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# Optimal Design of Future Campus Energy Systems for Carbon-Neutrality

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**ABSTRACT**

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 heat 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 lake source cooling system. Peak load will be fulfilled by introducing heat pumps, 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.

**Keywords:** carbon-neutral hybrid energy systems, earth source heat, lake source cooling, heat pump, thermal energy storage, green hydrogen

**NONMENCLATURE**

| *Abbreviations* | |
|---|---|
| LSC | Lake source cooling |
| MINLP | Mixed-integer nonlinear programming |

## 1. INTRODUCTION

Cornell's Climate Action Plan called for reaching climate neutrality at its Ithaca campus by 2050 when it was first proposed. In 2016, the Senior Leaders Climate Action Group calls for analyzing viable energy alternatives for the Ithaca campus to achieve carbon neutrality by 2035 to accelerate its efforts [1]. Carbon neutrality refers to attaining net zero-direct carbon dioxide emissions by balancing carbon emissions with carbon sequestration. 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, such as lake source cooling (LSC), earth source heating, and green hydrogen, among others, coupled with advanced energy storage technologies [2].

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-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 fuel cell. Another option is fulfilled by electricity-driven heat pumps. 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

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discharged to provide additional heat during cold winter days. 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 [3,4].

system, we develop a multi-period optimization model to minimize the total annualized costs of the campus energy system. The aim is to determine the optimal configuration of the campus energy systems and corresponding capacities of technology units by

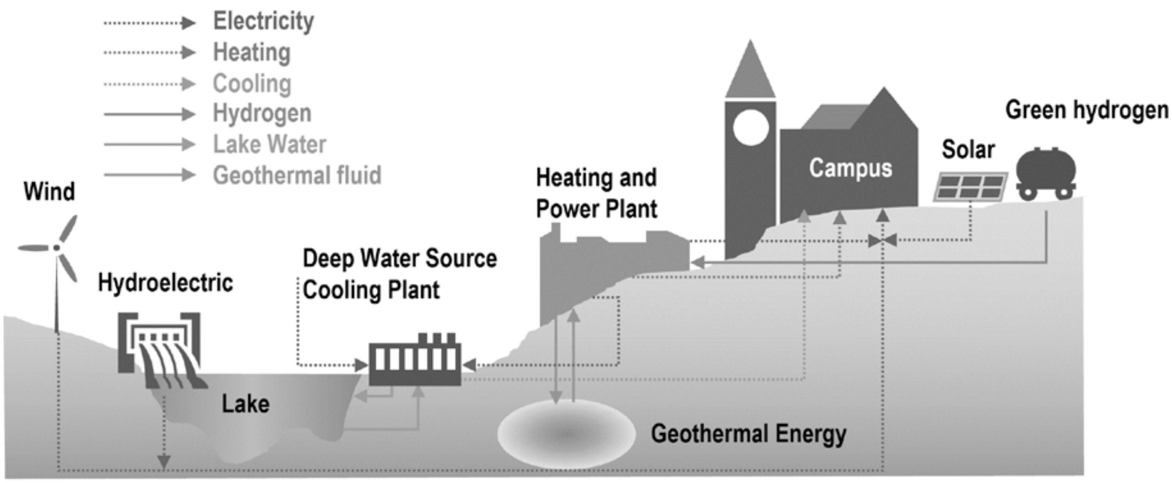


Fig 1 Schematic of the campus energy systems of future.

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 [5] is proposed to embrace all the aforementioned generation and energy storage technologies, as shown in Fig 2. We will consider monthly demand over the year 2035. Based on the superstructure of the proposed hybrid energy minimizing the total annualized cost. The applicability of the proposed modeling framework will use real data from Cornell University's main campus located in Ithaca, New York State.

## 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

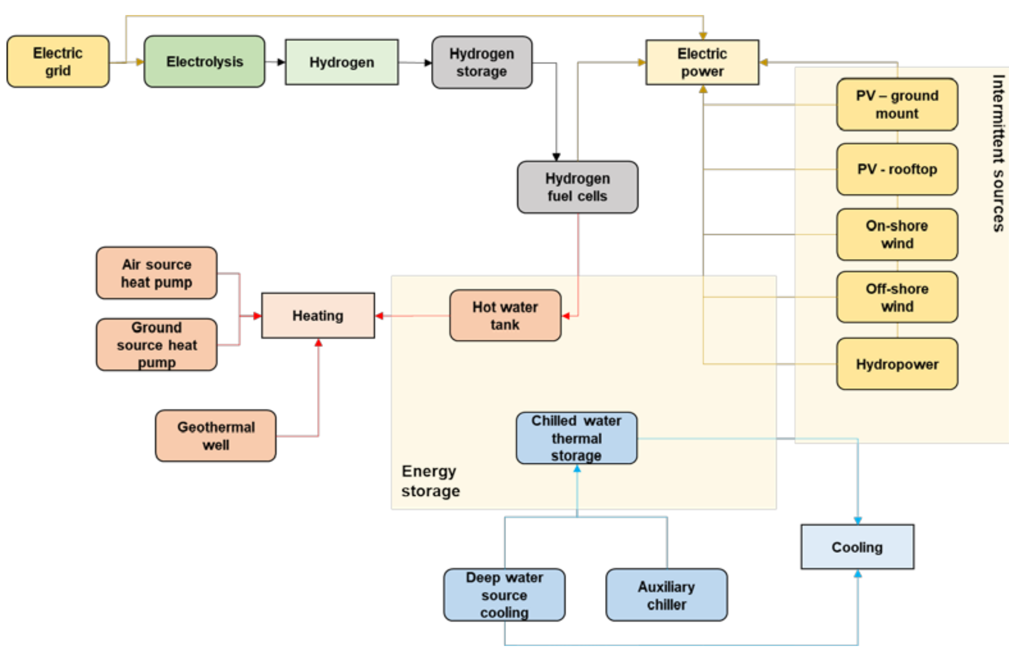


Fig 2 Superstructure of the campus energy systems.

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. Earth source heat, i.e., geothermal energy, is deemed as the supplier of base-load renewable heat [6,7]. 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, including green hydrogen generated onsite using low-cost off-peak electricity from the grid, and heat pumps.

### *2.1 Assumptions*

- The temperature of geofluid is linearly based on the local geothermal gradient.
- The heat capacity of geofluid is the same as that of water [8].
- The temperature drop within the geothermal well is countered by aquifer thermal storage [9].

### 2.2 Given

- The physical property of fuel, geofluid, and hot water.
- The efficiency of fuel cell 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.

### *2.3 Determine*

The major decision variables include:

- Integer variable representing the total number of well sets.
- 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 a hot water tank and discharge rate.
- Hydrogen generated from the electrolyzer, the historical amount of hydrogen in the vessel, and consumption rate.
- Material and energy input during the operations of the proposed campus energy systems.
- Capital investment and operating cost breakdowns.

## 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 [10]. The optimization problem is developed for total annualized cost minimization. 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. 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 Total annualized cost
s.t. Network configuration constraints
Mass balance constraints
Energy balance constraints
Logic constraints
Non-negativity constraints
Techno-economic evaluation constraints

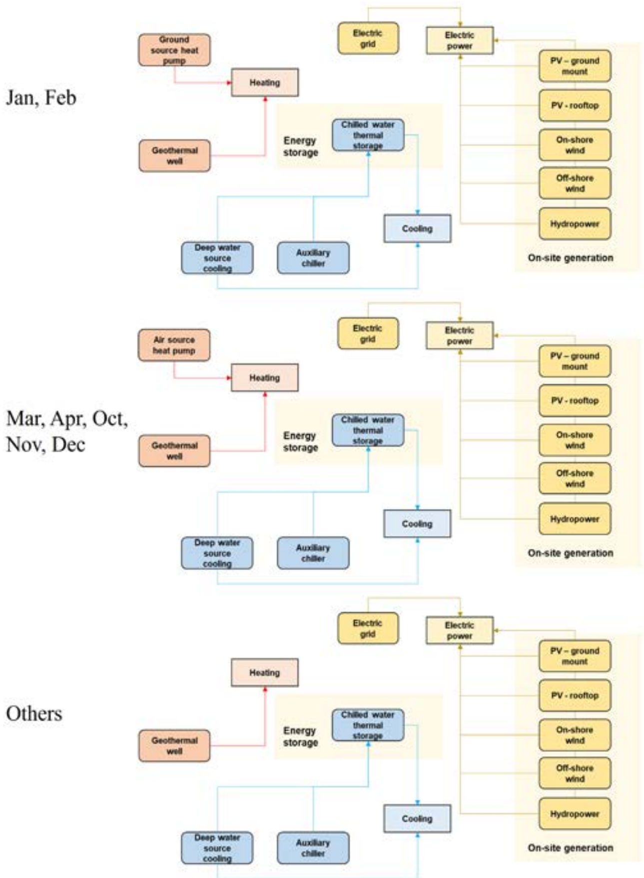


Fig 3 Monthly technology/process configurations for case study 1 considering heat pump as the peak fuel technology.

## 4. RESULTS AND DISCUSSION

Two case studies are explicitly considered with different assumptions and problem settings.

- Case study 1: Heat pumps as a peak fuel option. In this case study, we explicitly consider ground-source heat pumps and air-source heat pumps as the peak fuel technologies to handle the peak load of heat. The local grid serves as the major electricity source with small-scale on-site generation based on the current practice at Cornell's Ithaca campus. LSC is the primary cooling provider with conventional chillers as the auxiliaries.
- Case study 2: Heat pump technologies are excluded from the scope of this case study, indicating that the peak-load of heat should be managed by thermal energy storage and green hydrogen. The remaining settings of the problem are the same as that of the first case study.

Both case studies consider at most five geothermal well set as the base-load heat supplier because approximately five well sets are sufficient to meet the campus-wide heat demand. Via optimization, we can obtain the optimal solution in each case studies and the analysis is enriched by quantifying the sensitivity of well set number on the objective function.

### *4.1 Case study 1*

Selections of technologies vary from month to month. The block flow diagrams in different months are shown in Fig 3. In case study 1(heat pump as peak fuel), seasonal energy storage using hot water tank and green

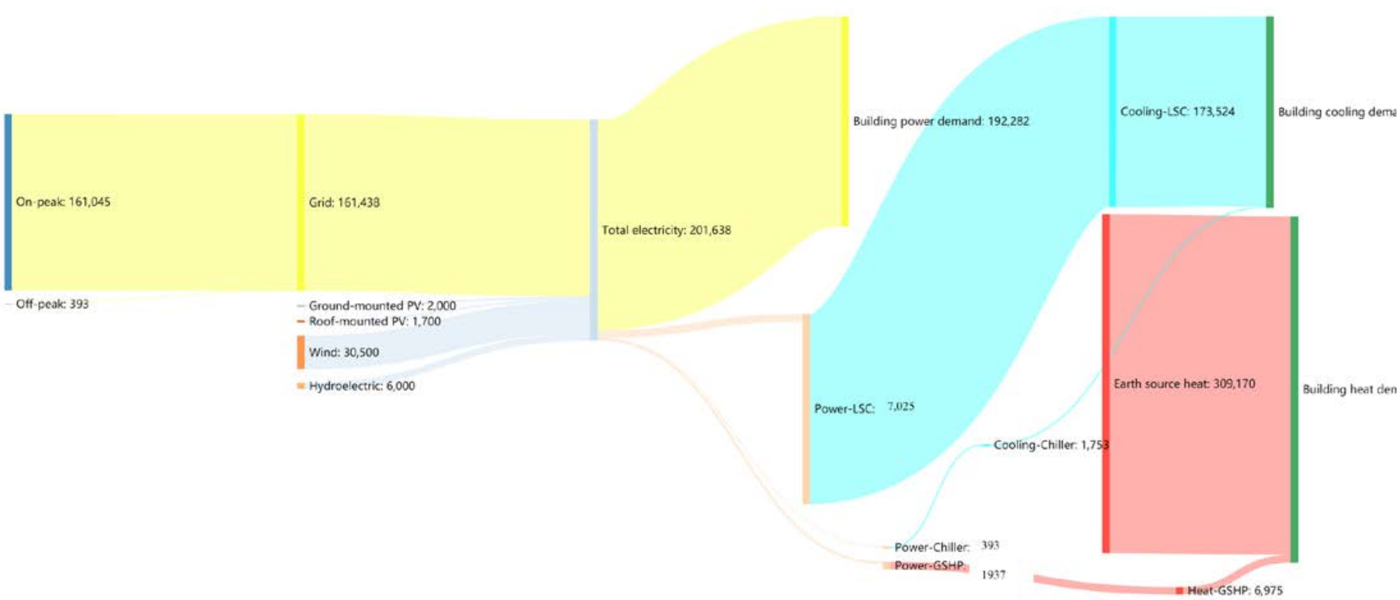


Fig 4 Optimized annual energy flow profiles for case study 1.

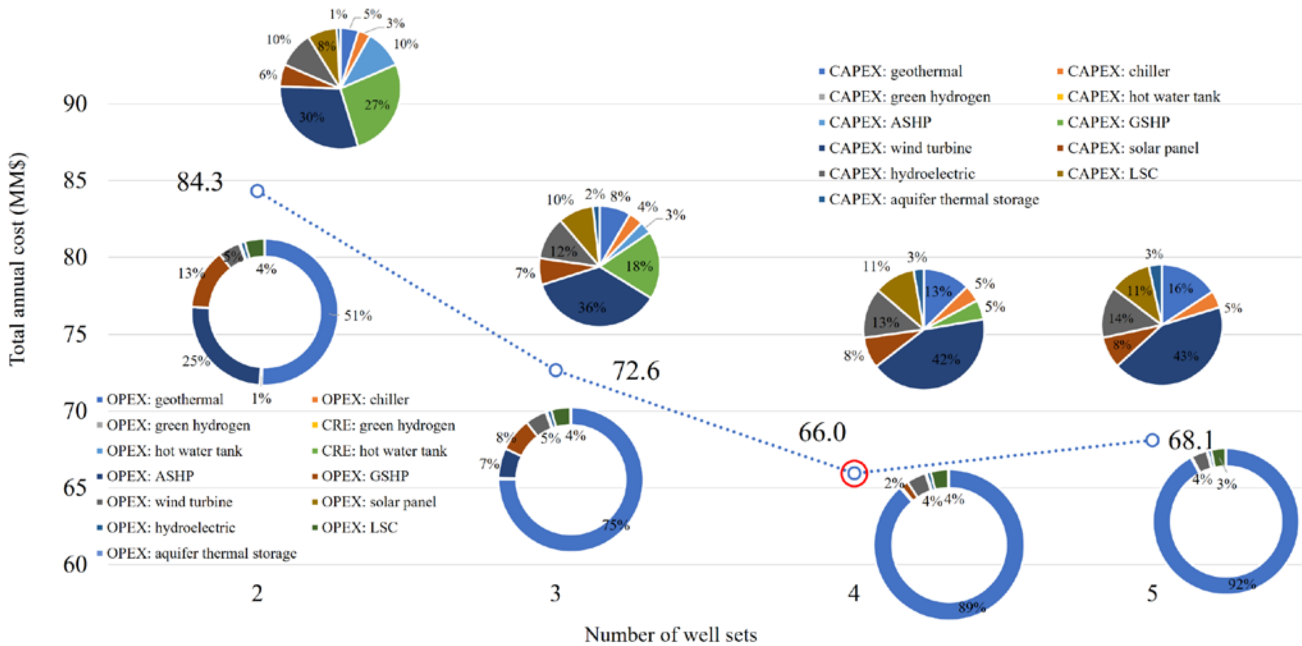


Fig 5 Sensitivity analysis of base-load geothermal well set number. CAPEX refers to the annualized capital investment, OPEX refers to the annual operating cost, and CRE refers to the replacement cost.

hydrogen is excluded. Heat pumps are utilized to generate extra heat to handle the large heat demand. Air source heat pumps are normally used due to their relatively lower capital investment compared to the ground source heat pump. However, during the cold winter days in Ithaca, the adoption of air source heat pump is limited by the low coefficient of performance and performance loss in extracting heat from extremely cold air. To this end, ground source heat pumps are selected to generate extra heat during these cold winter days. Detailed annual energy flow is shown in Fig 4.

In the optimal solution, four well sets are considered as the base-load heat provider with a minimal total annualized cost of $66 MM/yr, with detailed breakdowns of capital investment, operating cost, and replacement cost shown in Fig 5. In addition, we conduct a sensitivity analysis of the number of geothermal well sets on the results of total annualized cost, shown in Fig 5. The solution with two, three, and five base-load geothermal well sets correspond to a total annualized cost of $84.3 MM/yr, $72.6 MM/yr, and $68.1 MM/yr.

### *4.2 Case study 2*

In this case study, heat pumps are excluded, and thus seasonal thermal energy storage and green hydrogen are used to tackle the peak-load heat demand. The optimal energy systems configuration is shown as the block flow diagram in Fig 6. In addition to the breakdown results regarding total annualized cost, we can also track the change of thermal energy stored in the hot water tank

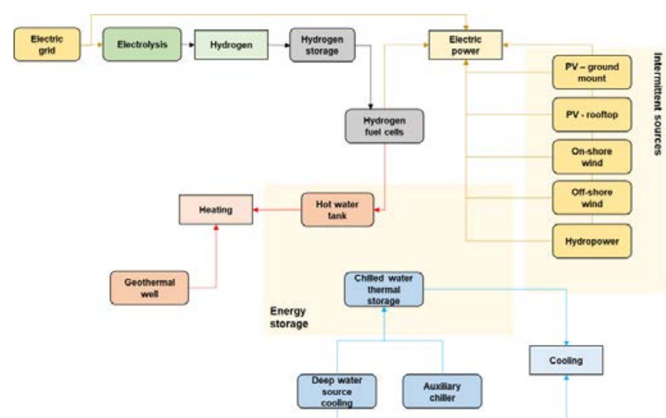


Fig 6 Optimal technology/process configurations for case study 2 without heat pumps.

and chemical energy of hydrogen in the hydrogen storage tank, as shown in Fig 7.

## 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, green hydrogen and heat pumps as peak fuels, 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 two case studies based on Cornell's real data.

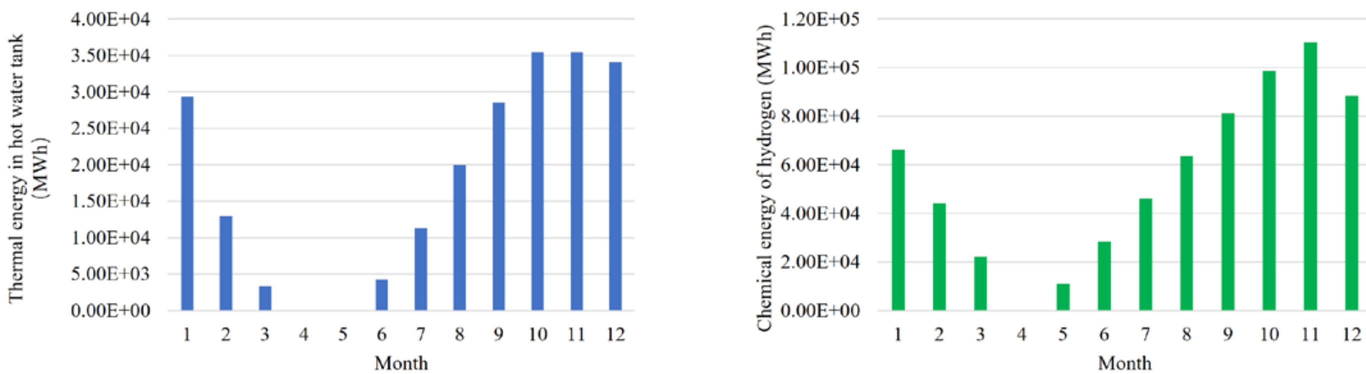


Fig 7 Monthly change of thermal energy stored in hot water tank and chemical energy of hydrogen in hydrogen storage tank.

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