.95
13	325	1.98	1.97
14	322	1.97	1.95
15	311	1.92	1.9
16	311	1.9	1.9

Energy Generation Model

The biogas yield obtained from anaerobic digestion of waste water were used to power a micro gas turbine in order to determine electrical energy output from the system, a process that have now been commercialized for economic benefits. Equation 3.24 was derived and its consequent solution, equation 3.27 was used for that purpose. Figure 4.6 shows the energy output for experimental reactor 1. The result obtained shows a close fit between the turbine output and the model output. Precisely, a CORR value of 0.96 was obtained with a small error of estimate of 2.34 and 8.00 respectively for MAPE and RMSE. Similarly, figure 4.7 shows energy output for experimental reactor 2. In this, the coefficient of correlation was found to be 0.94 with MAPE and RMSE being 2.15 and 3.55 respectively. Figure 4.8 and 4.9 shows the energy output for model reactors 1 and 2 respectively. The CORR, MAPE and RMSE were 0.95, 3.78 and 5.51 respectively for model reactor 1 while a similar value of 0.97, 1.73 and 5.02 were recorded for model reactor 2 respectively. In all, a very good correlation values were obtained to show that energy generation from treatment plant can be modelled given the biogas yield data. It should be noted that turbine plant operational mechanism may vary slightly depending on their capacities; consequently, an updated recalibration of the model would be necessary.

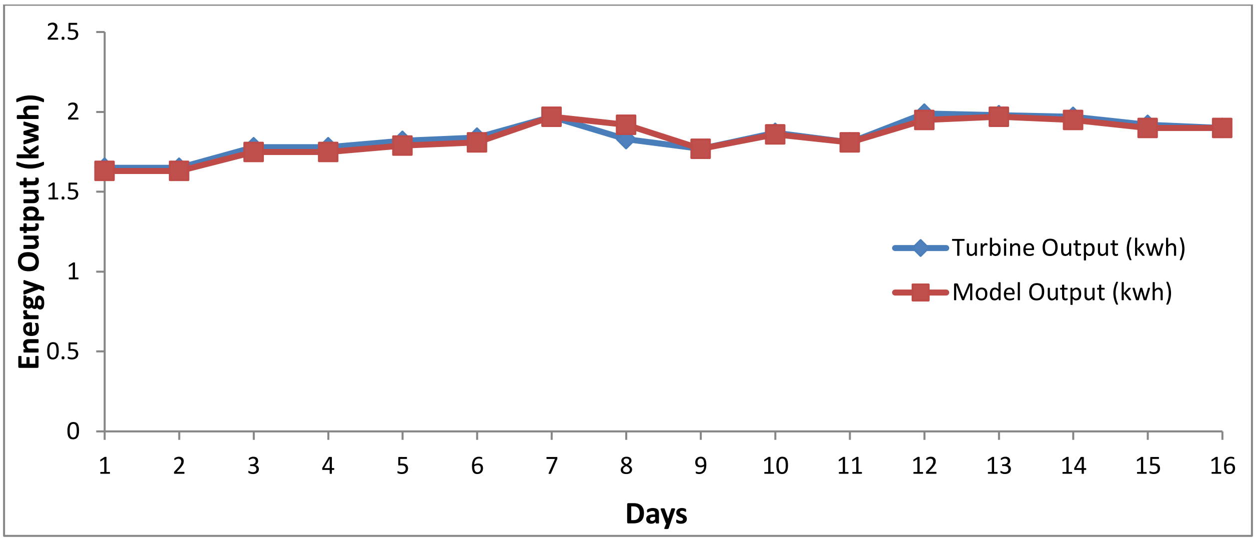

Fig. 4.6: Graph of Energy Output for Experimental Reactor 1

Table 4.8: Electrical Energy Generated from Daily Gas Yield from Experimental Reactor 2

	Experimental Reactor 2		
Day	**Gas yield (mL/gVS)**	**Turbine Output (kwh)**	**Model Output (kwh)**
1	270	1.72	1.69
2	279	1.77	1.74
3	289	1.81	1.78
4	289	1.82	1.78
5	298	1.83	1.83
6	298	1.83	1.83
7	300	1.87	1.84
8	282	1.79	1.75
9	285	1.8	1.77
10	257	1.7	1.67
11	257	1.69	1.64
12	285	1.77	1.77
13	295	1.85	1.81
14	314	1.95	1.92
15	309	1.89	1.89
16	285	1.79	1.77

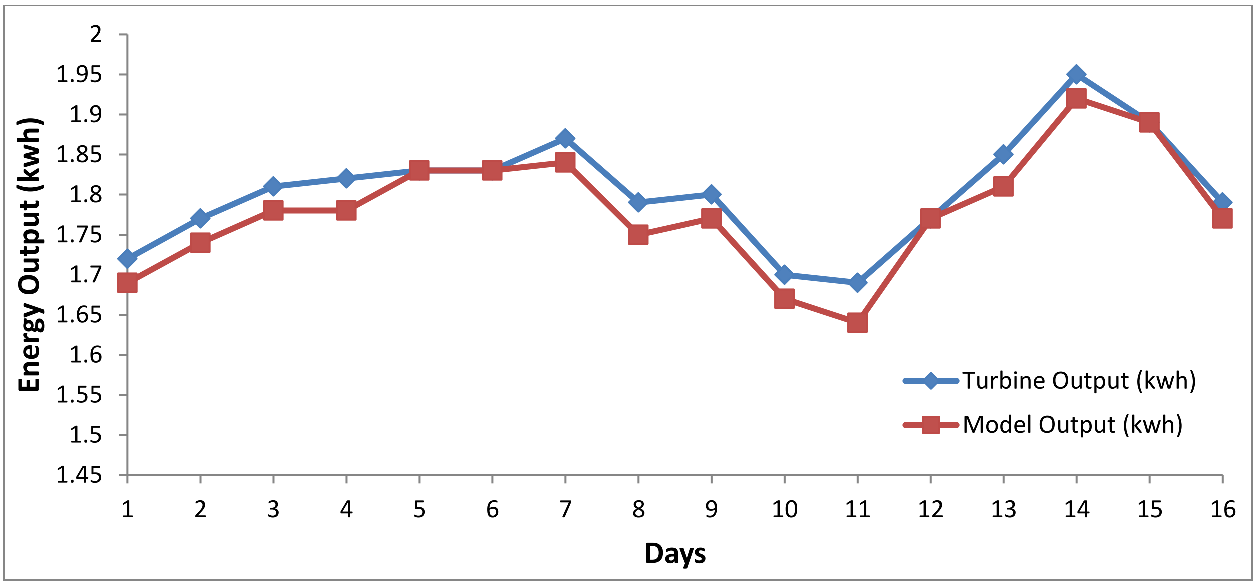

Fig. 4.7: Graph of Energy Output for Experimental Reactor 2

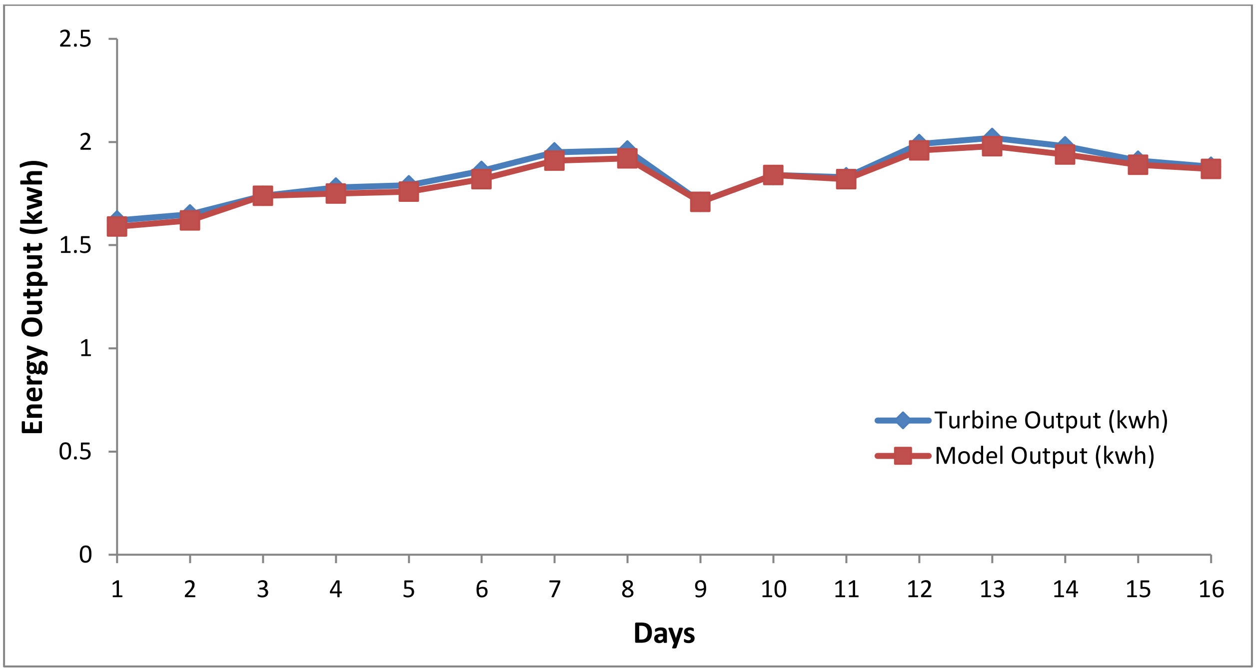

Fig. 5.8: Graph of Energy Output for Model Reactor 1

Table 4.9: Electrical Energy Generated from Daily Gas Yield from Model Reactor 1

	Model Reactor 1		
Day	**Gas yield (ml/gVS)**	**Turbine Output (kwh)**	**Model Output (kwh)**
1	248	1.62	1.59
2	252	1.65	1.62
3	280	1.74	1.74
4	281	1.78	1.75
5	283	1.79	1.76
6	296	1.86	1.82
7	312	1.95	1.91
8	314	1.96	1.92
9	275	1.71	1.71
10	300	1.84	1.84
11	296	1.83	1.82
12	323	1.99	1.96
13	327	2.02	1.98
14	318	1.98	1.94
15	309	1.91	1.89
16	306	1.88	1.87

Table 4.10: Electrical Energy Generated from Daily Gas Yield from Model Reactor 2

	Model Reactor 2		
Day	**Gas yield (ML/gVS)**	**Turbine Output (kwh)**	**Model Output (kwh)**
1	266	1.7	1.67
2	277	1.74	1.73
3	281	1.74	1.75
4	284	1.78	1.76
5	299	1.85	1.83
6	299	1.85	1.85
7	300	1.88	1.84
8	280	1.77	1.74
9	287	1.78	1.78
10	248	1.6	1.59
11	249	1.6	1.6

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12	288	1.82	1.78
13	290	1.84	1.79
14	309	1.92	1.89
15	304	1.87	1.86
16	270	1.73	1.7

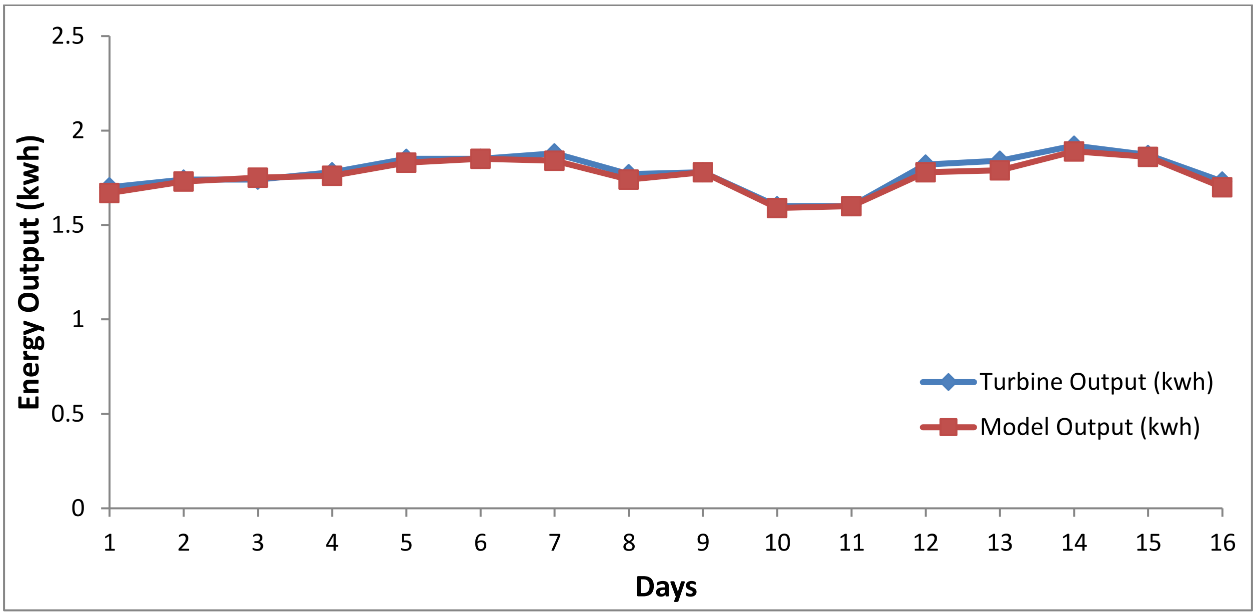

Fig. 4.9: Graph of Energy Output for Model Reactor 2

CONCLUSION AND RECOMMENDATIONS

Conclusion

In this, the model gave a well fitted prediction with an average correlation of 0.96. energy recovery from the treatment of wastewater has become a potent tool in proffering solution to the energy crises facing many developing countries and in turn reduce the over dependency on petroleum as the major source of energy.

Recommendation

The model developed in this study shows a high level of accuracy and is recommended for use in the design and operation of treatment plants as well as energy generation processes.

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