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Superstructure Optimization of Geothermal Binary Combined Cooling, Heating and Power System Using Life Cycle Optimization

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This article addresses the optimal design of a geothermal binary trigeneration system for simultaneous cooling, heating, and power generation. A new processing network with alternative processing pathways is proposed. The major processing sections include geofluid production, Organic Rankine Cycle (ORC) evaporation, power generation, heat redistribution, cooling generation, condensing, and geofluid injection. Based on the superstructure, a cradle-to-gate life cycle analysis and techno-economic analysis are integrated with multiobjective optimization to simultaneously optimize the life cycle environmental impacts and the economic performance. To this end, a mixed integer nonlinear programming (MINLP) model is proposed to select the optimal processing pathway in terms of both greenhouse gas emissions and total annualized cost. A case study is also presented to cope with the seasonal demand of cooling, heating, and power to illustrate the application of the proposed modelling and solution methods.

1. Introduction

Considering the depletion of fossil fuels and severe environmental concerns induced by combusting fossil resources, it is critical to exploit alternative sustainable energy resources to accommodate the increasing demand of primary energy. Primary energy is further converted to diversities of secondary energy, such as electricity, cooling, heating, etc. Among the suitable primary energy alternatives, geothermal energy is advantageous because it provides unceasing power regardless of the climate and time of the day while avoiding the high risks associated with other constant energy sources such as nuclear (Frick et al., 2010). In addition, low-temperature heat source including geothermal energy has aroused great interest among researchers recently (Kansha and Ishizuka, 2017).

Another issue in energy utilization is the energy conversion efficiency. While power is conventionally generated along with heating utility by burning fossil fuels, cooling utility is produced by electric chillers or from surface water. A combined cooling, heating and power (CCHP) system can accomplish energy utilization efficiency up to 90 %. Low-temperature energy demand, ranging from 0 to 260 °C occupies approximately one third of the entire U.S. energy demand (Fox et al., 2011). Most of U.S. low-grade heat demand is currently satisfied by burning fossil fuels, among which natural gas and oil rank in the top. However, the chemical energy reserved in fossil fuels is more efficiently captured by utilizing high combustion temperatures, limiting their suitability for low-grade heat generation (Lukawski et al., 2013). The energy carrier in geothermal energy systems, such as geofluid, generally has a much lower temperature than the flue gas generated by fossil fuel combustion, allowing low-temperature heat demand to be met with much higher efficiency. Therefore, geothermal CCHP system is a promising trigeneration system for high efficiency domestic energy usage.

Recent studies on life cycle optimization (LCO) methodologies have been applied to sustainable design of hydrocarbon biofuels (Gebreslassie et al., 2013), algal biofuels (Gong and You, 2017), polygeneration systems (He et al., 2015), and biodiesels (Gong et al., 2014). However, there is no systematic study on LCO of geothermal energy systems. In this work, a new superstructure for a supporting fossil fuel based geothermal binary CCHP system is proposed, which is capable of producing cooling, heating, and power, simultaneously. Based on the proposed superstructure, a cradle-to-gate life cycle analysis (LCA) is conducted to account for the

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life cycle greenhouse gas (GHG) emissions during trigeneration. Furthermore, the LCA, as well as the techno-economic analysis, is integrated with multi-objective optimization to optimize both the life cycle environmental performance and economic performance based on the proposed superstructure of geothermal trigeneration, following the LCO methodology (You and Wang, 2011). An MINLP model is formulated and solved according to an ε-constraint method.

2. Problem statement

2.1 Process description

As shown in Figure 1, a new superstructure of geothermal binary CCHP is proposed for trigeneration to accommodate the seasonal demand of cooling, heating, and power. Geofluid serves as the heat source of the proposed energy system, and the thermal energy from the geofluid is transferred and converted into combined cooling, heating and power. There are seven major sections in the trigeneration network: geofluid production, ORC evaporation, power generation, heat redistribution, cooling generation (Tippawan et al., 2015), condensing, and geofluid injection (Boyaghchi and Chavoshi, 2017). Thermal energy can be supplemented by combusting fuels in case that the total demand of cooling, heating, and power cannot be fully accommodated by the available geothermal energy, especially during winter.

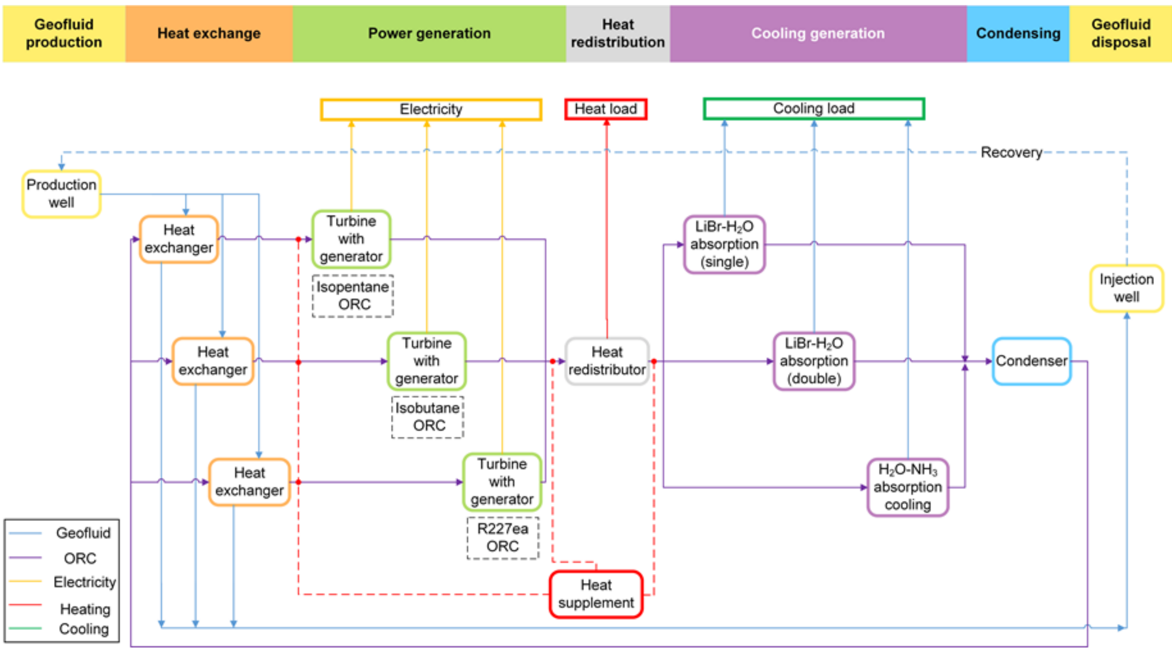

Figure 1: Superstructure of geothermal binary CCHP system

After the drilling, casing, and cementing phases, geothermal wells are stimulated either in a hydraulic way or in a chemical way. Next, geofluid is pumped from the underground reservoir and serves as the heating medium to evaporate the ORC secondary working fluid via the central heat exchanger. Three types of organic working fluids are considered for the ORC - isopentane, isobutene, and R227ea. Isopentane is investigated because of its high critical temperature, a very suitable property for a working fluid in ORC. However, such working fluid is inefficient for power generation, because isopentane itself leads to a slight cooling of thermal water. Isobutane and R227ea are selected because they demonstrate advantageous performance in parallel-circuit CHP (Heberle and Brüggemann, 2010), even though their critical temperatures are relatively low. High-pressure steam from the evaporator is then directed to a steam turbine with generator for power generation. Afterwards, organic steam enters another heat exchanger, where thermal energy is transferred from ORC to the water cycle to produce domestic hot water. Surplus thermal energy within the organic steam is further exploited by thermally-activated absorption chillers, where thermal energy is converted to cooling utility. Herein, three commercialized thermally-driven cooling technologies are considered, namely, single-effect LiBr-H_2O absorption chiller (Srikhirin et al., 2001), double-effect LiBr-H_2O absorption chiller, and H_2O-NH_3 absorption chiller (Deng et al., 2011). They differ from each other in terms of purchase cost, operating condition and coefficient of performance. In the next section, exhausted organic steam is fully condensed and pumped backed to the central heat exchanger for the next round of ORC. To dispose of the waste geofluid, it's directly pumped back to the underground reservoir for natural recovery. In case that the geothermal energy is not capable of accommodating the seasonal demand for cooling, heating, and power, a fuel combustion section is integrated into the proposed CCHP superstructure for supplementing thermal energy to the ORC. Three common alternative fuels are considered in the combustion section: natural gas, biodiesel, and anthracite coal, which vary in terms of heat value, environmental impacts in both production and emission phases, and market prices.

2.2 Assumptions

- The temperature of geofluid is linearly based on ambient temperature and geothermal gradient;
- The heat capacity of geofluid is the same as that of water.

2.3 Given

Major parameters involved in the calculation are listed as follows:
- The physical and chemical properties of organic working fluid, fuel, and geofluid; (The pressure and enthalpy of geofluid are not included in the mathematical model, and thus are not provided.)
- The efficiency of heat exchangers, furnace, chillers, and turbine with generator;
- The geological condition-related parameters;
- The loss proportion of organic working fluid under the normal operating conditions;
- The seasonal demand of chilled water, domestic hot water, and electrical power;
- The total hours of operations in a year;
- The project lifetime;
- The interest rate;
- The characterization factors of relevant chemicals;
- The market prices of raw material, utilities, etc;
- The capital cost for the involved equipment.

2.4 Determine

The major decision variables include:
- Technology selection;
- Production level of cooling, heating, and power;
- Overall capital cost, operation cost;
- Life cycle environmental impacts measured by GHG emissions.

3. Model formulation and solution strategy

According to the problem statement in the previous section, a multiobjective MINLP model is proposed to address the sustainable design and synthesis of geothermal binary CCHP system (Gong and You, 2015). The economic objective is to minimize total annualized cost (*tac*), which is the sum of annualized investment cost evaluated based on purchase cost (*pc*) and annual operating cost (*aoc*). Three types of operating costs are investigated in our mathematical model, namely, feedstock cost, utility cost, and operating and maintenance cost. Carbon price is not considered in this work. The competing environmental objective is to minimize the global warming potential (*gwp*), which is mainly contributed to by the inevitable leak of organic working fluid, production and combustion of fuels, and power generation. The corresponding characterization factors are denoted as Φ. *IR* represents the interest rate and *LS* stands for the life span of the geothermal project.

$$\min\ tac = K \cdot \sum_{equ \in EQU} pc_{equ} \cdot \frac{IR \cdot (1+IR)^{LS}}{(1+IR)^{LS} - 1} + aoc \qquad (1)$$

$$\min\ gwp = \sum_t m_{orc} \cdot \Phi_{orc,t} \cdot LR + \sum_t m_{fuel} \cdot \Phi_{fuel,t} + gwp_{power} \qquad (2)$$

s.t. Superstructure network configuration constraints
Mass balance constraints
Energy balance constraints
Techno-economic evaluation constraints
Environmental impact assessment constraints

The resulting multi-objective MINLP problem is solved following ε-constraint method, and the Pareto-optimal curve is obtained, indicating the trade-off between *gwp* and *tac*. The superstructure optimization models are coded and solved in GAMS 25.0.2.

4. Results and discussions

As shown in Figure 2, the Pareto-optimal curve separates the whole space into an infeasible region, which is beneath the Pareto-optimal curve and a suboptimal region, which is above the curve.

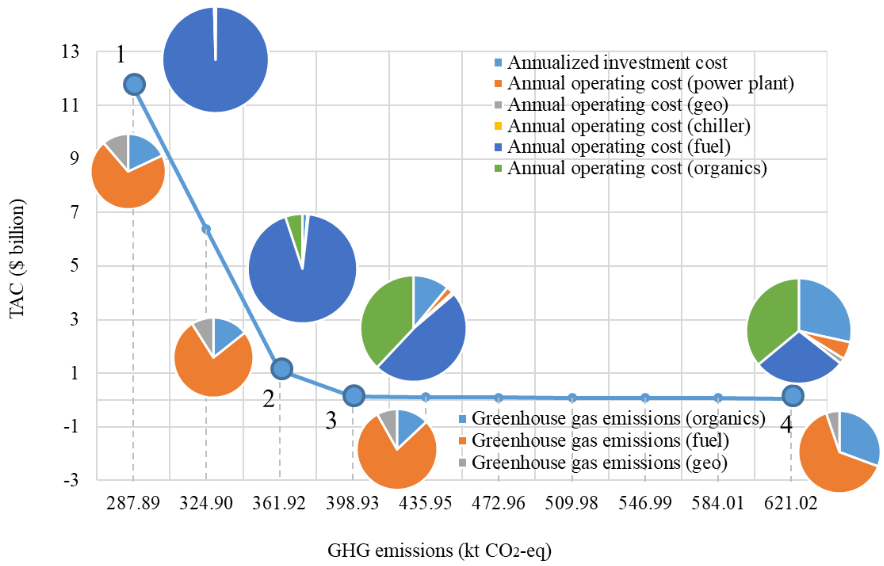

Figure 2: Pareto-optimal curve and breakdowns of TAC and GHG emissions

Four points are emphasized on the Pareto-optimal curve, including 2 extreme points corresponding to the minimum life cycle GHG emissions and the minimum TAC, respectively, and two points located near the 'corner' of the Pareto-optimal curve. From the perspective of both criteria, point 3 is a balanced choice because the corresponding TAC is quite close to that of point 4, and the GHG emissions are also close to that of point 2. The detailed information about the technology selection is listed in Table 1, and corresponding profiles of the economic and life cycle environmental performance is presented above and below the Pareto-optimal curve in Figure 2 in the form of a pie chart.

As shown in Table 1, at point 1, natural gas is always selected to supplement thermal energy to the ORC, while at point 2, natural gas is only selected for several months and biodiesel is chosen for the rest of the year. At point 3, anthracite coal and biodiesel are selected for a few months per year each, while anthracite coal is the only fuel selected at point 4 in order to achieve the lowest TAC. Furthermore, isobutane is selected as organic working fluid in ORC at the first three points, but for the fourth point, isopentane is chosen. In terms of the selection of thermally-driven chillers, all scenarios select the double-effect LiBr/H_2O absorption chiller. Specific seasonal demand of CCHP is listed in Table 2.

Table 1: Technology selection of the four points on the Pareto-optimal curve

	Point 1	Point 2	Point 3	Point 4
Fuel	Natural gas	Natural gas or biodiesel	Anthracite coal or biodiesel	Anthracite coal
Organics	Isobutane	Isobutane	Isobutane	Isopentane
Chiller	Double-effect LiBr/H_2O	Double-effect LiBr/H_2O	Double-effect LiBr/H_2O	Double-effect LiBr/H_2O
TAC ($ billion)	11.68	1.10	0.14	0.05
GWP (kt CO_2-eq)	287.89	361.92	398.93	621.02

When it comes to the detailed economic performance profile for the 4 typical points, the proportion of annual operating costs associated with fuel decreases significantly as the optimal life cycle GHG emissions increases. Also, the annualized investment cost occupies more of the TAC with the decrease of the optimal TAC. As for the breakdowns of the life cycle GHG emissions, shown in Figure 2, the proportion of GHG emissions associated with the fuels increases with the increase of the optimal life cycle GHG emissions, while the other two main sources of GHG emissions demonstrate a decreasing trend. The detailed information of about technology selection in each life cycle stage is illustrated in Figure 3.

Table 2: Seasonal demand of CCHP per building

	Season 1	Season 2	Season 3	Season 4
Cooling (kW)	48.09	181.97	346.99	176.65
Heating (kW)	25.97	11.89	20.76	29.05
Power (kW)	269.26	263.26	272.30	274.98

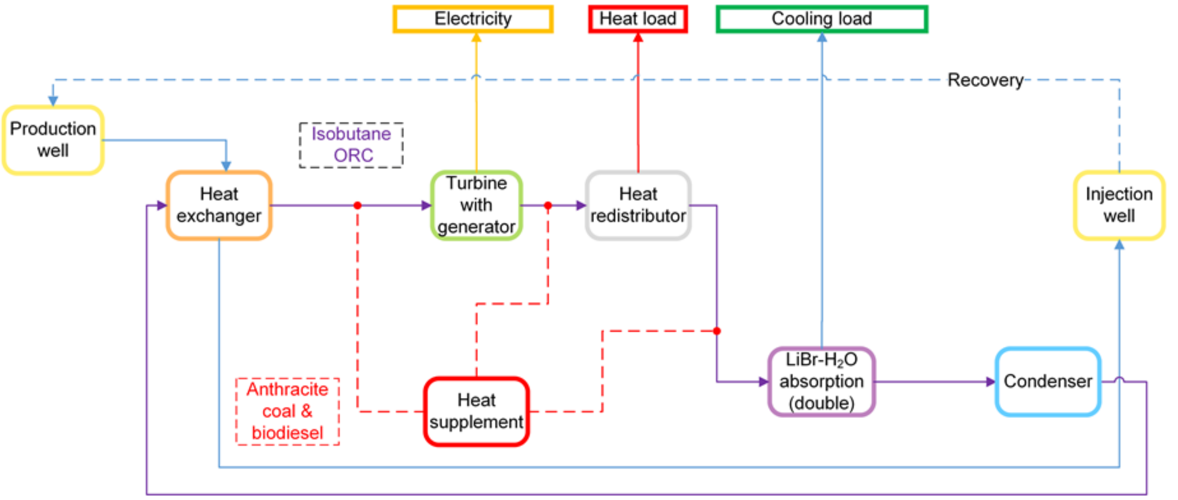

Figure 3: Technology selection of the balanced choice (point 3)

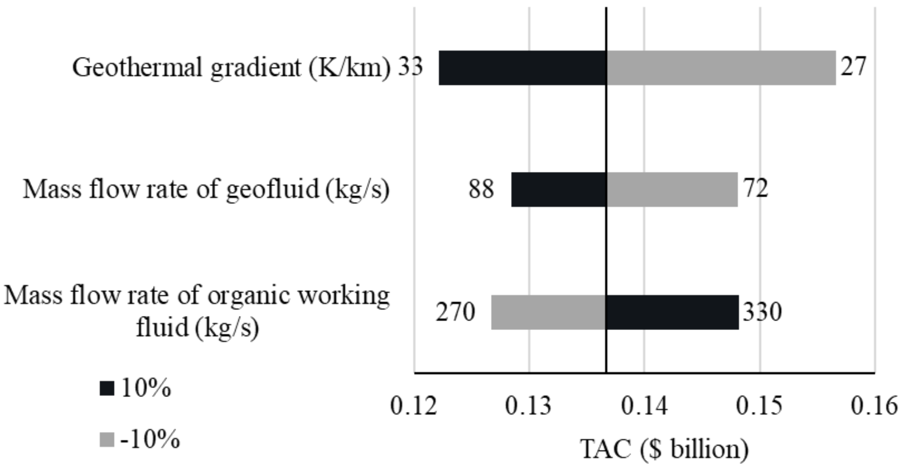

Figure 4: Sensitivity analysis results for the balanced choice (point 3)

4.1 Sensitivity analysis

The parameters considered in the superstructure optimization can be classified into parameters relevant to the geological conditions and the parameters irrelevant to the geological conditions. As mentioned in the previous sections, the drilling phase of geothermal energy system is usually site-specific, as geological conditions may have great impacts on the geothermal gradient and limit the maximum mass flow rate of geofluid. Therefore, in order to quantify the impacts of these ‘uncertain’ parameters, sensitivity analysis can be conducted. Very similarly to upstream shale gas related projects (Hirschberg et al., 2014), the geological condition could result in significant differences in the energy consumption during the well drilling phase. For example, it’s harder to get access to the expected depth via drilling on the site under tougher geological condition. Tougher geological condition will undoubtedly induce more energy consumption during drilling phase, and thus leads to heavier environmental burdens.

Based on the proposed framework, sensitivity analysis is conducted to explore the impacts of parameter deviation on the performance of point 3, which is the balanced solution. Herein, two parameters related to geological condition are considered, namely geothermal gradient and the maximum mass flowrate of the geofluid. The impacts of deviation of the flowrate of the organic working fluid in ORC is also taken into account. The results of the sensitivity analysis considering ±10 % deviation from the nominal value are illustrated in Figure 4. As shown in the tornado chart, the maximum mass flowrate of geofluid and geothermal gradient are in negative correlation with the TAC, with the geothermal gradient having a much stronger influence. The mass flow rate of organic working fluid is in positive correlation with the TAC value. Moreover, Figure 4 reveals that the two factors related to the geological condition influence the results asymmetrically around their nominal values.

5. Conclusions

In this work, a new superstructure for the trigeneration of cooling, heating, and power based on a geothermal energy system was proposed. Organic Rankine Cycle was considered as the secondary working cycle to exploit the thermal energy contained within the low-temperature geofluid. On the basis of the proposed superstructure, a cradle-to-gate LCA and techno-economic analysis are integrated with a multiobjective optimization framework to simultaneously optimize the economic and environmental performance in terms of TAC and life cycle GHG emissions. Trade-offs between the two competing objective functions were analysed by generating and exploring the Pareto-optimal curve.

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