The technology selection analysis based on bi-level environo-economic optimization of a biomass-powered CHP

Masoud Rezaei[1], Fuzhan Nasiri[2*]

1. The building, Civil and Environment Engineering Department, Concordia University,
1. Email: mas_rez@encs.concordia.ca
Address: Engineering, Computer Science and Visual Arts Integrated Complex, 1515 St. Catherine west S. EV11-177, H3G 2W1, **Tel :**(514) 8031359,

2. The building, Civil and Environment Engineering Department, Concordia University
2. Email: fuzhan.nasiri@concordia.ca
Address: Engineering, Computer Science and Visual Arts Integrated Complex, 1515 St. Catherine west S-EV 6207, **Tel:** (514) 848-2424 ext. 4172

Abstract

In this research, a three-phase bi-level environo-economic optimization approach for biomass-powered systems is introduced. 40 scenarios are evaluated by considering eight biomasses and five technologies under two strategies. The multi-objective optimization coupled with multiple criteria decision-making technique is used in this methodology.

Four cost and pollution objectives as the functions of operating parameters are optimized to deliver optimal values. They have been selected to explicitly express environmental and economic sides of the biomass-fueled systems. At the first level of this approach minimum cost and pollution of numerous scenarios along with their optimal operating parameters are derived. At the second level, the alternative optimal scenarios by multiple criteria decision-making techniques are specified.

This research aims to gain two targets. First, development of a bi-level method for optimization of a biomass-fueled energy system without case specificity. Second, prioritization of the alternative scenarios with related optimal parameters. The methodology can be extended to accept nonrenewable fuels or energy conversion technologies.

Keywords: Biomass, technology selection, bi-level optimization, CHP, MCDM

1- Introduction

Biomass is currently one of the most dispersed renewable resources across the world. At least one form of the biomass resources can be found almost everywhere. From wastewater in urban areas to agricultural wastes, specific sorts of the biomass are achievable everywhere. CO_2-neutrality is the unique privilege of biomass compared to other hydrocarbon resources. Although it is discussed that biomass could be considered CO_2-neutral when the rate of carbon generation becomes equal to that of its generation, the use of the biomass is theorized that released CO_2 by biomass combustion can be absorbed with plants; hence, the net emission of CO_2 to the atmosphere is zero.

Even by considering biomass carbon-neutrality, the cost efficiency remains challenging. Besides, from the supply chain to processing and conversion, there are several problems concerning biomass use that have deterred its widespread application in energy systems, in particular in large scales.

The biomass feedstock supply and processing are of the most importance in the design and definition of the energy systems. They influence dramatically the cost and pollution of the installed system and affect the maintenance and operational costs. Feedstock processing features including heat value, moisture level, and chemical elements, shall be considered in technology adoption and biomass selection. Biomass feedstocks largely determine the cost and pollution of the energy generation. Hence, along with energy analysis, exergy analysis of the biomass-fueled energy systems is paramount. Critical parts of the energy systems for exergy destruction are in combustion chambers where biomass is burned or in gasifiers where it is gasified.

To overcome the challenges of making biomass-powered systems reliable and sustainable, one of the globally-applied approaches is combined heat and power (CHP) generation which simultaneously generates electricity and heat. CHP is also called cogeneration. CHP systems are characterized by the quantity of the energy they deliver as well as the quality of the prepared energy.

CHP technologies can be configured in many ways to deliver energies in various forms and amounts, ranging from small values in fuel cells to large scale sizes up to 300 MW in steam turbine power plants. Tackling various parameters to achieve multiple conflicting objectives, highlights the optimization. Minimization or maximization of the objective functions within the constraints is the topic of optimization. Numerous approaches, methods, and solvers are defined based on the problem.

Despite being a powerful design and operation tool, optimization is not ensuring the success of the systems in practice. Energy systems coupled with complex technologies might fail with high probability because of ignoring or underestimating the parameters. This may occur at implicit optimization, fading the trace and footprints of elements in the objectives and constraints formulation. Therefore, explicit optimization is a more effective approach to optimization.

To enhance the resiliency of the systems, alternative strategies and scenarios tackling uncertainties should be defined. To do this, synergy shall be created among multiple strategies and scenarios. This multiplicity, generating a front of solutions needs criteria/indices to help to decide among the optimal solutions, rank and prioritize alternatives. Multiple Criteria Decision Making (MCDM) is used at this point to help decision making.

At this research, four nonlinear objective functions in the permitted areas of operating parameters are defined. Optimization is performed at the first level by a multi-evolutionary method and vector evaluated genetic algorithm (VEGA). In this level, optimized scenarios and strategies with their optimum parameters are extracted. At the second level and in two phases, the multi-criteria decision-making technique is used to rank the scenarios among Pareto front and to introduce top scenarios for each fuel and top scenario among all fuels. This is sufficiently flexible to accept an unlimited number of objective functions, parameters and other technologies or fuels including non-renewable ones.

This paper is arranged as follows. The background identification and literature review of the research in MOO of the biomass and energy system is carried out in section 2. Section 3 elucidates the hierarchy, notion, and concept of the methodology defined to integrate MOO and MCDM in a bi-level approach. In section 4, the application of the model for the selected fuels and technologies cases is studied and results are discussed. Section 5 is devoted to the summing up the conclusions. Model and method limitations and future studies exploration.

2- Literature Review

Biomass is any recurring organic matter, primarily supplied from forestry and agricultural residues, landfills or wastewater treatment. Biomass for energy generation purpose has been studied in the biomass supply chain, processing, and conversion domains. A multitude of parameters in technology adoption exists that shall be addressed for energy purpose use [1, 2]. Technology adoption for energy conversion is critical because of typically lower heat content of biomass, compared to fossil fuels.

One of the first remarkable works in this field was by Gustavsson et al [3]. Gustavsson et al. economically analyzed and compared the potential for using biomass for CHP and biofuel for the transportation sector. Gustavsson analyzed the ratio between heat and electricity generation called α-value. It is an indicator for evaluating the system efficiency and feasibility. Variations of price for different biomass resources as the function of the land fertility, water preservation, energy content of biomass, etc. were investigated. Studies on using biomass are not confined to small-scales. Girones researched large-scale generation to monitor resource availability and technology flexibility [4].

Economizing biomass-fueled systems is not restricted to CHP and biofuel generation. Providing other forms of energy supply lies within the concept of multi-generation. Prakash et al. thermodynamically evaluated the function of a biomass-powered CHP system equipped with a steam turbine. [5]. In tri-generation systems, cooling is also provided for consumers. Lian et al. thermodynamically analyzed the application of the biomass for tri-generation [6-8]. Unal evaluated the operational optimization of a tri-generation system via linear programming (LP) to deliver the performance parameters of the Internal Combustion Engine (ICE), Gas Turbine and Chillers [7]. Other cycles such as organic Rankine cycle have been researched by Rivarolo et al. for analyzing the system's performance [9-10].

In an approach called thermoeconomic, a thermodynamic analysis coupled with economic evaluation is simultaneously done to analyze the system [10]. Moharamian et al. investigated a thermoeconomic evaluation of three biomass and biomass-natural gas combined cycles. Different parameters like working fluids with turbine inlet temperature and compressor pressure ratio effects on the overall performance of powerplant and its cost efficiency were examined [11].

Distribution of the prepared energy from biomass via district heating systems (DHS) was another step taken to deliver CHP and multi-generation systems more profitable. System configuration modeling and CHP-DHS performance operation optimization for economic or environmental metrics have been performed in various studies. [12-14]

Optimization of the energy systems has been studied both for energy generation and distribution. Wang et al. tried to minimize the cost of district heating systems in a nonlinear problem [14]. For energy distribution, Vesterlund et al. investigated the optimization of a DHS by meshed network technique to derive the DHS system hydraulic performance in various operation scenarios [15]. Gerber et al. presented a systematic approach for multi-objective, multi-period optimization. This was carried out by multi integer linear programming (MILP) with evolutionary algorithms [16]. Proskurina et al. investigated the impact of torrefied-biomass for optimal operation as part of hybrid energy systems. Process integration methodology was used in this research [17].

Ondeck et al. described optimal integration of a CHP plant providing electricity, heating, and cooling as a utility producer for a residential district, and evaluated the potential for combining CHP with photovoltaic power generation. It was modeled and evaluated in the residential project in Austin, TX [18]. Weber et al presented a tool, based on MILP technic to give an optimal mix of technologies that resiliently guarantees the heat demand of an eco-town via DHS [19]. Pirkandi et al optimized the integration of CHP system with a micro gas turbine. Two objective functions including energy efficiency and net power output were chosen to achieve their maximum level [20]. The optimization of a biomass-fueled CHP system incorporated with thermal storage is a quite new concept. [10, 21-22]. Life cycle assessment (LCA) of the CHP system equipped with thermal storage system was performed by Haeseldonckx et al to minimize the cost and CO_2 [22]. Noussan et al. took a real DH system as a case study, and by considering the varying heat demands and component sizes, carried out the optimization of a biomass-fired power plant and a heat storage system [23].

Sartor et al. presented a methodology to render estimates about the performance of a CHP biomass plant and DHS in an environoeconomic analysis. A simulation model of a DHS was employed to demonstrate the efficacy of the methodology considering the economic evaluations [24]. Hongqiang et al. proposed and analyzed a co-generation system with gasified-biomass and ground source heat pumps. [25]. Chang et al assessed using the fuel cell integration in energy system with fuzzy multiple criteria making method [26]. Moradi et al used the fuzzy programming with hybrid optimization method for the improvement of the performance of a CHP system [27]. Jing et al assessed the performance of a CHP system with LCA approach for optimization of multiple objectives including all costs. The same work for a wind-power energy system carried out by Martinez et al [28].

3- Methodology

In the methodology described in this study, the optimization of the enviroeconomic objective functions including the annualized capital and fuel costs, annual carbon and sulfur dioxide emissions is carried out by the explicit nonlinear functions. Various fuels and multiple technologies are analyzed as part of the scenarios based on minimizing four objective functions.

A three-phase bi-level optimization approach is defined that at the first level, delivers minimum costs and pollutions via VEGA. Then, at the first phase of the second level, by MCDM technique called TOPSIS, the top scenario for each fuel is yielded and forty optimal scenarios are yielded. Proceeding to the second phase, scenario ranking and top scenarios are delivered. A schematic of the bi-level methodology used in this study is illustrated in figure 1.

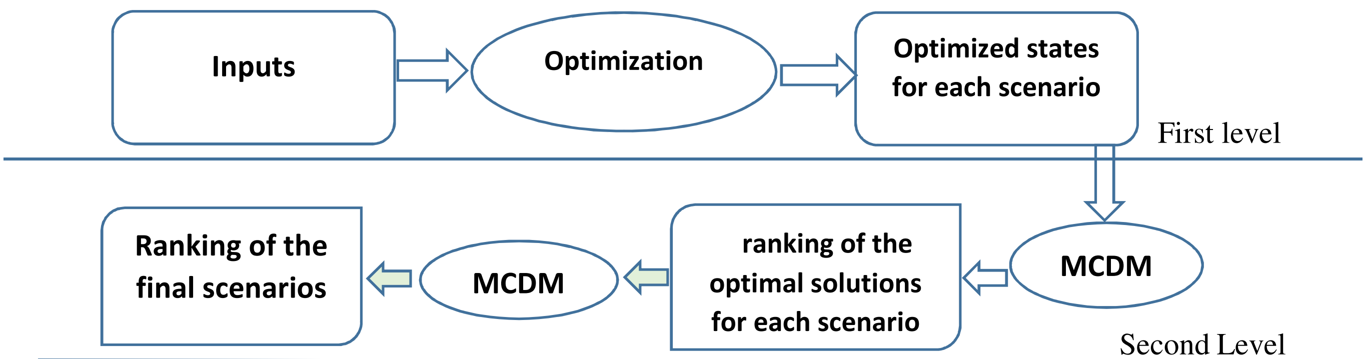


Figure 1. The bi-level optimization modeling used in this study

The methodology gets started with fuel characterization. Biomass composition is a decisive criterion in the power generation costs and pollution, thereby determining the required process for fuel preparation, storage, transportation, etc. It directly affects both annualized costs and pollutions. CmHnOxNySz is used as the generic formula for biomass combustion modeling. C, H, O, N, S stand for Carbon, Hydrogen, Oxygen, Nitrogen, and Sulfur. m,n,x,y,z indicate the molar mass fraction of the corresponding elements in the formula [18]. Other chemical elements could be added or eliminated to represent more fuels, even fossil fuels. The compositions of the eight fuels used are given in table 1.

Table1. The composition of 8 biomasses commonly used for energy generation.

N	Fuel Type	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
1	Bagasse	48.64%	5.87%	42.85%	0.16%	0.04%	2.44%
2	Pit	58.20%	5. 7%	33.20%	1.4%	0.30%	8.2%
3	Rice husks	38.83%	4.75%	35.59%	0.52%	0.05%	20.26%
4	Switch grass	47.45%	5.75%	42.37%	0.74%	0.08%	3.61%
5	Wheat straw	46.96%	5.69%	42.41%	0.43%	0.19%	4.32%
6	High Heat Value (HHV) wood	52.10%	5. 7%	38.90%	0.20%	0.00%	3.10%
7	Medium Heat Value (MHV) wood	52.00%	4.00%	41.70%	0.30%	0.00%	2.00%
8	Low Heat Value (LHV) wood	48.85%	6.04%	42.64%	0.71%	0.06%	1.70%

Derivation of the cost and pollution emission formulas was the next step to establish the methodology. Cost modeling could be implicit by deeming the cost as a total block, or explicit as the function of the operating factors. This study chooses an explicit approach. The objective functions have been developed as the annualized cost of the capital, fuel and maintenance costs (Canadian Dollars per kilowatt hour (CAD)/KWh) and annual CO_2 and SO_2 emissions (ton). The formulas are originated from the formulas delivered by Z.T. Lian [6], Rivarolo et al [9], Sartor et al [24], Vallios et al [29].

$$y_1 = \text{Annualized Capital } Cost = \frac{(C * \emptyset + U_{fix}) - (y_{el}) * P_{el}\tau_{el}}{(P_{el} * \tau_{el}) + (P_{th} * \tau_{th})} + \frac{y_f}{\eta_{th}} + U_{var} \qquad Eq.1$$

$$y_2 = Fuel\ Cost = \frac{(Cost\ Per\ Ton) * 3.6}{1000 * NHV} \qquad Eq.2$$

$$y_3 = m_{co2} = \frac{((P_{el} * \tau_{el}) + (P_{th} * \tau_{th})) * 44 * Biomass\ Carbon\ Mass\ Fraction}{(\eta_{el} + \eta_{th}) * 3.6 * NHV} \qquad Eq.3$$

$$y_4 = m_{So2} = \frac{((P_{th} * \tau_{th})) * 64 * Biomass\ Sulfur\ Mass\ Fraction}{(\eta_{el} + \eta_{th}) * 3.6 * NHV} \qquad Eq.4$$

In which,
$P_{el} = Electricity\ Power\ Capacity\ (Kw)$, $P_{th} = Thermal\ Power\ Capacity\ (Kw)$
$\tau_{el} = Utilization\ time\ of\ Electricity\ Energy$, $\tau_{th} = Utilization\ of\ Thermal\ Energy$
$\eta_{el} = fficiency\ of\ Electricity\ Generation$, $\eta_{th} = Efficiency\ of\ Thermal\ Generation$
$Net\ Heating\ Value\ (NHV)$ =(34.1C+101.98H-9.85O+6.3N+19.1S)(1-MCWB/100)-0.02452MCWB

MCWB is moisture content of wet-based biomass. Equations 3 and 4 are based on complete combustion and stoichiometric analysis. For gaseous fuels, typical gasification formula is used. [33].

$CH_\alpha O_\beta N_\gamma S_\delta + wH_2O + m\ (O_2 + \lambda N_2) \rightarrow n_{H2}H_2 + n_{CO}CO + n_{CO2}CO_2 + n_{CH4}CH_4 + n_{H2O}H_2O + n_{N2}N_2$ Eq. 6

As can be seen, even in biomass gasification Co_2 is generated. The produced CH_4 is assumed to be burned in combustion as below.

$CH_\alpha O_\beta N_\gamma S_\delta + [1+\alpha/4-\beta/2+\gamma+\delta]\ O_2 \rightarrow CO_2 + \alpha/2H_2O + \gamma N_2 + \delta SO_2$ Eq. 7

In which α, β, δ, γ are the ratios of molar mass fractions of Carbon to Hydrogen, Oxygen, Nitrogen, and Sulfur dry ash free basis, respectively. Since the boiler or burner is devoted to providing heat, and electricity generation is supported by the turbines or combustion engines, the contribution of the electricity generation in SO_2 generation is neglected. That is mainly due to the fact that prior to combustion of synthesis gas, the sulfur contents are largely removed in gasification processes. [30].

Two strategies to model methodology outreach are defined. In the first, called design-based strategy, assuming fixed and predetermined economic data, the system performance for the design phase of energy systems is addressed. Biomass purchase cost and annuity factor are input to the model.

In the second strategy, named operation-based, the economic parameters such as fuel purchase price, annuity factor, or electricity selling price are added to the optimization variables and the electricity selling price is input. This strategy assists to deliver the optimum system operation

3.1 Strategies, Concepts and Scenarios Description.

After strategy definition, optimization and MCDM technique selection, two concepts of the CHP and heat-only are defined. In the first concept, electricity and heat are generated while in the second strategy only heat is produced. The concepts and technologies can be summarized in table 2.

Table 2. The heat-only and CHP concepts for biomass-powered CHP system.

Concepts	Technology Involved
Heat Only	Boiler
Heat and electricity	Boiler+ Gas Turbine
	Boiler+ Steam Turbine
	Boiler+ Steam Turbine+ Gas Turbine
	Boiler+ICE

Based on the technologies involved and the related concepts, the cost formulas necessary for annualized initial and operation costs are indicated in table 3. The maintenance and operation costs are varying based on the cases but 2.5 % of the initial investment cost has been seen for this purpose.

The details of the formulas expansion for the concepts are from the literature reviews and manufacturing technical documents [6, 9, 24, 29]. Because the study focuses on the Canada, economic data and cost index for Canada were used. A MATLAB code using the VEGA algorithm for the first level optimization and another code for the TOPSIS method to perform decision making and scenario ranking were developed.

Eight fuels and five technologies were selected for the scenario definition. As previously stated, in the first strategy, biomass purchase prices and annuity factors are input. Meanwhile, the average fuel prices per ton for eight fuels were determined based on the prices from the suppliers across Canada and the U.S.A. (see table 4). These values are typical for biomass with 30% moisture content. For the annuity factor, the value equal to 0.06 (for an interest rate equal to 0.0175 and 20 years' service life) was chosen based on the typical economic and operation of the projects in Canada.

Table 3- Capital cost per operating parameters for various CHP technologies

Concept	Technologies	Capital Cost Formula
Heat Only	Steam Boiler	$\frac{(924P_{th}^{0.6}) * \varphi)}{P_{th}\tau_{th}}$
Heat and electricity	Steam Boiler+ Steam Turbine	$\frac{(924P_{th}^{0.6} + 6600\,P_{el}^{0.7} + 66P_{el}^{0.95}) * \varphi}{P_{th}\tau_{th} + P_{el}\tau_{el}}$
	Steam Boiler+ Gas Turbine	$\frac{(924P_{th}^{0.6} + 66P_{el}^{0.95} + 2662P_{el}^{0.872}) * \varphi}{P_{th}\tau_{th} + P_{el}\tau_{el}}$
	Steam Boiler+ Combined Cycle	$\frac{(924P_{th}^{0.6} + 6600\,P_{el}^{0.7} + 66P_{el}^{0.95} + 2662P_{el}^{0.872}) * \varphi}{P_{th}\tau_{th} + P_{el}\tau_{el}}$
	Steam Boiler+ICE	$\frac{(924P_{th}^{0.6} + 66P_{el}^{0.95} + 2415P_{el}^{0.855}) * \varphi}{P_{th}\tau_{th} + P_{el}\tau_{el}}$

Table 4. The average price (CAD/ton) for consideration in the first scenario.

N	Fuel Type	Price (CAD/Ton)
1	Bagasse	50
2	Pit	180
3	Rice husks	60
4	Switchgrass	125
5	Wheat straw	45
6	Wood high HV	250
7	Wood medium HV	200
8	Wood low HV	150

In the second strategy, the electricity selling price to the grid is set equal to 12 cents per KWh. For each strategy, 40 scenarios of various Fuel Type-Technology combinations is defined based on table 5. As previously stated, for bounded optimization, constraints on power generation are used based on the typical existing capacities in the market, enlisted in table 6. They are gathered from literature reviews and manufacturer's catalogs [31]. Other constraints are 0.1< y_{el} < 0.2 $/KWh ,$0 < \tau_{el} < 8760, 0 < \tau_{th} < 8760$.

Table 5. The fuels and technologies used for the definition of the scenarios

Fuel Index	**Fuel Type**	**Technology Index**	**Technology**
F_1	Bagasse	T_1	Boiler
F_2	Pit	T_2	Boiler+ Gas Turbine
F_3	Rice husks	T_3	Boiler+ Steam Turbine
F_4	Switchgrass	T_4	Boiler+ Steam Turbine+ Gas Turbine
F_5	Wheat straw	T_5	Boiler + ICE
F_6	HHV wood		
F_7	MHV wood		
F_8	LHV wood		

Table 6. The operating parameters constraints for the selected technologies.

No.	**Energy Type**	**Technology**	**Technology Involved**	**Constraints**
1	Heat Only	Steam Boiler	$0 < P_{th} < 350000\ Kw$	$0.5 < \eta_{th} < 0.7$
2	Heat and electricity	Steam Boiler+ Gas Turbine	$0 < P_{el} < 50000\ Kw$ $0 < P_{th} < 50000\ Kw$ $0 < P_{el} + P_{th} < 50000\ Kw$	$0.2 < \eta_{el} < 0.3$ $0.6 < \eta_{th} < 0.8$ $0 < \eta_{el} + \eta_{th} < 0.8$
3	Heat and electricity	Steam Boiler+ Steam Turbine	$0 < P_{el} < 300000\ Kw$ $0 < P_{th} < 300000\ Kw$ $0 < P_{el} + P_{th} < 300000\ Kw$	$0.2 < \eta_{el} < 0.4$ $0.4 < \eta_{th} << 0.8$ $0 < \eta_{el} + \eta_{th} < 0.8$
4	Heat and electricity	Steam Boiler+ Combined Cycle	$0 < P_{el} < 325000\ Kw$ $0 < P_{th} < 325000\ Kw$ $0 < P_{el} + P_{th} < 350000\ Kw$	$0.2 < \eta_{el} < 0.4$ $0.5 < \eta_{th} << 0.9$ $0 < \eta_{el} + \eta_{th} < 0.9$
5	Heat and electricity	Steam Boiler+ICE	$0 < P_{el} < 310000\ Kw$ $0 < P_{th} < 310000\ Kw$ $0 < P_{el} + P_{th} < 310000\ Kw$	$0.2 < \eta_{el} < 0.5$ $0.5 < \eta_{th} < 0.8$ $0 < \eta_{el} + \eta_{th} < 0.8$

4. Results Discussion

4.1 First strategy- Design –based Strategy

The optimization code was run and after iterations, the Pareto fronts for each fuel were found. After applying TOPSIS, the optimal scenarios for each fuel comprised of seven decision variables (system operating parameters) and four objective functions are obtained and tabulated in table 7.

Figures 2, 3 and 4 show the variation of thermal, electrical energy generations and final annualized costs of forty optimal scenarios. For each fuel, optimized parameters have been illustrated.

	Cost (CAD/KWh)		Emission (ton)		KWh	KWh	Hour				CAD/KWh	CAD/KWh
	Investment	Fuel	CO_2	SO_2	P_{el}	P_{th}	τ_{el}	τ_{th}	η_{el}	η_{th}	Y_{el}	Final cost
F1T1	0.0002	0.0415	4,444,449.4	5,316.3	0.00	5,932.26	0	6,887	0.00	0.67	0.00	0.042
F1T2	-0.1281	0.0350	1,784.8	0	7.47	0.00	2,617	8,184	0.20	0.60	0.18	0.087
F1T3	-0.0148	0.0350	199.0	0.2	1.01	0.00	2,160	6,600	0.40	0.40	0.20	0.220
F1T4	-0.1655	0.0311	36,437.1	43.6	58.87	0.70	7,508	6,633	0.25	0.64	0.20	0.064
F1T5	-0.0430	0.0350	1,423.9	0	9.85	0.58	2,205	6,605	0.30	0.51	0.10	0.077
F2T1	0.0003	0.0894	1,379,374.2	1,034.2	0.00	2,510.35	0	7,008	0.00	0.67	0.00	0.090
F2T2	-0.1416	0.0752	2,721.2	0	18.46	0.00	2,251	6,644	0.20	0.60	0.19	0.124
F2T3	-0.1827	0.0752	75,194.5	56.4	175.02	2.31	6,447	6,622	0.39	0.40	0.20	0.090
F2T4	-0.1186	0.0674	144,039.7	108.0	742.12	22.21	3,084	6,728	0.33	0.56	0.17	0.108
F2T5	-0.0925	0.0752	477.1	0	1.73	0.02	4,127	6,602	0.26	0.54	0.13	0.110
F3T1	0.0002	0.0635	7,806,887.6	14,622.0	0.00	7,440.29	0	7,905	0.00	0.69	0.00	0.064
F3T2	0.0178	0.0544	0.1	0.0	12.6	0.00	3,801	8,537	0.20	0.60	0.11	0.182
F3T3	-0.1858	0.0544	320,463.9	600.2	445.94	1.43	6,214	7,664	0.25	0.55	0.20	0.068
F3T4	-0.1712	0.0492	302,046.9	565.7	496.92	3.04	5,903	6,685	0.40	0.50	0.20	0.077
F3T5	-0.1254	0.0544	190.6	0	0.76	0.00	2,162	6,600	0.30	0.50	0.20	0.129
F4T1	0.0002	0.1050	9,687,746.8	23,757.7	0.00	12,439.36	0	7,259	0.00	0.69	0.00	0.105
F4T2	-0.1831	0.0907	84,945.3	0	161.99	0.95	5,624	6,850	0.20	0.60	0.20	0.106
F4T3	-0.1848	0.0920	680,539.0	1,668.9	1,952.16	15.10	3,675	6,601	0.21	0.58	0.20	0.104

F4T4	-0.1450	0.0816	27,223.7	66.8	89.24	0.33	3,638	6,612	0.38	0.51	0.20	0.135
F5T1	0.0002	0.0376	11,140,203.3	65,561.1	0.00	14,228.71	0	7,302	0.00	0.70	0.00	0.038
F5T2	-0.1754	0.0337	164,566.0	0	505.79	0.43	3,467	6,887	0.20	0.60	0.20	0.058
F5T3	-0.1848	0.0363	275,616.4	1,622.0	392.81	5.76	6,659	6,625	0.29	0.43	0.20	0.049
F5T4	-0.1752	0.0298	207,775.8	1,222.8	407.43	1.44	6,082	6,618	0.27	0.63	0.20	0.054
F5T5	-0.1759	0.0337	93,277.5	0	219.12	3.45	4,432	6,860	0.27	0.54	0.20	0.053
F6T1	0.0002	0.1620	8,307,830.4	0.0	0.00	12,214.37	0	7,470	0.00	0.69	0.00	0.162
F6T2	-0.1737	0.1387	98,941.9	0.0	333.33	2.37	3,750	6,970	0.20	0.60	0.20	0.162
F6T3	-0.1828	0.1426	122,242.2	0.0	245.21	0.34	6,224	7,627	0.24	0.54	0.20	0.159
F7T1	0.0002	0.1140	3,955,999.2	0.0	0.00	7,060.99	0	7,246	0.00	0.66	0.00	0.114
F7T2	-0.1475	0.0946	1,216.8	0.0	2.91	0.14	6,154	7,879	0.20	0.60	0.18	0.117
F7T3	-0.1761	0.0946	108,118.6	0.0	610.25	2.26	2,729	6,758	0.39	0.41	0.20	0.117
F7T4	-0.1588	0.0855	71,287.5	0.0	205.75	5.13	5,813	7,189	0.28	0.61	0.19	0.111
F7T5	-0.1752	0.0946	659.4	0.0	1.57	0.02	6,483	7,023	0.21	0.59	0.20	0.117
F8T1	0.0002	0.1244	4,755,115.8	8,495.2	0.00	5,880.04	0	7,575	0.00	0.69	0.00	0.125
F8T2	-0.1795	0.1063	8,500.6	0	11.98	0.10	7,680	7,372	0.20	0.60	0.20	0.125
F8T3	-0.1898	0.1063	679,880.6	1,214.6	1,641.74	0.06	4,510	7,797	0.21	0.59	0.20	0.116
F8T4	-0.1531	0.0959	17,352.2	31.0	33.93	0.40	6,111	6,601	0.31	0.58	0.19	0.130
F8T5	-0.0107	0.1063	0.3	0.0	1.5	4.5	3,875	6,600	0.29	0.51	0.15	0.243

Table 7. Optimized values of the objectives and operating parameters for all scenarios in the first strategy

Figure 2. Generated thermal energies for CHP scenarios of the first strategy

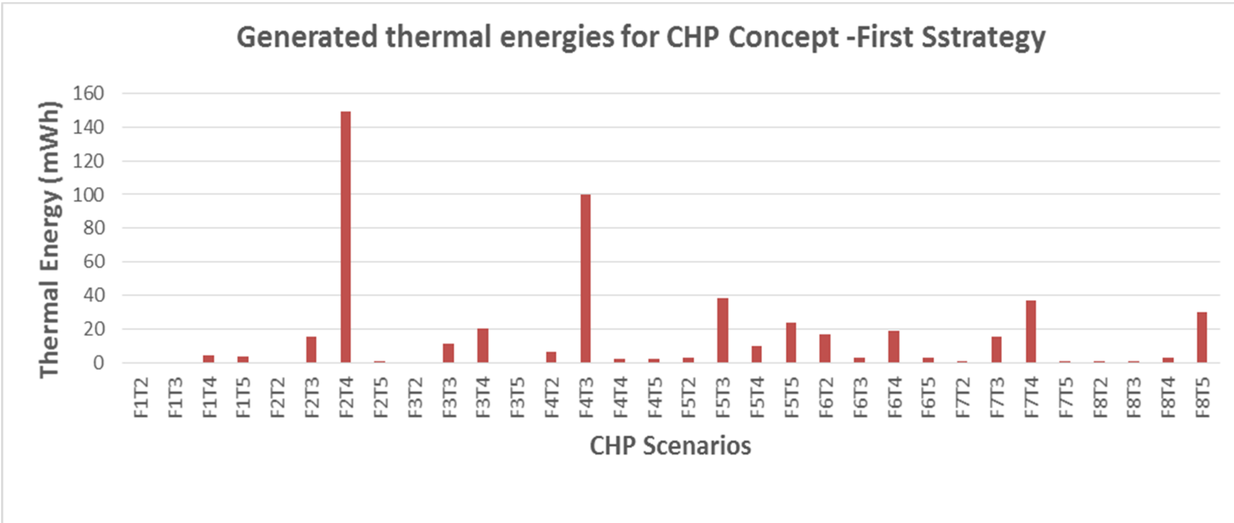


Figure 3. Generated electricity energies for CHP scenarios of the first strategy

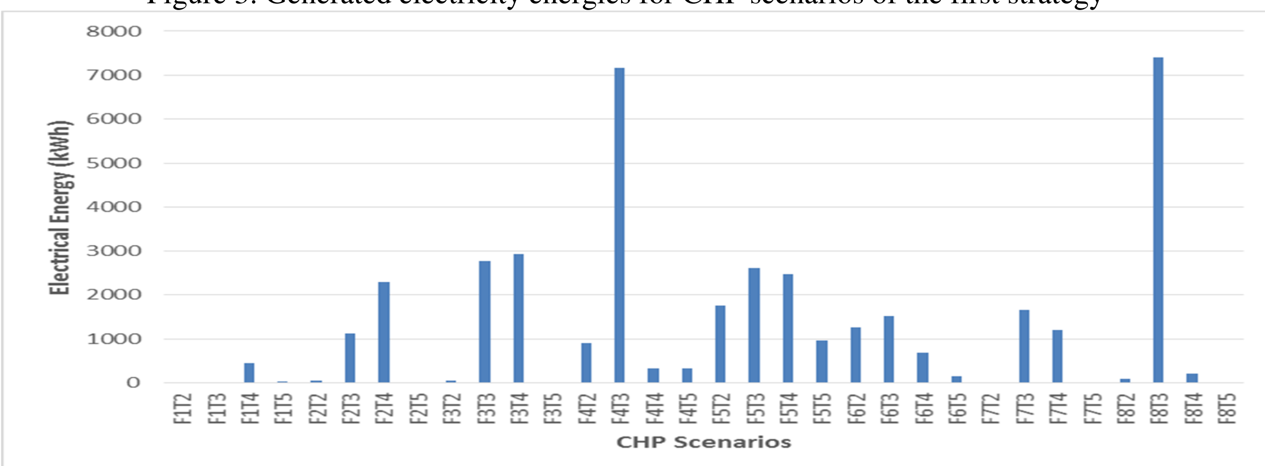
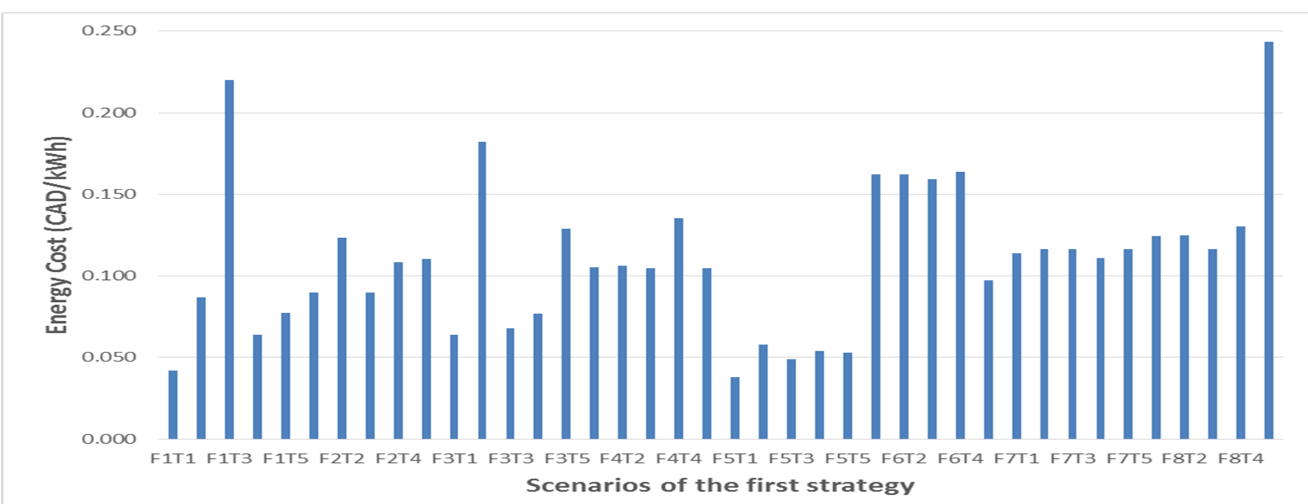


Figure 4. The final annualized cost of the scenarios in the first strategy



Very interesting results are achievable from very first level optimization. For example, as is obvious, some scenarios are more inclined towards small-scale energy generation. For example, F3T2 scenario that is gas turbine using syngas from rice husk delivers very low optimal values for electricity generation equal to 47megawatt-hour (MWh) and zero heat generation. On the other hand, F4T3 scenario which is steam turbine power plant consuming switchgrass should generate about 7 and 100 MWh electricity and heat, respectively, to be in optimum operation. Scenarios with ICE deliver the lowest energy generation values, compared to other technologies.

Exceptions such as F6T2 scenario, namely gas turbine operating on syngas from HHV wood owns the top position among scenarios from an efficiency standpoint. It is mainly due to the minimum electricity efficiency with high thermal efficiency which is more dependable in real conditions. They also demand lower electricity generation for delivering the optimized results. As per figure 4, heat only concept with bagasse and wheat straw have the lowest final costs, less than 4 cents per KWh in optimal operating conditions. However, they are the most pollutant scenarios. In CHP concepts the lowest cost belongs to F5T3, equal to 5 cents per KWh. It is the scenario of using the wheat straw and steam turbine.

As figure 5 exhibits, from the market viewpoint, the best scenarios are the F3T2 and F1T5 because they need selling prices equal to 0.1 and 0.11 CAD/KWh. These values make them compete with electricity prices from other sources.

Figure 5. Optimal electricity selling price to the grid for all scenarios in the first strategy.

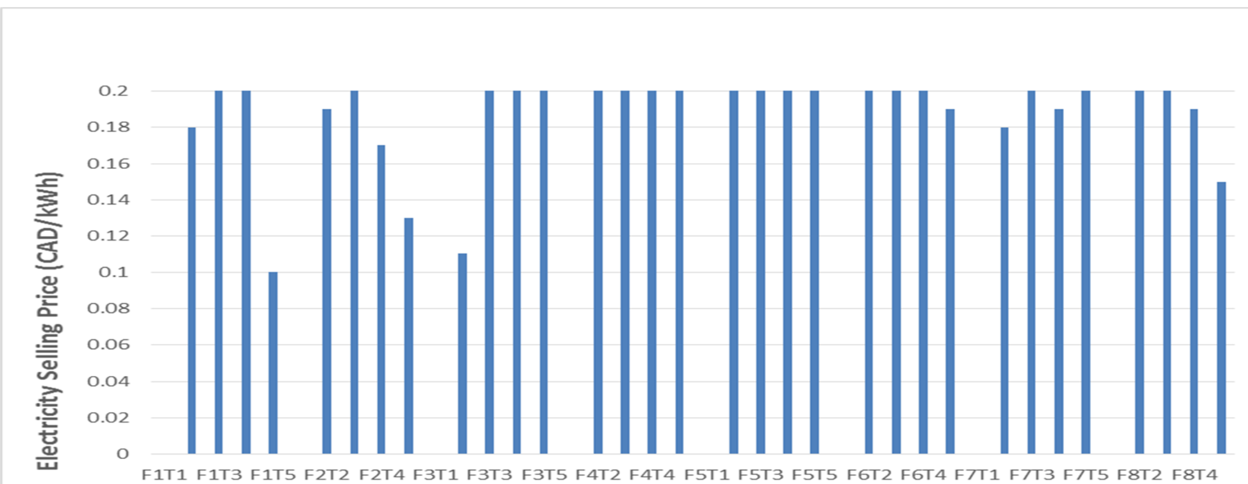


Figure 6 demonstrates that some scenarios such as F1T3, F1T5, F3T2 and F8T5 even in CHP concept do not raise income. Furthermore, the lowest and highest predictable ratio of income to cost is for F3T5 and F5T3, respectively. This figure also compares the predictable income and final cost for forty optimal scenarios. It helps to find out the appropriate scenarios for initial investment or long-run profitability.

TOPSIS is utilized at the second level to rank the optimal scenarios. To that end, the same procedure for the criteria analysis performed in the first phase is followed. The results are classified for each fuel (see table 8). F1T4, F2T4, F3T3, F4T3, F5T4, F6T4, F7T3, and F8T3 are top scenarios for each fuel. Table 9 summarized the operating parameter of the top scenarios. The switchgrass with steam turbine owns the largest values for the total energy generation approximately equal 7274 MWh. The electricity generation in CHP scenarios contributes much more than heat generation to minimize the system cost by electricity selling to the grid. To find the ranking of the top scenarios, regarding criteria for operating parameters, the ranking of the scenarios in the CHP concept is F2T4, F7T3, F4T3, F1T4, F5T4, F6T2, F3T3, and F8T3 respectively. Table 10, shows the operating and performance parameters of the top scenario of all scenarios, namely F2T4. Consequently, the top scenario of the first strategy is using the pit and combined cycle turbine in CHP concept.

Figure 6. The trend of the final cost and predicted income for scenarios in the first strategy

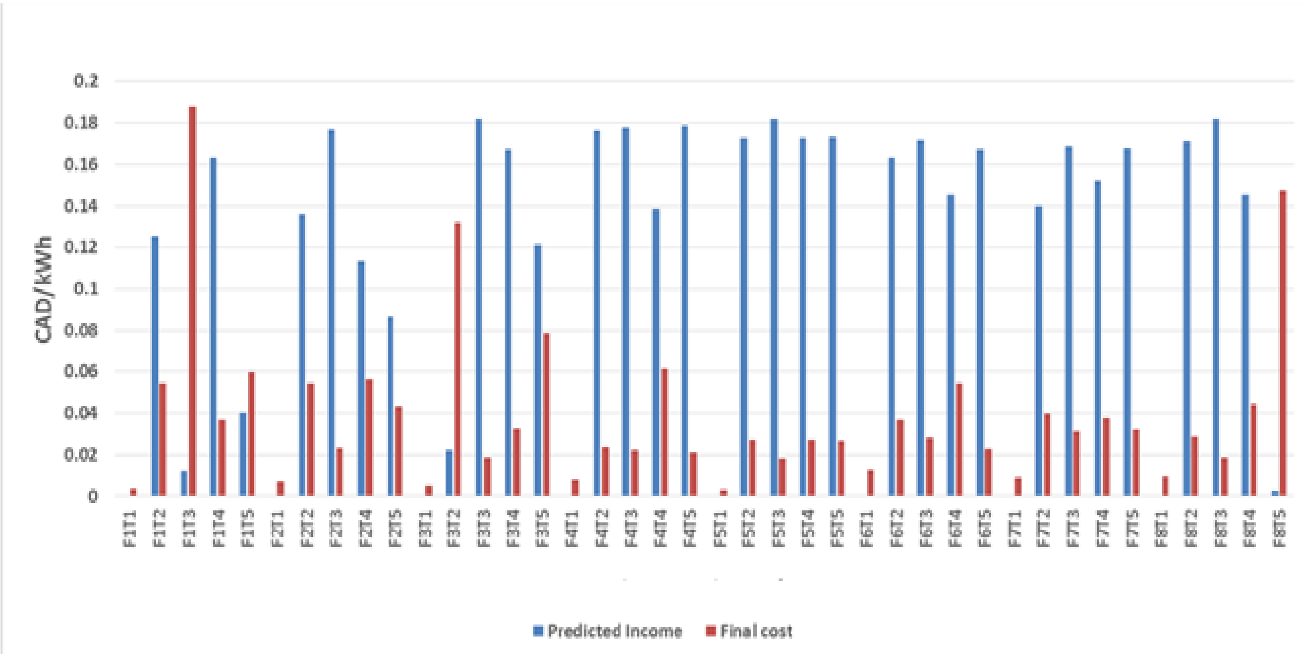


Table 8: second level-first phase results for scenario ranking in the first strategy.

Fuel	Scenarios in order
F1	F1T4, F1T2, F1T5, F1T1, F1T3
F2	F2T4, F2T2, F2T5, F2T3, F2T1
F3	F3T3, F3T4, F3T5, F3T2, F3T1
F4	F4T3, F4T2, F4T4, F4T5, F4T1
F5	F5T4, F5T2, F5T5, F5T3, F5T1
F6	F6T4, F6T2, F6T3, F6T1, F6T5
F7	F7T3, F7T4, F7T2, F7T1, F7T5
F8	F8T3, F8T2, F8T4, F8T5, F8T1

The whole process carried out in this bi-level optimization can be repeated for the heat-only concept. The second level is performed on eight heat-only scenarios using boiler technology.

TOPSIS methodology indicates combusted bagasse in the boiler, is the top scenario in the heat-only concept, followed by MHV wood. Although wheat straw delivers lower final cost, huge amounts of SO_2 and CO_2 generation overshadow their superiority to bagasse and MHV wood. In the TOPSIS method, the scoring mechanism shows that MHV wood owns the second rank after bagasse with a slight difference. Therefore, if the total pollution criteria are used instead of considering SO_2 and CO_2 separately, bagasse could be replaced by MHV wood. (See table 11). Figure 7 shows the generated thermal energy of heat-only scenarios.

Table 9. Optimized values of the objectives and operating parameters for selected scenarios.

	Final Cost (CAD/KWh)	**Total Pollution (ton)**	**$P_{el}\ \tau_{el}$ (KWh)**	**$P_{th}\ \tau_{th}$ (KWh)**	**η_{el}**	**η_{th}**	**Electricity Selling Price (CAD/KWh)**
F1T4	0.064	36,480	441,996	4,643	0.252	0.643	0.2
F2T4	0.108	144,148	2,288,698	149,429	0.33	0.557	0.168
F3T3	0.068	321,063	2,771,071	10,960	0.25	0.55	0.20
F4T3	0.104	682,208	7,174,188	99,675	0.21	0.58	0.19
F5T4	0.054	208,999	2,477,990	9,529	0.27	0.63	0.20
F6T4	0.164	48,854	675,255	18,645	0.36	0.53	0.20
F7T3	0.117	108,118.6	1,665,372	15,273	0.39	0.41	0.2
F8T3	0.116	681,094	7,404,247	467.8	0.21	0.59	0.2

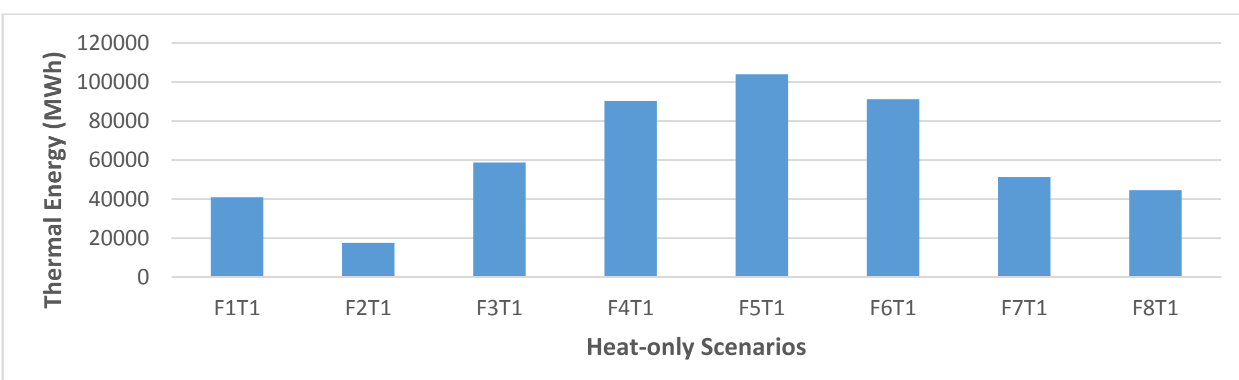
Table 10: the F2T4 optimized performance and operating parameters in the first strategy.

	Final Cost (CAD/KWh)	**Total Pollution (ton)**	**$P_{el}\ \tau_{el}$ (kW)**	**$P_{th}\ \tau_{th}$ (kW)**	**η_{el}**	**η_{th}**	**Electricity Selling Price (CAD/KWh)**
F2T4	0.108	144,148	2,288,698	149,429	0.33	0.557	0.168

Table 11: the operating parameters for the eight heat-only scenarios

Fuel	**Final Cost (CAD/KWh)**	**CO_2 (ton)**	**SO_2 (ton)**	**P_{th} (Kw)**	**τ_{th} (H)**	**η_{th}**
F1	0.0035	4,444,449	5,316.33	5,932	6,887.21	0.67
F2	0.0072	1,379,374	1,034.2	2,510	7,008.253	0.668
F3	0.0050	7,806,887.6	14,622.03	7,440	7,904.8	0.694
F4	0.008	9,687,746.8	23,757.67	12,439	7,258.95	0.69
F5	0.003	11,140,203	65,561.05	14,228.7	7,301.51	0.7
F6	0.0127	8,307,830.3	0	12,214.4	7,470.14	0.69
F7	0.009	3,955,999.1	0	7,061	7,246.12	0.66
F8	0.01	4,755,115.8	7,573	5,880.04	7,574.55	0.688

Figure 7. Generated heat of heat-only scenarios in the first strategy



4.2 Second Strategy

In the second strategy, biomass purchase costs and annuity factors become decision variables and electricity selling to grid goes to the decision variable with a constant value of 0.1 per KWh. It means that in the new approach, electrical and thermal power generations, utilization times and efficiencies together with biomass purchase costs and annuity factors constitute eight decision variables.

After running the MATLAB code and iterations, the optimal values are yielded. The small values (less than 5 KWh) of the power generation for fifth technology, namely ICE show that this technology may not be justified, when the selling price is less than or equal to 10 cents per KWh. Following the method steps, top scenarios are F1T2, F2T3, F3T3, F4T4, F5T1, F6T3, F7T3, F8T3. The ranking of the scenarios for each fuel is illustrated in table 12. It is noteworthy that the heat-only concept appears among the top scenarios. It is logical because the electricity generation from low-energy fuels such as bagasse or wheat straw may not be economic when electricity selling to grid decreases.

Table 12: Ranking of the second strategy's scenarios based on the methodology

Fuel	Scenarios in order
F1	F1T2, F1T3, F1T4, F1T1, F1T5
F2	F2T3, F2T4, F2T2, F2T1, F2T5
F3	F3T3, F3T4, F3T2, F3T1, F3T5
F4	F4T4, F4T2, F4T1, F4T3, F4T5
F5	F5T1, F5T4, F5T2, F5T3, F5T5
F6	F6T3, F6T1, F6T2, F6T4, F6T5
F7	F7T3, F7T4, F7T2, F7T1, F7T5
F8	F8T3, F8T4, F8T2, F8T4, F8T5

The steam turbine in this strategy is more apt for CHP, either solely with all woody biomass, pit, and rice husk or in the combined cycle for switchgrass. Combined cycle considering both steam and gas turbine cycles is also among the second alternative scenarios for several fuels, namely, pit, rice husk, wheat straw, MHV, and LHV woods. Optimal biomass purchase costs are zero or near to zero. It emphasizes this point that the biomass feedstocks are more adapted with landfill gases or forestry residues, where feedstocks can be yielded at negligible costs. Contrary to the first strategy, the scenarios could be income raising, given maintaining other optimal values during the operation. The negative values of final cost columns in table 13 highlights the possibility of money raising during system lifetime.

Second level scenario ranking shows that for the bagasse, electricity generation via the gas turbine cycle is the top scenario. Wheat straw in heat-only concept is the last in the ranking mainly due to the highest final cost, lowest total energy generation, and a rather low annuity factor. Considering the small scale heat generation for this scenario, designers may opt it out among other scenarios. F4T4 optimal performance is yielded at the highest annuity factor, equal to 3.6 %, while the minimum value is near to 0.02 for F1T2. The less annuity factor makes the plants or powerplants more vulnerable to stop functioning le in volatile economic situations.

Pit and LHV wood also have the highest electricity efficiency that put their optimality at risk, because keeping the electricity generation efficiency at higher values is a tougher job for operators than keeping higher thermal efficiencies. The HHV and LHV woods are the scenarios that possess the highest heat and electricity generations among all scenarios for their optimal operation. They should generate approximately 59.6 and 34.2 gigawatt hour (GWh) electricity and 962 MWh and 3.36 GWh heat respectively.

Table 13. Optimized values of the objectives and operating parameters for selected scenarios in the second strategy.

	Final Cost (CAD/KWh)	**CO_2 (ton)**	**SO_2 (ton)**	**$P_{el}\ \tau_{el}$ (KWh)**	**$P_{th}\ \tau_{th}$ (KWh)**	**η_{el}**	**η_{the}**	**Annuity Factor**
F1T2	-0.040	257,044	30,750	2,818,505	0	0.20	0.60	0.020
F2T3	-0.040	35,836	2,690	545,251	1,991	0.40	0.40	0.023
F3T3	-0.039	1,218,706	228,260	8,461,967	66,131	0.20	0.40	0.027
F4T4	-0.080	96,766	23,730	1,092,127	19,841	0.30	0.60	0.036
F5T1	0.251	15,788	720	0	8,760	0.00	0.50	0.024
F6T3	-0.047	70,326,573	0	59,590,746	961,926	0.30	0.40	0.035
F7T3	-0.066	13,126,246	0	15,446,931	3,964	0.20	0.60	0.020
F8T3	-0.044	45,083,651	6,215	34,230,555	3,363,409	0.40	0.40	0.022

Next phase of the second level is to determine the ranking of the final alternative scenarios. Applying the TOPSIS at the second phase, the top scenario is F6T4 which is the syngas from MHV wood used in a steam turbine with the related operating parameters enlisted in table 13. A similar procedure is applied to heat-only scenarios. Their operating parameters are indicated in table 14.

Table 14: Operating and performance parameters for the eight heat-only scenarios of the second strategy

Scenario	**Final Cost(CAD/KWh)**	**CO_2 (Ton)**	**SO_2 (Ton)**	**Power (KWh)**	**Efficiency**	**Purchase Cost (CAD/Ton)**	**Annuity Factor**
F1T1	0.041	11,762,602	14,070	112,767,157	0.7	7.7	0.02
F2T1	).047	574,445	431	7,615,707	0.7	3.5	0.0327
F3T1	0.05	8,454,831	15,836	64,088,150	0.7	8	0.0263
F4T1	0.052	2,476,628	6,074	18,934,740	0.6	0	0.02
F5T1	0.250	1,218	7	8,760	0.5	0.8	0.0239
F6T1	0.01	118,402	0	1,135,133	0.6	0	0.0276
F7T1	0.038	7,348,161	0	74,417,122	0.5	0.7	0.02
F8T1	0.049	1,508,269	2,695	11,352,458	0.6	3.3	0.0321

4.3 Sensitivity Analysis.

In this phase, the electricity selling price to the grid was chosen for performing sensitivity analysis. Sensitivity analysis is just applied for CHP concept scenarios and the electricity selling price increases up to 0.15 CAD per KWh. The sensitivity analysis shows the ranking variation of scenarios for the pit, switchgrass wheat straw, and LHV wheat. Table 15 demonstrates the results of ranking shift after the sensitivity analysis. Moreover, both objective values and decision variables change. For example, the change from the boiler to the gas turbine for wheat straw and electricity generation up to 12 MWh is justified by increasing the electricity selling price up to 0.15 CAD per KWh.

Such a trend is visible by introducing gas turbine as the top technology for fuels such as pit, wheat straw, and LHV wood and introducing combined cycle as the second alternative technology for other biomasses. The results of the optimized scenarios for both strategies and sensitivity analysis are summarized in table 15.

Table 15: the ranking of the CHP scenarios for CHP concept of strategies and sensitivity analysis

	First Strategy	**Second Strategy**	**Second Strategy Sensitivity Analysis**
F1	F1T4	F1T2	F1T2
F2	F2T4	F2T3	F2T2
F3	F3T3	F3T3	F3T3
F4	F4T3	F4T4	F4T3
F5	F5T2	F5T1	F5T2
F6	F6T2	F6T3	F6T3
F7	F7T3	F7T3	F7T3
F8	F8T2	F8T3	F8T2

It is worth mentioning that increasing the selling price and the opportunity for raising money, does not necessarily result in higher electricity generation in all scenarios. As reflected in table 16, the optimality of further electricity generation should be investigated case by case, because the electricity generation might bring about much more pollutions. In this methodology, the pollutions have the same weight as the economic objectives.

Table 16: Optimal parameters of the top scenarios after sensitivity analysis.

	Final Cost (CAD/KWh)	**CO_2 (ton)**	**SO_2 (ton)**	**Pel τel (MWh)**	**Pth τth (MWh)**	**Biomass purchase cost (CAD/Ton)**	**Annuity Factor**
F1T2	0.014	99894	11949	10.95	0.00	0	0.035
F2T2	0.08	58946	4420	876.39	24.99	0.1	0.020
F3T3	0.006	903840	69286	7,674.89	17.07	0.2	0.041

F4T3	0.003	551839	13533	5,839.91	17.97	0.1	0.023
F5T2	0.007	1109839	65315	11,678.76	165.98	0.2	0.020
F6T3	0.002	801268	0	9,132.26	2.26	0.30	0.025
F7T3	0.003	1380709	0	19,322.51	102.78	0.25	0.023
F8T2	0.006	803295	143512	8.77	0.00	0.20	0.021

5. Conclusion:

For the investigated cases, the results show the intense sensitivity of the optimal scenarios, particularly biomass purchase and electricity selling prices. The scenarios are also sensitive to the biomass composition, the efficiency, and economy of the scale. Sensitivity analysis showed when electricity selling price decreases, the lower heat-content fuels are more inclined to gas turbine cycles in CHP concept. For higher electricity selling prices, the steam turbine appears the top technology for such fuels, either independently or joint with a steam turbine as a combined cycle.

It could be said by moving from low electricity selling prices towards higher prices and from low-heat content towards the high-heat content fuels, the technology selection has a tendency to go from boiler towards gas turbine, steam turbine, and combined cycles, respectively. On the other hand, moving from lower heat content fuels and energy conversion efficiencies towards higher levels, scenarios prefer to use boilers, steam turbine, gas turbine, and combined cycles, successively.

The analysis of the results implies that increasing electricity selling price does not result in further electricity generation. Moreover, sensitivity analysis showed that by increasing the electricity selling price, the final cost increases. It is due to the difference between heat and electricity generation efficiencies. By generating more electricity, more biomass is consumed that at lower efficiency values for energy generation results in higher costs. The electricity generation is restricted by pollution levels, mainly due to considering the equally important pollution objectives with cost objectives. Finding the best selling price and best electricity generation could be subject to more investigations.

The combined cycle can be said as the joint technology of the gas turbine and steam turbine cycles. If the initial investment cost does not matter, or the environmental issues outweigh the cost-related objectives, the combined cycle utilizing both steam and gas turbine cycles provides more versatility. ICE is not among the alternative technologies for large scale energy generation. Gas turbine provides an opportunity of using natural gas as an alternative, either completely or partially mixed with syngas. It helps to improve the reliability and availability of biomass-fired energy systems.

In the model, all criteria and objectives are equally important. Nevertheless, the model has the flexibility to address the design or operation needs and priorities by changing the weights of the criteria.

The environmental objectives such as CO_2 and SO_2 were considered as pollutions, not as the cost. First, due to environmental concerns, second, the carbon taxes, tariffs or incentives for reducing the carbon emissions are basically site-specific. The model has the flexibility to convert environmental objectives to cost, if necessary by converting to cost and adding a term to current cost functions. The model has the versatility to accept more fuels, technologies, and concepts for analysis. The layered nature also empowers the proposed model to involve more considerations such as reliability in the future analysis.

Biomass purchase cost and electricity selling price to the grid are two important parameters for system optimization. They are subjects of dramatic uncertainties. The seasonality of feedstocks and varying energy demands highlights the short time period operation analysis. Therefore, an optimization model more focusing on the system daily or hourly behavior is necessary. The practicality of scenario shift in shorter operation time periods should be studied.

Despite considering the system flexibility by introducing alternative scenarios and covering supply uncertainty, reliability evaluation is still lacking. Biomass-fueled system reliability can dramatically affect the pollutions and costs of the scenarios. It might totally change the biomass technology configuration or operating parameters. Hence, more comprehensive analysis to deliver the optimized costs and pollutions under reliable operation is vital.

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