CHEMICAL ENGINEERING TRANSACTIONS

VOL. 94, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN 978-88-95608-93-8; **ISSN** 2283-9216

DOI: 10.3303/CET2294210

Sustainable Design of Hybrid Campus Energy Systems with Economic, Environmental, and Social Optimization

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Driven by the Paris Agreement for curbing global greenhouse gas (GHG) emissions, extensive research efforts are undertaken in pursuit of a carbon-neutral future. The energy sector is the first to bear the brunt of climate change due to its large share of GHG emissions, and a decarbonization strategy is urgently needed. In compliance with three main lines of Corporate Social Responsibility, this study explores the environmental, economic, and social impacts of hybrid energy systems decarbonization by integrating the environmental sustainability, techno-economic and sociological considerations through a multi-objective optimization framework. The proposed model simultaneously minimizes the total annualized costs, minimizes the scope 1, 2, 3 emissions for environmental justice, and maximizes medium opportunity hours by integrating life cycle assessment and economic input-output analysis. The optimization results provide guidance for sustainable design and operations of energy systems, identify environmental hotspots and associated mitigation strategies, and inform the resulting social benefits. The applicability of the proposed modeling framework is illustrated through case study using Cornell's main campus.

1. Introduction

Extensive research on deep decarbonization of energy systems is conducted at the city-level (Wiryadinata et al., 2019), state-level (Zhao and You, 2020), and country-level (Vaillancourt et al., 2017). Electrification of heat and cooling generation and decarbonization of electricity generation is identified as a promising lever to address the ambitious climate goals (de Chalendar et al., 2019). However, heat and cooling generation stand a chance to destroy the stability of the power system due to the surge in electric load involved if electrified in an uncontrolled way. Therefore, it seems to be a reliable and promising decarbonization option by exploring renewable heat and cooling generation technologies rather than simply using electrified counterparts (Sánchez et al., 2017). Among the vast array of renewable heat and cooling technologies, earth source heat (ESH) (Tester et al., 2019) and deep water source cooling systems (Tian et al., 2019) show great potentials for the decarbonization of energy systems. Recent research efforts have also identified the values of green hydrogen (Andersson and Grönkvist, 2019), large-scale heat pumps (Nielsen et al., 2016), biomass and biogas (Kassem et al., 2020), and thermal energy storage (Ochs et al., 2020) for decarbonizing the heating system. Biomass can be converted into biogas through anaerobic digestion (Gunaseelan, 1997) or treated via torrefaction (Lukawski et al., 2013) for direct combustion or combined heat and power (CHP) purposes. Thermal energy storage can be defined as short-term and seasonal storage according to the charging and discharging cycle (Alva et al., 2018) and is widely investigated for peak-load management and shaving (Lee et al., 2019). The force that drives a community to invest more in pursuit of the goal of decarbonization is associated with its own brand image and pressure from the public (Yue et al., 2014). However, most studies only handle the techno-economics and environmental facet while neglecting its interaction with the whole society (You et al., 2012). There is currently no existing study addressing the social impacts, such as its contribution to working opportunity, associated with energy systems decarbonization in a quantitative and systematic manner.

Social life cycle assessment (LCA) is a systematic approach to evaluating the social impacts, either positive or negative social indicators (Iribarren et al., 2022). To fill the gap, this study explores the sociotechnical details and socioeconomics by integrating the techno-economic and sociological considerations through a multi-objective optimization framework in addition to environmental LCA. The optimization results unmask the enviro

Paper Received: 01 June 2022; Revised: 28 July 2022; Accepted: 28 July 2022
Please cite this article as: Tian X., You F., 2022, Sustainable Design of Hybrid Campus Energy Systems with Economic, Environmental, and Social Optimization, Chemical Engineering Transactions, 94, 1261-1266 DOI:10.3303/CET2294210

techno-economic details associated with the adoption of renewable energy for combined cooling, heating, and power generation as well as the social objective's impacts on the energy systems design.

2. Problem statement and model formulation

First, a superstructure for carbon-neutral energy systems is given, including a set of renewable electricity generation technologies and a set of renewable and electrified heating and cooling options. The energy systems design, operations, and retrofitting not only induce investment but also influence the total greenhouse gas emissions and social impacts from the community it operates in. Based on the proposed superstructure of carbon-neutral energy systems (Tian et al., 2022), we consider systems expansion to incorporate procurement, commuting, air travel, electricity sales to the grid, municipal solid waste treatment, and wastewater treatment. The schematic of the expanded systems is shown in Figure 1. We note that scope 1 emissions refer to direct emissions from owned or controlled sources; scope 2 emissions refer to indirect emissions from the generation of purchased energy; scope 3 emissions include upstream and downstream emissions for which an organization has some control but also shares decision making or impact with other organizations, or individual choice (Sun et al., 2022), including greenhouse gas (GHG) emissions from commuting, air travel, procurement of products, electricity sales to the grid, municipal solid waste treatment, and wastewater treatment (Bora et al., 2020). The model aims to assess and optimize the performance of the expanded systems in three aspects, namely environmental impacts, economic performance, and social impacts. The multi-period optimization problem of the proposed carbon-neutral energy system for simultaneous total annualized cost minimization, scope 1, 2, 3 emission minimization, and contribution of the sector to economic development maximization is formally stated in this section. The key input parameters needed in the optimization model are summarized below.

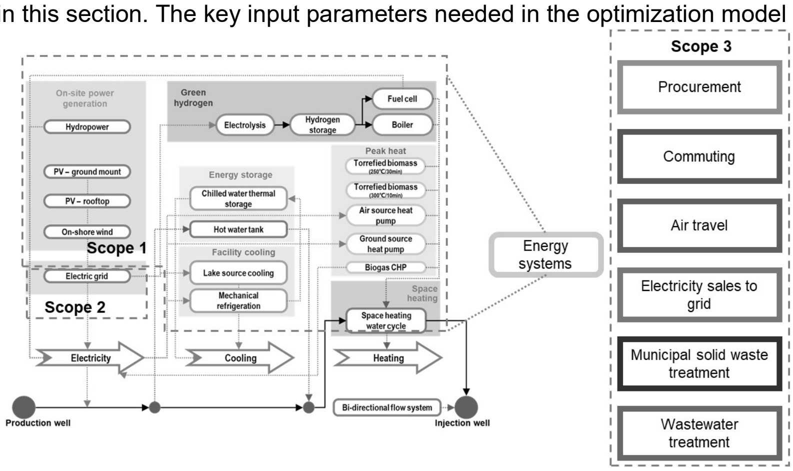

Figure 1: Expanded systems boundary where the scope 1, 2, and 3 are shown in the dotted-line boxes

In this problem, we are given the following parameters:

- Economic parameters for techno-economic analysis.
- Annual electricity generation by renewable technologies, including the hydroelectric power plant, solar farms, and wind farms.
- Seasonal demand for electricity, heat, and cooling.
- Electricity, heat, and cooling consumption of each technology.
- Feedstock prices and prices of external utilities.
- Efficiency of each electricity, heat, and CHP generation technology.
- The cost associated with vehicles, procurement, commuting, air travel, municipal solid waste treatment, wastewater treatment.
- Direct working hour for specific process from the Product Social Impact Life Cycle Assessment (PSILCA) database (Maister et al., 2020).
- Social characterization factors from the soca or PSILCA database. The social impact factors retrieved from the PSILCA V3 database are associated with 1 USD of process (or sector) output.
- Emission factors based on economic input-output (EIO)-LCA model. The EIO-LCA tool used in this study is developed by the Green Design Institute at Carnegie Mellon University.
- Economic flows (social life cycle inventory) based on techno-economic results.
- Emission factors associated with commuting, air travel, municipal solid waste treatment, wastewater treatment, among others.

Major decision variables include:

- Consumption rates of torrefied biomass, biogas, and hydrogen.
- Energy mix.
- Capacities for other generation and storage technologies.
- Annualized investment cost and annual operating cost.
- Scope 1, 2, 3 emissions. The GHG emission analysis of scope 1 and 2 are estimated following the IPCC 2013 method, while the scope 3 GHG emissions are calculated using the EIO-LCA method.
- Social profiles depending on the selected social indicator.

In line with the problem statement, the proposed multi-objective multi-period optimization model is subjected to six groups of constraints, namely mass balance and configuration constraints, energy balance constraints, logic constraints, techno-economic constraints, environmental life cycle impact assessment constraints, and social life cycle impact assessment constraints. In this study, the multi-objective multi-period optimization models are coded and solved in GAMS 35. The general-purpose mixed-integer nonlinear programming (MINLP) solvers, such as BARON and SCIP, are adopted.

$$\min \ tac = aic + aoc + re + ct \quad (1)$$

$$\min \ telci = elci^{scope1} + elci^{scope2} + elci^{scope3} \quad (2)$$

$$\max \ tslci = slci^{bottomup} + slci^{topdown} \quad (3)$$

s.t. mass balance and configuration constraints
energy balance constraints
logic constraints
techno-economic constraints
environmental life cycle impact assessment constraints
social life cycle impact assessment constraints

where the total annualized cost (*tac*) consists of four terms: *aio* denotes the annualized investment cost, which is calculated by multiplying the total investment cost with capital recovery factor; *aoc* refers to the annual operating cost, which is calculated by adding up the total feedstock costs, utility costs, and O&M costs; *re* indicates the replacement cost; *ct* refers to the carbon tax. Total life cycle environmental impacts are comprised of scope 1, 2, and 3 emissions. The GHG emission analysis of scope 1 and 2 are estimated following the IPCC 2013 method, while the scope 3 GHG emissions are calculated using the EIO-LCA method. Total life cycle social impacts are computed using a combined bottom-up and top-down approach. For bottom-up term, the social impacts for specific unit process are linked to the social impact factor from soca database, an "add-on" to the Ecoinvent database. For top-down term, the expenditure in each segment is multiplied by the corresponding sector-level multiplier associated with 1 USD of process (or sector) output (from PSILCA V3 database) in terms of medium opportunity hours. These two approaches are complementary, depending on the data availability.

3. Results and discussion

The proposed optimization model is adopted to handle the optimal design and operations of campus energy systems of the future, using the real-world data for the Ithaca campus of Cornell University, New York State. The case study aims to obtain the optimal solution of the multi-objective multi-period optimization problem with a monthly model resolution for the proposed carbon-neutral energy systems with ESH (Lee et al., 2019), lake source cooling (LSC), on-site electricity generation, and peak heating options, while identifying the economic, environmental, and social hotspots. The electricity powering the whole campus energy systems and accommodating the seasonal building demand is mainly purchased from the local electric power grid. On-site generation is also considered based on the current practice of the main campus of Cornell University located in Ithaca, including hydroelectric power plant, solar farms, and wind farms. ESH serves as the base-load heat supplier due to its advantageous economic performance over an electrified heating system based on heat pumps under the current electricity price (Zhao et al., 2021). According to the current practice at Cornell, LSC serves as the base-load cooling supplier due to its high coefficient of performance and extremely low GHG emissions (Tian et al., 2020). For Cornell case, scope 3 emissions account for the emissions from procurement of goods, commuting, air travel, municipal solid waste treatment, and wastewater treatment. Considering the highly aggregated data for procurement activities, EIO-LCA method is used to estimate the procurement related scope 3 emissions.

By solving the multi-objective multi-period optimization problem, only one optimal energy system configuration is determined, as shown in Figure 2. This is primarily because both the economic and social objectives are dominated by the contribution associated with ESH well-pairs as the base-load heat supplier, and the economic and social objectives are not conflicting with each other. In the optimal design, four geothermal well-pairs serve as the base-load heat supplier, and 493 ground-source heat pumps handle the peak-load heat demand.

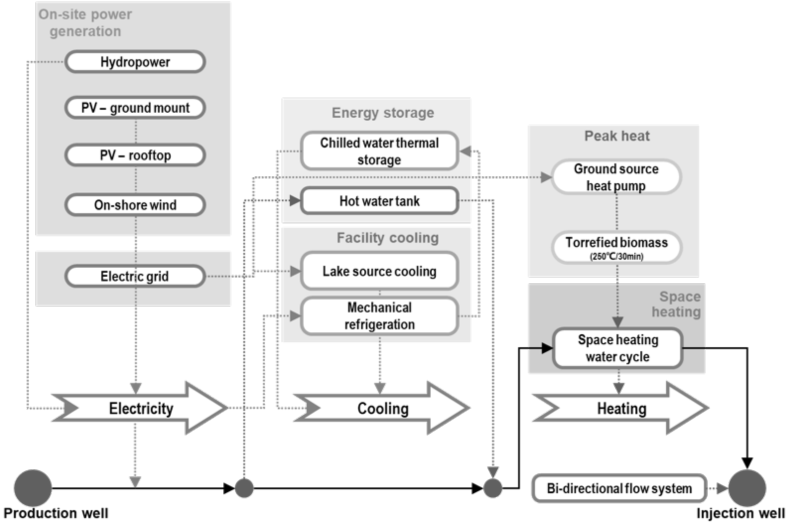

Figure 2: Optimal configuration of campus energy systems

The breakdowns of the social indicator "contribution to economic development" in terms of medium opportunity hours (mohs) are shown in Figure 3. Figure 3 facilitates the identification of social hotspots for the selected social indicator. The optimal design of energy systems corresponds to four base-load ESH well-pair. During one-year operation, there is a total of 32.3 million mohs generated. The geothermal well-pair drilling alone contributes to 65.6 % of the total social impacts. To this end, the sensitivity of base-load heating capacity is systematically analyzed. The number of ESH well-pair is selected as the investigated input parameter in the sensitivity analysis. As the number of base-load geothermal well-pairs decreases to three, the social indicator "contribution to economic development" decrease by 19.8 % in terms of mohs, and geothermal drilling contributes to 61.3 % of the total value. When the number of geothermal well sets attains two, the social indicator "contribution to economic development" becomes 38 % less compared to the optimal solution.
Figure 4 demonstrates the breakdowns of the total annualized cost. It is worth noting that as the number of ESH well-pairs decreases from four (optimal solution) to two, the annualized investment cost decreases from 94.73 MUSD/y to 93.73 MUSD/y. The annual operating costs corresponding to the three cases are 29.27 MUSD/y, 28.57 MUSD/y, and 28.35 MUSD/y. When the number of base-load ESH well-pairs equals two and three, torrefied biomass treated at 250 ºC for 30 min is selected, accounting for 3 % and 2 % of the annualized investment cost, respectively. When the number of ESH well-pairs attains four, 493 ground source heat pumps with a typical capacity of 19 kW in the North American region are employed to address the peak-load heat demand.

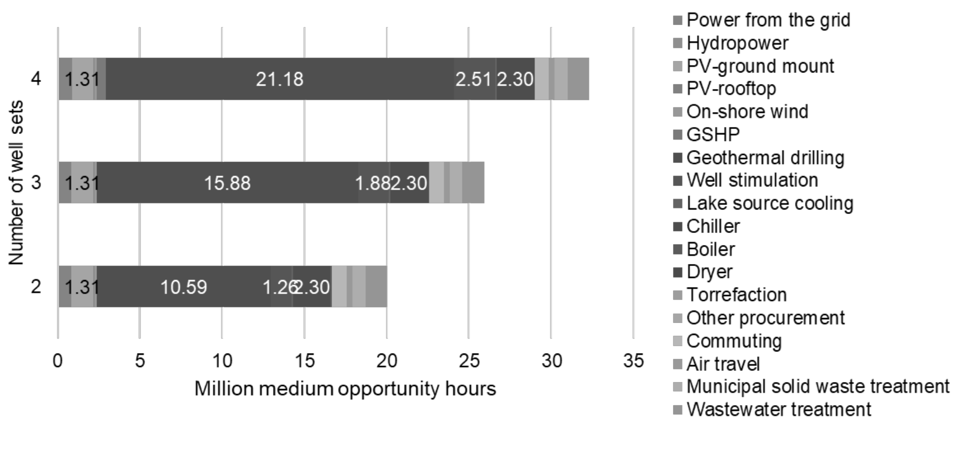

Figure 3: Social life cycle profile with sensitivity analysis on the number of ESH well-pairs

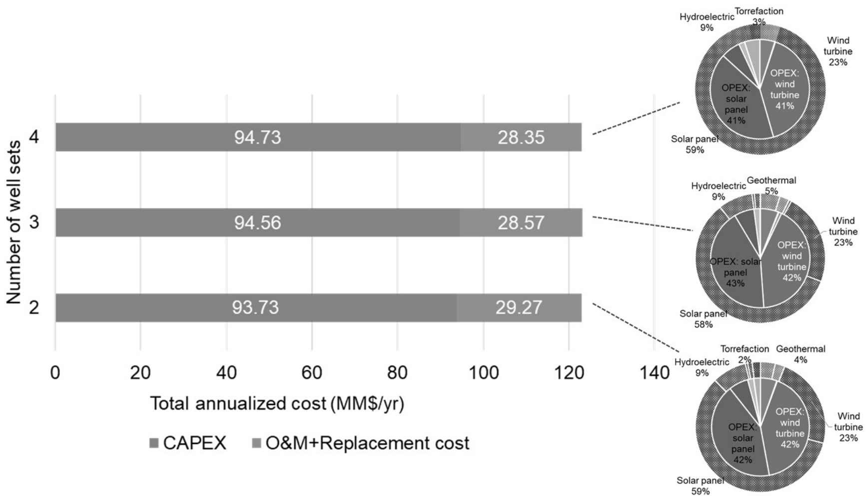

Figure 4: Techno-economic analysis results of the optimal solution for different numbers of ESH well-pairs

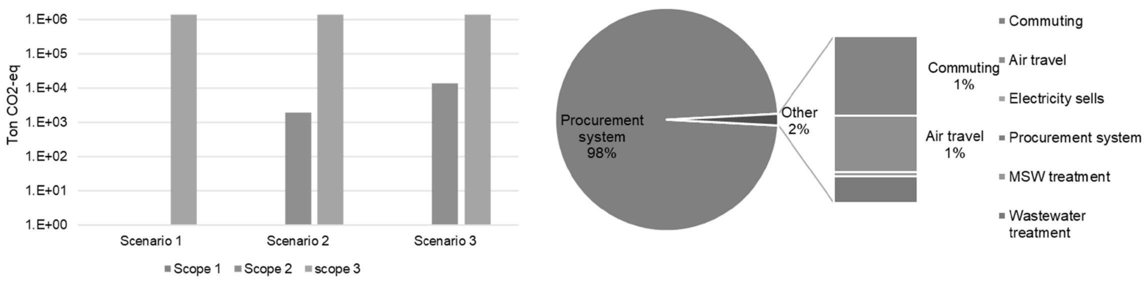

Figure 5: Greenhouse gas emissions of different power grid structures (column chart on the left) and breakdowns of scope 3 emissions (on the right)

The GHG emissions are estimated considering three different electric power mix scenarios (Zhao et al., 2022), as shown in Figure 5. Scenario 1 refers to the grid with 100 % renewable energy sources, scenario 2 refers to an estimated New York State (NYS) electric power mix in 2035, and scenario 3 refers to the current NYS electric power mix in 2020. We note that the only possible source of scope 1 emissions is the on-site torrefaction of raw biomass. Since such technology is not selected in the optimal solution, the scope 1 emissions are zero for all the scenarios. The breakdowns of scope 3 emissions are shown in Figure 5. The procurement of goods corresponds to approximately 98 % of total emissions, making the contribution from the energy systems negligible as well.

4. Conclusion

In this work, a superstructure of renewable hybrid energy systems with earth source heat, lake source cooling, on-site renewable electricity generation, and sustainable peak heating systems was first proposed. Based on the proposed superstructure, a multi-objective multi-period MINLP model was developed for simultaneous total annualized cost minimization, scope 1, 2, 3 emission minimization, and contribution of the sector to economic development maximization. The applicability of the proposed optimization framework was illustrated through a case study using the real-world data from the main campus of Cornell University. The optimal design highlighted the contribution of geothermal drilling to both social and economic objectives. There is a total of 32.3 million medium opportunity hours generated. The geothermal system contributes to 65.6 % of the total social impacts.

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