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# Sustainable Design of Hybrid Energy Systems towards Carbon Neutrality

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As Cornell is transitioning to a carbon-free energy system by 2035, the campus energy system of the future will be based on 100% renewable energy sources. Specifically, the electricity will be mainly sourced from the local electric grid, which is expected to be carbon-free in the next two decades. Earth source heating and lake source cooling will serve as the major source for base-load renewable heating and cooling, respectively. Multiple geothermal wells will be drilled to meet the base-load heating demand. A conventional chiller will continue to provide auxiliary cooling sources for hot summer days in addition to the LSC system. Peak load will be fulfilled by introducing thermal energy storage and green hydrogen. This study addresses the economically optimal future design by developing a multi-period optimization model, to provide insights for the campus energy systems transition. A systematic life cycle assessment is adopted to examine the extent of carbon neutrality based on the optimization results.

## 1. Introduction

Cornell's Climate Action Plan (CAP) called for reaching climate neutrality at its Ithaca campus by 2050 when it was first proposed. In 2016, the Senior Leaders Climate Action Group (SLCAG) called for analysing viable energy alternatives for the Ithaca campus to achieve carbon neutrality by 2035 to accelerate its efforts. Carbon neutrality refers to attaining net zero-direct carbon dioxide emissions by balancing carbon emissions with carbon sequestration (Opel et al., 2017). The concept has been widely adopted in infrastructure development (Beecham, 2020). The choices Cornell makes today to enable a carbon-neutral campus of the future will lead to investment, which would insulate Cornell from unknown future volatility in fossil fuel markets and associated carbon fees. This study aims to address the sustainable design and economic optimization of the Cornell campus energy system towards carbon neutrality. The proposed 100% renewable campus energy system involves the combination of renewable energy technologies and options based on local conditions and resources (Zhao and You, 2020), such as lake source cooling (LSC), earth source heating, and hydrogen, among others, coupled with advanced energy storage technologies (Mehrjerdi, 2019).

The main design and operations challenges of the proposed sustainable campus energy systems are on meeting the peak energy demand (peak load) and on long-/short-term energy storage. To accommodate the peak-load heat demand, there are two promising approaches. The first one is to generate hydrogen using the low-cost off-peak electricity from the electric grid and utilize the stored hydrogen to fulfill the peak-load demand using the hydrogen boiler (Andersson and Grönkvist, 2019). Another option is fulfilled by thermal energy storage. Energy storage can be categorized into short-term and long-term (or seasonal) storage, based on the charge and discharge cycle. Long-term/seasonal energy storage is an effective alternative to manage the peak-load of heating demand. Aquifer thermal storage is a viable technology that stores the excessive thermal energy generated during hot summer, including the solar thermal energy, in the subsurface, such as the geothermal wells. The stored heat could be discharged to provide additional heat during cold winter days and as a result, high heat demand in winter is shaved to a moderate level. Hot water thermal storage tanks can also be considered for seasonal storage of heat (e.g., summer to winter) to manage the peak load in the winter (Ochs et al., 2020). Short-term thermal energy storage relies on an existing chilled water tank, which is cooled using spare chilled water during off-peak times and warmed by the campus-wide cooling load during the day. Typical

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short-term heat storage can be fulfilled using phase change materials (PCMs). While PCMs might be used for seasonal heat storage as well, the economic feasibility needs further investigation in future work. Figure 1 presents a schematic of the proposed hybrid campus energy systems that include a fraction of these energy generation and storage technologies to be considered in this study.

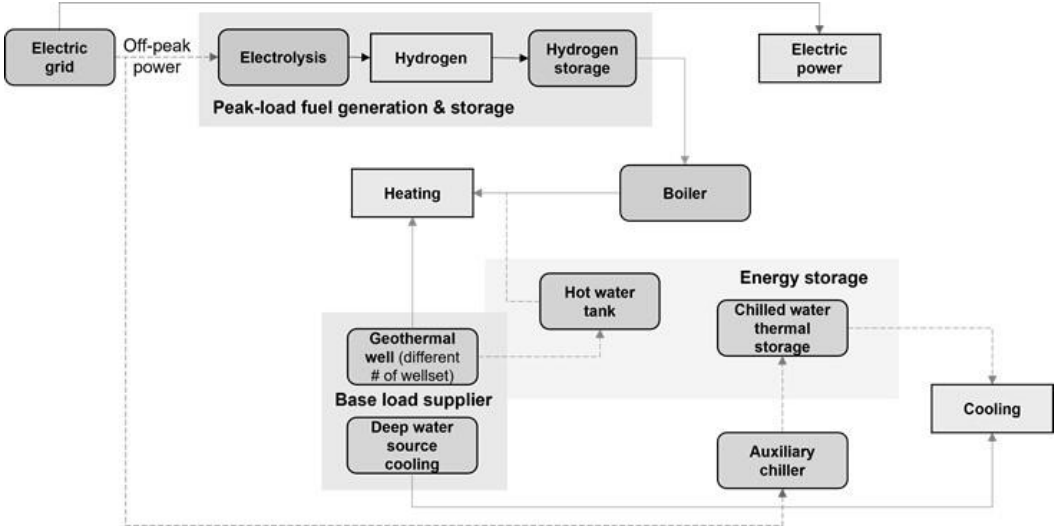

*Figure 1: The schematic of the proposed sustainable campus energy systems*

This work addresses the economically optimal and environmentally sustainable design of the campus energy systems with earth source heat, LSC, and peak load, as well as long-term energy storage. The proposed hybrid energy system generates heat, cooling as products. A novel energy systems superstructure is proposed to embrace all the aforementioned generation and energy storage technologies (Gong and You, 2015). We will consider monthly demand over the year 2035. Based on the superstructure of the proposed hybrid energy system, we develop a multi-period optimization model to minimize the total annualized costs of the campus energy system, while assessing the corresponding environmental impacts (including carbon emissions) using the rigorous life cycle assessment. The aim is to determine the optimal configuration of the campus energy systems and corresponding capacities of technology units by minimizing the total annualized cost while assessing the life cycle environmental impacts for environmental justice. The applicability of the proposed modeling framework will use real data from Cornell University's main campus located in Ithaca, New York State (NYS).

## 2. Problem statement

The primary goal of this study is to determine the optimal design of the carbon-neutral campus energy system of the future. The sustainable campus energy system is designed to accommodate the seasonal demand of campus-wide electricity, cooling, and heating based on low-carbon generation technologies. The electricity is expected to mostly come from the electric power grid. The cooling is supplied by the LSC system using Cayuga Lake as the heat sink to provide chilled water circulating in the second cycle that never contacts the deep lake water. Possible expansion including a chilled water storage tank and an additional backup chiller is considered to meet the peak-load cooling demand that may exceed the capacity of the existing LSC system. Earth source heat, i.e., geothermal energy, is deemed as the supplier of base-load renewable heat (Beckers et al., 2013). Seasonal hot water storage is considered to store the surplus heat and release it for load shaving. Another option to satisfy the peak-load heating demand is using peak-load fuel, namely green hydrogen generated onsite using low-cost off-peak electricity from the grid.

### 2.1 Assumptions

- The temperature of geofluid is linearly based on the local geothermal gradient (Tian et al., 2020).
- The heat capacity of geofluid is the same as that of water.
- The temperature drop within the geothermal well is neglected for the one-year time frame.
- The flow rate of hot water within the district heat systems is proportional to the heat load.
- The production and reinjection temperature of the geothermal fluid is fixed (Lee et al., 2019).
- The hydrogen vessel is assumed to be empty at the very beginning of the year.

### 2.2 Given

- The physical property of fuel, geofluid, and hot water.
- The efficiency of boiler and coefficient of performance of chiller and lake source cooling.
- The geological condition-related parameters.
- Monthly average and peak-load demand data for electricity, cooling, and heat. Peak-load data are given to determine the capacity of generation/storage technologies, which stand chance to be zero by using average data alone.
- The total hours of operations in a year.
- The project lifetime.
- The interest rate.
- The characterization factors of relevant input materials and utility.
- Economic parameters for techno-economic analysis.

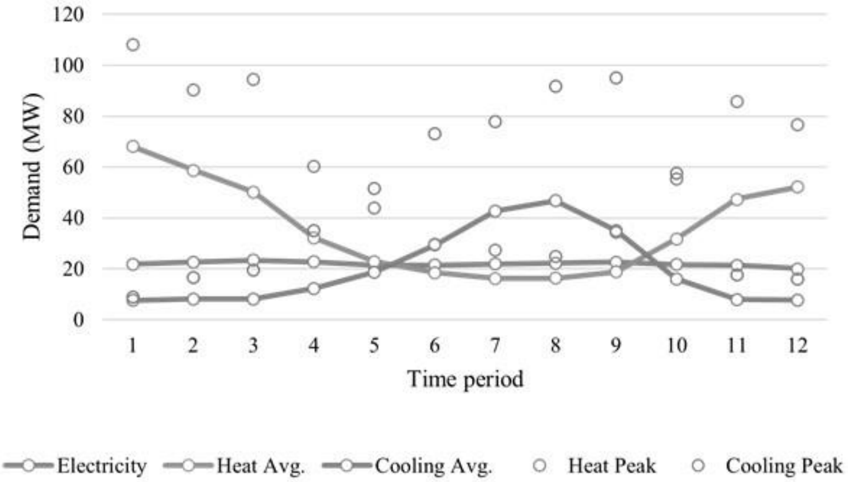

*Figure 2: Monthly average/peak-load demand for heat and cooling, and monthly electricity demand.*

### 2.3 Determine

The major decision variables include:

- Integer variable representing the total number of well sets and the number of base-load well set in each time period.
- Binary variables that depict the selection and operating condition of generation and storage technologies.
- The production level of cooling and heating.
- Thermal energy stored within hot water tank and discharge rate.
- Hydrogen generated from the electrolyser, the historical amount of hydrogen in the vessel, and consumption rate.
- Temperature profile along with the district heating systems.
- Material and energy input during the operation of the proposed campus energy systems.
- Capital investment and operating cost breakdowns.
- Life cycle greenhouse gas (GHG) emissions.

## 3. Model formulation

Compliant with the general problem statement in the previous section, a detailed multi-period MINLP model is proposed to determine the optimal design and operating condition of the proposed hybrid energy systems (Grossmann, 1990). The optimization problem is developed for total annualized cost minimization, which is defined as the sum of annualized investment cost and annual operating cost. The proposed optimization model is subjected to six groups of constraints, namely, network configuration constraints, mass balance constraints, energy balance constraints, logic constraints, non-negativity constraints, and techno-economic evaluation constraints. The selection and operating conditions (on/off) are represented by binary variables. The number of geothermal well sets/base-load well sets are defined as integer variables. Other major decision variables including the mass and energy flow, the capacity of generation, and storage technologies are continuous variables. Nonlinear terms mainly come from economies of scale for capital investment estimation, as well as bilinear terms in energy balance relationships, similar to most superstructure optimization problems (Gong et al., 2018). In this work, general-purpose MINLP solvers, such as Baron, are used. The superstructure optimization models are coded and solved in GAMS 35. A tailored global optimization algorithm should be implemented as the model scale boosts in future work.

$$\min \quad tac = tpic \cdot \frac{IR \cdot (1+IR)^{LS}}{(1+IR)^{LS} - 1} + aoc \qquad (1)$$

s.t. Network configuration constraints
Mass balance constraints
Energy balance constraints
Logic constraints
Non-negativity constraints
Techno-economic evaluation constraints

## 4. Results and discussion

The proposed optimization model is employed to address the optimal future design of an envisioned campus energy system using the historical data for Cornell’s campus in Ithaca, NYS. The problem is addressed over a course of 12 time periods of the same length. Figure 3 shows the monthly temperature profile along with the district energy system. T1 represents the temperature of hot water after receiving base-load energy input from the base-load geothermal well sets. T2 stands for the boosted hot water temperature due to the use of peak-load heat suppliers, including the hot water stored in the hot water tank from the previous time period and peak-load fuel. We note that peak-load technologies are utilized when the weather is relatively cooler, specifically in Jan, Feb, Mar, Nov, and Dec, while base-load heat suppliers are sufficient to accommodate the heat demand for the rest of the year. Table 1 summarizes the number of base-load well sets for each time period. We note that in order to achieve the lowest annualized cost, two geothermal well sets are drilled instead of five in previous work presumably due to the introduction of energy storage and peak fuel (Tian and You, 2019). In addition, one well set operates year-round as the base-load heat supplier.

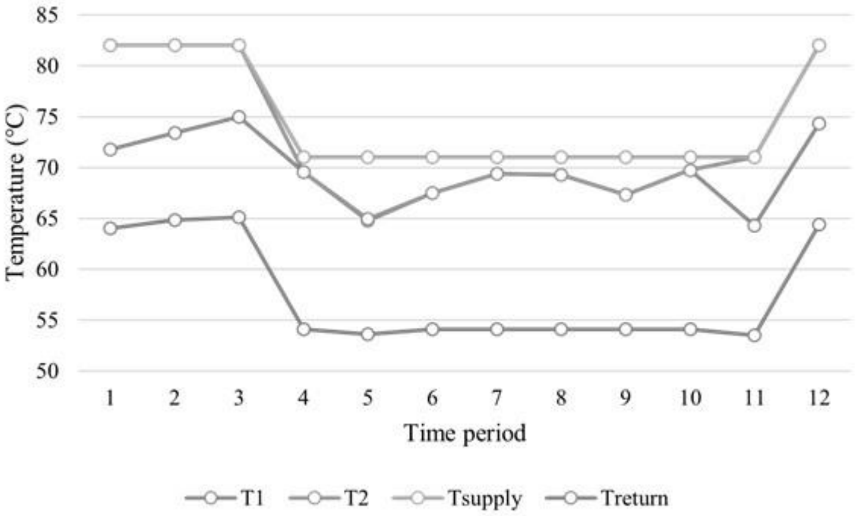

*Figure 3: Monthly temperature profile along with the district energy system.*

*Table 1: Number of base-load well sets for each time period.*

| Time period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of base-load well sets | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 |
| Total number of well sets | | | | | | 2 | | | | | | |

Figure 4 demonstrates the amount of hydrogen in the storage vessel and thermal energy carried by the hot water within the tank. We found that hydrogen generation using off-peak electricity mainly occurs from Jan to May and a large amount of hydrogen is consumed from May to Jul. The use of hydrogen does not necessarily reflect the large heat demand, but the critical gap between the average energy demand and base-load energy supply. In contrast, the stored thermal energy is typically released during cold winter days when heat demand is extremely high.

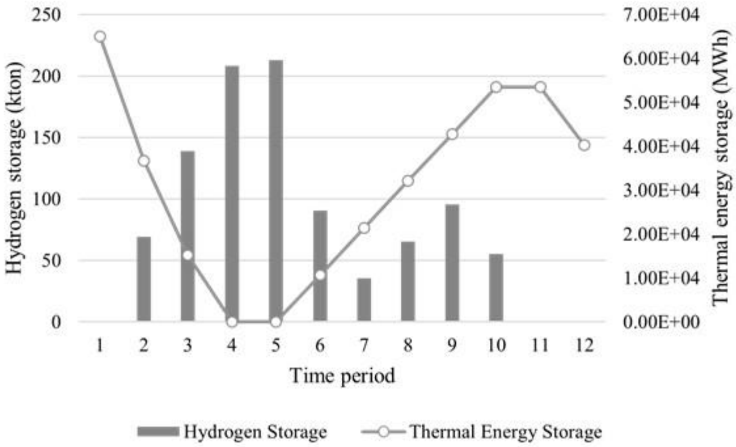

*Figure 4: Monthly profiles for hydrogen and thermal energy storage.*

Figure 5 shows the results for techno-economic analysis and life cycle GHG emissions. The optimal design corresponds to the total project investment cost of $50.3 billion – 80% contributed by the energy storage, 12% from the electrolyser for hydrogen production, and 8% from hydrogen storage. The total annual operating costs are $527MM/y, consisting of three major components – 78% by feedstock costs, 18% by O&M costs, and 4% by utility costs, while the remaining contributors can be neglected. Annual GHG emissions are estimated based on the optimization results to examine the extent of carbon neutrality following the IPCC 2013 method with a 100-year time frame. The system boundary covers four life cycle stages from geothermal well drilling, base-load utility generation, peak-load utility generation, to energy storage. We note that 87% of the total annual GHG emission of 28.6 kton/y comes from electricity, and would be substantially reduced as the NYS grid becomes carbon-free in the coming two decades. This work does not follow the systematic life cycle optimization (Gong and You, 2017), but this could be a direction of future extention.

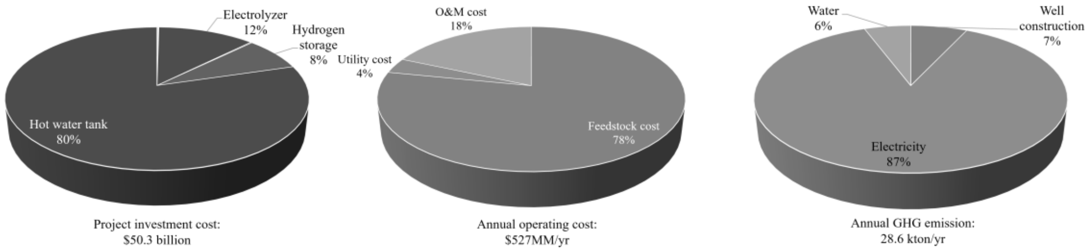

*Figure 5: Techno-economic analysis and life cycle assessment results.*

Future work lies in simultaneously optimizing the energy systems over the long-term planning horizon for the next 15 years to 2035, and accounting for short-term fluctuation of energy supply and demand (e.g. hourly) to optimize the technology selection and capacity of the short-term energy storage systems, including PCM-based thermal energy storage systems and batteries for electrical energy storage. Another task is to design and optimize the 100% renewable campus energy systems (Zhao et al., 2021), so that the resulting process and energy system would be resilient to potential disruptive events like blackouts and power loss (Gong et al., 2018).

## 5. Conclusions

In this work, a new superstructure of carbon-neutral campus energy systems consisting of lake source cooling with auxiliary chiller, earth source heat, hydrogen peak fuel, and seasonal hot water storage was proposed. A multi-period MINLP model was developed based on the superstructure to address the optimal design and operations of the proposed campus energy systems. The applicability of the proposed framework was illustrated via a study based on Cornell's real data. The optimal design highlights the major contribution of energy storage to capital investment (80%) and feedstock to the operating costs (78%). An 87% reduction in annual GHG emissions was predicted as the NYS grid becomes carbon-free in the coming two decades

### Nomenclature

tac – total annualized cost, MM$/y
tpic – total project investment cost, MM$
aoc – annual operating cost, MM$/y
IR – interest rate, %
LS – project life span, y

### References

Andersson J., Grönkvist S., 2019, Large-scale storage of hydrogen, International journal of hydrogen energy, 44(23), 11901-11919.

Beckers K.F., Lukawski M.Z., Reber T.J., Anderson B.J., Moore M.C., Tester J.W., 2013, In Introducing GEOPHIRES v1. 0: Software Package for Estimating Levelized Cost of Electricity and/or Heat from Enhanced Geothermal Systems, Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, USA.

Beecham S., 2020, Using Green Infrastructure to Create Carbon Neutral Cities: An Accounting Methodology, Chemical Engineering Transactions, 78, 469-474.

Gong J., You F., 2015, Sustainable design and synthesis of energy systems, Current Opinion in Chemical Engineering, 10, 77-86.

Gong J., You F., 2017, Consequential Life Cycle Optimization: General Conceptual Framework and Application to Algal Renewable Diesel Production. ACS Sustainable Chemistry & Engineering, 5, 5887–5911.

Gong J., You F., 2018, A New Superstructure Optimization Paradigm for Process Synthesis with Product Distribution Optimization: Application to An Integrated Shale Gas Processing and Chemical Manufacturing Process. AIChE Journal, 64, 123–143.

Gong J., You F., 2018, Resilient Design and Operations of Process Systems: Nonlinear Adaptive Robust Optimization Model and Algorithm for Resilience Analysis and Enhancement. Computers & Chemical Engineering, 116, 231-252.

Grossmann I.E., 1990, Mixed-Integer Nonlinear Programming Techniques for the Synthesis of Engineering Systems, Research in Engineering Design, 1, 205-228.

Lee, I., Tester, J.W., You, F., 2019, Systems analysis, design, and optimization of geothermal energy systems for power production and polygeneration: State-of-the-art and future challenges. Renewable & Sustainable Energy Reviews, 109, 551-577.

Mehrjerdi H., 2019, Off-grid solar powered charging station for electric and hydrogen vehicles including fuel cell and hydrogen storage, International journal of hydrogen Energy, 44(23), 11574-11583.

Ochs F., Dahash A., Tosatto A., Janetti, M. B., 2020, Techno-economic planning and construction of cost-effective large-scale hot water thermal energy storage for Renewable District heating systems, Renewable Energy, 150, 1165-1177.

Opel O., Strodel N., Werner K. F., Geffken J., Tribel A., Ruck W. K. L., 2017, Climate-neutral and sustainable campus Leuphana University of Lueneburg. Energy, 141, 2628-2639.

Tian X., You F., 2019, Carbon-neutral hybrid energy systems with deep water source cooling, biomass heating, and geothermal heat and power, Applied Energy, 250, 413-432.

Tian, X., Meyer, T., Lee, H., You, F., 2020, Sustainable Design of Geothermal Energy Systems for Electric Power Generation Using Life Cycle Optimization. AIChE Journal, 66, e16898.

Zhao N., You, F., 2020, Can renewable generation, energy storage and energy efficient technologies enable carbon neutral energy transition? Applied Energy, 279, 115889.

Zhao, N., You F., 2021, New York State's 100% renewable electricity transition planning under uncertainty using a data-driven multistage adaptive robust optimization approach with machine-learning. Advances in Applied Energy, 2, 100019.