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2013

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### Recommended Citation

Reddi, Krishna R.; Li, Weilin; Wang, Bochao; and Moon, Young B., "System Dynamics Modeling of Hybrid Renewable Energy Systems and Combined Heating and Power Generator" (2013). *Mechanical and Aerospace Engineering*. 17.  
<https://surface.syr.edu/mae/17>

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## System dynamics modelling of hybrid renewable energy systems and combined heating and power generator

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*(Received 23 September 2011; final version received 23 April 2012)*

The role of energy in the present world is critical in terms of both economical development and environmental impact. Renewable energy sources are considered essential in addressing these challenges. As a result, a growing number of organisations have been adopting hybrid renewable energy system (HRES) to reduce their environmental impact and sometimes take advantage of various incentives. When a HRES is being planned, the ability to model a HRES can provide an organisation with numerous benefits including the capability of optimising sub-systems, predicting performances and carrying out sensitivity analysis. In this paper, we present a comprehensive system dynamics model of HRES and combined heating and power (CHP) generator. Data from a manufacturing company using HRES and CHP generator are used to validate the model and discuss important findings. The results illustrate that the components of a HRES can have conflicting effects on cost and environmental benefits; thus, there is a need for an organisation to make trade-off decisions. The model can be a platform to further simulate and study the composition and operating strategies of organisations that are venturing to adopt new or additional HRESs.

**Keywords:** hybrid renewable energy systems; combined heating and power generator; modelling and simulation; system dynamics

### 1. Introduction

Energy is crucial for supporting day-to-day life and continuing human development (Amin and Gellings 2006). Over the past few decades, though, demand for energy has been steadily increasing due to population growth, economic development and improved standard of living throughout the world (Cai *et al.* 2009). As a result, traditional energy sources such as fossil-fuel reserves have been depleting while their price has been rising (Akisawa *et al.* 1999, Marechal *et al.* 2005). How to maximise the use of energy resources and services through an energy management system has become one of the most important issues for increasing the number of corporations (Muñoz and Sailor 1998, Yeoman *et al.* 2003, Turton and Barreto 2006).

Energy is also a major contributor to environmental problems. Since burning fossil fuels for power generation and transportation is a substantial contributor of greenhouse gases to the atmosphere (Jacob 1999), various efforts have been made to replace conventional power sources with renewable sources of energy such as wind power, solar power, tidal power, geothermal power, hydro-power along with cleaner fuels from natural gas (Jefferson 2008).

The energy issues may be examined from the perspective of efficiency, which can be improved in the supply side as well as in the demand side. For the supply side, new technologies have been developed to convert a portion of the chemical energy of fuels into electrical

energy (e.g. using the waste heat to re-heat or produce power) (Turner 1999). Some organisations have started generating their own power and heat using technologies such as combined heating and power (CHP) generator (Block *et al.* 2008). By doing so, they are able to reduce their dependency on the grid as well as environmental impact and utility costs. In the demand side, electronic appliances with better efficiencies and low energy consumption have been developed and introduced into the markets, as an example (Colombier and Menanteau 1997).

Other efforts to address the energy issues include using energy from renewable sources to produce power along with the conventional energy system. One of the examples is hybrid renewable energy system (HRES) (Deshmukh and Deshmukh 2008). A HRES may consist of more than one type of energy sources such as a conventional diesel powered generator or micro-turbines powered by natural gas, and renewable energy sources such as photovoltaic (PV), wind, geothermal and/or combinations of these. The planning of a HRES usually starts with a feasibility study with estimation of available resources and load requirements. The sizes and number of necessary equipment, which are constrained by the load requirements and resource availability, further determine the economy and reliability of the HRES (Nema *et al.* 2009). The cost of the HRES depends on the type of equipment and its capacity, while the reliability of the HRES is characterised by the capability of

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the HRES to always provide the required load. A HRES with sufficient capacity may utilise storage technologies to store the energy in surplus and use it when the energy is in deficit.

When a HRES is being planned, an ability to model a HRES can provide an organisation with numerous benefits, including the capability of optimising sub-systems, predicting performances and performing sensitivity analysis. In modelling a HRES, individual components typically are modelled first. Then, the entire system needs to be modelled by combining the components. Therefore, a system-of-systems approach (Haskins 2011) is natural to model a HRES (Deshmukh and Deshmukh 2008).

In this paper, we present a comprehensive model to simulate the use of various combinations of energy sources such as natural gas, wind energy, solar energy and CHP to meet a specific heat and power load requirement. The goal of the model is to provide the decision makers a perspective of the overall system performance considering the performance of each individual energy source. The economic costs and environmental impacts are analysed for different combinations of specifications and quantities for the components comprising energy systems. The simulation model enables organisations to effectively configure and assess a HRES, given a set of budget constraints and environmental goals. The model is based on an integrated system dynamics (SD) (Sterman 2000) simulation model representing a HRES with separate modules of system components. The dynamic interactions among sub-systems and macro-scale performance of the HRES were investigated with the model. The model was developed using Vensim (VENTANA Systems, Inc. 2010) SD simulation tool and was verified and validated using real data from the Harbec Plastics, Inc. (2011).

SD is a methodology used to model and simulate complex systems. It represents a system in the form of stocks, flows, time delays, variables and feedback loops. A 'stock' is analogous to a bathtub, while the 'flows' is to its inlet and outlet. Stocks are connected by flows that regulate the accumulation of modelled system variables. The system variables define the values assumed by the flows and thus implement the system logic. During each simulation run, the difference between the inlet and outlet accumulates in the stock. At any point of time, the levels of all the stocks represent the state of the system. And the feedback loops are modelled using the information representing the systems' state to further influence the system variables that manage the system logic.

The unique feature of the SD methodology is the feedback modelling within modelled systems (Sterman 2000). In a HRES system, taking note that the output of the renewable energy systems (like solar panels and wind turbines) typically fluctuates and cannot be estimated or forecasted with good accuracy; the unmet power demand should be provided by unconventional sources of the HRES (such as micro-turbines, diesel generators and so on)

A constant feedback is necessary to estimate the power needed from the unconventional sources to meet the current power demand. And this makes SD apt for modelling this problem. Another distinctive feature of the SD methodology is its comprehensibility and flexibility. The modelling of a system by creating its structure is similar to the manner in which people associate and identify any system as 'mental maps'. This makes it easier to understand the system model even with minimum knowledge of SD methodology. Expansions to an existing model can be done easily by adding new variables and defining their relations with the existing variables. It is natural to model modular systems in which each module or system model can be modelled separately and assembled together later to represent a system of systems (Guo *et al.* 2001, Anand and Vrat 2006). As the result, the SD methodology provides more general and flexible modelling capabilities than other modelling methodologies adopted in the past to model these types of systems.

The rest of the paper is organised as follows. In Section 2, a literature review on past works on HRES models as well as CHP models is presented. In Section 3, the components of the developed model and the underlining logic of each of the components are explained. Then, the simulation results using the data from the Harbec Plastics, Inc. are presented in Section 4. The paper concludes with discussion and future research suggestions in Section 5.

## 2. Literature review

Papers containing 'energy systems' in the title were reviewed; however, only the papers that have considered the system level design of energy systems and modelled the control strategies of multiple energy systems were included in the literature review (Table 1). The results are presented in two sections: (i) modelling and simulation of HRES design and control to meet specific energy demands and (ii) modelling and simulation of CHP applications. The survey results are divided into the two sections since HRES and CHP systems rarely were considered together. Among the surveyed papers, only a couple of papers have considered both the renewable energy systems and CHP systems, which reveals a significant gap present in the existing research.

### 2.1 Design and control of HRES

Deshmukh and Deshmukh (2008) presented a review of commonly used methodologies to model and simulate individual HRES components and HRES configuration. They reported that typical HRES components include a PV system, wind energy system, diesel generator and battery system. General criteria used to select the combination of energy sources were reviewed along with several HRES simulation models.

Table 1. HRES literature summary.

References	Type	CHP	PV	Wind	Conventional energy system			Storage/ backup	Model performance measures
					Diesel generator	Micro- turbine			
Deshmukh and Deshmukh (2008)	Review/general methodology		X	X	X			X	N/A
Bernal-Agustin & Dufo-Lopez (2009a)	Mathematical model		X	X	X			X	Cost; unmet load
Nema <i>et al.</i> (2009)	Review		X	X	X				N/A
Ender <i>et al.</i> (2010)	Simulation model (HOMER)		X	X	X			X	Weighted series of criteria (e.g. capacity shortage, renewable fraction and so on)
Demiroren and Yilmaz (2010)	Simulation model (HOMER)		X	X	X			X	Net present cost; levelised cost of energy
Lund <i>et al.</i> (2007b)	Simulation model	X <sup>b</sup>	X	X <sup>a</sup>	X		X <sup>b</sup>	X	Electricity and heating supply
Trinkl <i>et al.</i> (2009)	Simulation model (dynamic system)	X <sup>c</sup>	X				X <sup>c</sup>		Utilisation of solar energy without heat pump operation; maximum degree of solidification
Mazhari <i>et al.</i> (2009)	Simulation Model (hybrid, object based)		X					X	Cost
de Durana & Barambones (2009)	Simulation model (hybrid, object based)		X	X	X			X	Source intensity; load intensity

<sup>a</sup> This model uses solar, wind and hydro as renewable energy sources.

<sup>b</sup> This model includes heat production from solar thermal, industrial CHP, CHP units, heat pumps and heat storage and boilers.

<sup>c</sup> This model has modelled a heating system supported by solar energy along heat pump.

A multi-objective design of an isolated HRES was proposed by Bernal-Agustin and Dufo-Lopez (2009a) to minimise cost and unmet load simultaneously. The authors applied the Pareto evolutionary algorithm as the main algorithm and a genetic algorithm as the secondary algorithm to find out the optimal system configuration and control strategy for the HRES. The methodology was demonstrated in detail by designing a PV–wind–diesel system in Spain.

In another paper, Bernal-Agustin and Dufo-Lopez (2009b) reviewed simulation and optimisation techniques to simulate and design stand-alone hybrid systems for generating electricity. Their review included design and control of hybrid systems with battery and hydrogen energy storage, multi-objective design and simulation/optimisation tools. The literature on design and control of hybrid systems with battery energy storage was further categorised into three different categories: (i) design and simulation, (ii) economic optimisation and (iii) control strategies.

Nema *et al.* (2009) reviewed the current state of design, operation and control requirements of the stand-alone PV–wind hybrid energy systems with diesel generator or grid as backup sources. They covered modelling of PV system, wind energy system and diesel generator, in addition to pre-feasibility analysis of hybrid system. The pre-feasibility analysis addressed the assessment of the wind speed and

solar insolation to ensure proper sizing of the equipment as well as optimisation of the sizing.

Ender *et al.* (2010) developed an interactive decision-making tool for HRES portfolio planning using the system-of-systems approach. Multi-attribute decision-making process, quality function deployment and dynamic analysis enabled by neural network surrogate modelling were also utilised in their tool. Data of a notional scenario that included PV arrays, a wind turbine, a diesel generator and batteries were collected from HOMER (HOMER Energy LLC 2010). It was then used for the regression of surrogate models to generate performance variables as a function of control and sensitivity variables.

An integrated model from several small isolated power systems was developed by Demiroren and Yilmaz (2010), using HOMER software to analyse how island Gökçeada in Turkey can be served by a HRES. The HRES consisted of PV system, wind turbines, batteries, together with the grid connection and diesel generator as energy backup.

Lund *et al.* (2007b) presented a comparative study of two energy system analysis models: EnergyPLAN and H<sub>2</sub>RES. Both were designed to analyse electricity systems with a substantial share of fluctuating renewable energy. The differences between two models are (i) the H<sub>2</sub>RES model focused on small islands, while the EnergyPLAN model focused on large region, (ii) the H<sub>2</sub>RES focused on technical

analysis, while the EnergyPLAN model included both technical and market exchange analysis and (iii) the H<sub>2</sub>RES model included only the electricity supply, while the EnergyPLAN model also included the district heating supply.

In another paper, Lund (2007a) evaluated whether a 100% renewable energy system is possible for Denmark. Three key technological changes and suitable implementation strategies were identified: (i) replacing oil with electricity for transportation, (ii) inclusion of small CHP plants and heat pumps and (iii) inclusion of wind power in electricity supply. All changes were simulated using the EnergyPLAN (Lund *et al.* 2007b) energy system analysis models. The consequences of each of the three sustainable technological changes and their combinations were analysed.

A dynamic system model was developed by Trinkl's research team (Trinkl *et al.* 2009). They investigated and optimised a heating system comprising of solar thermal collectors, heat pump, stratified thermal storage and water/ice latent heat storage systems. Based on a system control strategy developed particularly for this project with two storage tanks, the influence of the parameter on the proposed system in terms of seasonal performance factor and maximum degree of solidification was identified by simulation. The optimal system configuration was then derived.

Mazhari *et al.* (2009) developed a capacity planning tool of solar energy resources using hybrid simulation (i.e. SD models for generation and storage segments and agent-based models for demand segment) and meta-heuristic optimisation to obtain the most economical configuration of the solar generators and storage units. Effects of demand increment rate, storage efficiency and PV panel efficiencies are analysed through experiment and sensitivity analysis. Storage techniques, compressed air energy storage and super-capacitors, are also compared in terms of total cost.

de Durana and Barambones (2009) proposed an object-oriented HRES model using AnyLogic for the purpose of micro-grid design and control strategies (e.g. supervisor control, local decentralised control and centralised/decentralised load dispatching) analysis. In particular, among seven object elements, the DC Bus object, to which the others (e.g. wind turbines, diesel generator, battery, PV and so on) are connected, is constructed using SD.

## 2.2 CHP system

Only a few computer simulation models included CHP system as a component. Kaikko and Backman (2007) applied component-specific models to analyse the performance of a single-shaft micro-turbine in CHP in which the load level of the micro-turbine is controlled by the heat demand of the system. They studied the effect of *recuperation* (both recuperated and non-recuperated configurations) and different *load control methods* on the

technical and economic performance of the operation and the optimal sizing of the micro-turbine.

Aguiar *et al.* (2007) presented a daily simulation model to analyse natural gas micro-turbine applications for a residential complex. The electric and the thermal load curve of the building were investigated. And the micro-turbine configurations were analysed: (i) to satisfy the entire thermal demand and part of the electrical demand by purchasing the rest of the required electricity from the grid, (ii) to meet the electricity demand and have an excess of thermal energy.

Takagi *et al.* (1999) developed a simulation model of an absorption chiller for its dynamic characteristics in order to evaluate energy consumption for the heating, ventilation, and air conditioning (HVAC) systems and the control strategies. The model consists of equations programmed in FORTRAN language which describes heat transfer among the evaporator, the absorber, the generator and the condenser. Two scenarios, (i) an independent single-effect absorption chiller and (ii) an integrated HVAC system with chillers, were examined.

Hatzigryriou *et al.* (2007) used a distributed energy resources customer-adoption model (DRE-CAM) to select the optimal (1) equipment combination which includes CHP equipment and renewable sources and (2) the corresponding operational schedules for each installed technology, to minimise the annual energy cost while meeting energy balance, and operational, regulatory, investment and storage constraints. DRE-CAM was formulated as a mixed-integer linear program and was enhanced by the incorporation of electrical and thermal storage capacities. The proposed model was applied to a hypothetical San Francisco hotel. Four scenarios – doing nothing, invest, low storage price and force low storage price – were performed to assess the value of DRE and storage systems by comparing the annual costs and CO<sub>2</sub> emissions. The optimal technologies and their optimal schedules were presented.

Except the DRE-CAM by Hatzigryriou *et al.* (2007), most of the surveyed research works have limited scope in terms of types of energy systems that they modelled. The DRE-CAM is similar to our work that HRESs are modelled along with CHP. But since their approach is based on a mixed-integer linear program, dynamic interactions between various energy systems cannot be explicitly captured as in our model. We intend to model the CHP along with the renewable energy systems to enable the study of the cumulative benefits and available integration options for the systems.

## 3. Model logic

In this section, each component of the comprehensive model is explained and the interactions between each of the components are described. The operation logic of the entire model is outlined.

Table 2. HRES parameters.

System parameters	Specifications/values		
Micro-turbine (kW)	30	65	250
Solar panel (W)	175	210	280
Wind turbine (kW)	250	600	1250
Chiller	SC10 (120MBH)	SC20 (240MBH)	SC30 (360MBH)
Number of wind turbines	1	3	5
Number solar panel modules	0	520	1040
Outlet temperature at heat exchanger (°C)	121.1	148.9	176.7
Outlet temperature at LTPGT (°C)	82.2	87.8	93.3

Our HRES model includes a micro-turbine-based CHP system consisting of chillers and low temperature power generation turbines (LTPGTs), wind turbines and solar panel modules. The micro-turbine, wind turbines and solar panels generate power, while the heat exchangers, chillers and LTPGT manage the waste heat. The main goal of the model was to evaluate available options for planning and operating a hybrid energy system to meet known heat or power demand. The model has the capability to calculate the economic and environmental impact (i.e. CO<sub>2</sub> emission) for every possible combination of the energy sources. Each HRES set-up varies in terms of the specifications and quantity of each component which constitute the system.

To ensure better integration and control of the elements in the CHP system, the heat exchangers are assumed to be custom built. This allows avoiding any integration issues between the components such as micro-turbines, LTPGT and chillers, thus offering more flexibility for modelling different scenarios of HRES composition and operation. The HRES parameters include the specifications, quantity of wind turbines and solar panel modules, the CHP system parameters, specific heat,

flow rate and outlet temperature of water at LTPGT and heat exchanger as shown in Table 2. The operating temperatures define the amount of energy being produced and managed within the CHP system. The temperatures of system operation define the system performance, but they are also measured and controlled while monitoring HRES system operation (Harbec Plastics, Inc. 2011). The overall schematic model logic is given in Figure 1.

### 3.1 Wind energy

The sub-model calculates the power generated by the selected wind turbine based on its power curve supplied by the manufacturer. The coefficient of performance which denotes the efficiency of a specific turbine at specific ambient considerations is also considered for calculating the net power generated. The value of the coefficient of performance is influenced by factors such as the maintenance of the turbine gear box, type of generator used and so on. The coefficient of performance is assumed and used in the model as a constant. A value of 0.95 for mechanical efficiency and 0.8 for generator efficiency are

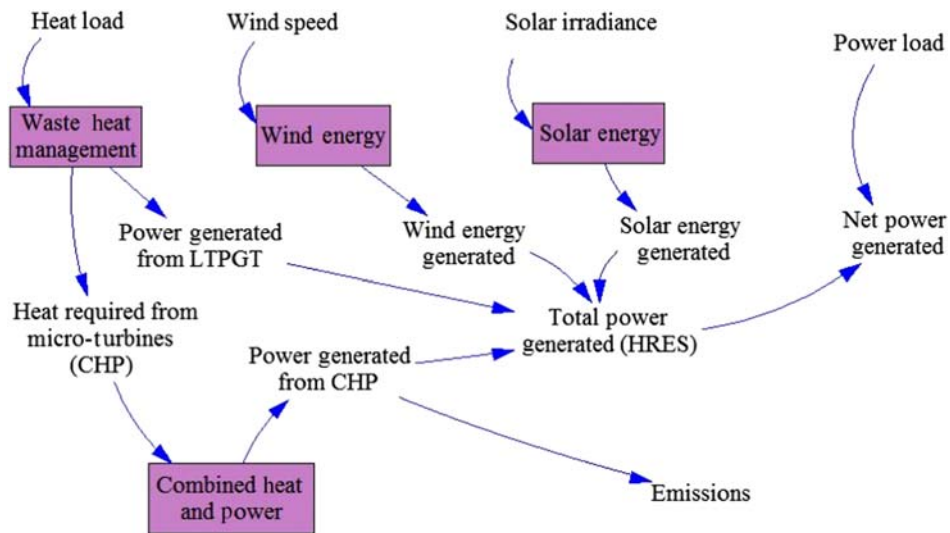


Figure 1. Schematic logic of the model.

assumed, the product of which yields the coefficient of performance of 0.76 (Power Tech Wind Energy 2011). The average daily wind speed data at the turbine hub height are used to calculate the power generated by the turbine at testing conditions. In this model, the height of the hub is assumed to be 40 m above the ground and the wind speed at that height is obtained from National Aeronautics and Space Administration (NASA) (Kusterer 2011). The power generated at testing conditions multiplied by the coefficient of performance gives the net power generated at the wind speed in the location under consideration (Equation (1)). Fuhrländer Akteingellschaft (2011) makes wind turbines of capacities 250, 600 and 1250 kW which are considered in the model.

$$\text{Wind power output} = \text{power generated at testing conditions} \times \text{coefficient of performance.} \quad (1)$$

In this model, three wind turbines (250, 600 and 1250 kW capacities) manufactured by Fuhrländer (2010) are considered. The variable ‘time’ represents the simulation unit, i.e. day (refer to Figure 2). The variable ‘average wind speed’ is an input variable that represents the wind speed for each day of the year. The variable ‘wind speed’ represents the wind speed on any given day and is defined by the time of the year and average wind speed at that time. The variables ‘wind power output 250 kW’, ‘wind power output 600 kW’ and ‘wind power output 1250 kW’ represent the power curves (power output vs. wind speed) for wind turbines 250, 600 and 1250 kW, respectively. The variable ‘wind turbine selected’ defines the wind turbine selected for any simulation run and is used to pick the appropriate power curve to determine the ‘wind power output’ at the average wind speed on any day. The variable ‘power generated from wind source’ represents the wind energy produced on any given day. The stock ‘wind energy’ represents the accumulated wind energy produced throughout the year.

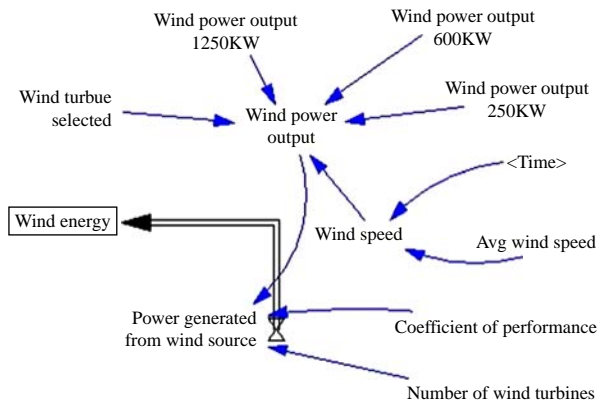


Figure 2. The wind energy system logic.

### 3.2 Solar energy

The estimated daily AC output from a solar system is the product of maximum power at standard testing conditions (STC), peak sun hours (converted from monthly solar radiation cited from a national database), de-rating factor [an estimation of 78.9% (HARMONY FARM SOLAR 2011) is used in this model], temperature de-rating factor (see Equations (3) and (4) for detail) and number of modules.

$$\begin{aligned} \text{Estimated daily alternating current (AC) output from a solar source} \\ (\text{Whr/day}) = & \text{maximum power at STC (Watts)} \\ & \times \text{peak sun hours (hr/day)} \times \text{de-rating factors} \\ & \times \text{temperature de-rating factor} \times \text{number of modules.} \end{aligned} \quad (2)$$

$$\begin{aligned} \text{Temp de-rating factor} = & 1 + \text{temp coefficient of } P_{\max} \\ & \times (\text{STC module temp} \\ & - \text{instantaneous operating cell temp}). \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Instantaneous operating cell temp} \\ = & \text{instantaneous ambient temp} \\ & + \frac{\text{NOCT} - \text{normal operating ambient temp}}{\text{normal operating solar irradiance}} \\ & \times \text{solar radiation.} \end{aligned} \quad (4)$$

Maximum power at STC, temp coefficient of  $P_{\max}$  and nominal operating cell temperature (NOCT) are the product electrical and temperature characteristics provided by the manufacturer. In our model (Figure 3), STP210-18/Ud polycrystalline solar module by Suntech Power was used for the PV system. From the product datasheet (Suntech 2011),

$$\text{Maximum power at STC} = 210 \text{ or } 280 \text{ W}$$

$$\text{Temp coefficient of } P_{\max} = -0.47\% / ^\circ\text{C}$$

$$\text{NOCT} = 45 \pm 2^\circ\text{C}.$$

### 3.3 Micro-turbine

The structure of the micro-turbine model differs from the controlling or managing criteria of the turbine. The turbine can be used to produce the required electricity, in which the heat produced is a by-product. Or, the turbines can be used to produce the required heat, and the electricity produced is considered as a by-product. This model illustrates the use of a micro-turbine to address the heat load, while generating electricity as a by-product. The parameters such as available heat output, power to heat ratio, effect of ambient temperature and fuel input associated with a specific micro-turbine are defined from the specifications of the micro-turbine selected.

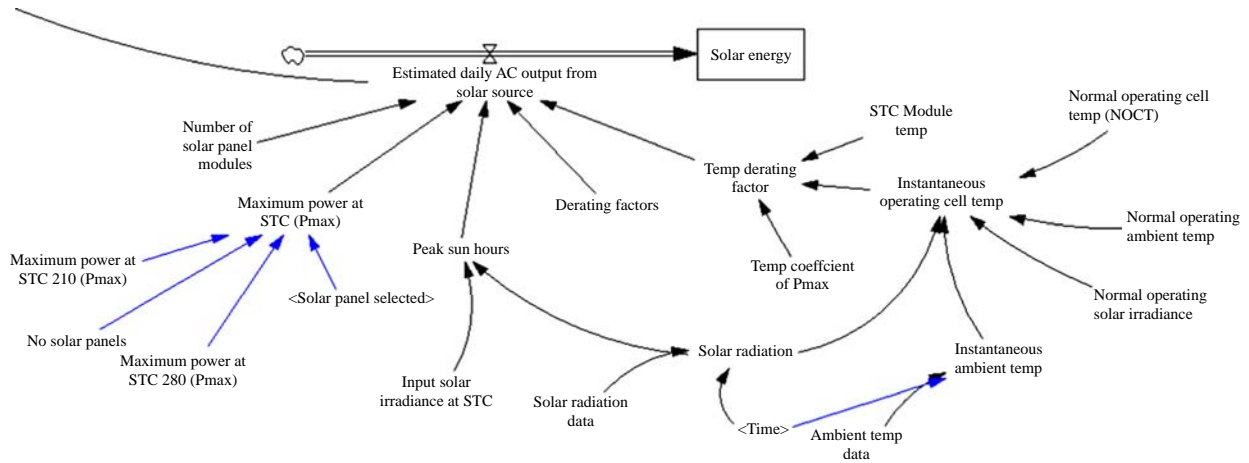


Figure 3. The solar energy system logic.

The available heat output of the micro-turbine is useful heat generated from the exhaust gases. Power to heat ratio is the ratio of electric power output to useful heat output. Fuel input is the rate at which the fuel is consumed by the micro-turbine. The average heat content of the fuel is determined by the type of fuel burnt to power the micro-turbine. The heat load and electric load are the inputs to the model and the natural gas used and energy required from/given to the grid are the outputs. The specifications of three micro-turbines of 30, 65 and 250 kW capacities manufactured by Capstone Turbine Corporation (2010) are used in this model.

The total daily heat demand represented by the variable 'total heat required' in Figure 4 is calculated from the minimum operating conditions of the selected chiller, desired temperatures at heat exchanger and LTPGT outlets and the required daily heating represented by 'heat load

rate'. For any particular day, the daily heat load determines the number of chillers required to be operating, which further determines the required hot water flow rate. The hot water flow rate along with the specific heat of water and inlet and outlet temperatures of water at the heat exchanger determines the total heat required.

In this model, the 'total heat required' for any particular day is used to calculate the natural gas required to produce the heat. The power generated is then calculated using the power-heat ratio. The performance of the turbine at the ambient temperature is used for determining the de-rating factor, which is further used in calculating the power generated. Three micro-turbines of 30, 65 and 250 kW capacities manufactured by Capstone Turbine Corporation (2010) were chosen. In Figure 5, variables 'daily power load' and 'daily heat demand' are the inputs to the model and represent the daily power load

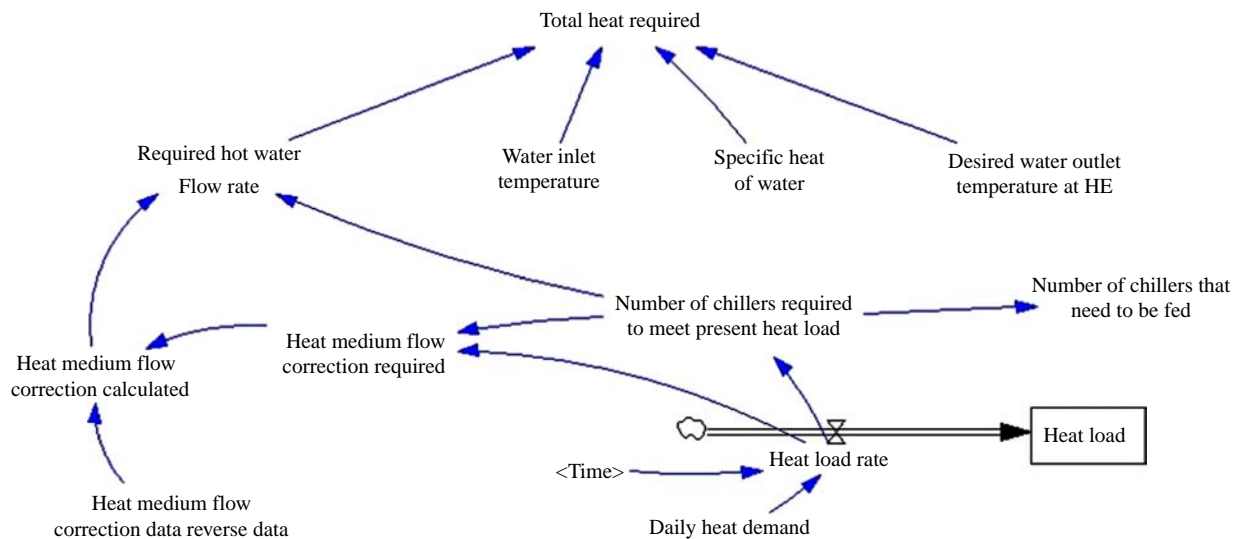


Figure 4. Calculation of the total heat required to be produced by the micro-turbines.



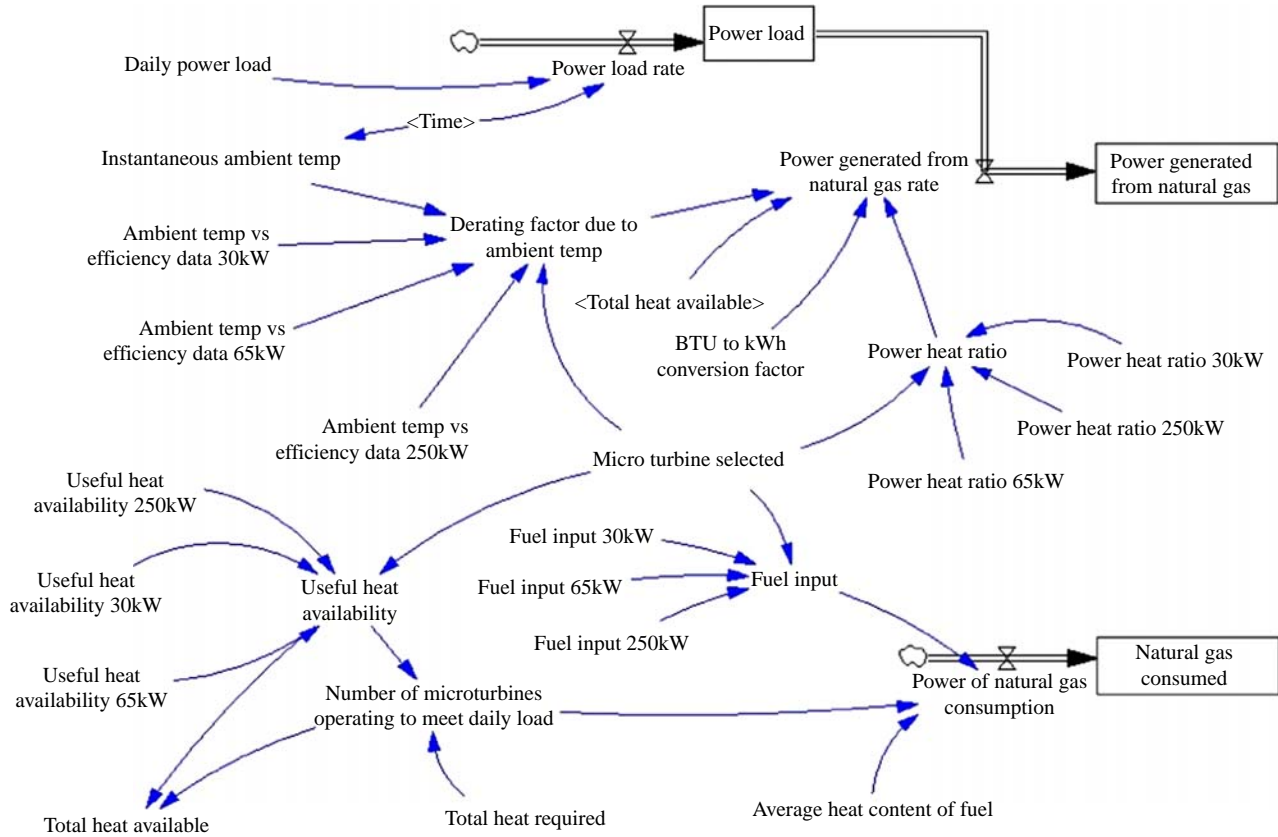


Figure 5. The logic of the CHP system using micro-turbines.

and heat load, respectively. Variable ‘instantaneous ambient temp’ represents the ambient temperature on each day of the year and variable ‘max heat load’ represents the maximum daily heat load in a year. Variable ‘useful heat availability’ represents the heat output of the selected micro-turbine by its specifications.

### 3.4 Waste heat management

The heat energy (Equation (5)) from the exhaust gases of the micro-turbines was used to heat water to a preset temperature via a heat exchanger (refer to Figure 6). The flow of water (Equation (6)) was controlled to attain the desired outlet temperature of the hot water. The hot water from the heat exchanger (HE) outlet was used to power the binary Rankin cycle of the LTPGT. The water was assumed to lose some energy during the low temperature power generation process that is indicated by the fall in temperature of the water. Although the specification of the LTPGT determines the temperature at the outlet of the LTPGT, a pre-defined value is used in the model due to unavailability of a mature commercial product with historical performance data. The available energy from the hot water at the LTPGT was determined from the inlet and outlet temperatures at the LTPGT.

The maximum efficiency to source temperature curve, provided by Nichols (1986) for a geothermal source, was used to determine the efficiency of the LTPGT considering the hot water temperature at the inlet. In the present model, the amount of hot water was limited unlike the geothermal source in which lot of hot water is available. However, it is considered acceptable because the maximum and minimum efficiencies from the graph are in agreement with efficiencies of the LTPGT in development which are presently being tested (Ener-G-Rotors 2011). The product of the available energy (Equation (7)) and the efficiency determines the power generated from LTPGT.

$$\text{Total heat available} = \text{number of micro-turbines} \times \text{available heat output.} \quad (5)$$

The water from the LTPGT was used to power a chiller with heating and cooling capability (Yazaki Aroace 2011). The temperature and flow rate were used to determine the factors such as cooling capacity factor, heating capacity factor and flow correction factors that affect the performance of the chillers (refer Figure 7). The rated capacity of the chiller was then multiplied by these factors to determine the heating and cooling capacity of the hot water exiting the LTPGT. The chillers’ rated operating tempera-

ture is ranges from 70°C to 95°C and the chillers do not operate when the temperature of the heating medium is out of this range. Also the chillers operate only when the flow rate of the heating medium (hot water) is at least 30% of the rated flow. Using these constraints, the number of chillers

where ‘useful heat availability’ is determined from heat output parameter of the micro-turbine specifications.

- The number of micro-turbines operating at full load is used to calculate the total amount of heat available

$$\text{Required flow rate of water} = \frac{\text{heat transfer rate to water}}{\text{specific heat of water}} \times \frac{\text{desired water outlet temperature at HE} - \text{water inlet temperature}}{60} \quad (6)$$

Available heat from HE outlet = required water flow rate × specific heat of water

$$\times \frac{\text{desired water outlet temperature at HE} - \text{desired water inlet temperature at LTPGT}}{60} \quad (7)$$

that can be fed is calculated from the heating medium flow rate and the rated flow rate of the selected chiller.

### 3.5 Summary of the working logic of the HRES model

The overall working logic of the HRES model is summarised below:

- Based on the outlet temperature of the LTPGT and daily heat load, the number of chillers and required hot water flow rate to address the heat load is calculated using Equations (8) and (9).
- Considering the required flow rate and the desired

(Equation (5)).

- The power generated from all sources including wind, solar, LTPGT and micro-turbines is added and compared to the power load to determine the net demand of power.
- The total cost of the entire system is then calculated, including the operating cost of each component along with its installation and maintenance costs.
- The peak heat load determines the number of components that need to be installed and the daily heat load determines the number of components that operate on a given day.

$$\text{Number of chillers required} = \frac{\text{daily heat}}{\text{heating capacity factor of chiller} \times \text{standard heating capacity}} \quad (8)$$

Total heat required = standard flow rate × number of chillers required to meet present heat load

$$\times \frac{\text{heat medium flow correction calculated}}{100} \quad (9)$$

Total heat required at micro-turbine outlet = required water flow rate × specific heat of water

$$\times \frac{\text{desired water outlet temperature at HE} - \text{water inlet temperature}}{60} \quad (10)$$

temperature at the heat exchanger outlet, the required heat energy (output) from the micro-turbines is calculated using Equation (10).

- The number of micro-turbines that are needed to work to meet the heat demand is calculated.

$$\begin{aligned} &\text{Number of micro-turbines} \\ &= \text{integer} \frac{\text{total heat required}}{\text{useful heat availability}} + 1, \quad (11) \end{aligned}$$

The duration for simulation experiments was set as 1 year and the base time unit for each simulation run is a day, without loss of generality. To limit the scope and number of simulation runs, the number of options (specifications and quantity) considered for each element of the system is limited to three. It is therefore assumed that the required preliminary analysis for selection of these three specifications of each of the sub-systems is done. The three capacities of each of the sub-systems (micro-turbines, chillers, wind turbines and solar panels) along with other

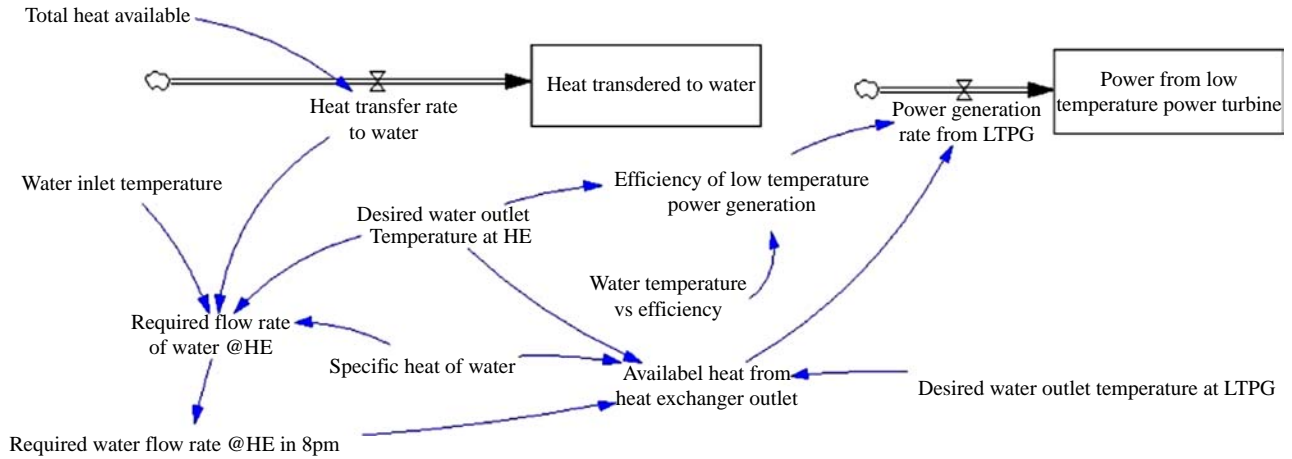


Figure 6. The logic of the LTPGT.

HRES parameters are given in Table 2. While the specifications for solar panels and wind turbines are picked based on the availability of resources such as wind and solar insolation, the micro-turbine and chiller specifications were picked based on the required power load and head load. The outlet temperature at the heat exchanger is defined by the micro-turbine specifications and the intended quantity of energy available for low temperature power generation. The outlet temperature of the LTPGT is determined from the chiller minimum operating requirements such as flow rate and temperature range. Each of the possible combinations is simulated to study the dynamic interactions among HRES elements influencing CO<sub>2</sub> emission and cost.

All the micro-turbines operate at full load to ensure maximum efficiency. The total heat demand on any day was calculated based on the desired temperatures at the

heat exchanger outlet and the flow requirements of the chiller selected, which addresses the heating load. The number of micro-turbines operating on a specific day was calculated from the heat demand on that specific day.

Since the micro-turbines always run at full load, they normally generate heat in excess of the requirement. The number of operating micro-turbines determines the amount of natural gas consumed per day. The electricity produced and the heat available, from the micro-turbine exhaust gases, were calculated from the specifications of the micro-turbine. The hot exhaust gases from the micro-turbine were then used to heat water to a predetermined temperature. The flow rate of the water was determined from the desired temperature at heat exchanger outlet and available heat from the exhaust gases. The maximum efficiency of LTPGT, and thereby the amount of power

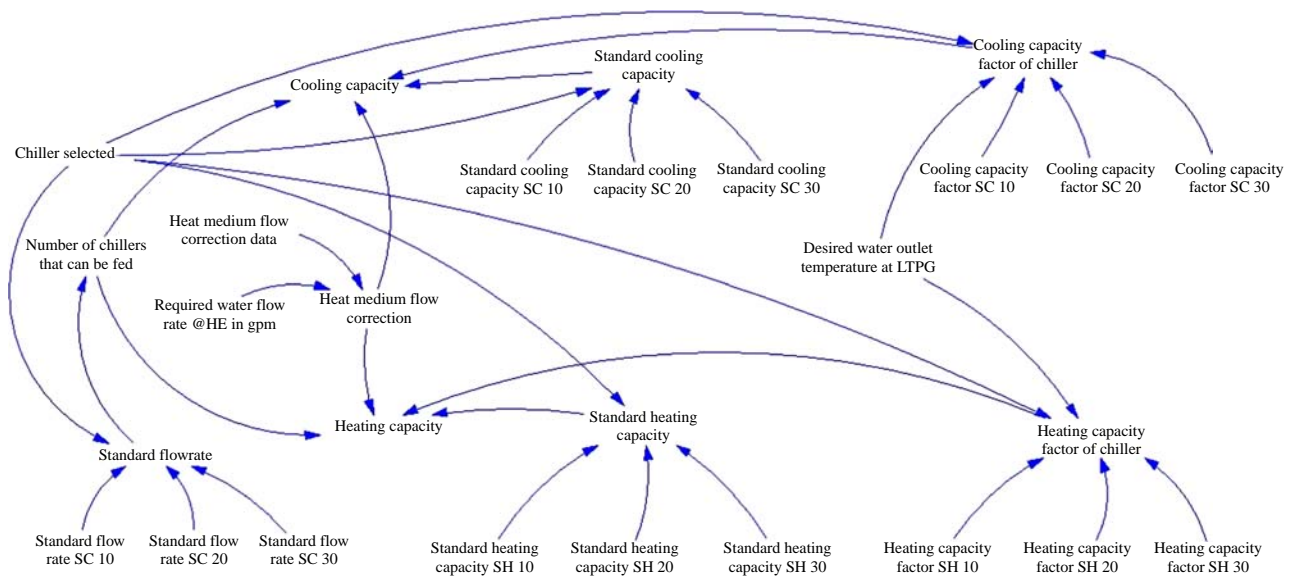


Figure 7. The logic of chiller operation.

generated from it, was determined from the temperature of the hot water at the inlet (Nichols 1986, Glassley 2010). The heating or cooling capacity was determined from the selected chiller specifications based on the temperature of the hot water and its flow rate at the exit of the LTPGT. The total power generated is the sum of the power generated from the micro-turbines, solar, wind and LTPGT systems. The generated power was then compared to the electric load for the day, and the net power demand was calculated. The net power demand can be positive or negative determining whether the power is given to the grid (negative) or drawn from the grid (positive).

### 3.6 Validation

We used both quantitative and qualitative tools to validate our model. We conducted structural verification and validation test followed by behaviour validation test as described below.

Structural verification test means comparing the structure of the model against the structure of the real system to ensure that the model is technically correct. The structural validation test assesses the validity of the model on its structure and assumptions by comparing it with available knowledge from the real system being modelled (Harbec Plastics, Inc. 2011) complemented by theoretical knowledge.

We used a simplified framework along with a flowchart to describe important assumptions, logics and features in order to ensure whether we incorporated all the important issues in a proper way. Then we compared the model's structure with the structure of the Harbec Plastics, Inc. The process proved that our assumptions, logics and structure indeed reflect thoroughly and correctly the system we intended to study. The structural verification and validation also helped us to get ready for the following behaviour validation tests.

Behaviour validation aims to demonstrate that the model behaviour considerably reflects the real system

behaviour and generally follows the structural verification process. We reconfigured our model to mimic the HRES system installed in Harbec Plastics, Inc. and compared the output behaviours for consistency. Particularly, we adapted our model framework according to the Harbec's logical control framework (Harbec Plastics, Inc 2011) by using one wind turbine, several micro-turbines and one absorption chiller but without solar panels when we conducted extreme condition test, relationship test and trend test.

The extreme condition test was used to evaluate parameters under extreme conditions and gauge the reasonability of the result. The boundary parameter values were used to see whether the results were still consistent. For example, for environment policy we increased the cost of electricity to a large extent, and also we referred to the usage history of the Harbec, Inc. (Harbec Plastics, Inc. 2011). Peak values such as demand and efficiency were used to testify their corresponding power usage and emission. The extreme condition test results were satisfactorily found to be around the upper or lower range of the actual Harbec's HRES operation, which indicated to be plausible.

The relationship test was used to testify relationships between entitles against the knowledge of the real system. We extended our results on sensitivity to cost and best configuration validation. For example, lowest cost or most environmental-friendly configuration was tested as shown in the three-level DOE test in Section 4. At the same time, some strongly paired relationships between two entitles or parameters were tested and proved that the relationship matches the reality throughout design-of-experiment studies explained below.

For the trend test, time-series behaviour of a certain output was tested. We implemented the tests on each module one by one to compare the trend in 1-year, 30-day and 24-h time span due to seasonal demand and generation difference as well as amplitude of important factors. For example, the power output curve from simulation and the turbine manufacturer specification were compared (Figure 8).

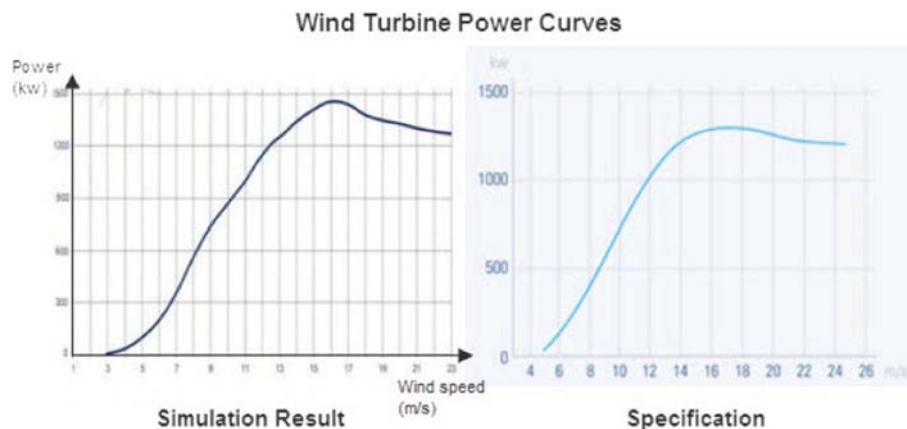


Figure 8. Wind turbine power curve simulation result compared with its specification.

The same pattern from these two figures can be observed and their amplitude can be verified. Also the relationships match each other even though the simulation curve is not as smooth as the given specification curve. Still this is understandable since the specification describes the ideal situation without any disturbance from outside.

**4. Results**

The model is simulated and from the results the effect of the HRES parameter on various response variables such as power generated, annual maintenance cost and annual CO<sub>2</sub> emissions was studied. The relationship between the system cost and the reduction in emissions is discussed.

**4.1 Effect of HRES parameters**

**4.1.1 Total power generated**

Figure 9 shows the relationship between various parameters of the HRES and the total power produced. From Figure 9, it can be observed that, for higher capacity of the chiller, the total power produced by the HRES is higher. This can be explained by the fact that, for higher chiller capacities, the minimum hot water flow rate to keep the chiller working is higher. With constant temperature at the heat exchanger and the LTPGT, any increase in flow rate would increase the demand for input heat at the heat exchanger. The greater the demand for heat at heat exchanger input is, the higher the number of micro-turbines operating to meet the heat demand is. The higher the number of micro-turbines operating is, the greater the generated electricity is.

Low temperatures at the heat exchanger outlet seem to favour the amount of power produced, whereas it is the opposite for the temperatures at the LTPGT. The micro-turbine with 65 kW specification seems to produce more power, while the 250 kW turbine generates lowest power of the three considered micro-turbine specifications.

The solar panel capacity does not seem to have any effect on the total power generated. This is because the increase or decrease in the solar power produced, between the considered solar panels, is very small compared with the magnitude of the total power produced by the energy system. Although the wind turbine capacity clearly shows an increase in power produced with increase in capacity, the difference in the power generated by the 1250 kW rated turbine and 600 kW rated turbine is quite small. Considering the costs of these two turbines, it may be wise to install a 600 kW turbine instead of a 1250 kW turbine, because the benefits of choosing the 1250 kW turbine are minimal. The number of solar panels and wind turbines positively influences the power produced.

**4.1.2 Annual maintenance cost**

The influence of various system parameters on the annual system maintenance cost is shown in Figure 10. From Figure 10, it can be stated that there is a considerable decline in the system maintenance cost, when the chiller with highest specification is chosen. Low temperatures at the heat exchanger and the LTPGT outlets result in lower system maintenance cost. And the micro-turbines with specifications 30 and 250 kW result in higher system maintenance cost, while the 65 kW micro-turbine drasti-

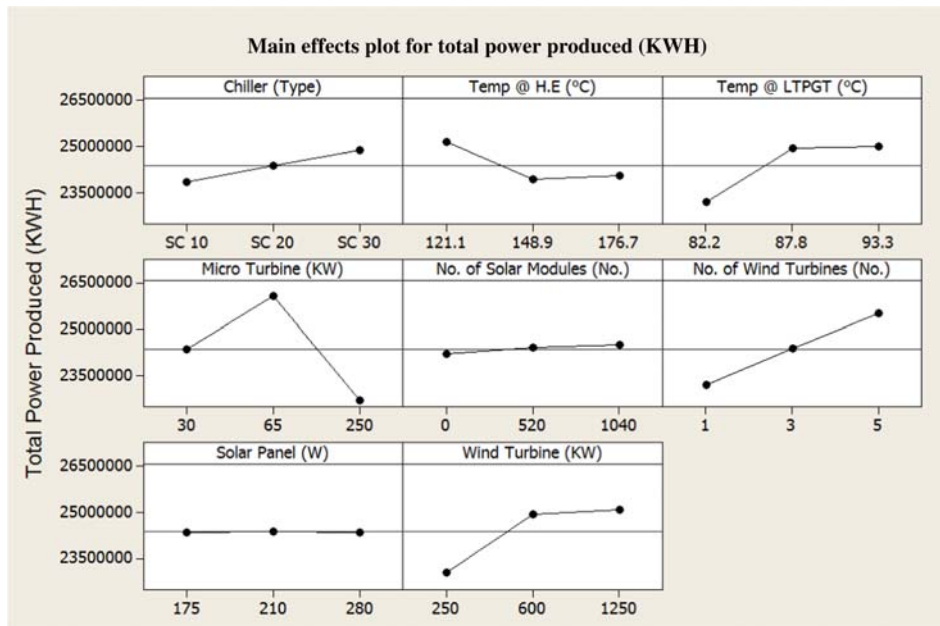


Figure 9. Design of experiments (DOE) result of factor effects on total power generated.

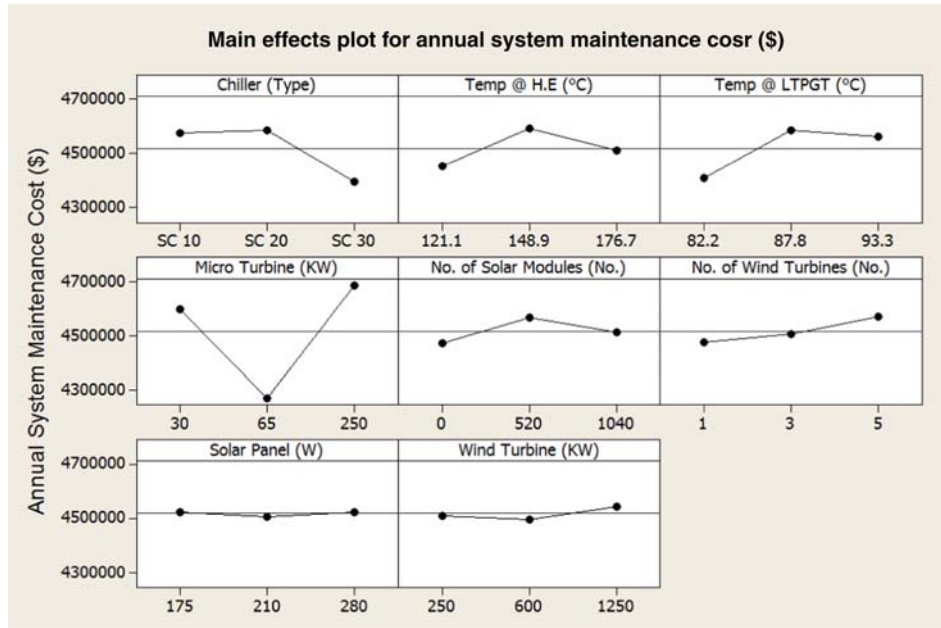


Figure 10. DOE result of factor effects on maintenance cost.

cally decreases the system maintenance cost. Finally, the solar panel capacity, wind turbine capacity and their numbers does not seem to influence the system maintenance cost significantly.

4.1.3 Annual CO<sub>2</sub> emissions

Figure 11 shows the individual effects of each system parameters on the HRES annual CO<sub>2</sub> emissions. The

emissions of the 250 kW micro-turbine are the lowest compared with those of the 30 kW and 65 kW micro-turbines. Given the small difference (only \$500) (Energy and Environmental Analysis 2008) in the plant costs of the considered micro-turbines, it would be advantageous to install a 250 kW micro-turbine ahead of other considered option on both the economic and environmental front. There is noticeable reduction in emissions with increase in the wind turbine capacity, while there is no noticeable

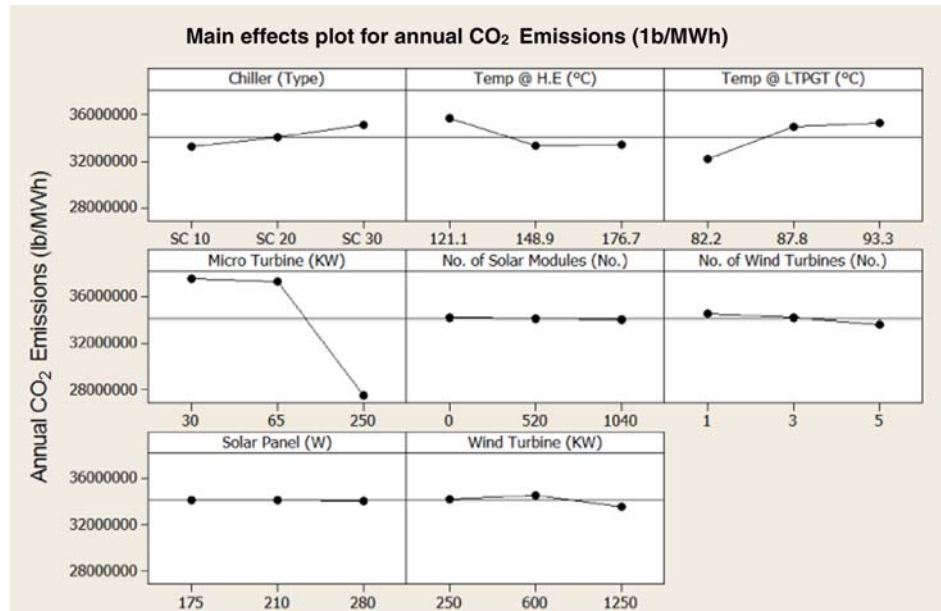


Figure 11. DOE result of factor effects on annual CO<sub>2</sub> emissions.

reduction for solar panels. Lower temperatures at heat exchanger outlet and LTPGT outlet along with low capacity chiller result in lower emissions. This can be explained from the fact that higher temperatures require higher heat energy that would require more number of operating micro-turbines, generating more emissions. Similarly, low capacity chiller requires lower minimum flow rate to operate, which results in lower demand of heat energy and lower emissions.

#### 4.2 Cost analysis

The Pareto chart shows the relative effect of the important factors affecting the system parameter of interest. In Figure 12, the effect of various parameters on the annual total cost is shown. For the time span of 1 year, the major

factors contributing to the HRES cost are outlet temperature at LTPGT, number of wind turbines, outlet temperature at heat exchanger, wind turbine selected and chiller selected, in the order of decreasing influence. The outlet temperatures define the amount of heat required from the micro-turbines that further defines the number of micro-turbines installed and amount of natural gas consumed. Though the maintenance cost of wind turbines is low, installation cost is high and hence its quantity would drive the costs upwards.

But for the span of 10 years (refer to Figure 12), the contribution of the parameters to the total cost decreases (refer to the x-axis values of Figure 12). The parameters influencing the total cost remain the same except that the wind turbine selected no longer is a major contributor as it provides low cost energy with the least or no maintenance.

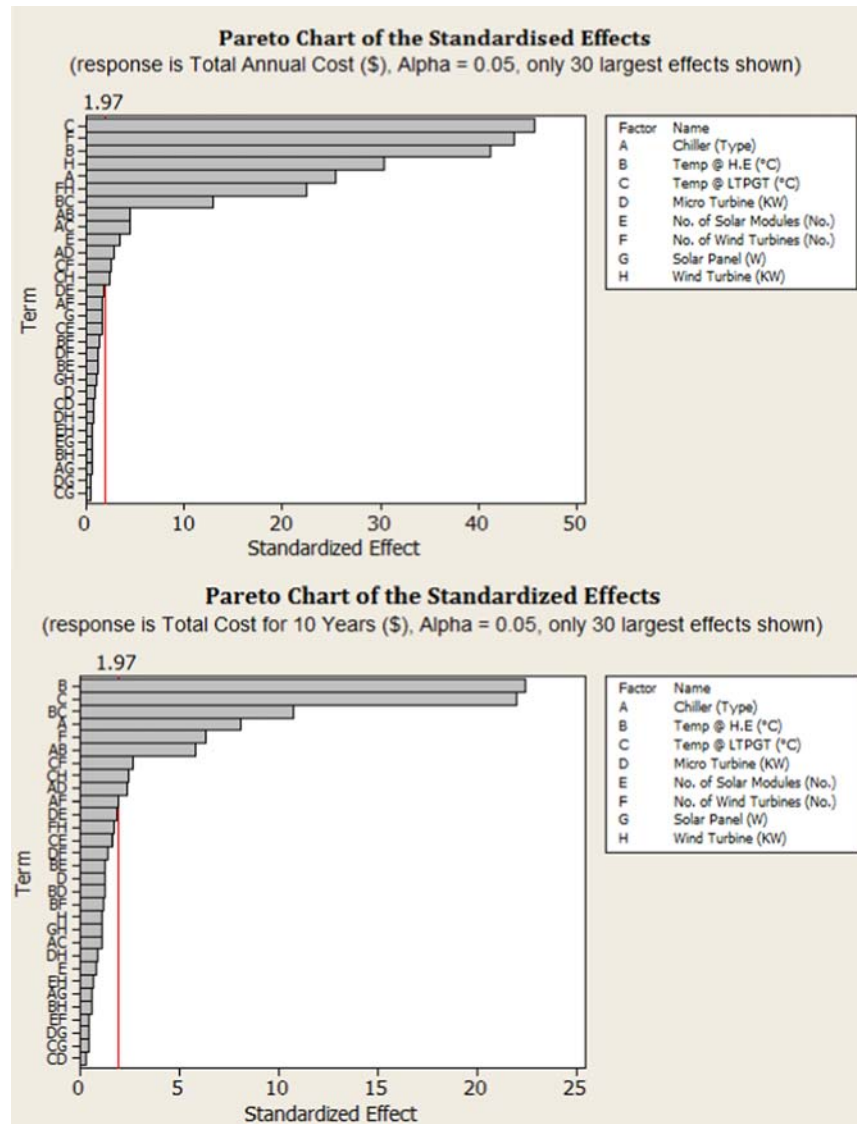


Figure 12. Comparison of factor effect significance on annual cost and 10-year cost.

Considering the effects of various system parameters on HRES cost, it can be stated that in planning a HRES, the temperature settings and the chiller capacity should be selected with care in order to keep the total cost to a minimum.

**4.3 Emission analysis**

The Pareto chart showing the effect of the HRES parameters on CO<sub>2</sub> emissions is given in Figure 13. It shows that micro-turbine capacity, wind turbine capacity, number of wind turbines and chiller capacity along with outlet temperatures at the heat exchanger and LTPGT are critical parameters in determining the best environmental-friendly configuration. Large capacity micro-turbines results in lower total emissions than smaller micro-turbines delivering the same power. The combined effect of wind turbine capacity and the number of wind turbines indicates the amount of green energy that can be produced. With higher capacity wind turbines and higher number of wind turbines, the amount of green energy produced is higher. Since green energy does not have any emissions, the emissions that would have been produced if the same energy were generated using micro-turbines are avoided. Though initial cost of the wind turbine is high, it can be justified by the amount of emissions avoided by it in the long term.

Low chiller capacity, higher or moderate heat exchanger temperature and lower LTPG temperature are preferred for low CO<sub>2</sub> emissions, while they are not preferred when considering the cost analysis. This implies that we cannot find an overall optimal configuration with

least cost and least emission at the same time. Trade-off decisions are necessary to meet both the expense and the emission requirements and the solutions for any case would be unique and would be determined by the cost and emission targets or constraints for that case.

The lowest emissions resulted from a combination of 10 kW chiller, 148.9°C outlet temperature for heat exchanger, 82.2°C outlet temperature for LTPGT and 250 kW micro-turbine. The optimal level was achieved by a combination of the highest wind turbine capacity, the largest quantity of the wind turbines, the highest solar panel capacity and the largest quantity of solar panel modules, indicating that considerable amount of renewable power is required to ensure low emissions.

The lowest cumulative cost over 10 years was achieved with the type of 30 kW chiller, 65 kW micro-turbine, 121.1°C outlet temperature at heat exchanger and 93.3°C outlet temperature at LTPGT. Due to the high installation cost of wind turbines and the solar panels, their quantity should be kept to minimum or not considered at all, to ensure lowest possible HRES cost.

The HRES parameters that result in lowest cost have 80% more emissions than the lowest emissions possible by the HRES. And the HRES parameters that result in lowest emissions cost 268% more than the lowest cost achievable for the HRES system. This indicates that there are no optimal parameters existing when both economic burden and environmental benefits of the HRES are considered. Hence, the organisation has to balance the system parameters based on its economic and environmental commitments.

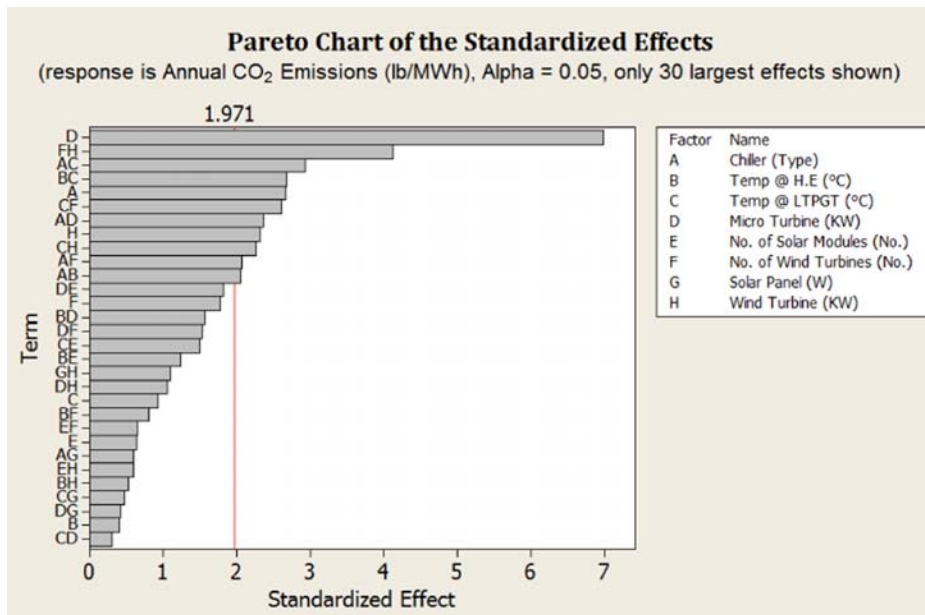


Figure 13. DOE result of factor effects on annual CO<sub>2</sub> emissions.



## 5. Conclusions

This model predicts the performance of the HRES system for a given configuration, which is defined by the specifications and quantity of each sub-systems. The model output for every combination of the system parameters is analysed in order to determine the effect of the sub-system on the HRES output. However, this model can also be utilised to:

- (1) observe how the capacity and quantity of each HRES component affects the total cost and environmental impact of the HRES;
- (2) evaluate the relative significance of each HRES component on its overall performance, along with the strength of any associations among multiple components of the HRES in establishing its performance and
- (3) determine the capital expenditure and environmental impact of various configurations of the HRES in order to determine the best, given the limitations such as budget, regulations or emission goals. To find the optimum system configuration, weights can be assigned to the model outputs, total cost and CO<sub>2</sub> emission, resulting in the best configuration given the constraints like cost and emissions.

Models like this would definitely be useful to decide the energy system parameters (Nema *et al.* 2009) given various constraints such as cost, climate, environmental commitments and so on. This would give an opportunity to foresee the performance of an energy system under various operating strategies and system parameters, based on which the configuration of an energy system can be decided. Though the renewable energy systems are beneficial through lower or no carbon emissions, there is a payback period until the net benefits are realised. However, the payback period is not explicitly represented in the model presented in this paper. The net decrease in overall CO<sub>2</sub> emissions can be obtained only after the cumulative decrease in CO<sub>2</sub> emissions resulting from the installed HRES system surpasses the CO<sub>2</sub> emissions contributed by the manufacturing of the renewable energy systems. The HRES model discussed here can be expanded to include the footprint or physical space required to install each system components. Space requirements are critical when the available space is limited and securing additional space is costly. The HRES model also can be modified to simulate the operating strategy of the energy system. Instead of operating the micro-turbines to meet the heat load, we can operate them to meet the power load and study the implications of the strategy change.

The comprehensive model discussed here consists of individual sub-models representing each energy source or constituents of a HRES. The model can be expanded by including a database of all HRES component specifications,

thus eliminating any need for manually entering such specifications into the model. Incorporating capabilities such as estimation of the climatic parameters, the solar insolation, wind speed and ambient temperatures at the specific location of interest would be an advantage for a new model. With advanced programming, capabilities of proposing a list of system configurations for a given budget and emission targets, through optimisation, can also be incorporated in the presented model. The limitation of this model is that it considers the annual fluctuation in power generated from renewable energy sources but ignores the intra-day fluctuations. In the future, the simulation duration for an hour can be considered so that it takes the intra-day fluctuations in the energy from renewable sources.

## Acknowledgement

The authors appreciate the help given by Harbec Plastics, Inc.

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