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An enviro-economic optimization of a hybrid energy system from biomass and geothermal resources for low-enthalpy areas

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ABSTRACT

In this paper, a combined biomass-geothermal system, intended to supply heat in low enthalpy areas with an extremely cold climate, is optimized based on a nonlinear optimization methodology. A Multiple Criteria Decision-Making technique is coupled with a two-step optimization to achieve the most exploitable energy with the least pollution and cost possible. Three nonlinear objective functions for optimization with three criteria for decision-making were used to minimize the heat generation cost and pollution for a modeled building in Kuujjuaq, Canada. The biomass-geothermal system is split into two parts, surface, and subsurface parts. Twelve scenarios, including three wood pellet types, in four distance ranges from pellet mills, are first defined. Then, via modeling a building for heat demand analysis, the required heat is yielded. Afterward, in the first step of optimization, the cost and pollution functions for surface parts are developed and optimized using the genetic algorithm and screened by the MCDM technique, called TOPSIS, to size the biomass and geothermal subsystems. In the second step, using the sizing from the first step as a constraint, the cost of the geothermal ground heat exchanger is minimized. Twelve scenarios are optimally configured in this way with minimum cost and pollution in relation to operational parameters, such as utilization time and rated powers. The research proposes a methodology that sizes the biomass geothermal (bio-geo) system and can be extended to other technologies, such as turbines, energy storages, or fuel. Furthermore. It provides a correlation between cost and heat generation from biomass-geothermal systems for Kuujjuaq, Canada, and twelve optimal scenarios with system operating parameters. A basis for system sizing and system selection for baseload and peak demand shaving is also considered. Geothermal- and biomass-rated capacities vary with scenarios from 44% to 56% of the total rated capacity.

Acronyms

τ	Utilization time (hr)
η	Efficiency
φ	Annuity Factor
P	Heat generation (kW)
E	Pollution or Emission (tons)
C	Cost (CAD)
D	Drilling depth (m)
N	Number of bore holes
L	Total piping length (m)
Q	Total load (mWh)
m, n	Number of atoms
x, y, z	Number of atoms
T	Service lifetime (yr)
i	Interest rate

Subscript

b	Boiler
geo	Geothermal system
bio	Biomass system
elc	Electricity
sur	Surface
$subsur$	Sub-surface
max	Maximum
tot	Total

Abbreviations: ASHP, Air source heat pumps; BUT, Biomass utilization time; CCHP, Combined cooling, heat and power; CHP, Combined heat and power; DHS, District heating power; GA, Genetic algorithm; GEX, Ground heat exchanger; GSHP, Ground Source Heat Pumps; GUT, Geothermal utilization time; LCA, Life cycle assessment; HHV, High heat value; MHV, Medium heat value; LHV, Low heat value.

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1. Introduction

The polar regions of planet Earth are usually low-enthalpy ground heat energy areas. Sparsely populated communities, harsh climate, and poor transportation infrastructure make low-cost energy supply for these regions very complicated.

In Northern Quebec, Canada, the required energy for heating is supplied from fossil fuels. The high cost of fossil fuels and the low efficiency of energy generation are the primary motivators for turning to renewable energy such as biomass [1].

Biomass, as another renewable energy source, exists in a variety of forms, such as municipal waste, wastewater, and agricultural or forestry residue. Biomass could be a free resource and incorporated with less cutting-edge and cheaper technologies for energy conversion; however, biomass has solid leftovers and gaseous pollutants and may have large feedstock transportation costs [2].

Biomass is defined as any organic matter that is available on a recurring basis in various forms, such as agricultural and forestry residue or waste in solid, fluid, and gaseous states. [1].

For energy generation purposes and to reduce pollution, biomass feedstock is normally processed to be of high quality. Techniques, such as pyrolysis, Fischer-Tropsch synthesis, synthetic natural gas production, and torrefaction, have been used to process raw biomass for energy generation purposes [2].

Energy generation from processed biomass has been the topic of research and optimization where Ref. [3] provides a strctured review on that integrated with thermal storage. The design, modeling, and optimization of biomass-based systems is more unwieldy than fossil fuel systems, mainly because of the additional processing parameters, such as moisture content, working fluid, operating cycle, char and tar production, or gas to biomass ratios [4]. Therefore, research on biomass processing and energy conversion has been performed from various perspectives. To deliver a biomass-based system that is affordable and reliable, many issues such as cost, technology, and chemical, thermodynamic, or environmental aspects shall be carefully addressed. To that end, a wide range of the parameters should be reviewed for optimization modeling or sensitivity analysis [5].

Ahmadi et al. examined the influence of energy and energy efficiencies on the biomass-fueled energy system cost and CO_2 emissions via a thermodynamic model [6]. Moharamian et al. compared three configurations of a mixed biomass-natural gas energy system from technological and economic viewpoints. In an organic Rankin cycle setting, they evaluated the sensitivity of the hybrid systems with a change in the energy generation pathways [7].

System cost efficiency, with ever-increasing environmental concerns, encouraged researchers to pursue more novel trends in combined heat and power (CHP) concept analysis. [8]. Diversifying the product is one of the trends that has been investigated. Moret et al. investigated a hybrid energy system composed of deep geothermal energy and woody biomass for CHP and biofuel production. They used an environ-economic multi-period optimization with the life cycle assessment (LCA) approach in their research [9]. Gustavsson et al. economically analyzed the feasibility of using biomass to generate heat, electricity, and biofuel for cars [10]. A linear optimization method was taken by Tock et al. to evaluate the possibility of hydrogen production for cost reduction in a biomass-based CHP plant. The trade-off of hydrogen and electricity generation was analyzed in their research to deliver an optimized profile for energy and fuel generation from biomass [11]. Østergaard et al. investigated the supply energy demands of the Aalborg municipality in Denmark via a hybrid system comprising low-temperature geothermal, wind, and biomass resources. They modeled the proposed scenarios in EnergyPLAN to simulate the demand profile and energy generation [12].

Nakao investigated the potential of a hybrid energy system composed of biomass and geothermal subsystems for Japan. He took an environ-economic approach for modeling a nonlinear optimization in EnergyWinTM software. The geothermal subsystem provides heat to preheat the operating fluid before being heated by the biomass-fed boilers [13].

Zhang et al. performed a thermo-economic analysis of a combined cooling, heating, and power (CCHP) system for rural areas, based on biomass, geothermal, and natural gas resources. The influence of critical parameters such as gas-mass ratio and economic factors were verified, and the results proved further efficiency and lower costs [14].

The environmental aspects of a biomass-based system, such as ash, particulate, or other non-carbon emissions are important subjects that may dramatically affect the effectiveness or operability of the system. The significance of taking combustion or gasification leftovers into consideration was highlighted by researchers such as Sarigiannis et al. They showed that the particulate from biomass use can cause some of the health and technological losses [15].

Although biomass has always been presumed to be a carbon-neutral fuel for energy conversion purposes, the carbon footprint of energy generation, because of feedstock transportation cannot be neglected. Girones et al. considered various biomass conversion pathways from the feedstock sites to consumption areas to analyze the best CO_2emission mitigation strategies [16]. Carbon footprint analysis was pursued by other researchers, such as McKechnie et al. and Ter-Mikaelian et al. [17, 18]. In a research performed by the Fraunhofer Institute, the economic aspects of transportation pollution and the emission of non-carbon pollutants, such as NO_x and PM10 were studied. Considering all of the costs, including pollution from logistics, it was concluded that energy generation from biomass could be rendered more costly than natural gas [19]. Boukherroub et al. researched the parameters and factors affecting the biomass supply chain for Quebec, Canada. They implemented the downstream-upstream approach to optimize the cost of woody biomass and the size of wood pellet mills [20]. Prakash et al. conducted a case study on the optimization of the system operation based on various gasification levels. The temperature range in which gasification occurs was the subject of the optimization [21]. Proskurina et al. analyzed torrefied biomass and concluded that completely torrefied biomass offers higher efficiency and fewer emissions [22]. Li et al. carried out a thermo-economic simulation for biomass and geothermal hybrid systems and found that partly gasified biomass can economize and sanitize hybrid energy systems [23].

A multi-objective optimization model in an enviro-economic approach was investigated by Jørgensen et al. [24], and they used the Multi Integer Linear Programming (MILP) technique to optimize the biomass supply chain and energy delivery, considering biomass processing and supply, and energy conversion parameters. The same approach was followed by Schüwer et al. to maximize the energy reserve minutes in the German energy market [25].

Widely used around the world, geothermal energy is considered a renewable resource for electricity or CHP production. The application of geothermal systems in low-enthalpy areas or cold climates is restricted to heat-only purposes via heat pumps and district heating. According to the International Energy Agency (IEA), 30% of the houses in Sweden are equipped with mostly vertical-loop GSHP systems. They cover 90% of the annual heat-energy demand with an electric heating system as the backup heat source [26, 27].

Ground source heat pumps (GSHP) are low-maintenance systems that work in a temperature range between -6 °C to 50 °C. Their Coefficient of Performance (COP) can increase up to around 6, but at cold climates the COP reduces to a range between 2 to 3.8. The variation in COP values refers to various soil conditions, heat sources, and system operations [28].

Cottrell et al. performed a study for the technology assessment and performance analysis of the GSHPs and air source heat pumps (ASHP) in cold climates for a case in Yukon, Canada. They did not suggest the GSHPs for deployment in the Yukon because of the higher price of hydroelectricity in winter [29]. Sanyal et al. performed an economic sensitivity analysis for geothermal systems that considered the capital, operations, and maintenance costs [29].

Research in the cold climates supports the application of geothermal resources with district heating for urban communities. Via a scenario-based approach, Tol et al. tried to optimize a low-temperature DHS supplied with renewable energy, including geothermal energy [30].

Andrushuk et al. used a ten-home case study in Canada to address the feasibility of GSHP in urban areas, where 97%, and up to 100%, of the heat demand for the ten homes was provided by GSHP systems [31]. In another study performed by Rybach et al., they concluded that using DH systems fed by GSHP could result in excavating vertical boreholes closer to each other and reducing the required area, in heating-dominated regions [32].

Geothermal systems have been approached from the thermodynamic or thermo-economic perspective. Thermodynamic and thermo-economic approaches employing numerical and analytical analyses have been employed by researchers, such as Renz, Bernier, Raymond, and Therrien [33–39].

In all this research, the balance of heat extraction and heat formed within operation was highlighted. Ground thermal degradation because of large heat extraction in colder seasons and low heat injection in warmer seasons has been reported in research. Andrushuk et al. reported COPs were between 2.8 to 2.6 because of a gradual degradation during operation [31]. In the research carried out by Genest et al., in 2006, a commercial building in Quebec, equipped with GSHP, was thermodynamically analyzed [40].

Thermal degradation in this project was not reported because of the groundwater flow. It showed that groundwater can play a balancing role in counteracting thermal degradation. Because of the lower efficiency of heat pump operations in cold climates, researchers, such as Yang et al., suggested the hybrid systems as an alternative [41]. The U.S. Department of Defense recommended the coupling of the GSHPs with solar panels in extreme climates, such as Alaska, to supplement the heat obtained from the ground in winter. A hybrid system that is laid out in this way can be a means for improving the cost-effectiveness of the GSHP system in cold climates [42].

The potential for using hybrid geothermal energies has been studied economically by Karanasios et al. [43], and hybridization of the products was researched in an economic analysis by Kanoğlu et al. that examined the utilization of geothermal energy to deliver cooling, heating, and electricity. Using electricity generation, they earned up to six times the revenue [44].

A geothermal-solar hybrid system with heat storage and a heat-recovery ventilator was investigated by Stene et al. for one year to monitor the building heat demand in Canada. The results show that the electrical cost for running the GSHP was less than the fuel cost. Additionally, the research demonstrated that solar panels are useful in recovering the ground temperature where groundwater flow is not sufficient [45]. Hu et al. carried out a case study in China that showed heat pump COP increased by 0.25 using solar energy [46].

Traditionally, electricity generation cost estimation in power plants is performed using indices to estimate the construction costs. However, the fragility of economic analysis for hybrid renewable systems cannot be addressed by conventional index systems. The hybrid systems increase the cost of installing additional equipment, such as solar panels or storage. Availability of the renewable resource, financial incentives, or emission penalties to promote using renewable systems is largely different in many areas and cases [47, 48].

For geothermal systems, the performance is dramatically sensitive to geographic and geotechnical properties, loop sizing, well depth, thermal degradation, and seasonal climate variations. Such parameters drastically manipulate the final energy costs [49].

Considering all of these factors, it could be said that a hybridization of renewable resources for energy generation is largely site-specific, which may explain why many geothermal systems have been coupled with solar or wind energies and are equipped with storage to balance the energy exploitation cost and diversify provisions for customers [45, 46, 50]. Biomass integration with geothermal resources has been investigated by researchers for energy purposes in urban areas [9, 12–14, 50, 51]. However, explicit optimization, environ-economic analysis, or low-enthalpy area requirements have not been completely addressed in many studies. They are mostly considered for integration with facilities in urban communities that use DHS.

Considering the literature review above, hybrid systems, including biomass and geothermal resources for low-enthalpy areas, could be worth investigating in Canada. Geothermal energy is a highly available resource with low operating costs and no fuel expenses. Nevertheless, geothermal energy utilization demands high capital costs. Additionally, economic issues, global warming, and concerns about greenhouse gas emissions highlight the urgency of environmental analysis of renewable systems. Because biomass integration, both in combustion and gasification settings, generates pollution, an environmental-economic (enviro-economic) approach is used for this research. Minimizing cost and pollution entails technical, thermodynamic, or economic parameters that build up objective functions and decision variables. Such parameters are interrelated in linear or nonlinear fashion and can be referred to within the optimization, in multiple steps, as objective functions and constraints. To address such complexity, a layered methodology is needed to take into account the nonlinearity and multiplicity of the parameters in the system optimization.

A hybridization of the biomass and geothermal subsystems, hereafter bio-geo system, is considered in this study. The bio-geo system is configured into two parts, subsurface and surface parts. The term “surface” corresponds to the whole biomass subsystem and geothermal heat pump and accessories, while the term “subsurface” addresses the geothermal system’s borehole field. Such a system is modeled to provide the annual energy of a building in Kuujjuaq, Nunavik, and Northern Quebec, Canada. This paper has been organized as below. First, a review of the related studies is carried out. Then, the methodology used for two-step optimization is described in detail. An office building in Kuujjuaq, Northern Quebec, is modeled and analyzed based on the defined methodology. The scenario definition, mathematical modeling, and cost-performance correlations are formed to carry out multi-objective nonlinear optimization. Then, scenarios for the optimal operation of the bio-geo system are configured and prioritized, and the results are discussed. The main contributions of the current research are to:

- Provide a basis for sizing the system and selection of the system for baseload and peak demand shaving.
- Provide an optimization algorithm for sizing hybrid geo-bio system;
- Provide a formulation for optimization that allows examining other technologies and biomass fuels, generating new products such as electricity and biofuels;
- Use two-steps methodology that optimizes the geothermal subsection in two levels for both heat pump sections and borehole excavations. The optimization first determines the size of heat pump based on the least surface cost and pollutions, then minimizes the excavation costs by optimizing the borehole depth and configuration.
- Propose a new layered and step-by-step methodology for sizing and minimizing a hybrid system for low-enthalpy areas.
- A specific case study is carried out to develop a correlation between cost and heat generation from biomass geothermal systems for Kuujjuaq, Canada, and twelve optimal scenarios with their operation parameters.
- This method optimizes the sizing of the system using its operating parameters and is expandable to incorporate other technologies and fuels which covers other energy carriers, such as electricity.

2. Methodology

The primary purpose of this research is a two-step enviro-economic optimization of a bio-geo energy system for dominantly low-enthalpy regions. Optimization is conducted on two nonlinear functions: (1) A cost function which is decomposed to surface (above the ground) and

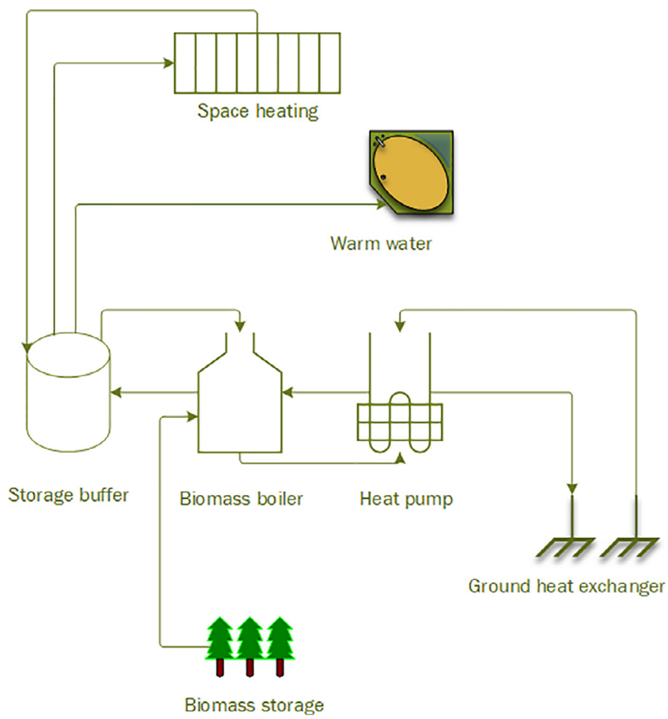

Fig. 1. A schematic view of the subsystem blocks and their configurations.

sub-surface costs (below the ground), and (2) A pollution function or emission function. Pollution function is an explicit formula for CO_2 and SO_2 emissions from the biomass combustion in boilers and the pollution caused by the electricity consumption for the heat pumps. Fig. 1 shows the schematic view of the sub-system blocks. The heat pump system operates in a series with the biomass boiler to provide space heating and to satisfy the hot water demand. Additionally, this configuration can be used for cooling; however, cooling is not discussed in the current study.

As Fig. 2 depicts, the methodology has different steps as follows:

2.1. Building heat demand simulation

It starts with the modeling of a two-story building in Kuujjuaq, Canada, in eQuest software, to provide the hourly, monthly, and yearly heat demands. The building is modeled according to the building construction regulations for Kuujjuaq. The case study has the area of 22,604 ft^2.

2.2. Optimization process

Optimization process is composed of two steps including where step 1 optimizes all components above the ground including the biomass system entirely, the geothermal heat pumps, and accessories. Step 2 addresses borehole settings for the geothermal subsystem. As Fig. 2 depicts, the steps are as follows:

- Step 1 of optimization: Total cost of all systems installed and operates above the ground as can be seen in Fig. 1, i.e. cost for heat pump itself and biomass boiler and required fuel cost for their operation as well as the related pollution caused by their operation. The objective functions at this step is called *surface cost* to highlight the components installed above the ground. At this step, optimization is completed on the surface part based on two explicit functions, one for the surface equipment costs and the other for the combustion pollution. Optimization is performed using the genetic algorithm by manipulating six operating parameters as decision variables. These decision variables as depicted in Fig. 2 are boiler- and heat pump-rated capacities, utilization times, and efficiencies. The pollution function is the sum of the CO_2 and SO_2 emissions from biomass combustion and electricity for the heat pump while it is running. A genetic algorithm (GA) code is developed in MATLAB to carry out the minimization of the surface part cost and pollution.

The GA MATLAB code delivers a Pareto front of the optimal solutions for each scenario. That means a cloud or set of solutions are delivered as a trade-off for cost and emission. The MCDM technique, TOPSIS, is then implemented at this step of optimization to find the optimal solution among the Pareto fronts (cloud or set of solution) using three criteria. The criteria are defined based on the system performance parameters, such as heat power, utilization time, and boiler efficiency. The results of the first step are the biomass boiler and geothermal heat pump sizing performance parameters. These sizing performance parameters are then passed to the second step of the optimization which minimizes cost of the equipment under the ground.

- Step 2 of optimization: At this step in Fig. 2, the cost function refers to the equipment under the ground which is called *sub-surface cost* i.e. optimization is performed for the subsurface cost as a function of the borefield specification [30]. The borefield specifications, including total length, pipe type, aspect ratios, and pipe diameter, are restrained by the heat pump specifications in addition to the site geotechnical characteristics [54]. The geotechnical characteristics of the region and ground load are derived from the geological and weather reports for Kuujjuaq, Canada [52, 53].

- Final output: As it can be seen for the last step of flowchart in Fig. 2, the minimum cost calculated in the second step is then added to the minimum cost from the first step to deliver the optimal configuration for the system.

2.3. Setting of scenarios

Twelve scenarios are defined with three biomass types and four distances from the feedstock mill. The biomass used in the research are high heat value (HHV), medium heat value (MHV), and low heat value (LHV) woods. Four distances of 50, 150, 250, and 350 kilometers from the mills are considered for the scenario definitions to help render the sensitivity analysis with respect to the cost and distance.

2.4. Formulation

The cost function modeling of the biomass-geothermal system is performed based on an annualized cost analysis [56] using:

$$C_{tot} = C_{sur} + C_{subsur} \quad (1)$$

$$C_{sur} = \left(C_{cap} + C_{op}\right)_{sur} \quad (2)$$

$$C_{subsur} = \left(C_{cap} + C_{op}\right)_{subsur} \quad (3)$$

Once this is known, the above formula can be rewritten as follows where it is decomposed to biomass and geothermal subsystems:

$$C_{sur} = \left(C_{cap} + C_{op}\right)_{bio} + \left(C_{cap} + C_{op}\right)_{geo} \quad (4)$$

$$C_{subsur} = \left(C_{cap}\right)_{geo\ subsur} \quad (5)$$

The capital costs were correlated to the nominal capacities of each subsystem. The operation cost consists of the biomass purchase, transportation, and geothermal heat pump electricity costs that have been derived from the literatures and surveys [20, 30, 56–58]. Two objective functions of surface cost and pollution (emission) are derived below.

$$C_{sur} = \frac{\left(1114 P_{bio}^{0.67} + 38065 P_{geo}^{0.4225}\right)\varphi}{P_{bio}\tau_{bio} + P_{geo}\tau_{geo}} + \frac{0.0036\left(C_{fuel} + 20 + 10(D-50)\right)}{\eta_b NHV} + C_{elc} \quad (6)$$

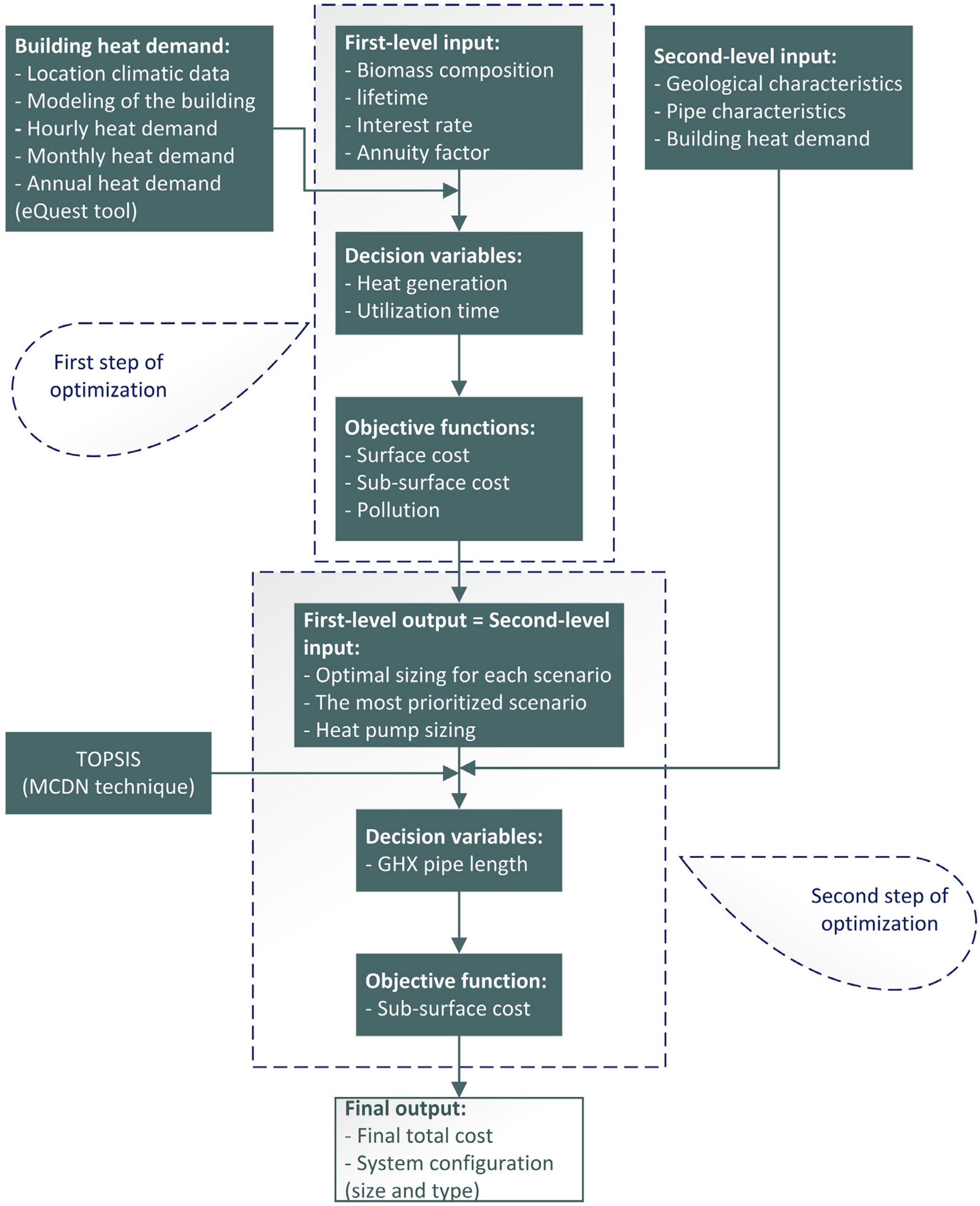

Fig. 2. The methodology flowchart and pathway.

and

$$E = \frac{P_{bio}\tau_{bio}(44m + 64z)}{\eta_b NHV(12m + n + 16x + 14y + 32z)} + 1.2 \times 10^{-6} P_{elc}\tau_{geo} \quad (7)$$

where

$$NHV = [34.1Ca + 101.98H - 9.85O + 6.3N + 19.1S][1 - 0.01MCWB] - 0.02452MCWB \quad (8)$$

In eq. (6), annuity factor φ is defined as:

$$\varphi = \frac{i}{1 - (1 + i)^{-T}} \quad (9)$$

C_{elc} based on the Hydro Quebec data was set to 6.08 CAD cents per kWh. The economic parameters, such as service life and interest rates, necessary for the annuity factor, are set to 25 years and 3.25%, respectively [59, 60]. A ratio of the operation and maintenance cost equal to 10% has been added to the investment costs [30]. Additionally, m, n, x, y, and z stand for the number of atoms, and Ca, H, O, N, and S represent the biomass mass fractions of the Carbon, Hydrogen, Oxygen, Nitrogen, and Sulfur in the biomass. The number of atoms is obtained from the biomass mass percent as illustrated in Table 1 for each type of fuel.

The pollution share for the heat pump electricity is set to 1.2 grams per kWh for Kuujjuaq, Canada [59, 60]. Biomass purchase prices are

Table 1
Mass percent for biomass composition [55].

Fuel Type	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash
HHV Wood	52.10%	5. 7%	38.90%	0.20%	0.00%	3.10%
MHV Wood	52.00%	4.00%	41.70%	0.30%	0.00%	2.00%
LHV Wood	48.85%	6.04%	42.64%	0.71%	0.06%	1.70%

set to 250, 300, and 350 CAD per ton for LHV, MHV, and HHV woods, respectively. These values are yielded and estimated from the literature review and inquiries made throughout Canada [20, 59, 60].

The thermal conductivity of 2.29 W/mK, the mass density of 2,540 kg/m^3, the specific heat of 1,000 $J/kg°C$, and the granitic thermal diffusivity of 0.10368 are used to size the geothermal ground heat exchanger (GEX). The undisturbed ground temperature for the case study region was equal to 8°C. The operating fluid in the geothermal system is a solution composed of water and 40% ethylene glycol with a specific heat capacity equal to 3,472.72 $J/kg°C$ [52, 54, 61]. The cost functions at the second step include the piping and drilling costs. The drilling cost is a main part of the geothermal subsurface formulation, and the contributions of other parts in the cost function can be neglected. The cost is extracted via the correlation below [30]:

$$C_{subsur} = \frac{1.934 \times 10^{-7} L^2 + 1.664 \times 10^{-3} L + 0.38}{N\left(P_{bio}\tau_{bio} + P_{geo}\tau_{geo}\right)} \tag{10}$$

where N stands for the number of bore holes, D is the drilling depth (m), and L is equal to the total piping length in meter (m), which is ND. Both N and D are considered to be positive as a constraint. The other applied constraint is related to maximum building heat demand as:

$$P_{bio} + P_{geo} = Q_{max} \; 0 \le \tau_{geo}, \tau_{bio} \le 7876 \tag{11}$$

2.5. Optimization considerations

With the minimum of the surface/subsurface costs and pollution acting as the objective functions, and the configuration of the hybrid system (size of the biomass and geothermal supply system, heat generation, utilization time, and pipe-length) acting as the optimization variables, Genetic Algorithm (GA) is employed to search for the optimized point within design space. This choice of optimization techniques relies on previous experiences in the field of hybrid energy systems design as reported by Ref. [62]. With the theory of biological evolution, it obtains the optimized point by several generations evoluted from the initial population. Individuals of each generation are decided by the value of the objective function of each individual of the last generation and the randomness of selection, crossover and mutation. The optimization is conducted using MATLAB. The population size is 250. It should be noted that increasing population size after 200 basically did not change the optimization results. The maximum number of iterations is 10000. The selection function is set as stochastic uniform function. The mutation function is set as adaptive feasible function. The flow chart shown in **Fig. 3** includes the procedure of optimization method used in the present study. In step 1 of the optimization, the GA code is run for each scenario, 60 times, to cover the solution areas and to find close to global, optimal solutions. The results are averaged, and the outliers are screened for this purpose in the "results and discussions" section. The parameters used or the optimization purpose are as follows:

- Population size: 250 (performed from 100 to 1000 with no change when exceeds 200)
- Creation function: default (Constraint dependent)
- Fitness scaling: default (Rank scale)
- Selection function: default (Stochastic uniform)
- Elite count: 0.05 × population size
- Crossover fraction: 0.5, also tested with default (0.8)
- Mutation/Crossover function: default (0.2)
- Migration direction: forward (fraction: 0.2 interval: 20 by default)
- Constrain parameters: default (Augmented Lagrangian)
- Stopping criteria: (Stall generations: 50; Function tolerance: 10^{-6}; constraint tolerance:10^{-3})

It is known that there is no mathematical proof that in practical, complex cases the GA converges to the global optimum (or minima). To gain confidence that the results are accurate enough and to the global optimum, the code was run with different values of parameters mentioned above and each trial is repeated several times especially with the fact that the success of the search depends heavily on the positions of the points of the starting population as well as the location of the generated new points. To boost the confidence, the results of the GA algorithm is compared for a specific scenario with another meta-heuristic technique using close or the same parameters as GA as shown in the results section.

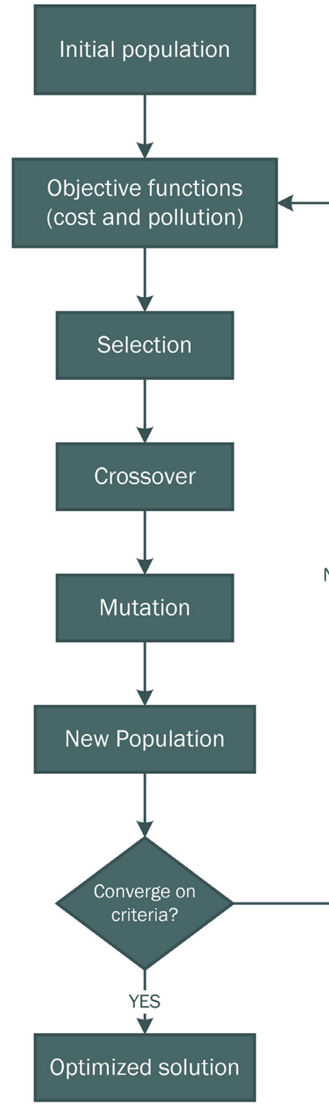

Fig. 3. Flowchart for the optimization by Genetics Algorithm (GA)

3. Results and discussions

The eQuest software result for building energy modeling was used to specify the hourly, monthly, and yearly loads. Based on the maximum heat demand required for the month of January, the bio-geo system should provide 611.25 $kBtu/hr$ or 171.2 kW for heating. The two-step optimization is carried out first, and a full result of Pareto front for a specific case of MHV-250km is illustrated in **Fig. 4** while a sample of these results after applying TOPSIS (see flowchart in **Fig. 1**) is tabulated in **Table 2**. The scenarios are represented with biomass-distance notation that shows the biomass type and the distance from the mills. As can be seen from Fig. 4, the second meta-heuristic technique (hunting search) shows very close solutions to the results of the GA technique, providing a confidence on the accuracy of the other scenarios.

Table 3 categorizes the optimum scenarios with their performance parameters; each scenario was run 60 times to find the average. The op-

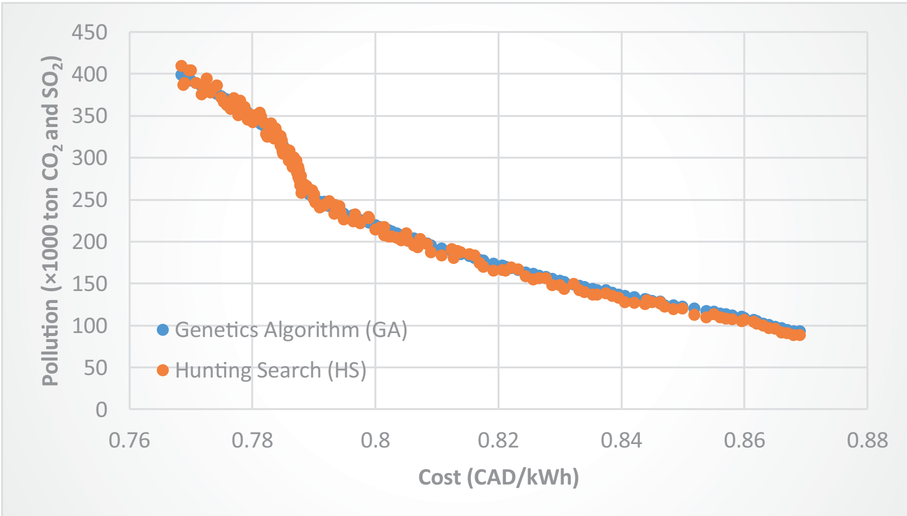

Fig. 4. Pareto front for MHV-250km scenario and optimization techniques comparison.

Table 2
A sample of 160 optimized solutions derived for the MHV-250km scenario.

Cost (CAD/kWh) bio	geo	Pollution ($tons$)	P_{bio} (kW)	P_{geo} (kW)
0.405	0.299	238,146	95.4	76.6
0.402	0.303	236,669	95	77
0.400	0.305	236,246	94.8	77
0.397	0.308	235,116	94.5	77.2
0.394	0.311	234,109	94.2	77.7
0.382	0.323	231,895	93.3	78.6
0.473	0.331	229,598	93.2	78.7
0.357	0.349	228,125	92.3	79.6
0.314	0.391	224,895	90.9	81

Table 3
The final optimal operating and performance parameters for all scenarios.

	Distance (km)	Cost (CAD/kWh)			P_{bio} P_{geo} (kw)		Bio Load (kWh)	Geo Load (kWh)	Total Load (kWh)
		bio	geo	total					
HHV	50	0.04	0.28	0.32	78	94	619650	418600	1038250
	150	0.19	0.31	0.5	81	91	621800	455470	1077270
	250	0.32	0.29	0.61	89	83	661700	448214	1109914
	350	0.48	0.32	0.8	83	89	661900	499630	1161530
MHV	50	0.03	0.32	0.35	95	77	745960	315058	1061018
	150	0.25	0.34	0.59	85	86	664000	439660	1103660
	250	0.41	0.3	0.71	95	77	681700	438741	1120441
	350	0.59	0.4	0.99	98	74	713780	471255	1185035
LHV	50	0.02	0.3	0.32	90	82	681700	338582	1020282
	150	0.16	0.32	0.48	82	89	657640	402725	1060365
	250	0.32	0.28	0.6	85	87	625560	473572	1099132
	350	0.39	0.4	0.79	85	87	691900	438984	1130884

timum sizes of biomass and geothermal subsystems have been detailed in Fig. 5.

The HHV-50 scenario has the lowest and highest shares for the biomass and geothermal subsystems, respectively, and is equal to 78 and 94 kW. Conversely, the MHV-350 scenario has the lowest share for the geothermal subsystem and the highest share for the biomass subsystem. Additionally, scenarios with HHV woods are biomass-dominated while MHV scenarios are geothermal-dominated. The share of the biomass subsystem increases with distance for HHV and MHV woods. Alternatively, the share of biomass subsystem decreases for LHV wood when the distance increases. On average, increasing the distance up to 350 km causes a 5% change in the optimal capacities for each system.

Despite the fact that the heat pump– and boiler-rated capacities varied, the total load of the biomass subsystem dominates the total load of the geothermal subsystem in all scenarios. It is attributed to the heat pump cost correlation, which results in a much lower utilization time of the geothermal subsystems. The total heat cost for all scenarios has been illustrated in Fig. 6.

The cost sensitivity to transportation distance is more than the biomass purchase prices. Simply said, the variation of cost to fuel in the same distance is much less than the variation of cost to distance for the same fuel. The sharpest increase in rates occurs at a distance range within 50 to 150 km, and the lowest cost variation occurs at distances between 250 and 350 km.

The highest costs are for the MHV, HHV, and LHV scenarios, respectively. Although the purchase price of HHV is higher than that of MHV, the HHV within the same distances has a lower total cost than MHV. In summary, more biomass is used when MHV has a lower heat content, and a higher heat content of HHV wood cannot offset the need to use more biomass for MHV wood.

Fig. 7 shows the variation of the total cost and total heat generation for scenarios. As is visible, the total cost is affected by heat generation. Additional heat generation, when constrained by minimum pollution, increases the geothermal share of heat generation that increases the final cost because of larger capital costs.

The total cost and total load in all scenarios, can be linearly correlated to each other. To derive a reliable correlation between the heat cost and generation, the biomass purchase prices for LHV, MHV, and HHV were considered within ±25% variation from the initial values with 5% incremental steps.

The sensitivity of the results to the purchase price uncertainty was examined, and the results were screened. The correlation between total cost and total load can be formulated as:

$$C_{tot} = 0.0042Q_{tot} - 4.0595 \quad (12)$$

and

$$Q_{tot} = 225.73C_{tot} + 964.54 \quad (13)$$

Twelve optimal scenarios, illustrated in Table 3, are subject to TOPSIS to rank the scenarios based on the three aforementioned defined criteria. The results are summarized in Table 4.

Considering the pollution as an objective with cost may result in prioritizing more distant scenarios, such as LHV-350, than less distant scenarios, such as MHV-250, at higher costs.

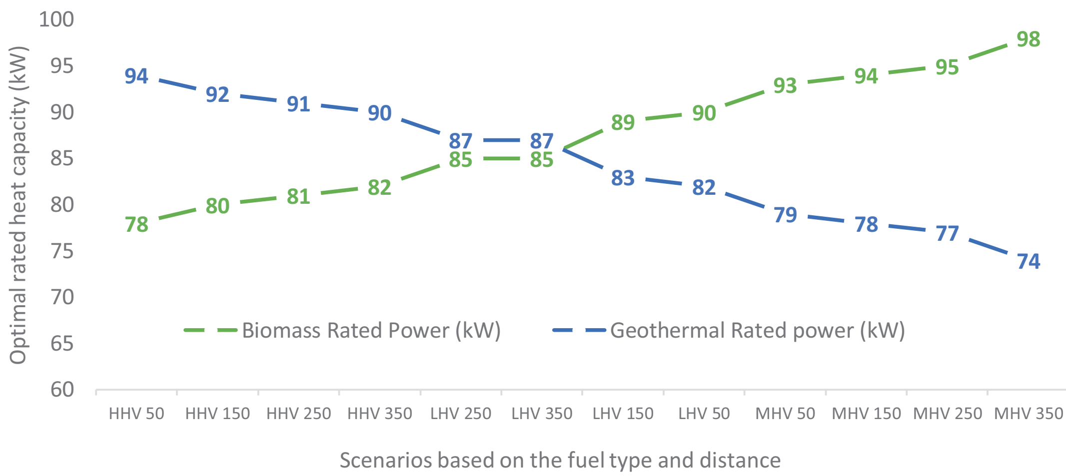

Fig. 5. Optimized sizing of each subsystem for all scenarios.

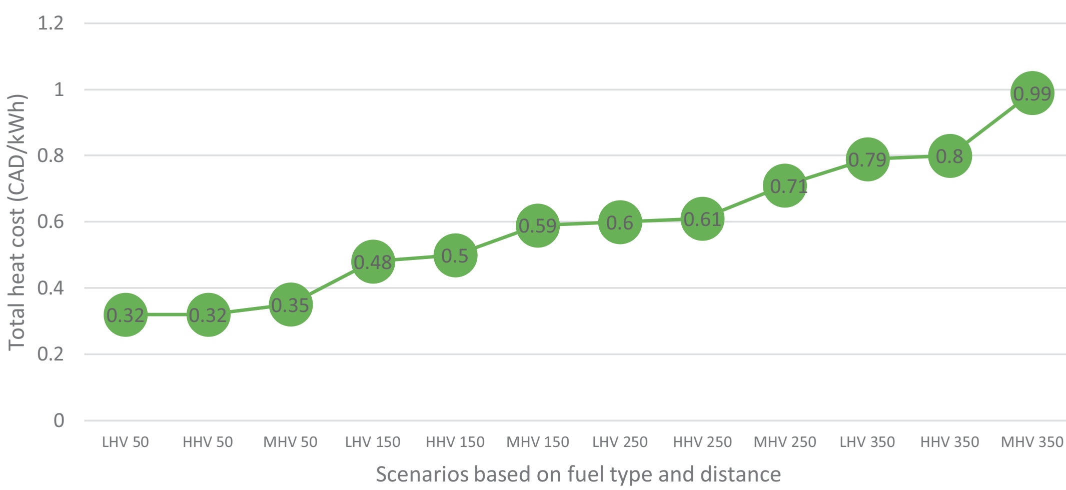

Fig. 6. Total cost (CAD/kWh) for the heat generated from biomass in all scenarios.

Table 4
A ranking of twelve optimal scenarios with their finalized cost, pollution, and total load.

No	Wood pellet type Distance from mill	Total pipe Length	Total cost (CAD/kWh)	Total load (mWh)	Pollution ($tons$)
1	LHV-50	2749	0.30	1,020,282	15728
2	HHV-50	2692	0.32	1,038,250	16547
3	MHV-50	2861	0.35	1,061,018	23711
4	LHV-150	2805	0.48	1,066,725	14315
5	HHV-150	2815	0.50	1,077,270	18469
6	LHV-250	2688	0.6	1,099,132	14576
7	HHV-250	2667	0.61	1,109,914	18960
8	MHV-150	2695	0.59	1,097,300	21327
9	LHV-350	2600	0.79	1,130,884	15033
10	MHV-250	2584	0.71	1,120,441	23814
11	HHV-350	2340	0.8	1,161,530	17666
12	MHV-350	2324	0.99	1,185,035	24494

Considering the pollution as an objective with cost may result in prioritizing more distant scenarios, such as LHV-350, than less distant scenarios, such as MHV-250, at higher costs.

4. Conclusions and future remarks

An optimization of a biomass-geothermal energy system for a residential building in Northern Canada was performed. Despite being defined for a specific application, the developed methodology is flexible enough to adopt other fuels and technologies by replacing the economic factors and the chemical composition of fuel. Delivering optimal configurations for twelve scenarios with minimum cost and pollution for a hybrid system was the main objective of this research. By splitting the system into surface and subsurface parts, at the first step of optimization, the minimum cost and pollution with sizing of the biomass subsystem and geothermal heat pump is carried out. The same approach is used in the second step, by sizing the ground heat exchanger and minimizing its cost. The cost from the second step is added to the cost in the first

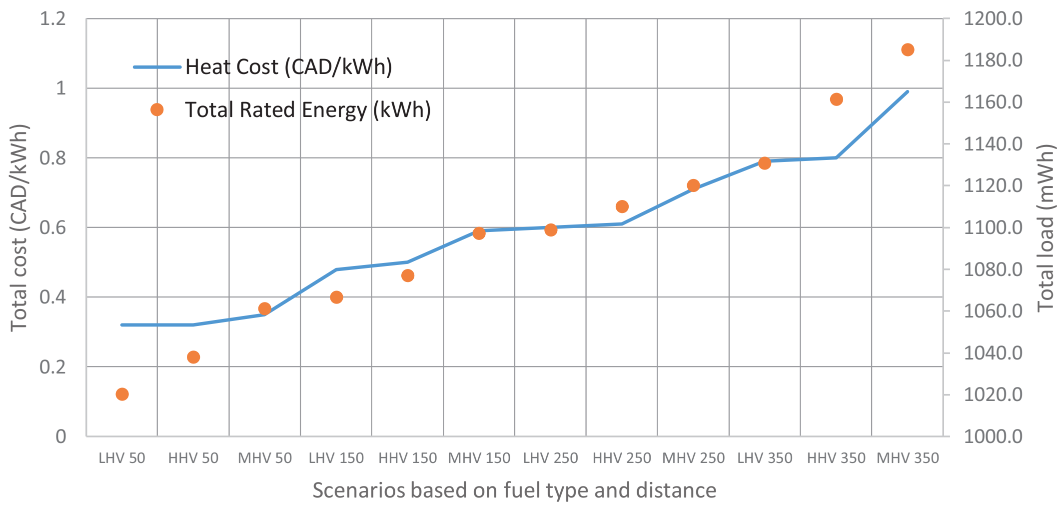

Fig. 7. The total cost and total load for twelve scenarios.

step to deliver the optimal system configuration for all scenarios. The optimization process shows a high sensitivity to the optimized performance and biomass type, purchase price, and distance from the supply source.

The cost sensitivity to biomass transportation distance is more than its sensitivity to biomass purchase price. The biomass subsystem cost, by changing the distance, can increase up to 20 times more than the primary cost. For the geothermal subsystem, the cost varies up to 1.43 when changing the distance.

On the other hand, the sensitivity of cost to purchase price is more than the heat content. In other words, increasing the heat content of the biomass may not necessarily lead to lower costs. Geothermal- and biomass-rated capacities vary with scenarios from 44% to 56% of the total rated capacity; however, the heat generation and utilization time of the biomass subsystem dominates the corresponding values for the geothermal subsystem. This is mainly because the utilization time for the geothermal subsystem is less than that of the biomass subsystem. It demonstrates that the biomass subsystem is a better fit for base load meeting, whereas the geothermal system is better for peak demand shavings.

For all scenarios, the more heat that is generated, the more it costs. Increasing the total load generated from the whole system translates to larger geothermal subsystems that, because of their higher capital costs compared to the biomass subsystem, lead to higher total costs.

A low impact of biomass heat content on the total cost and a higher cost for additional heat generation and restriction on energy generation from low-cost LHV woods are all attributed to pollution as an independent objective function, with the same weight as the cost objectives. Pollution as an independent objective function causes some unpredictable behavior for scenarios, such as prioritizing more costly scenarios than less expensive ones because of lower polluting scenarios. Taking into account the independent environmental objectives and not combining them into cost objectives is a reason to describe the high sensitivity of the biomass system sizing and configuration to the fuel heat content and purchase price transportation distances.

If biomass and geothermal subsystems are in full operation, the total heat produced is more than the heat required for the whole system. The additional heat can be stored or sold to the grid. In other words, the results of the research powerfully highlight the potential for a more economic operation of the hybrid energy systems using storage to connect to the smart thermal grids or district heating systems. Using heat storage also raises the system's reliability and versatility in harsh climate and emergency situations.

Declaration of Conflict of Interests

The authors (Masoud Rezaei, Fuzhan Nasiri, and Mohammad Sameti) declare that there is **no conflict** of interest regarding the publication of the article "A bi-level optimization of a hybrid energy system from biomass and geothermal resources for low-enthalpy areas." Submitting **authors** are responsible for co-authors **declaring** their interests.

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