ABSTRACT

1. Introduction

The main drivers of the increased popularity in renewable energy electricity generation by wind, solar, biomass, small hydro and hybrid are due to emergence of cleaner and sustainable energy technologies brought along with financial incentives, promotion mechanisms, economic and regulatory changes introduced in various countries. The reasons of interests in small scale electricity generation are:

(i) development in distributed electricity generation technologies,
(ii) difficulties in laying new transmission lines,
(iii) demand of reliable electricity supply,
(iv) climate change, and
(v) liberalization of electric power market.

Other reasons of growth of distributed renewable energy system are due to:

(i) flexibility in deployment due to their small size,
(ii) shorter lead time for installation and commissioning, operation and capacity expansion,
(iii) cost effective source of electricity for peak load,
(iv) minimal cost of transmission and distribution which could be as high as 40%.
(v) insurance against volatile prices of electricity,
(vi) transmission and distribution losses may be avoided,
(vii) effective use of locally available cheap primary renewable energy sources such as biomass, biogas, landfill gas, etc.

2. Objectives of the study

To achieve the objectives of the thesis, the performance analysis of independent wind energy system (WES), photovoltaic (PV) and biomass energy systems is evaluated in various situations. The performance analysis is carried out also for integrated systems consisting of WES and PV energy system; PV and biomass energy systems; WES, PV and biomass energy systems; and hybrid system
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consisting of WES, PV system and diesel engine-generator (DG) set; and PV, biomass system and DG set. Sensitivity analysis and optimization technique are applied in each case to study the optimal renewable energy system. The following are detail of the objectives of this thesis:

- calculation of energy exported to grid from RE sources
- income from energy export
- Gross and net greenhouse gas (GHG) emission reduction
- GHG reduction income
- Total annual cost
- Total annual saving and income
- Financial viability including simple and equity payback
- Cumulative cash flow
- Sensitivity analysis with sensitivity variables
- Total net present cost (NPC)
- Cost of Energy (COE) of various configurations
- Optimization of various configurations

3. Methodology

The objective of the thesis is achieved by using two simulation software tools namely Renewable Energy Technology Screen (RETScreen) Version 4 and Hybrid Optimisation Model for Electric Renewables (HOMER).

3.1 Performance analysis tool - RETScreen

The RETScreen International Clean Energy Project Analysis Software is a unique decision support tool developed with the contribution of numerous experts from government, industry, and academia. RETScreen International is managed under the leadership and ongoing financial support of Natural Resources Canada's CANMET Energy Technology Centre – Varennes. The software is capable of analyzing RE, cogeneration and district energy, full array of financially viable clean power, heating and cooling technologies, and energy efficiency measures.
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The significant objectives of the software application are as follows:

- Development of new models to evaluate energy efficiency measures for residential, commercial and institutional buildings; communities; and industrial facilities and processes.

- Calculating of GHG emission from base case power generator and comparing it with proposed RE case. Providing income detail from GHG emission reduction due to proposed case.

- Expansion of the RETScreen Climate Database to 4,700 ground-station locations around the globe and incorporation of the improved NASA Surface Meteorology and Solar Energy Dataset for populated areas, directly into the RETScreen software.

- Integration of the existing RETScreen models for RE (e.g. wind energy) and combined heat and power, along with the new models for energy efficiency measures, all into one software file, and expansion of the capabilities of existing models to evaluate emerging technologies, such as ocean current and wave power.

3.2 Sensitivity analysis and optimization tool - HOMER

HOMER is one of the world’s most powerful and most widely used tools for designing hybrid renewable power systems. HOMER simulates and optimises standalone and grid-connected power systems comprising any combination of wind turbines, PV arrays, run-of-river hydro power, biomass power, internal combustion engine generators, microturbines, fuel cells, batteries, and hydrogen storage, serving both electric and thermal loads. Mistaya Engineering Inc., Canada, has provided software engineering, documentation, and technical support for HOMER, for the US National Renewable Energy Laboratory (NREL). It simulates the operation of a system by making energy balance calculations for each of the 8760 hours in a year. For each hour, it compares the electric and thermal demand in the hour with the energy that the system can supply in that hour, and calculates the flow of energy to and from each component of the system. For systems that include batteries or fuel-powered generators, the software also decides, for each hour, how to operate the generators and whether to charge or discharge the batteries. It performs energy
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balance calculations for each system configuration that it is required to consider. It then determines whether a configuration is feasible, that is, whether it can meet the electric demand under the specified conditions, and estimate the cost of installing and operating the system over the lifetime of the project. The system cost calculations account for costs such as capital, replacement, operation and maintenance (O&M), fuel, and interest.

After simulating all the possible system configurations, it displays a list of configurations, sorted by net present cost (also called lifecycle cost), that one can use to compare system design options.

When sensitivity variables are defined as inputs, the software repeats the optimization process for each sensitivity variable that is specified. For example, if wind speed is defined as a sensitivity variable, it will simulate system configurations for the range of wind speeds that are specified.

3.3 Validation of RETScreen off-grid model compared with HOMER hourly model

Mean annual and monthly relative error of 3% and 10%, respectively, are found in simulation results. The system configuration is close to the default off-grid PV/batteries/genset worked-out example one finds when opening the RETScreen PV model. The system modeled is a telecom station located near Neuquen, Argentina (latitude 39°S). Horizontal solar radiation and average air temperature are shown in Table 1 (http://www.retscreen.net).

Main parameters of the system are:

- Load: 500 W, continuous, ac load.
- PV array: 1 kWp mono-Si array; miscellaneous PV array losses are set to 10%, array tilted 50° facing north.
- Battery: 24 V, 2,500 Ah, nominal capacity 80%, round trip efficiency and 40% maximum depth of discharge, Cycle charging option; genset runs at full capacity; surplus power charges batteries; Set point State of Charge (SoC) option used, which means that the genset will not stop charging the battery bank until it reaches the specified state of charge.
- Inverter: 1 kW, 90% average efficiency.
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- Genset: 7.5 kW, with specific fuel consumption 0.46 L/kWh.
- Charger efficiency: 95%.

The results of the comparison are summarised in Table 1. On a yearly basis RETScreen predicts slightly less PV energy production than HOMER does (1,404 vs. 1,480 kWh, or a difference of 5%). Part of this difference (around 2%) is attributable to differences in the calculations of incident solar radiation, as shown in the table. Contributions from the genset are virtually identical (2,096 L vs. 2,079 L). Overall, these differences are insignificant and illustrate the adequacy of the RETScreen PV model for pre-feasibility studies.

Table 1: Summary of Calculation Results with RETScreen and HOMER

<table>
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<tr>
<th>Month</th>
<th>Global Solar Radiation kW/m²/d</th>
<th>Average Temp. °C</th>
<th>Incident Solar Radiation kW/m²/d</th>
<th>PV Energy Production kWh</th>
<th>Genset Fuel Consumption L</th>
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4. Conclusions

The results of the energy model of WES in Chapter 3 explain that 3,942 MWh energy is generated by using 1.5 MW WES giving an annual income of $275,940. GHG emission is 0 tCO₂/yr compared to 4,568 tCO₂/yr in base case generation which uses fossil fuel in India scenario. The model calculates the net annual reduction in GHG emissions estimated to occur if the proposed case is implemented. Net annual GHG emission reduction is 4,477 tCO₂/yr equivalent of 910 cars & light trucks not used annually giving total annual savings and income $365,469. The calculation is based on the gross annual GHG emission reduction and the GHG credits transaction fee. Total annual cost is $282,430 and equity payback 8.0 yr when cash flows become positive.

The number of turbine configured in the simulation is one; model GE 1.5sl with rated power 1500 kW selected which starts generating 40 kW at 4 m/s. Sensitivity and optimization results are carried out for wind speeds 4.300 m/s, 5.796 m/s and 6.700 m/s and WES life 20 yr and 25 yr, considering project life only 20 yr. the following results of WES are discussed:

- For project life of 20 yr, total NPC $3,966,440 is same for all wind speeds but COE is minimum of 0.050 $/kWh in case of highest wind speed 6.700 m/s; 0.058 $/kWh for 5.796 m/s; and 0.091 $/kWh for minimum wind speed 4.3 m/s.

- If the project life is raised to 25 yr total NPC and COE are reduced from $3,966,440 to $3,554,597 and from 0.050 $/kWh to 0.045 $/kWh respectively for sensitivity variable wind speed 6.7 m/s. For wind speeds 5.796 m/s and 4.300 m/s, NPC are same $3,554,597 also. But COE are 0.052 $/kWh and 0.082 $/kWh respectively.

- Capacity shortages are same for the same wind speeds irrespective of project lives.

- Initial capital $3,115,500 is same for all project lives and all wind speeds as number of wind turbine configured as one.

- Operating costs 60,376 $/yr and 31,155 $/yr are same for the same project lives of 20 or 25 yr irrespective of wind speeds.
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- Production from wind turbine is found 5,178,394 kWh/yr (100%), consumption by ac primary load 4,829,966 kWh/yr (100%) and excess electricity 348,430 kWh/yr (6.7%). The proportion of the total load that went unserved because of insufficient generation is unmet electric load, i.e. 8,203,102 kWh/yr (62.9%). The total amount of capacity shortage that occurred during the year is 9,594,032 kWh/yr (73.6%).

Chapter 4 contains the detail of 1.5 MW PV energy system indicating its performance analysis by energy model. Electricity generated annually and exported to load by the PV energy system is 2,628 MWh and income from export $ 183,960. Gross annual GHG emission reduction due to use of the RE is 3,045 tCO₂ and net annual GHG emission reduction 2,984 tCO₂, which is equivalent to 1,213,294 liters of gasoline not consumed annually. Income from GHG reduction is $ 59,686, hence total annual savings and income from the PV energy system $ 243,646. In this case, total annual cost is $ 202,319 and equity payback 2.9 yr when cash flow becomes positive.

Sensitivity results of PV energy system with capital cost multiplier 1 & 0.8, replacement cost multiplier 1 & 0.8, and PV life of 20 & 25 yr indicate that:

- NPC of $ 2,920,597 and COE 0.077 $/kWh are lesser when project life is 25 yr than NPC and COE of 20 yr value.

- If PV replacement cost multiplier becomes 0.8, NPC and COE remain same $ 2,920,597 and 0.077 $/kWh respectively for project life 25 yr. But the same sensitivity variables change marginally; NPC from $ 3,290,603 to $ 3,216,602 and COE from 0.086 $/kWh to 0.084 $/kWh.

- Change in NPC from $ 2,920,597 to $ 2,410,397 takes place when capital cost multiplier of PV is dropped from 1 to 0.8.

- Operating cost $ 1700 is lesser for project life of 25 yr than $ 43,253 for 20 yr project life.

Optimization results for PV energy system shows capital cost multiplier 1, PV replacement cost multiplier 1 and PV life 20 yr. Total NPC and COE are calculated as $ 3,293,603 and 0.086 $/kWh respectively in optimal results having 1700 kW PV system and 1300 kW converter. The PV cells of BP Solar make having 10000 units, model mono-Si - BP 4150 are opted. In the second best optimal system.
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one battery (Surrette S4KS25P) of nominal voltage 4V, nominal capacity 1,900 Ah (7.6 kWh) and lifetime throughout 10,560 kWh is added in the configuration suggested by the software. The total NPC and COE are figured as $3,292,043 and 0.086 $/kWh respectively with marginal rise in initial capital and operating cost. Similar optimization results are achieved for PV project life of 25 yr. A cash summary for the PV energy system is illustrated, indicating PV capital $2,040,800, replacement $717,839, O&M 239,597 $/yr, fuel cost nil, and salvage value $421,835. The capital cost of battery is taken as $800, replacement $520, O&M 282 $/yr, fuel cost nil, salvage cost $162. The capital cost converter is taken as $130,000; other costs are nil. Therefore, all these costs for entire system are shown.

In other optimization results electric production and consumption are shown for project life of 20 years. The results are shown in Table 4.8 indicating PV array production 3,122,355 kWh/yr (100%), ac primary load consumption 2,706.223 kWh/yr (100%), excess electricity 115,415 kWh/year (3.7%), unmet electric load 10,326,839 kWh/yr (79.2%) and capacity shortage 11,721,015 kWh/yr (89.9%).

Energy Model of 1.5 MW biomass energy project is shown in Chapter 5 indicating detail of performance analysis of proposed case power system, GHG emission analysis and financial analysis. Electricity generated by 6 units of biomass generator Entropic Energy made Turbion model and exported to grid is 12,089 MWh and income out of it $846,216. Emission analysis GHG emission base case 18,239 tCO₂ if a fossil fuel based generation is used. GHG emission from propose case of biomass generation is 513 tCO₂, gross annual GHG emission reduction 17,726 tCO₂, and net annual GHG emission reduction 17,371 tCO₂ equivalent to 14,765 acres of forest absorbing GHG emission. Income from GHG reduction is $347,427 and therefore, total annual savings and income $1,193,643. Equity payback starts just after 0.3 yr and cash flows become positive.

In sensitivity results of 1.5 MW biomass energy system with biomass resource availability 300 t/d, 360 t/d & 400 t/d, and biomass cost of $/t 20, $/t 30 & $/t 40 are underlined as under:

- Operating cost 1,509,280 $/yr, total NPC $21,971,714, COE 0.132 $/kWh, biomass consumption 35,661 t/yr and biomass operation hours 8,759 h/yr are same for biomass cost of 30 $/t for biomass resource supply 400 t/d, 360 t/d and 300 t/d until the biomass resource supply reduced to 90 t/d.
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- Similarly operating cost, total NPC, COE, biomass consumption and biomass operation hours are same for biomass cost of 20 $/t and 40 $/t.

- When biomass resource supply 90 t/d is insufficient operating cost reduced from 1,509,280 $/yr to 1,389,625 $/yr; total NPC reduced from $ 21,971.714 to $ 20,285,300; COE increased from 0.132 $/kWh to 0.133 $/kWh; biomass consumption reduced from 35,661 t/yr to 32,849 t/yr; and biomass operation hours decreased from 8,759 h/yr to 8,080 h/yr.

- Biomass consumption depends upon biomass resource supply. If the supply is reduced from 300 t/d to 90 t/d, the consumption slumped 35,661 t/yr to 32,849 t/yr and so the operation hours of biomass generator from 8,759 h/yr to 8,080 h/yr.

- It is found that if biomass operating cost increases, total NPC and COE also increase.

Optimization results of 1.5 MW biomass energy system are obtained for sensitivity variables biomass resource 400 t/d, 360 t/d, 300 t/d, 90 t/d, and 80 t/d; and biomass cost of $/t 20, $/t 30 & $/t 40. Optimal results are obtained for sufficient biomass resource supply to be able to operate the biomass generator throughout a year. Operating cost 1,152,675 $/yr, total NPC $ 16,945,732. COE 0.102 4/kWh and biomass operating hours 8,759 h/yr remain same for all values of sufficient biomass resource supply. These parameters starts changing when biomass resource supply becoming insufficient, i.e. when biomass resource supply becomes 90 t/d or 80 t/d.

Simulation results of cost summary of 1.5 MW biomass energy system are indicated. The results show capital cost of the project $ 700,000, O&M cost $ 5,457,828, fuel charges $ 8,888,194 and salvage value $ 16,370. In other simulation results electric production is indicated 11,823,917 kWh/yr (100%); ac primary load consumption 11,797,253 kWh (100%); excess electricity 26,668 kWh (0.2%); unmet electric load 1,235,808 kWh/yr (9.5%); and capacity shortage 2,100,556 kWh/yr.

Results of energy model Chapter 6 of 1.5 MW integrated energy project of WES 750 kW and PV energy system 750 kW indicate performance analysis of proposed case power system, GHG emission analysis and financial analysis. In the energy model 15 units of wind turbines of Atlantic Orient make, model AOC 15/50 – 23m and 3000 units of Uni-Solar make, model a-Si-SSR-256W are configured.
The electricity generated annually by the WES and PV energy system are 1,971 MWh and 1,314 MWh respectively. Income from both the generations is $229,950. Net annual GHG emission reduction due to use of RE is 3,730 tCO₂ and income from it $74,607; therefore total annual saving and income is $304,557. Simple payback is period is 9.5 yr whereas equity payback period 6.9 yr when cash flows become positive and project starts giving profit.

Sensitivity and optimization results of 1.5 MW integrated systems of wind energy and PV energy are obtained for sensitivity variable of 20 yr and 25 yr as elaborated as under:

- PV energy system, WES (FL 250), battery (S4KS25P) and converter are equipments chosen for optimal solution. The optimal equipments configured for 20 yr project life are PV 1300 kW and converter 850 kW with initial capital $2,685,000, operating cost 73,502 $/yr, NPC $3,720,939 and COE 0.131 $/kWh.

- The equipments configured in second optimal system are PV 1300 kW, 120 numbers of batteries S4KS25P and converter 800 kW with total NPC $3,863,323 and COE 0.137 $/kWh.

- If both PV energy system and WES are to be considered for integration anyhow, third optimal system is obtained. The simulation is configured for PV 1200 kW, one number of WES FL 250 and converter 900 kW with NPC $4,139,680 and COE 0.145 $/kWh.

- In other non-optimal system only 28 numbers of WESs FL 250 are configured with very high values of NPC $19,416,006 and COE 0.656 $/kWh.

- All above results are obtained for project life 25 yr with lower values of operating cost, total NPC and COE; but initial capital for various respective configurations are same as that of project of life 20 yr.

Results of energy model of 1.5 MW integrated energy project of PV system 750 kW and biomass energy system 750 kW indicate performance analysis of proposed case power system, GHG emission analysis and financial analysis. For PV energy system 6250 numbers of PV cells of Uni-Solar make, model a-Si-ASR-120W and 3 units of biomass generators Entropic Energy make, model Turbion of
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are selected for are configured. The electricity generated and exported to grid annually by the PV energy and biomass energy systems are 1,314 MWh and 7,358 MWh respectively. Income from export of both the generations is $515,088. Net annual GHG emission reduction due to use of RE is 8,105 tCO₂ and income from it $162,092; therefore total annual saving and income is $677,180. Simple payback period is 11 yr whereas equity payback period 13.7 yr when cash flows become positive and project starts giving profit.

Sensitivity results of 1.5 MW integration of PV and biomass systems for sensitivity variables of biomass price $30/t and $40/t are illustrated in Table 6.4. The following points are observed:

• In the simulation biomass generated, PV energy system, battery S4KS25P, converter are considered; but only biomass generator 1500 kW is configured.

• Initial cost is throughout same for sensitivity variables of biomass price $30 $/t and $40 $/t; and biomass resource supply 300 t/d, 360 t/d and 400 t/d.

• Operating cost $1,338,895, total NPC $17,285,586 and COE 0.118 $/kWh are same for biomass price $30 for all values of biomass resource supply.

• Similarly, operating cost $1,697,854, total NPC $21,759,016 and COE 0.148 $/kWh are found same for biomass price $30 for all values of biomass resource supply.

Optimization results of 1.5 MW integrated PV and biomass systems for sensitivity variables of biomass price $30 $/t yr and biomass supply 360 t/d indicate that biomass generator 1500 kW is configured only in the optimal system. PV system, battery, or converter are not configured at all with initial capital $600,000, operating cost $1,338,895 $/yr, total NPC $17,285,586, COE 0.118 $/kWh and biomass consumption 35,896 t/yr. The second optimal system consists of biomass generator 1500 kW, 12 numbers of batteries S4KS25P and converter 25 kW with more initial capital $618,300, operating cost $1,339,204 $/yr and total NPC $17,307,738; and same values of COE 0.118 $/kWh and biomass consumption 35,896 t/yr. Another non-optimal system is also available consisting of both REs - PV power 25 kW, biomass power 1500 kW and converter power 25 kW with different initial capital $707,500 and operating cost $17,388,968 $/yr; and same COE 0.118 $/kWh and biomass consumption 35,896 t/yr. One more non-optimal
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System is also possible configuring of all equipments – PV power 25 kW, biomass power 1500 kW, 12 numbers of batteries with different initial capital $ 718,300, operating cost 1,338,873 $/yr and total NPC $ 17,403,620; and same COE 0.118 $/kWh and biomass consumption.

Integration of PV and biomass systems are found practically and economically feasible only when the percentage of power share of biomass system is increased from 750 kW to 1000 kW and PV system power share is reduced 750 kW to 500 kW to get a total output power of 1.5 MW from the integrated system.

Energy Model of 1.5 MW integrated energy project of biomass 750 kW and wind energy system 750 kW indicating detail of performance analysis of proposed case power system, GHG emission analysis and financial analysis are indicated. For simulation purpose 3 units of biomass generator totaling 750 kW Entropic Energy make, model Turbion and 15 units of WES Atlantic Orient make giving 750 kW model AOC 15/50 – 25m are selected on the basis of the sites requirements. The annual electricity generated and exported to grid by the biomass generator and WES are 6,044 MWh and 1,971 MWh respectively – totaling 8015 MWh electricity generated and $ 561,078 income from the export. Net annual GHG emission reduction due to use of RE systems of biomass and wind energies is 8,850 tCO$_2$ and income from emission reduction $ 177,013 and total income from the integrated system $ 738,091. Cash flows become positive after equity payback period after 2.7 yr and simple payback period after 5.2 yr.

Sensitivity results of 1.5 MW integrated biomass system and WES for sensitivity variables biomass supply 300t/d, 360t/d, 400 t/d and biomass price 30 $/t, 40 $/t. The following points are concluded:

- Sensitivity results of 1.5 MW integrated biomass system and WES is exactly same as sensitivity results of 1.5 MW integrated PV and biomass energy systems. Therefore all the comments remain same as conclusion made for integrated PV and biomass energy systems.

- This concludes that biomass energy system plays a dominant role over other RES.

- The results show that biomass energy system is configured; WES is left out from configuration.

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Optimization results of integration of 1.5 MW of biomass and wind energy systems are shown for sensitivity variables of biomass price 30 $/t yr and 40 $/t. The optimal configuration consists of biomass energy system 1500 kW with initial capital $ 600,000, operating cost 1,338,586 $/yr, total NPC $ 17,285,586, COE 0.118 $/kWh and biomass consumption 35,896 t/yr for sensitivity variable biomass price 30 $/t. The same result is found for optimal system for integration of PV and biomass energy systems. In second optimal system 1 number of WES G20 is added with all other equipments of optimal system with initial capital $ 638,000, operating cost 1,339,269 $/yr, total NPC $ 17,328,252, COE 0.118 $/kWh, biomass consumption 35,883 t/yr for biomass price 30 $/t. When biomass price is increased to 40 $/t initial capital remains same ($ 600,000) but operating cost (1,697,854 $/yr), total NPC ($ 21,759,016), COE (0.148 $/kWh) and biomass consumption (35,896 t/yr) are increased.

Energy Model of 1.5 MW integrated energy project of WES 500 kW and PV energy 500 kW and 500 kW biomass energy systems for performance analysis is not possible to carry out by the software tool RETScreen. Therefore only sensitivity analysis and optimization technique are considered for this study. Sensitivity results of 1.5 MW integrated wind, PV and biomass energy systems are indicated for sensitivity variables of biomass price of 30 $/t and 40 $/t. The following points are concluded:

- Equipments considered for simulation are WES G20, PV energy system, biomass energy system and converter; but only biomass is configured for all sensitivity variables biomass supply 300 t/d, 360 t/d and 400 t/d; and biomass price 30 $/t and 40 $/t.
- For all sensitivity variables of biomass supply and price, initial capital is $ 600,000 as only biomass generator is configured.
- When biomass price is 30 $/t operating cost 1,340,518 $/yr, total NPC $ 19,493,186 and COE 0.117 $/kWh for biomass supply 300 t/d, 360 t/d and 400 t/d.
- Similarly, when biomass price is 40 $/t operating cost 1,699,478 $/yr, total NPC $ 24,552,342 and COE 0.148 $/kWh for biomass supply 300 t/d, 360 t/d and 400 t/d.

- These results are similar to sensitivity results of 1.5 MW integrated PV and biomass systems.

Optimization results of 1.5 MW integrated wind, PV and biomass energy systems for sensitivity variables of biomass price 30 $/t yr and 40 $/t are shown. All the optimization results are found in favor of biomass electricity generation. The optimal system consists of only biomass generator 1500 kW with operating cost 1,340,518 $/yr, total NPC $ 19,493,186 and COE 0.117 $/kWh for biomass price 30 $/t which is also shown in sensitivity analysis. In the third optimal system biomass 1500 kW and PV system 25 kW are configured with initial capital $ 657,500, operating cost 1,340,760 $/yr, total NPC $ 19,554,090 and COE 0.117 $/kWh with biomass price 30 $/t. WES is not configured at all for any value of sensitivity variable.

A hybrid system- a combination of various REs with a conventional fossil based electricity generation - WES and PV energy system are combined with a DG set to provide energy security to isolated electric load of Amini Island in Indian Ocean, elaborated in Chapter 7. Performance analysis based on energy model is not possible to carry out by the software tool RETScreen. Therefore, HOMER software tool is used to conduct sensitivity analysis and optimization of annual average energy 880 kWh/day (peak annual load 148.9 kW) from integrated energy project of WES, PV, biomass energy systems and DG set.

Simulation results of different sensitivity variables of wind speed of 4.61 m/s, 5 m/s, 6 m/s, 10 m/s, 15 m/s, 20 m/s, 25 m/s, and 30 m/s for diesel price 0.6 $/L, hub height 25 m and SoC 25% at Amini Island are indicated. As per weather data the island is suitable for installation of PV and wind generators. The following conclusions are derived from the simulation.

- Energy security is important for an island; therefore hybrid system is preferred over a system using one RE, so that strong points of conventional and RES may be availed.

- From average wind speed 4.61 m/s to extremely high wind speed 30 m/s, PV system is not configured. The equipments configured are 10 numbers of wind generator WES-18, DG set 100 kW, 168 numbers of batteries 6FM200D and converter 100 kW with initial capital $ 159,600, COE 0.125 $/kWh, DG running 903 h/yr and GHG emission 76,661 kg/yr when
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sensitivity variable of SoC 25% and hub height 25 m. For hub height 20 m, total NPC and COE are increased to $541,041 and COE 0.312 $/kWh respectively keeping other variables constant. Similarly if SoC is taken 75% and other variables same, total NPC $520,814 and COE 0.127 $/kWh.

- Number of wind generators 10 remains same for sensitivity variable wind speed up to 6 m/s and so the DG power and the converter power, number of batteries, COE, DG running hour and GHG emission decrease.

- For wind speed reaches 15 m/s, number of wind generators reduces to 4, DG power 50 kW, number of batteries 96, converter power 50 kW, COE 0.024 $/kWh, initial capital $74,200, DG running hour 85 and GHG emission 3000 kg/yr.

- For wind speed 20 m/s, number of wind generators decreased to 5, number of batteries 96, converter power 50 kW, minimal COE 0.020 $/kWh, initial capital $74,200 without DG power and zero emission. At higher wind speed (> 15 m/s), DG set is not configured, reducing GHG emission to zero.

Following are main points inferred from simulation results of different sensitivity variables of biomass price of 20 $/t, 30 $/t, 40 $/t, and 50 $/t for diesel price 0.6 $/L and SoC 25% at Hathras. As per weather and agricultural data the place in mainland is suitable for installation of PV and biomass generators.

- For sensitivity variable of biomass price 20 $/t, 30 $/t and 40 $/t. PV generator and DG set are not configured. The equipments configured are biomass generator, battery, and converter.

- The optimal configuration of system consists of biomass generating system 60 kW, 60 number of 6CS25P batteries and converter 25 kW initial capital $87,500, optimal COE 0.189 $/kWh, biomass generator annual running hour 5,894 hr/yr and small quantity of GHG emission 76.9 kg/yr in absence of DG set when biomass price is minimal 20 $/t.

- The above trend of various equipments and values remain nearly same for biomass price 30 $/t and 40 $/t, except COE whose slightly enhanced values are 0.232 $/kWh and 0.276 $/kWh respectively.

- When the price of biomass exceptionally high 50 $/t, too expensive to fuel the biomass generator, in that condition biomass is not configured. The
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equipments configured are PV power 50 kW, DG power 50 kW, 60 number of batteries, converter power 25 kW with COE 0.279 $/kWh, enormously high initial capital $ 305,417 and GHG emission 208,697 kg/yr.

- In case HRES containing PV, WES, and DG set, the simulation shows that COE (i) decreases as wind speed increases, (ii) increases with the increase in diesel price, (iii) decreases as hub height increases, and (iv) increases with setpoint SoC.

- Sometime optimal configurations simulated by the software are not practically possible to install, hence compromise has to be made in favor of second or third most economical configuration.

6. Future works and recommendations

This thesis explores the performance and feasibility of decentralized RESs consisting of wind, PV and biomass energy systems and their integrated systems in different conditions and situations. Since the analysis is conducted to study the performance, financial and GHG emission with sensitivity analysis and optimization, it is found that there is plenty of scope for further research. Some possible recommendations for future works in the directions are following:

- Efforts should be made by manufacturers to design, manufacture and install model and prototype experimental set up for research and development purpose. Those model/prototype set up may be allowed to produce electricity in artificially generated weather conditions. An approach may be made to verify simulated data by using the experimental set up. This approach will help find the validation of the software tools used for the simulation.

- Software may be developed for sensitivity analysis and optimization for fuel cell, geothermal, tidal, and other RESs or incorporated in the existing software for future study.

- Complete design detail of RESs is not incorporated in simulation software. Therefore it is required to develop software giving all design details of each RE equipments.
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- RETScreen software tool provides non-optimized simulation result for performance, financial, and GHG emission analyses; whereas the other software tool HOMER conducts only optimal simulation with sensitivity analysis and optimization. A sincere effort is required to develop software combining both RETScreen and HOMER so that positive points of both the software tools may be availed in one software.

- HOMER software simulation shows COE of electricity generated by biomass changes little or does not change at all even when biomass resource supply is reduced considerably. It shows reduction in biomass consumption and operation hours in a year. It should also show the change in COE when biomass generator running with short supply of biomass for whole year. Therefore some change is suggested in the software.

- Positive cash flow and equity payback period reaches earliest in biomass generation system than any other RES, giving back returns of the investment to investor. Therefore, it is recommended to prefer biomass generating system over other RES as far as possible for quick money-back.

- If biomass available it is always beneficial to use biomass energy so that GHG emission may be avoided. Biomass releases carbon dioxide when it is used for gasification. Because biomass absorbs carbon dioxide during sunlight hours as it grows; the entire process of growing, using, and regrowing biomass results in very low to zero carbon dioxide emissions. If proper balance is maintained between growing and gasifying of biomass in a particular area, zero emission may be achieved while generating electricity.

- Integration of biomass system with other REs used to generate power are found feasible only when the percentage of power share of biomass system is more than other REs. In optimal system of integrated RESs, only biomass system is found in configuration. No other RESs is configured in optimal results. Therefore, in future integrated RES, biomass generator should be allowed to share more load than other REs as far as possible to generate cheaper and cleaner electricity.

- Small-scale rural industries (such as flour and oil mills, paddy hullers, handicraft units etc.) requiring electricity in isolated villages should be encouraged to set up their own electricity generating units using biomass;
which is available in abundance in Indian villages. Government and manufacturers should provide subsidy and discount etc. on these activities.

- In coming days integration of REs will play vital role in power generation sector mainly due to growing demand of GHG emission mitigation. When WES and PV energy system are integrated and allowed to generate equal power for a particular load demand; it is found that WES generates nearly 1.5 times more power than PV system to meet the load. In another case when PV and biomass systems are integrated to deliver equal power, biomass system generates nearly more than six times the PV power to meet the same load demand. In the third combination of integration of biomass energy system and WES, biomass generates nearly three times power than wind power.

- In case of WES and PV system integration, net annual GHG emission reduction is lesser than half the case of integrated system of PV and biomass; or integrated system of biomass and wind. Therefore, total GHG emission reduction income in integration of WES and PV system is lesser than half the integrated system of PV and biomass; or integrated system of biomass and wind.

- Total annual saving and income of integrated system of wind and PV is found lesser than half the integrated system of PV and biomass; or integrated system of biomass and wind.

- The objectives and results of the thesis are unique; however there are some limitations. All the costs are taken from current market rate which may not be universal and applicable all the time. It was not possible to verify the results obtained from simulation in real time. Results obtained do not provide complete design details of RE components.