Innovative Thermal Strategies: Electrification's Best Friend

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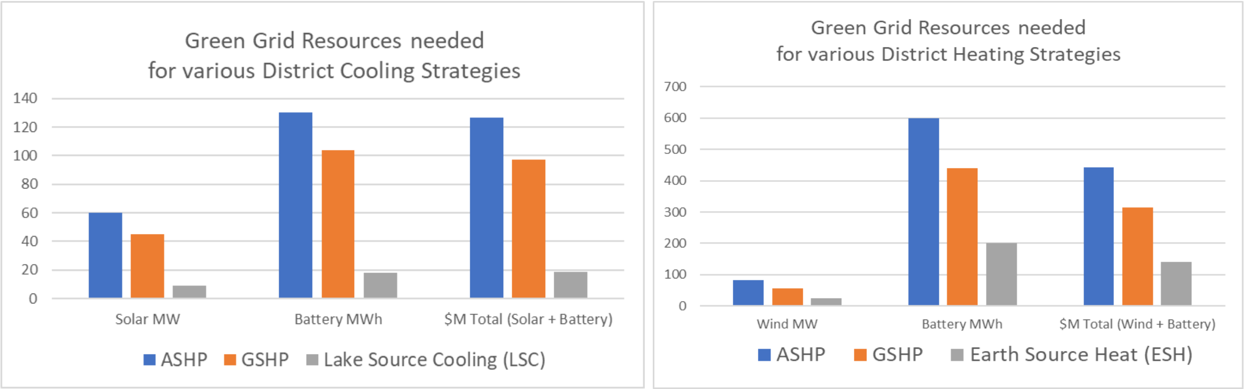
ABSTRACT

Because transportation and heat are the most significant contributors to greenhouse gas (GHG) emissions in the northern U.S., electrification of transport and heat are prominent elements of many decarbonization plans, such as that of New York State (NYS). A key challenge is then to decarbonize the electric supply and distribution system ("the grid") that supplies electricity, a process colloquially known as "greening the grid", so that the saved *direct* carbon emissions are not offset by additional *indirect* emissions from electrical generation on the grid.

Applying this "simple" decarbonization plan to locations with high winter heating loads and modest renewable resources is challenging. Understanding the impact of thermal system design to grid demands in these locations and the related *marginal power* source for electrification options is critical to allocating proper resources to solve decarbonization challenges and quantifying the resultant carbon emissions impact.



Figures 1a and 2b: Grid Resources for various district thermal strategies. Innovative renewable cooling (left) and heating (right) systems dramatically reduce the size of solar and wind farms, respectively, and battery storage systems needed to create a 100% renewable electrical grid compared to conventional Air Source Heat Pump (ASHP) and Ground Source Heat Pump (GSHP) technologies. Cost data is based on referenced National Renewable Energy Laboratory (NREL) reports.

This paper compares different thermal "electrification" strategies by calculating the renewable electricity and electrical storage that would be required to support each strategy to match NYS's goals for a **100% renewables grid**. Using Cornell University's campus heating and cooling demand data as an example, this paper compares several example thermal strategies, ranging from commonplace (air source heat pumps) to innovative (Lake Source Cooling and Earth Source Heating) to show how the choice of thermal systems impact needs for electrical renewables and battery storage. Specifically, facilities using high-efficiency strategies help decarbonize the grid. Key results of this analysis are ilustrated in Figures 1a and 1b. More detailed results, summarized in the conclusions section of this paper, include the following:

- Cornell's innovative renewable cooling solution, Lake Source Cooling (LSC), effectively reduces grid renewable electricity (solar PV) needs by **~50 megawatts** (MW_e) and battery storage needs by **~100 megawatt-hours** (MWh_e) compared to ASHP systems while requiring less raw materials, lower land use, higher reliability, and reduced dependence on refrigerants. Thus, LSC saves NYS an equivalent of over **$100 million US dollars** ($100M) in renewables for grid decarbonization compared to ASHPs. When compared to a GSHP solution, the total modeled savings of the LSC system is ~**$80M**.

- Chilled water storage, if operation is coordinated with the grid, could provide an additional equivalent of up to **$20M** (equivalent battery value) in support of grid decarbonization. This "storage equivalent" is for a shorter duration (hours to days depending on usage).

- Renewable geothermal heat system like Earth Source Heat (EHS) would effectively reduce 100% renewable grid wind energy needs by **~58 MW_e** and electrical storage needs by **~400 MWh_e** compared to ASHP systems with the same broader benefits as LSC. Thus ESH, if successful, could provide not only Cornell's needs but reduce renewable electricity and battery storage capital costs to green the grid by about **$300M** compared to ASHPs.

- The addition of hot water storage to the Cornell district heating system will provide additional benefits, estimated through modeling at an additional equivalent of ~**$77M** in support of complete grid decarbonization.

Higher savings result if the additional infrastructure investment needed to build and maintain the robust transmission and distribution systems for our future electrified economy is included. Highly efficient thermal systems operating with lower temperature hot water (< 100°C) can significantly reduce the needed investment and impacts of grid improvements at all levels [i].

In summary, innovative district heating systems such as our planned "Earth Source Heat" significantly reduce the need for dispatchable renewable electricity from wind farms, battery storage, and new electricity transmission infrastructure For both heating and cooling applications, GSHPs, because of their higher coefficients of performance (COPs), are a better choice than ASHPs for locations without other viable renewable heating and cooling resources, resulting in smaller but still significant grid resource savings. Thus, policies that reward development of high-

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[i] The NY electrical grid operator (NYISO) is investing ~$2B to upgrade transmission lines for the near term: https://www.nyiso.com/-/the-road-to-2040-our-role-expanding-transmission-to-meet-the-needs-of-a-clean-energy-grid. Long-term studies are underway to understand the range of full investment needed.

efficiency systems by providing investment funding and /or tax or production credits will increase deployment and are recommended as a cost-effective means to help green the grid.

1. Introduction

Electrification of transportation and heat are prominent components of many future decarbonization plans, including that of NYS. Figure 3 shows estimates of statewide carbon emissions (carbon dioxide equivalent, or CO_{2e}) as provided by the New York State Energy Research and Development Corporation (NYSERDA). Electrification involves removing direct carbon emissions from the transportation sector by replacing fossil fuel vehicles with electric vehicles and removing direct carbon emissions from building systems by replacing heating systems that use fossil fuels with those that use electricity, primarily heat pumps.

The remaining challenge is then to decarbonize the electric system that now supplies all the energy – replacing fossil fuel power production with renewable water, wind, and solar (and perhaps nuclear power), a process colloquially known as “greening the grid”. For many locations, ambitious plans are already well underway for electrification and grid decarbonization; NYS is targeting net zero emissions by 2050. However, the challenges are immense, especially in areas (like NYS) with high winter heating loads and modest renewable resources. Electrification of heat is especially important in northern climates, where heat using fossil fuels represents significant greenhouse gas (GHG) emissions – rivaling transportation and grid electricity.

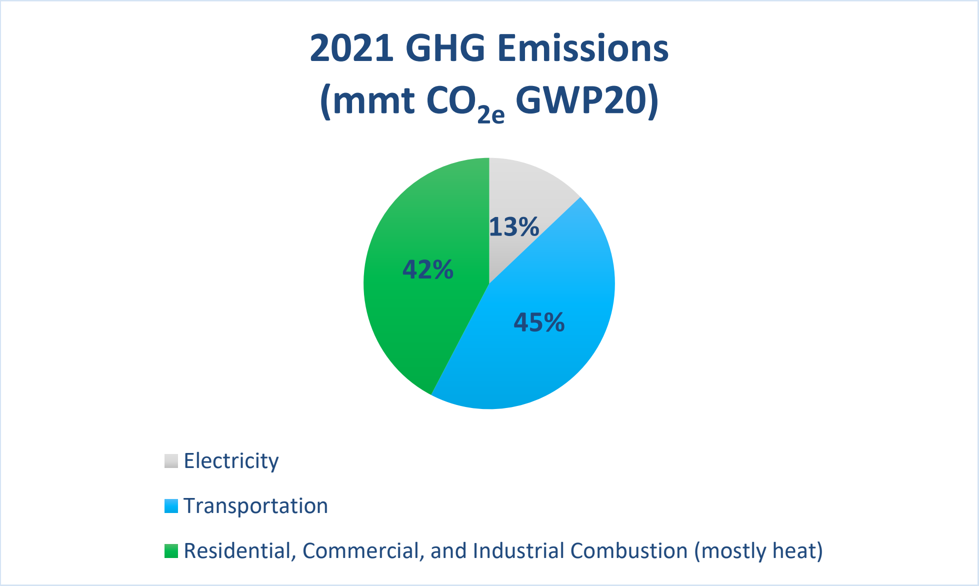


Figure 2 New York State’s Greenhouse Gas (GHG) Inventory[1]. Like other northern states, a significant portion of GHG emissions are direct emissions from heating and transportation. Electrification eliminates large direct sources of emissions but could add emissions in the (currently) smaller “electricity” category.

This report uses the following published data to estimate costs for infrastructure, all based on NREL capital cost estimates from nationwide surveys (surveys predated late 2021 and early 2022 overall increases in US inflation, which likely will impact future cost projections):

- $2,800 per KW$_e$ (peak generation capacity) capital investment for wind power[ii]
- $1,350 per kW$_e$ (peak generation capacity) capital investment for solar PV[iii]
- $350/kWh (peak storage capacity) for grid-level battery storage[iv]

This paper uses Cornell and NYS as sources of specific data to demonstrate how innovative heating technologies (in our case, geothermal heating) at the site level reduce the community resources needed to create a 100% renewable electric grid with fossil-generated electricity replaced primarily by renewable solar and wind resources[v].

The NYS Electrical Grid: Decarbonizing Challenges

The New York State Independent System Operator, Inc. (NYISO) is the public benefit corporation that operates the NYS power grid. NYISO operates with considerable transparency, providing real-time "dashboard" information and data sets showing the generation and distribution of energy within the grid and between interconnected grids. The NYISO grid also has ties to grids in Canada, Pennsylvania, and New England allowing for limited inter-grid power transfer.

The NYISO grid mix is depicted by Figures 3a and 3B from NYISO data; real-time data is also available on NYISO's real-time dashboard[vi]. Despite fast growth, grid solar remains barely perceptible at the grid level even in summer[vii]; and natural gas is the "balancing" or "marginal" energy source at all times. Conceptually, non-GHG-emitting sources like nuclear, wind, and solar power make up the grid "baseline" and gas-fired plants (along with imports/exports) make up the remainder. As shown, NYS has substantial hydropower, nuclear, and natural gas power generation. Figures 3a and 3b represent data from 2020; when the next (2022 Gold Book) report is published, the nuclear contribution will likely be significantly lower due to the retirement and closure of two of NYS's most significant plants (Indian Point) in late 2020 and early 2021 respectively. Those plants accounted for ~40% of NYS's nuclear capacity (about 2 GW) in 2020.

Many analyses of options in NYS use the "average" emissions profile of the grid (or even regional sub-grid) to evaluate options for GHG reductions, which represents a user's "fair share" of grid emissions, allowing for an equitable State-wide accounting of carbon emissions by energy users. The average emissions factor equals the total grid emissions divided by the total energy.

[ii] https://atb.nrel.gov/electricity/2021/offshore_wind#capital_expenditures_(capex). NREL reports grid wind prices nationally average of ~$1500/KW for land-based wind and ~$3000 for offshore wind. NYS has relatively poor land wind resources (see Figure 7, this paper) but better offshore resources (Lake Ontario and Atlantic Ocean) that form a large part of NYS's future energy plans and the State's current focus. We used $2800/KW as a reasonable estimate of the mix of wind resources likely to be deployed in NY.

[iii] https://atb.nrel.gov/electricity/2021/utility-scale_pv#capital_expenditures_(capex))

[iv] https://atb.nrel.gov/electricity/2021/utility-scale_battery_storage#capital_expenditures_(capex)

[v] Hydropower is a significant renewable energy source in NYS. However, in NYS (and most US areas), the resource availability, land use, and social and ecological impacts preclude extensive hydropower development. Expansion of nuclear power, a source generally considered non-GHG emitting but not renewable, is also not planned for NYS.

[vi] https://www.nyiso.com/real-time-dashboard

[vii] The category "other renewables" is currently dominated by waste and biomass combustion, which release GHGs, albeit arguably with lower net emissions.

However, using "average grid emissions" does not represent the *impact* of a user's energy choice. To better understand how energy choices *impact* GHGs, Figure 4 shows a "stacked" energy graph.

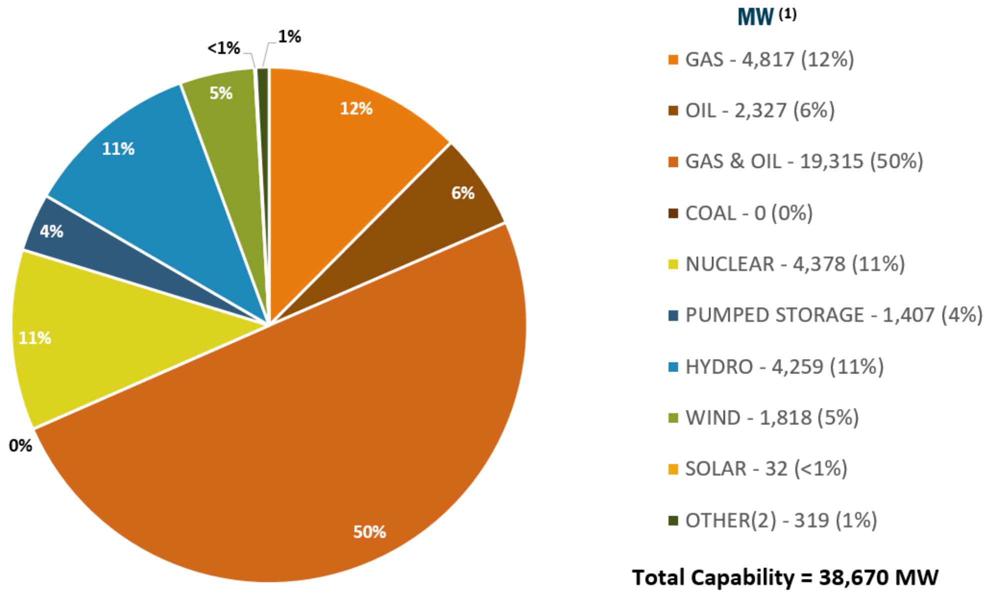
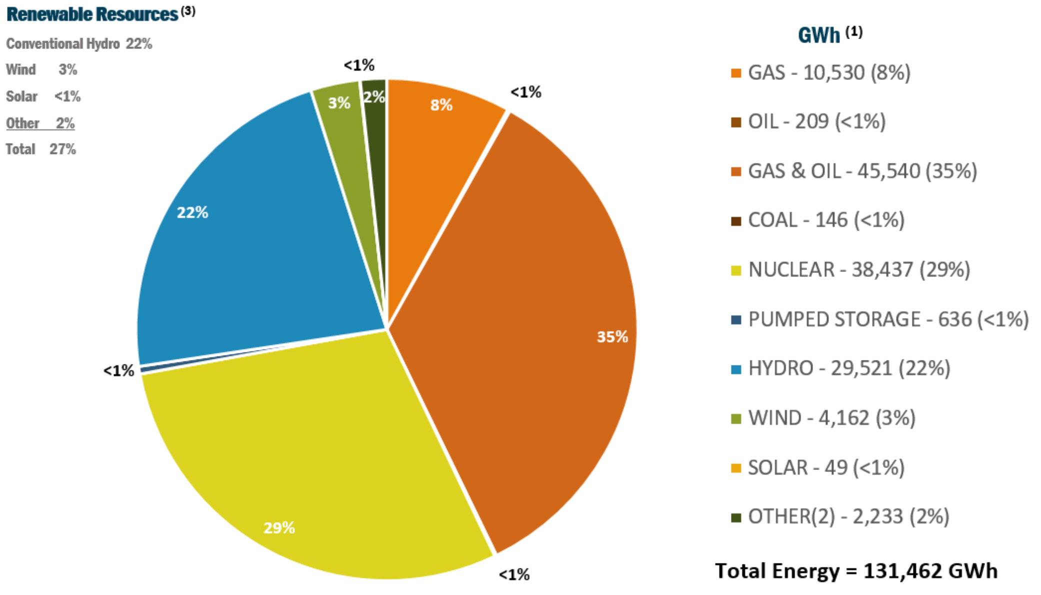


Figure 3a: NYS Grid Electricity Production Capacity, 2020 (NYISO) [2]. The region listed as "gas and oil" represent dual-fuel capability; for mostly economic reasons these plants burn only natural gas today.



(1) All values are rounded to the nearest whole GWh. Total may not match due to rounding.
(2) Includes Methane, Refuse & Wood.
(3) Renewable Resources do not necessarily match the NYS Clean Energy Standard (CES) definition.

Figure 3b: NYS Grid Electricity Annual Usage, 2020 (NYISO) [3]. Annual production from continuous sources like hydropower and nuclear are higher than their relative capacities (Figure 3A). The average fossil contribution (~43%) is lower than the capacity ratio (~68% from Figure 3b) because some fossil plants are only needed at higher loads and to balance and ensure capacity across varying needs.

Figure 4 provides approximate values only (values for each energy source vary hour-to-hour, day-to-day), but accurately communicates the continual use of fossil resources for power generation within the current NYS power grid. The arranging of the figure as a "stacked" grid profile conceptually illustrates how the grid functions with (green) "baseline" non-emitting sources[viii] "balanced" by variable added natural gas power (brown area) day and night, year-round. The current grid electrical demand in NYS is *always* higher than the current zero emissions power generation, just as it is for other northern States.

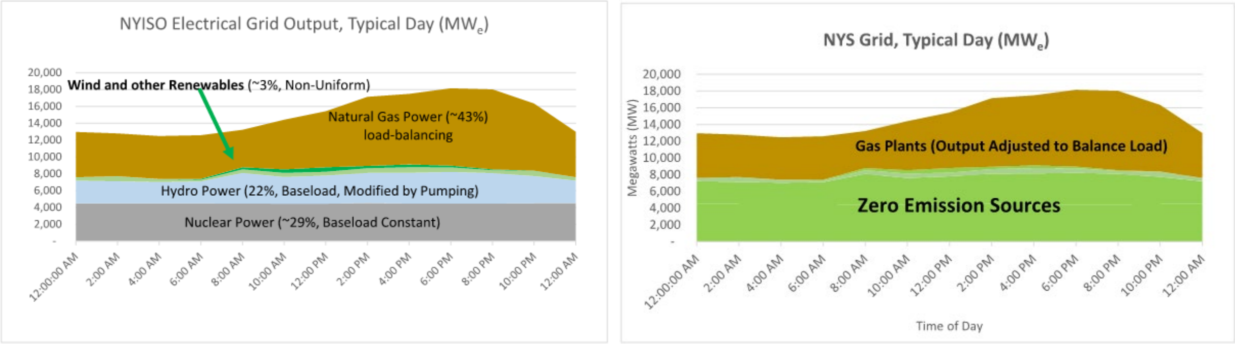


Figure 4: Current NYS Grid Power Generation Mix. The left graph shows approximate average contributions to the grid; the graph on the right combines the "zero emissions" sources (green) to demonstrate the concept of marginal emissions sources with (brown) natural gas sources balancing the load.

With natural gas as the balancing power source, energy decisions by customers will impact this balance – energy additions or subtractions impact how much natural gas power generation will occur, but do not significantly impact renewable energy production, which is "maxed out" wherever the local grid is sufficient to carry the locally generated power.[ix]

The fact that energy decisions impact gas generation may be considered "good and bad news" for those promoting renewable energy generation. The "good news" is that every kWh of energy conservation or renewable energy addition has a larger positive impact – these actions directly reduce fossil (natural gas) power production and associated emissions without curbing non-emitting sources; the per unit reductions from these strategies are much higher than the "grid average" in NYS (and for other grids "balanced" by fossil power). Conversely, there is the "bad news": every electrification project increases the need for fossil (natural gas) power production and results in those associated emissions, increases directly impact fossil electrical production and are much higher than the "grid average" in NY. Figures 5a through 5d show these impacts conceptually.

Average emission rates are the standard for measuring one's "carbon footprint" and marginal impact rates are difficult to calculate with accuracy for complex systems. Moreover, most public agencies and advocacy groups do not consider marginal emissions when they promote

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[viii] Nuclear power is shown in green as it does not directly emit carbon. Most nuclear plants in NYS are operating beyond their original permitted life span; two plants (Indian Point) were closed in 2021 and others are slated for closure over the next decade, reduced emission-free power. No new nuclear plants are formally planned.

[ix] Energy imports/exports also impact the overall energy mix. The NYISO grid is tied to grids in Ontario, New England, PA, and NJ and electricity is routinely shared between grids to balance load and reduce costs. Despite these complexities, the concept of natural gas as the balancing energy source remains valid today.

electrification. For instance, the EPA site[x] on vehicle electrification compares the gasoline emissions reductions against the electrical grid emissions based on the *regional average grid emissions* number. While this may work reasonably well for a grid that is mostly a mix of different fossil power sources or that regularly curtails renewable production, it significantly underestimates the additional emissions created each time an electrical vehicle is added in NYS today (or the emissions *savings* when someone opts for, say, public transit). Electric vehicles of appropriate size and efficiency may still be the better environmental choice in NYS compared to internal combustion (gasoline) vehicles, but when measuring against the added grid emissions, appropriate vehicle choices (considering size, efficiency, embedded carbon) is as important as fuel type.

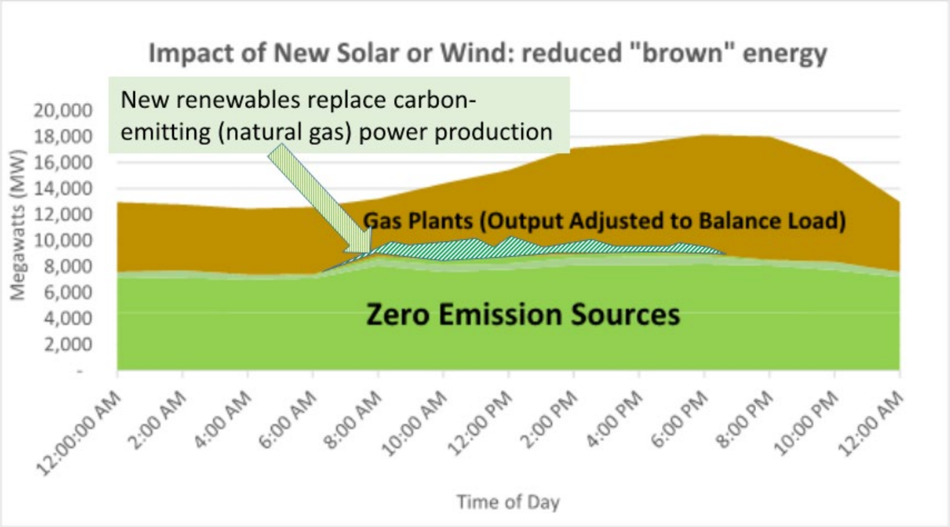

Figure 5a: New renewables directly replace natural gas emissions and improve "grid emission averages"

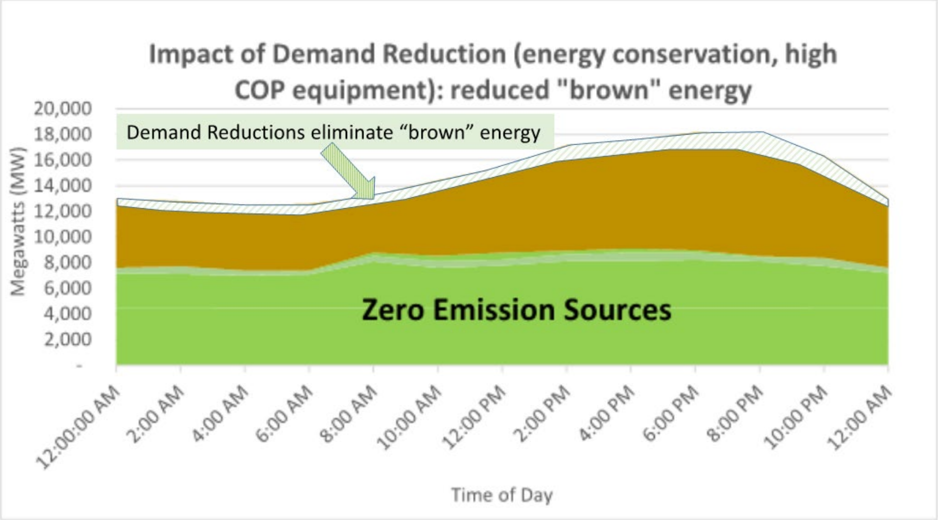

Figure 5b: Demand reductions directly reduce the amount of natural gas generation required to meet grid demand (with little or no impact to current renewable generation).

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[x] Per US EPA Tailpipe Emissions Calculator: https://www.fueleconomy.gov/feg/Find.do?action=bt2

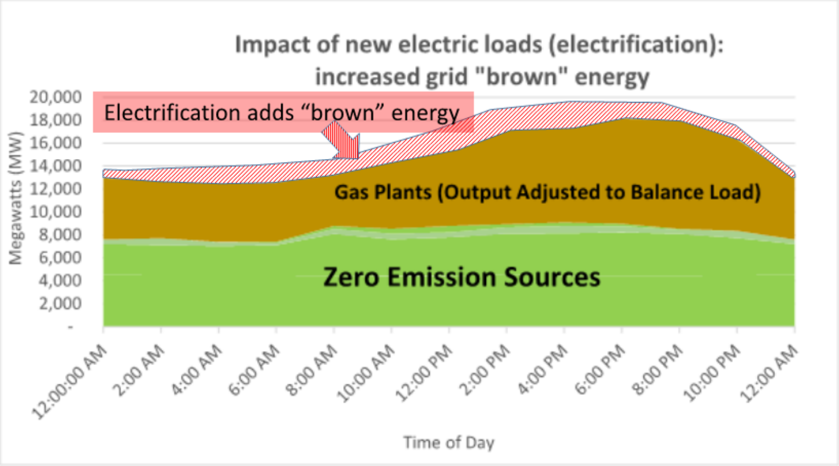


Figure 5c: New loads from electrification are directly balanced by more natural gas electric power generation.

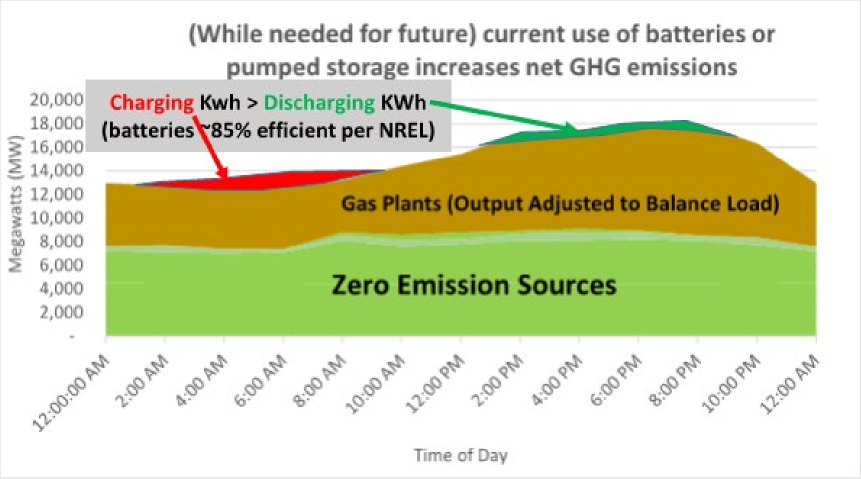


Figure 5d: Battery (or pumped) storage. Batteries and other load-shifting technologies shift the times of natural gas power production, smoothing the grid and reducing the need for excess capacity – but for a grid balanced with natural gas, may marginally increase overall emissions (since more power is needed to charge batteries than is returned).

NYS's Climate Leadership and Community Protection Act (CLACPA) requires complete decarbonization of the electric grid ("zero-emission electricity") by 2040. Assuming NYS can first develop enough renewable energy sources such that natural gas is *not* the balancing (or marginal) energy production source in NYS, under which conditions a comparison on emissions based on natural gas alone would not be accurate. As NY approaches that "zero-emission" goal, an emission calculation based on the "grid average" would still be inaccurate unless the *marginal* energy source (i.e., the power impacted by marginal increases or reductions) is of similar value, which logically will never be the case. For example, if NYS is successful in decarbonizing the grid to the point that 90% of electrical use is from renewables, added (or removed) loads will still disproportionally impact the balancing at times of low renewables with natural gas, while having less or no impact on at least the "baseline" of renewables, if the grid continues to be controlled to prioritize renewables. Thus, if the grid increases zero-emission sources, the "marginal mix" may not all be natural gas, but all remaining natural gas plants will still be part of the marginal mix.

This complication of marginal emissions, while intuitive, is difficult to precisely model since it requires numerous assumptions about grid design and capacity, grid operation algorithms, distribution of renewables, level of storage, and weather and energy use patterns – with weather less predictable due to climate change and energy use subject to technology and economics.

Individual energy choices calculated based on "grid average emission" could lead to insufficient GHG reductions or even increase GHG emissions overall. However, the focus of this paper is on GHG -reducing solutions, not criticism of calculation methods. Specifically, our calculations show how innovative heating and cooling solutions improve our odds of reaching our common GHG reduction goals. The key interrelationship between heat strategies (including renewable heat and storage) and the ability of the electrical grid to provide critical heating services is developed to help clarify how these interrelate.

1.2. NY's Future: Marginal Grid Emissions

If the grid is entirely decarbonized, as is NY's goal, there are no grid emissions. In planning for this ideal future, one must understand the enormous challenge of complete decarbonization concurrent with electrification to remove vehicle and heat direct emissions.

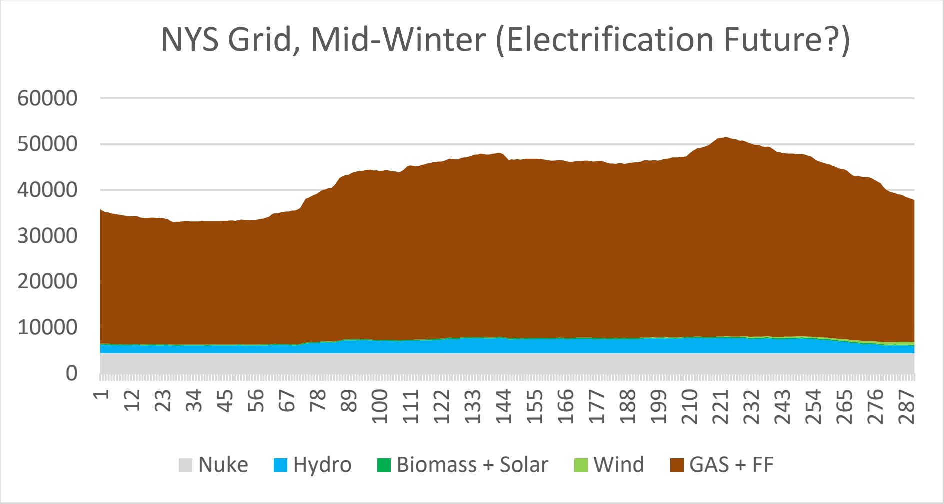


Figure 6: Projected future (2050) energy demand assuming current renewables.

To illustrate the scale of the challenge, Figure 6 shows a potential future grid profile for a situation in which *electrification* has advanced quickly, but *renewable energy* is still at about today's level. This figure replicates the estimate of overall demand by a local coalition of energy engineers and planners[xi] based on the assumption that a large percentage (75%) of vehicles and heat would be electrified. NYISO modeling[xii] of peak conditions shows a similarly daunting challenge, estimating that winter electric grid demands would about *triple* from current demand and that

[xi] The graph created for the figure uses estimates from the Tompkins County Energy Roadmap, a document created in March 2016 on behalf of the Tompkins County Planning Department by a broad-based team of academics and regional energy and sustainability experts.

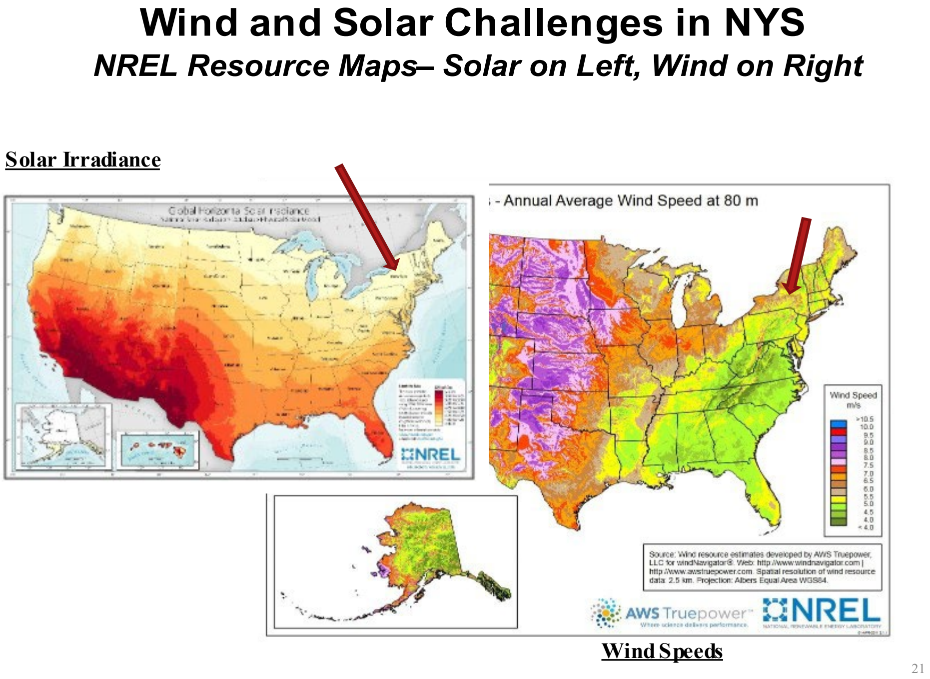
[xii] NYSO Climate Change Impact Study, Phase J, December 2019. NYISO tables predicted a future statewide winter peak electrical energy demand of over 73,000 MW_e, nearly three times the 2020 winter peak of 25,203 MW_e, assuming significant electrification occurs in parallel with significant energy conservation.

overall annual demand peaks would “switch” from summer to winter if both vehicles and heat were electrified. The peak would be even higher if not for the significant energy conservation (demand reduction) NYISO and Tompkins County assumed to occur during the same period.

Electrification’s higher grid demands, if not matched by additional renewable electricity, will increase overall state *grid* emissions. That does not mean that NYS will have higher *overall* emissions – indeed, as Figure 1 shows, direct emissions from vehicles and heating are currently about fivefold that of the grid. Eliminating direct emissions remains an appropriate goal for NYS. This paper explores how innovative thermal strategies are allies in meeting that challenge.

1.2.1. Renewable Energy Resources in NYS

Adding to the challenge of greening the grid are the sub-par wind and solar resources for many states with large heat loads. Figure 7 shows estimates of the resources published by the National Renewable Energy Laboratory (NREL).



Wind and Solar Challenges in NYS

NREL Resource Maps– Solar on Left, Wind on Right

Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.

Figure 7: NREL Resource Maps; central NY is shown by red arrows.

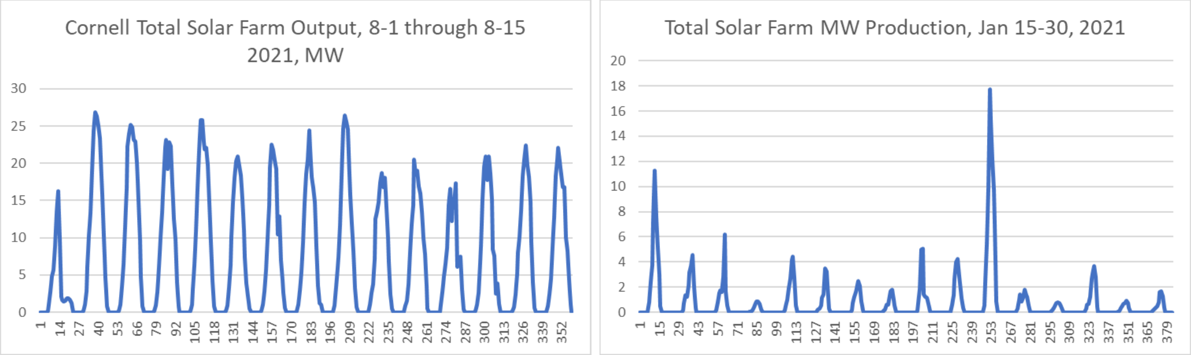
These maps show the relatively poor solar and land-based wind resources of NYS. In part due to these natural limitations, offshore wind has been an early target for NYS renewable development. Relatively low-level resources are just one of the challenges in greening the grid; variability presents another significant challenge. As we will show, solar production can be reasonably predictable, but solar production is especially low in winter, when heating demands are highest. In contrast, wind power provides better winter production overall and power is available day and night, but the high variability of wind within NYS creates large storage demands.

1.2.2. NYS Renewable Power Variability

A critical need for planning for renewable grid resources is to understand the consistency of those renewable power resources. Figures 8 and 9 show the local solar production in representative midsummer and mid-winter periods across all of Cornell's land-based solar farms (29 MW total peak capacity) located at various sites across upper New York State (none are on campus although several are within 20 miles). Figure 9 shows that solar supply in winter is very low in NYS.

Wind is a better winter resource, yet variability of NYS wind resources is significant; data for the entire statewide wind field indicates some very low production periods. Figure 10 shows regional wind output for a sample late winter period. Today, NYS has approximately 2,000 MW of installed wind capacity producing approximately 4,500 GWh per year of electricity, for an annual wind capacity factor of approximately 26%[xiii]. Much more is needed (and planned) to green the grid. NYS efforts currently are focused on developing more of NYS's offshore wind resources, which are more expensive to develop than onshore wind but are predicted to have a higher capacity factor.

Using this data on the temporal variation in renewable energy production, we created a simple model to evaluate how various thermal strategies equate to the amount of renewable solar (in summer) or wind (in winter), plus storage, would be needed to match typical cooling and heating demands, respectively, in a typical summer or winter (respectively) period.



Figures 8 and 9: Typical summer (left) and winter (right) solar production profile, Cornell solar farms (29 MW cumulative capacity). Note the scale differences. Summer sun is better; short days, low sun angle, snow, and lot of clouds limit solar production in the winter in Upstate New York.

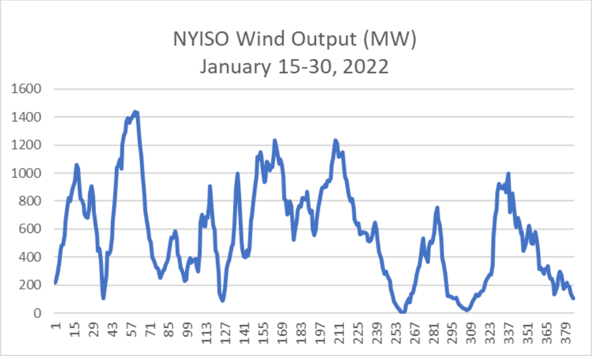


Figure 10: Typical NYS Wind Production – Winter (statewide totals). Data is from NYISO[xiv].

[xiii] https://windexchange.energy.gov/states/ny#capacity

[xiv] The NYISO public dashboard page provide free access to data on energy production for user-selectable periods. https://www.nyiso.com/real-time-dashboard This data was taken directly from that source.

2. Analysis of Thermal Systems

2.1.1 Modeling Objectives and Approach

The objective of the analysis in this paper is to demonstrate the direct impact that thermal system options can have on the amount of renewable energy resources needed to “green the grid”. This paper uses specific data – Cornell University’s heat demand and NYS’s grid impacts – to illustrate this impact, which will vary from location to location. However, these impacts are not unique to NYS but rather common to all US regions that have high heat loads and grids which aim to decarbonize; in locations with more coal or oil use on the grid, for example, the GHG reductions from using innovative heat systems will be even higher while the renewable resources saved will likely be similar. Matching system needs to renewable resource availability allows a simple assessment of the scale of resources needed to meet system demands. The public availability of hourly (or better) renewable power outputs in the state allows a sample analysis of any system with similarly well-documented loads.

To illustrate this concept, this paper models several heating and cooling systems against the winter and summer (respectively) load patterns for Cornell’s thermal loads. Table 1 shows Cornell University’s District Energy (Electric, Heat, and Chilled Water) loads serving about 16 million square feet of campus buildings.

Table 1: Cornell University District Energy Loads[xv]

	Peak	**Average**	**Minimum**
Electric	35 MW_e	22 MW_e	20 MW_e
Heat	90 MW_t	28 MW_t	8 MW_t
Chilled Water	90 MW_t	16 MW_t	11 MW_t

Like many northern states, Cornell is located in a region with relatively cold winters and warm, humid summers. Cornell’s “99% design temperatures” [xvi] are 0ºF (-18ºC) and 87ºF (30ºC) – with a predicted upward trend as global warming impacts our area. Temperatures exceed these standards ~1% of the time – or ~88 hours per year – which align with the “peak” heat and chilled water use periods. The high humidity of this region makes summertime temperatures less tolerable and reduces the effectiveness of natural ventilation and mechanical evaporative cooling strategies. Dehumidification is often accomplished by subcooling conditioned air to remove moisture before remixing or reheating the air for distribution, adding to both heating and cooling loads.

[xv] Throughout this paper when discussing energy we use the subscript “t” to designate “thermal” and the subscript “e” to represent electrical energy.
[xvi] https://www.energystar.gov/

2.1.2 Analysis of Cornell University District Cooling

Our first example uses Cornell's district cooling system, for which 20 years of detailed data is available. Lake Source Cooling (LSC), a form of deepwater cooling, provides over 98% of the annual cooling load distributed by the district system. Using the always-cold deep lake water of Cayuga Lake (39ºF/4ºC in summer) as the source, LSC uses only pumps and plate-and-frame heat exchangers, rather than refrigerants, to chilled water for campus cooling.

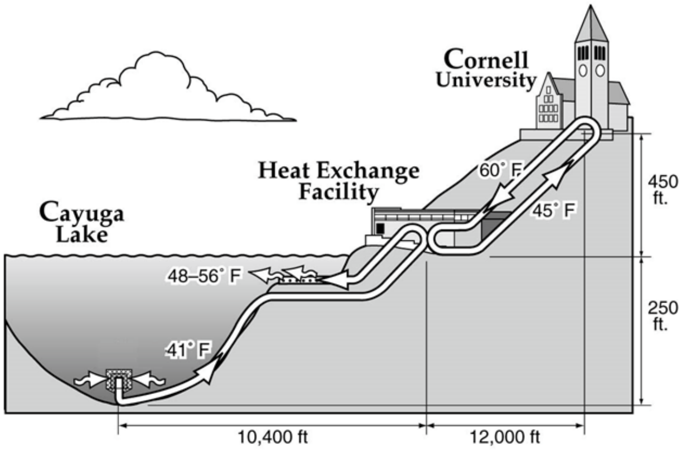


Figure 11: Schematic of Lake Source Cooling System (LSC)

As shown conceptually in Figure 11, lake water is pumped from a wet well (at lake level) within the Heat Exchange Facility across a set of parallel plate heat exchangers, cooling the (hydraulically separate) return campus chilled water loop. The same (slightly warmed but still cool) pure water is then returned to the lake. This allows for renewable, direct cooling of the district chilled water system without refrigerants, using just the modest energy inputs of the two pumping systems.

Figure 12 shows the entire Chilled Water Distribution system. While over 98% of the annual production of chilled water is from LSC, the district also has chillers and a chilled water storage tank for peak cooling needs to match the <2% of peak chilled water demand for campus. The storage tank allows this additional cooling water to be generated during non-peak periods when electric rates are lower and temperatures are conducive to more efficient generation by the chillers.

Because LSC supplies nearly all of the annual cooling load for the campus without the need for refrigerants or the associated mechanical work required to operate chiller equipment or heat pumps, the system operates with efficiency unmatched by conventional systems. The efficiency metric used for chillers and heat pumps is the Coefficient of Performance (COP), defined as the amount of cooling (or heating) energy divided by the amount of electricity required to produce that energy (e.g., a COP of 2 means that one unit of electricity produces 2 units of cooling).

The total electricity input for LSC (including both lake water pumping and district loop pumping) is small compared to the equivalent electrical input for heat pump or chiller solutions, with an "effective" COP of about 30 when operating alone; the chiller system COP is about 24 overall (including occasional chiller use for peaks). Our analysis assumes annual average COPs for heat pump systems operating in midsummer in our region of 3.5 for ASHPs and 4.5 for GSHPs.

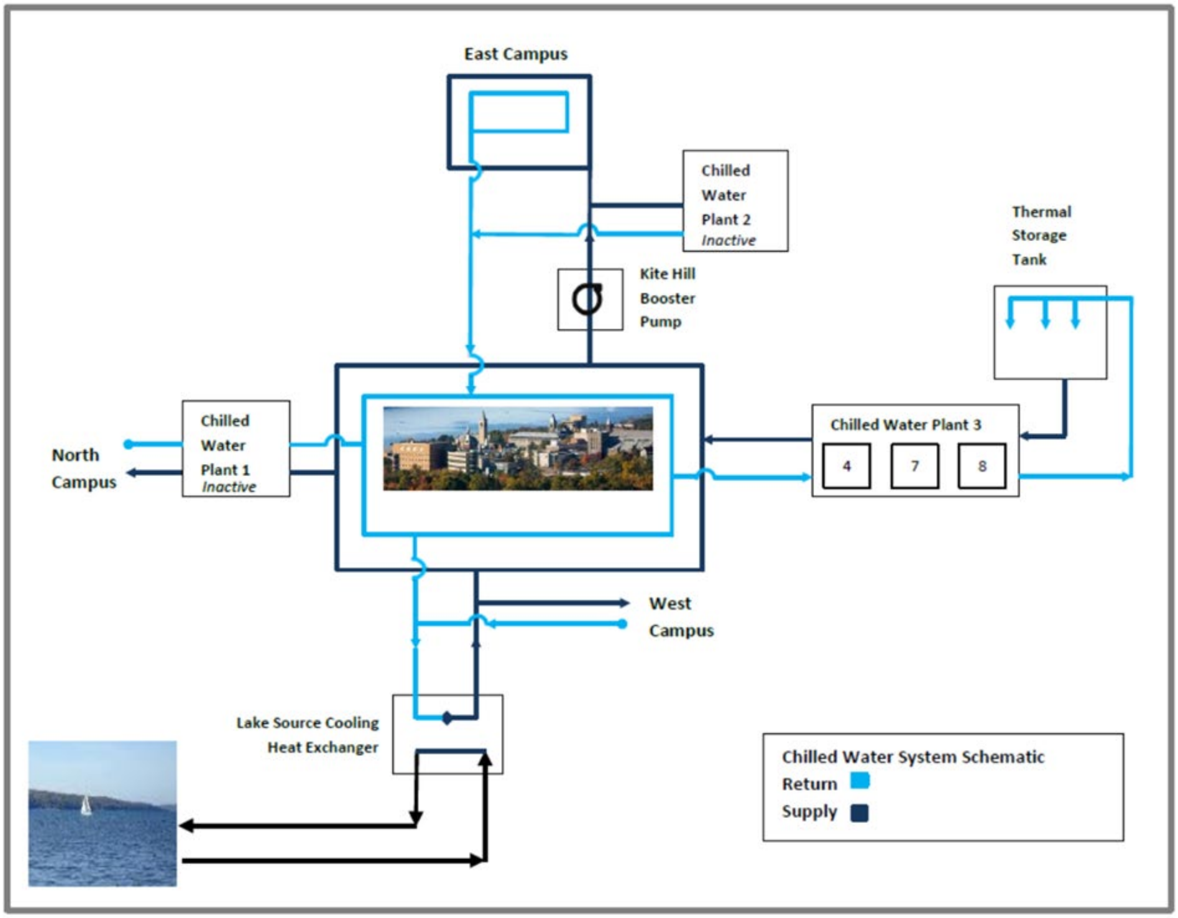


Figure 12: Cornell District Cooling System. LSC, one component of Cornell's district chilled water system, supplies over 98% of the annual cooling load. Chillers and a thermal storage tank supplement the system during hot, humid periods of summer.

The impact of LSC's high efficiency is seen in Figure 13, which compares the electrical energy required by our chilled water system (anchored by LSC) to conventional chillers with evaporative cooling (cooling towers) common at most large facilities in NYS; LSC similarly requires much less electricity for each unit of cooling output than ASHPs and GSHPs for cooling.

To calculate savings in renewable grid resources associated with these lower electrical needs, we also need to understand the demands of the system over time. While our modeling is not intended as a rigorous evaluation of resource needs, it serves as a reasonable "minimum resource" approximation using available public data showing typical seasonal thermal load patterns and renewable resource variability.

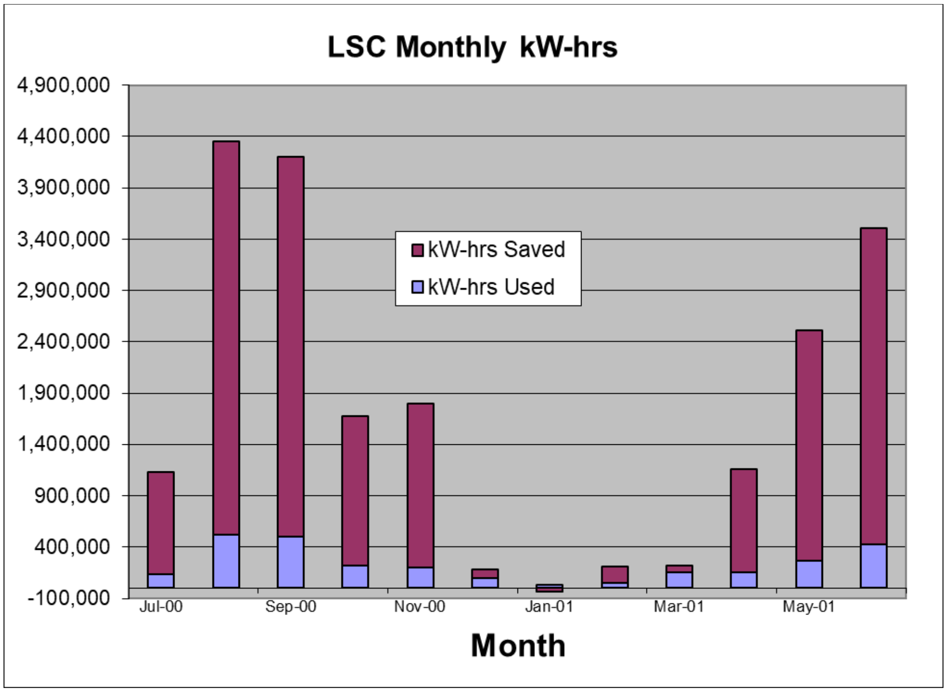


Figure 13: Chilled water electrical savings, kilowatt hours (kWh$_e$). Cornell's district cooling system requires much less electricity (light purple) than conventional (chiller or heat pump) cooling systems (magenta).

Figure 14 shows the chilled water load at Cornell in MW$_t$ (megawatts thermal). Comparing system Coefficient of Performance (COP) for difference cooling technologies provides a direct comparison of the associated electricity load required to provide this cooling load. In Figure 15 estimates of electric loads are compared for ASHPs and GSHPs, as well as use historic data to determine the "effective" COP of our LSC district system to provide that same cooling energy.

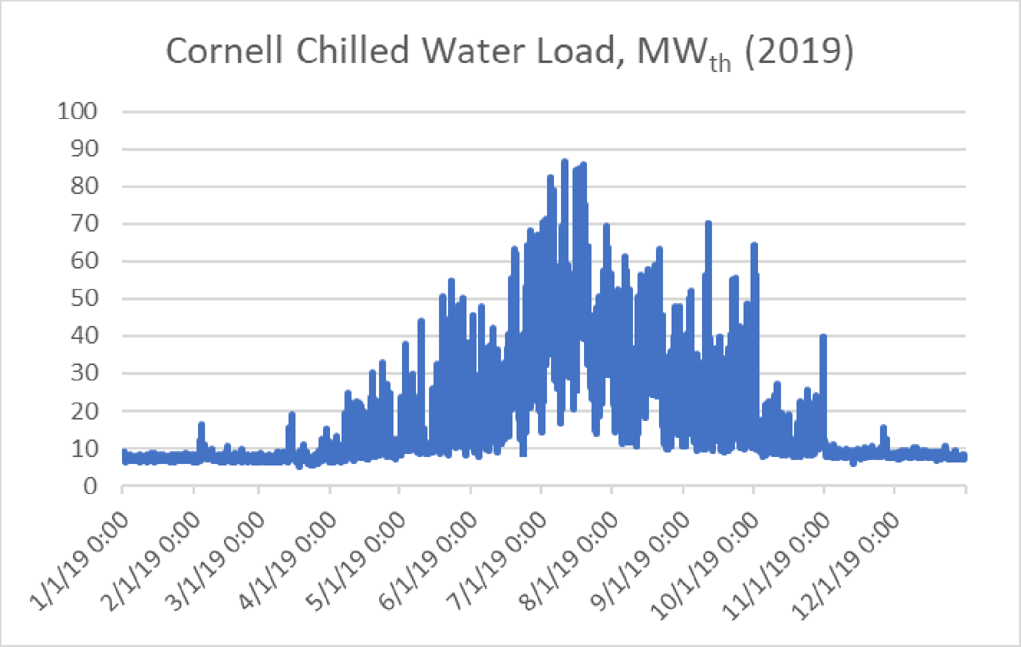


Figure 14: Daily Chilled Water Load for Cornell during a representative year (before COVID).

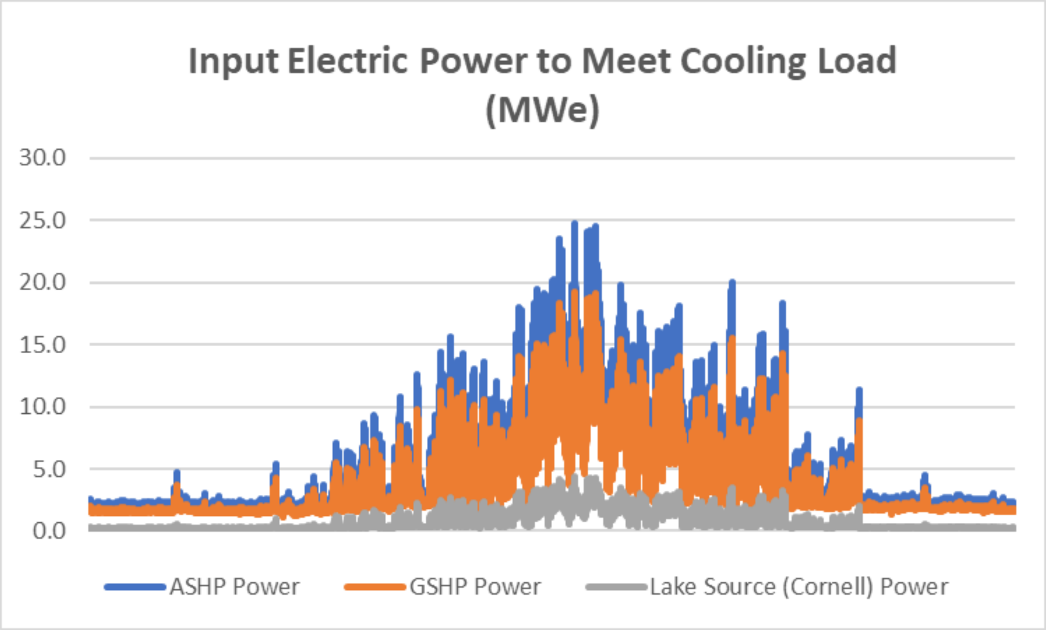


Figure 15: Hourly varying power requirements for each of three cooling strategies using data from Figure 14

Regardless of which strategy we use for cooling, solar power in our area appears to be a reasonable source to provide renewable power in summer. To help model how this system can impact the amount of solar power needed for cooling, we utilize actual data of solar farms on Cornell lands. The grid-linked solar sites on Cornell lands provide a total of about 28 MW_e in peak electricity generation[xvii]. Figure 16 shows the total solar production of these Cornell solar farms for a representative (early August) summer period when both solar output and cooling loads are higher.

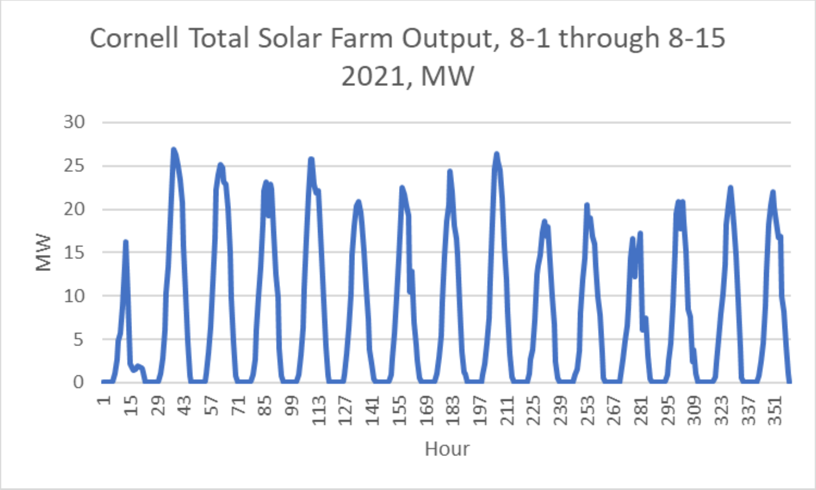


Figure 16: Summer solar output (MW_e) of solar farms on Cornell lands in Upstate New York. Days are long and the sun in high in NYS in summer, daily (and hourly) output varies due to cloud cover.

[xvii] https://sustainablecampus.cornell.edu/campus-initiatives/buildings-energy/solar-energy

To determine the approximate amount of solar farm capacity needed to provide electricity for campus cooling, a simple model is generated to match solar output to chilling needs over a typical summer cooling period. We first model a system using ASHPs matched to enough solar field to meet our needs over the same two-week summer period (we chose August 1 through August 15th) assuming that overproduction during midday will just balance (with storage) our needs when the sun is not shining. Our model assumed a slight overproduction (10%) to account for cycle losses during battery storage (including power transformation) and some minor distribution losses. Figure 17 is a graph showing this result:

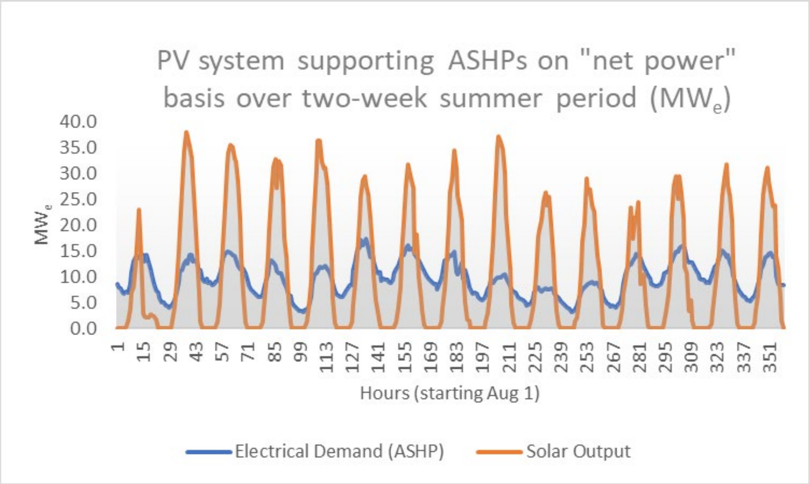


Figure 17: Hourly solar output (MW$_e$) matched to cooling demand for two-week summer period

Figure 17 suggests that we would need about 40 MW$_e$ of solar farm capacity to provide 100% of the renewable electricity we need to operate our chilled water system over a sample two-week period (the graph shows about 38 MW$_e$ at peak; our historic data shows our cumulative output in late summer is just shy of our cumulative solar field capacity).

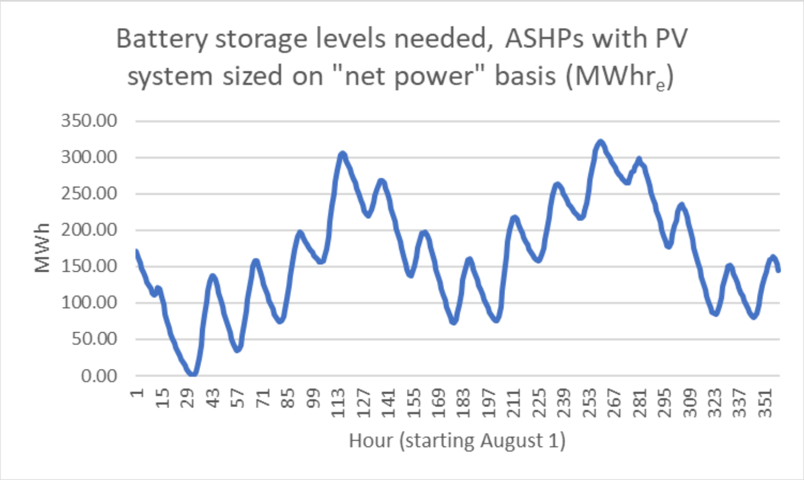


Figure 18: Battery storage (MWh$_e$) to balance solar production with chilled water demand. This hour-by-hour calculation assumes local solar power is sized without overproduction to support ASHPs for cooling.

An estimate of battery storage needs for a “100% renewable future”[xviii] is calculated by plotting the hour-by-hour electric “deficit” or “excess” for the same case, as shown in Figure 18 (in this and related figures, the x-axis is in hours over the referenced analysis period).

Figure 18 suggests extreme amounts of storage (>300 MWhrs) would be required relative to the system size, even during a relatively high output (summer) solar period. Since this amount of storage would be excessively expensive, we could opt to use a larger solar farm to reduce the storage needs. Although overbuilding would likely result in “wasted” renewable energy unless some other means of long-term storage is used, the total cost for renewables plus storage is still lower. One example is shown in Figure 18a and 18b, where a 50% excess solar farm capacity reduces storage needs to about 125 MWh – still huge but with a total capital cost (combining the costs of wind and batteries) that is lower. Based on the assumed solar and battery capital costs, a design in this range is, by observation, the most cost-effective.

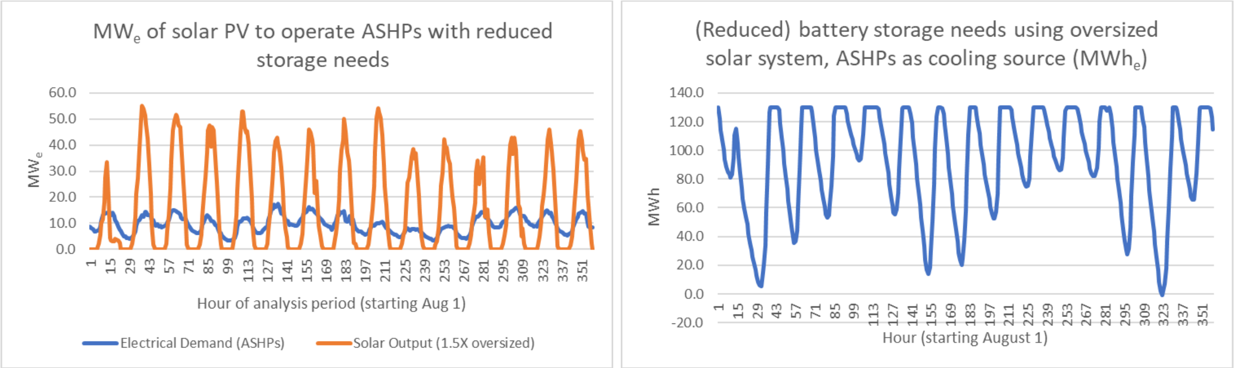


Figure 18a and 18b: Impact of oversizing solar fields. Overbuilding to produce 150% of net demand results in lost production and more resource use but significantly lower storage requirements and overall lower costs based on unit cost estimates. The example shown shows storage limited to 130 MWh just meets the needs in this same time frame, compared to 300 MWh in the “matched output” example.

A number of sample “overbuild” sizes were modeled; our observation of the results was that a system with a peak capacity of about 150% of the electrical need at the peak heating out provides an overall system with total costs near a minimum for all systems modeled. We performed the same analysis with GHSPs and our Lake Source Cooling system, which provide lower and much lower electric demand, respectively. Table 2 shows those results, where “1.5X” means the PV is sized at 150% of peak capacity to reduce battery storage needs.

Based on this sample analysis, assuming some “overbuilding” to reduce storage needs and optimize total investment, the use of LSC reduces solar field capacity by 36-51 MW_e and storage needs by 96-107 MWh compared to ASHP and GSHP options, respectively. Grid-greening capital investment savings (based on reduced need for renewables and batteries) for these modeled

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[xviii] Current Statewide plans mandate a 100% renewable energy grid and complete elimination of natural gas for electrical production. There is also at least one current (April 2022) bill supported by environmental proponents and some State Legislators to prohibit natural gas electrical production and any future gas pipeline construction in the State.

scenarios was between $79 and $107 million, respectively, for LSC compared to ASHP or GSHP systems.

Table 2: Renewable Grid Infrastructure Needed to Cool Cornell Campus [1]

Cooling Source/Sizing	**Required Solar Capacity (MW_e)**	**Required Battery Storage (MWh_e)**	**Renewable Grid Support Capital Cost ($US 2022)**
ASHP/Minimum Cap	40 MW_e	300 MWh_e	$159 M
ASHP/1.5X Min	60 MW_e	130 MWh_e	**$127 M**
GSHP/Min Cap	30 MW_e	250 MWh_e	$128 M
GSHP/1.5X Min	45 MW_e	104 MWh_e	**$97 M**
Cornell LSC/Min Cap	6 MW_e	45 MWh_e	$24M
Cornell LSC/1.5X Min	9 MW_e	18 MWh_e	**$18M**

Note 1: "Modeled" results are not "design" values, but "illustrative" figures based on actual data over a sample summer period. A renewable grid without backup power would likely require substantially higher investment to account for periodic weather conditions which could extend low-production periods. These costs include renewable production and storage only; they do not include wire transmission or distribution infrastructure.

As Table 2 shows, the use of naturally renewable (deep-water) cooling rather than mechanical cooling (chillers or heat pumps) results in substantially lower "green grid" electrical infrastructure needs, especially to meet seasonal system conditions.

Cornell's district system is likely the US's most efficient academic institutional district cooling system; only natural ventilation systems, which are not effective in our humid environmental, or other natural non-mechanical water-based systems might rival its performance. However, the use of deep-water resources is hardly optimized; several of the Finger Lakes are deep enough to maintain cold bottom water year-round, as are the Great Lakes. The City of Toronto uses deep lake cooling from Lake Ontario (and uses the same water for potable water distribution) and is currently working to expand that system[xix].

Considering that Cornell represents roughly only about 0.1% of the State in terms of energy demands, savings on the order of $100M, if replicated, could have large impacts on the amounts of infrastructure spending needed to green the grid. GSHPs provide smaller but still meaningful reductions in grid-greening costs and environmental impacts compared to ASHPs.

Grid renewable asset capital cost savings represent only a portion of the overall grid and environmental benefits. Other substantial savings include incremental avoided costs for improving wire transmission and distribution infrastructure and the maintenance costs (to the grid operator, and by extension to all electric customers) of the renewable energy systems, batteries, and infrastructure.

[xix] https://www.toronto.ca/community-people/get-involved/public-consultations/infrastructure-projects/deep-lake-water-cooling-expansion-study/

Having calculated the infrastructure savings using existing data from Lake Source Cooling, we next look at electric **heating** options to determine whether meaningful savings are possible.

2.1.3 Peak Heating Season

A sample profile of Cornell's mid-winter (January 15-30) heating demand is shown in Figure 19. As higher peaks (above 80 MW_t) have occurred, this data thus represents "typical winter conditions" only and not a "design basis". Nonetheless, it demonstrates the relatively high variability in load of a "typical" winter season, with hour-by-hour demand varying more than 3-to-1 over this 16-day period and occasional "sharp" changes in demand in response to weather.

Our electrical needs for electrified heating will follow the same profile as shown above, unless we alter this profile using thermal (hot water) storage. We will address thermal storage later in this paper.

For future campus heating, Cornell is considering a deep direct geothermal heating source (Earth Source Heat[4] [ESH]) that, if coupled with very high efficiency heat pumps ("SuperCOPs")[5] could provide "electrified" campus heat with an effective overall COP at least 8 (COP = 8 for this analysis). ESH aims to provide most campus heat; peak heating may also be accomplished with other low-carbon or no-carbon methods such as the use of waste biomass[6].

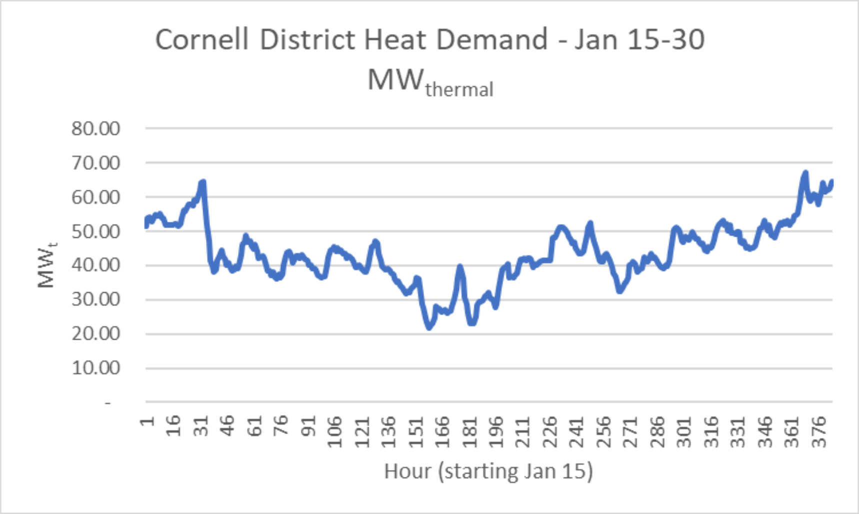

Figure 19: Typical Winter Variation of Cornell District Heating Load (MW_t), hour-by-hour.

Even with an efficient electrification solution, meeting our electrified heating needs is not feasible with solar northern regions. As Figure 9 showed, long days and high sun provide substantial solar power in summer, but winter includes longer periods with no sun or solar is limited by clouds. As shown in Figure 16, Cornell's solar farms (cumulative rated output of 28 MW) averaged ~0.75 MW (less than 3% of the rated capacity) over our sample winter period.

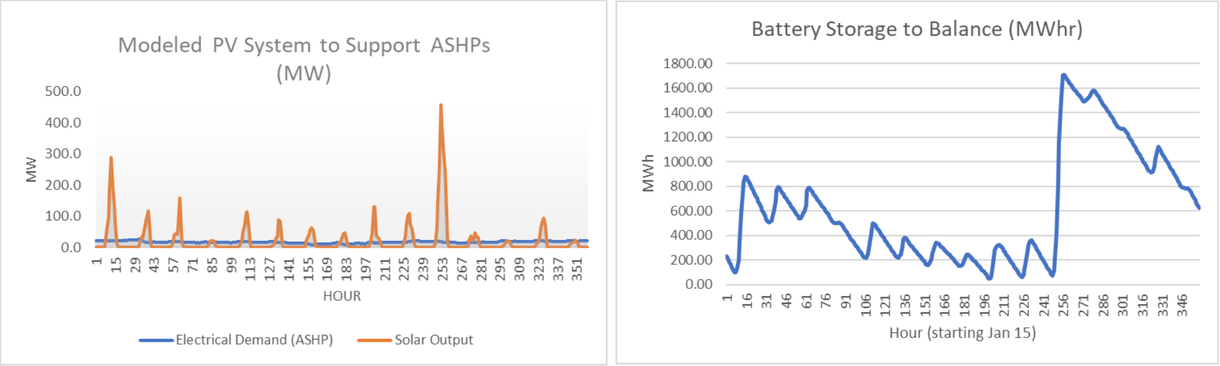

Figure 20a and 20b: Matching daily solar output to daily electrified heat input in upstate NY in winter. At least 450 MW of peak solar field output would be required to heat Cornell Ithaca campus in winter; an enormous storage system (about 1600 MWh) would also be needed.

Figures 20a and 20b, which show the results of applying similar logic (balancing two weeks of solar production with electrical needs), suggest the drastic solar shortfall. To capture ~500MW at peak the actual solar field capacity would be over 800 MW as even peak production was only about 55% of capacity in this winter period. Reducing the excessive storage needs (>1600 MWh) would require even more significant solar field oversizing (with lots of energy wasted in other times of the year) since output would be so much higher in other seasons (including spring and fall, when both heating and cooling demands in this region are modest). Solar panels could need to cover thousands of acres just to heat Cornell, with capital costs approaching $1B.

Since NYS solar is a poor match for institutional heating, this paper assumes that wind power, which is often higher in winter months in NYS, is used to provide renewable electricity during the heating season. To model how much wind might be needed to provide electrification of campus heat, we used NYISO[xx] data over a typical winter period (prior Figure 10).

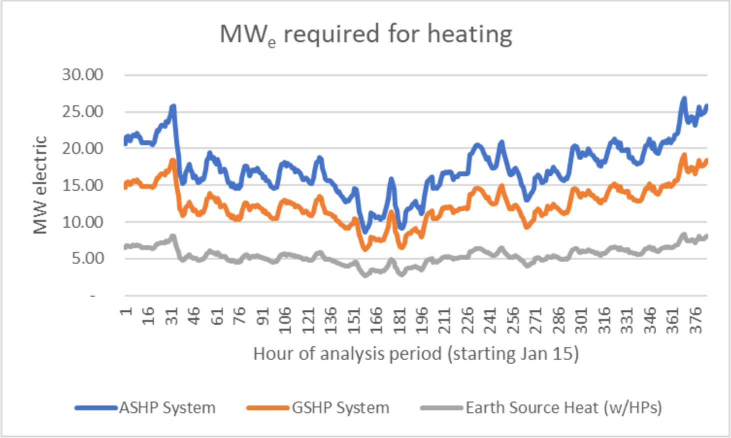

Figure 21: Power Needs (MW$_e$) to supply Cornell heat using three "electrification" options, mid-winter

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[xx] Alas, Cornell has no wind farms of its own, despite several efforts. Community opposition has been a problem for the sites most suitable for production locally.

Figure 10 shows that the combined output of all of NYS's grid-connected wind turbines in winter 2022 is significant, but much less predictable, than (diurnal) solar output. Relatively long periods of significant power generation are interlaced with periods of over 10-20 hours with much lower output and periods of almost no wind output. Longer periods of low output equate to high storage needs so that electricity can be continuously supplied to heating systems as needed in cold winter.

We use this data to estimate the capacity of wind turbines and storage needed to match electric loads during the winter heating season for several choices of heating system. Figures 22-24 and Table 3 show some of these results for the period from January 15th through January 30th.

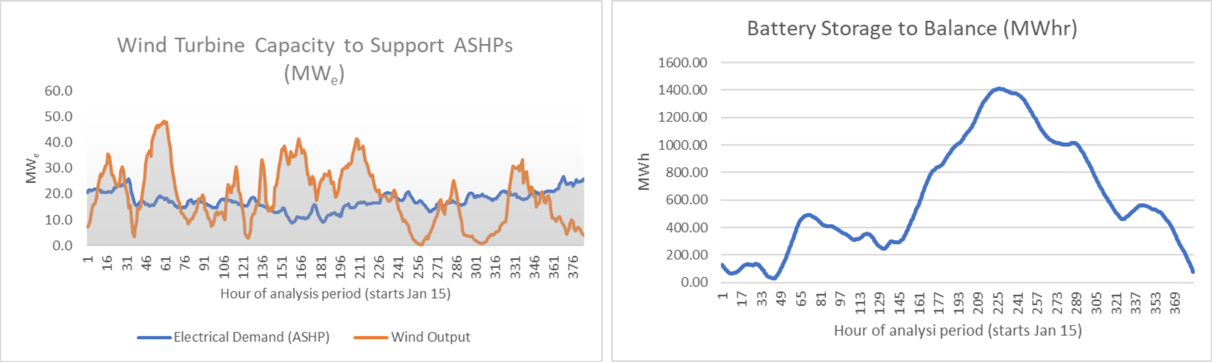
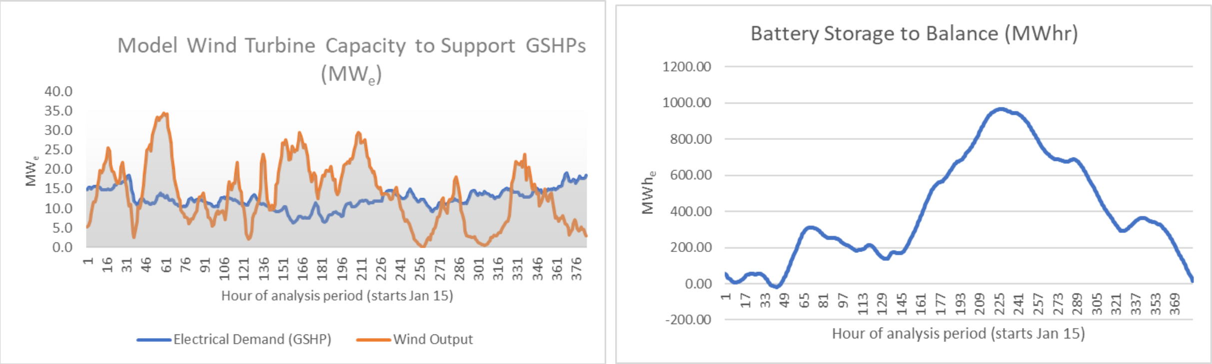
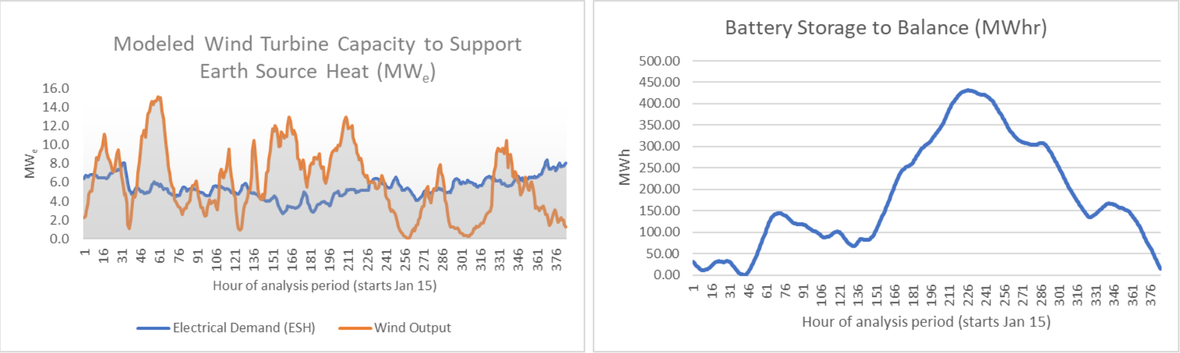


Figure 22a and 22b: Wind Resources ($\mathrm{MW_e}$) and Battery Storage ($\mathrm{MWh_e}$) needed to heat campus using ASHPs. In these figures, wind turbines were sized to just meet net power needs over period (no wind overbuild).



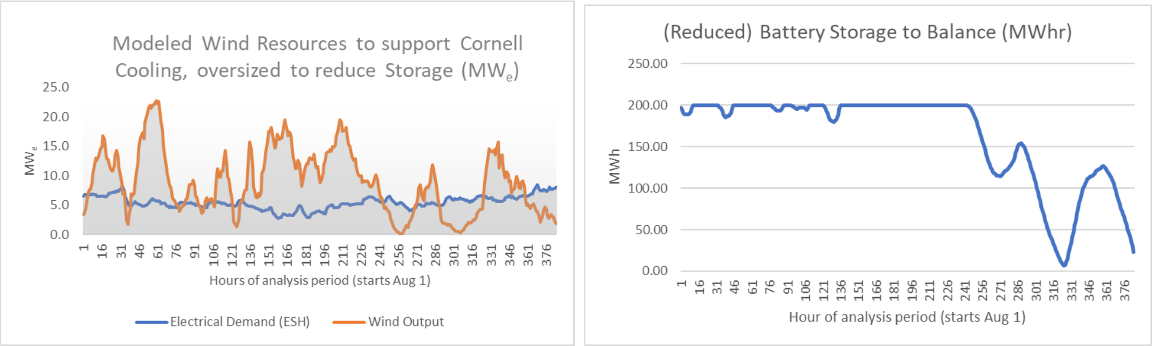
Figures 23a and 23b: Wind Resources and Storage needed to heat campus using GSHPs (no wind overbuild)



Figures 24a and 24b: Wind Resources and Storage needed to heat campus using ESH (no wind overbuild)

Like our modeling for the cooling district, our modeling for the heating district reveals the enormous electric battery development that would be needed to meet our “100% green grid” goals. Once again, we observe that by “overbuilding” wind we can significantly reduce the storage needs and (based on industry costs for each) provide a more economical solution.

Figures 25a and 25a show this solution for the ESH case; other cases are included in Table 3.



Figures 25A and 25B: *Overbuilt* Wind Resources (to reduce storage needs), campus heated with ESH

Table 3: Modeled Renewable Grid Infrastructure Needed to Support 100% Renewable Wind to Heat Cornell Campus based on Select Electrification Options[1]

Heating Source/Sizing	**Required Wind Capacity (MW$_e$)**	**Required Battery Storage (MWh$_e$)**	**Total Renewable Grid Support Capital Cost ($US 2022)**
ASHP/Minimum Cap	55 MW$_e$	1400 MWh$_e$	$644 M
ASHP/1.5X Min	83 MW$_e$	600 MWh$_e$	**$442 M**
GSHP/Min Cap	38 MW$_e$	1000 MWh$_e$	$456 M
GSHP/1.5X Min	57 MW$_e$	440 MWh$_e$	**$314 M**
Cornell ESH/Min Cap	16 MW$_e$	450 MWh$_e$	$202 M
Cornell ESH/1.5X Min	25 MW$_e$	200 MWh$_e$	**$140 M**

[1] *“Modeled” results are typical figures based on actual data over a sample winter period. A renewable grid without backup power would likely require substantially higher investment. These costs include renewable production and storage only and not wire transmission or distribution infrastructure.*

Table 3 shows that, as was the case with chilled water, our technology choices for hot water will greatly impact the renewable wind and battery resources to create a “green” (100% decarbonized) grid. In this case, the “savings” in reduced renewable supply capital investment (not including transmission and distribution improvements) is even higher – up to about $302 M for an ESH system compared to an ASHP system. A GSHP system also saves grid infrastructure investment when compared with ASHP systems ($128 M in savings).

2.2 Thermal Storage: Benefits to Greening the Grid

Having established that renewable heating and cooling systems with high COPs can substantially reduce the overall cost of greening the grid by reducing demands, we also consider a more conventional, but still underutilized, technology – **thermal storage**.

Cornell's Lake Source Cooling provides over 98% of campus district cooling on an annual basis. However, as was shown in Figure 14, the real-time campus cooling load is highly variable; to meet those relative few hours of peak needs (hot, humid summer days) requires activation of the campus chillers and chilled water storage, which are also part of the campus cooling system (Figure 12). On these days, Lake Source still provides the bulk of the cooling; however, the chilled water storage tanks, charged during periods of lower electrical grid usage (and therefore lower costs), provide the additional chilled water needed for those <2% peak periods.

2.3 Comparing Thermal Storage to Electrical Storage

By charging tanks during periods of low demand and using the chilled water during higher demand periods, the impact on the future "renewables based" grid is nearly identical to that of battery storage. If operated in concert with grid renewables, when excess solar and/or wind power is available, tanks can be "charged" so that the chilled water is available during periods of little renewable output, such as a night when solar power is not available. This reduces grid power needs so that grid electrical storage can be reduced. Ironically, the current use of chilled water storage is that tanks are charged overnight (electric power currently costs more during the hottest periods when demand is highest). In the future, if solar power is built to the levels planned and power is priced to encourage use during period of high solar output, the operation could readily be reversed (charging midday and using that cooled water when the sun is no longer available).

Figure 24: Cornell Chilled Water Storage Tank. Thermal storage tanks like this 4.4 M gallon storage tank on Cornell's campus allow operators to shift periods in which chilled (or hot) water is generated, thereby shifting the timing of electrical usage for chillers (or heat pumps) used to generate the resource.

This thermal storage can have the same impact <u>on the electrical supply system</u> (the grid) as battery storage. Cornell's existing thermal storage tank has the following characteristics:

- Storage capacity: 4.4 M million gallons and up to 258 $MW_t hr$[xxi] thermal capacity
- Up to 60 MW thermal peak heat delivery (max pumping rate while maintaining stratification)
- Equivalent to a ~57 MW_e[xxii] electric grid battery system, which would cost about **$20 M** to build, if operated to support a renewable grid.

Figure 24 shows Cornell's existing 4.4-million-gallon capacity thermal storage tank. In addition to grid benefits equivalent to battery storage, it can also provide other cost benefits (when time-of-day or real-time grid pricing is used) and owner/operator benefits (in smoothing out demand and reducing chiller capacity to reduce capital investment). For the future, a high-efficiency water-to-water heat pump arrangement is being considered which would allow chilled water to be generated from the (still cool) return water loop so that cooling towers might not be needed; this arrangement would allow for higher efficiency chilled water generation (lower electrical demand) during peak periods and extend the district service range.

2.4 Hot Water Storage

Hot water storage can also be used to "shift" peak energy use or levelized in a way very similar to that for Chilled Water Storage, while also providing user benefits such as reducing equipment peak capacity (capital cost). As part of our future Earth Source Heat demonstration project, we modeled the use of hot water storage to help "balance" the heating load and reduce peaks, which will help the operators reduce the need for supplemental heat during periods of high heat needs. Figure 25 shows an example of this modeling effort and the concept of shifting loads; in that example the overall system peak (served by ESH or other assets) is reduced from about 76 MW_t to about 64 MW_t – a significant reduction for a relatively modest investment that requires little maintenance. The model assumed a 12 Million (M) liter (~3 M gallon) hot water storage tank.

When comparing hot water storage to chilled water storage in terms of possible grid greening impacts, the value of hot water storage to the "Green Grid" is higher because the temperature difference between storage and returned water is higher; whereas a chilled water system was based on a maximum differential of about 23°F (39°F chilled supply and 62°F return), the Cornell's planned system would store hot water at ~180°F and return at ~120°F (and eventually to ~100°F as building heat transfer systems are improved). This initial difference of ~60°F (versus a max of 23°F for chilled water) equates to a 2.6× higher energy value per unit volume (gallon) of storage. Our analysis only looked at cold water storage; other thermal storage systems such as phase change

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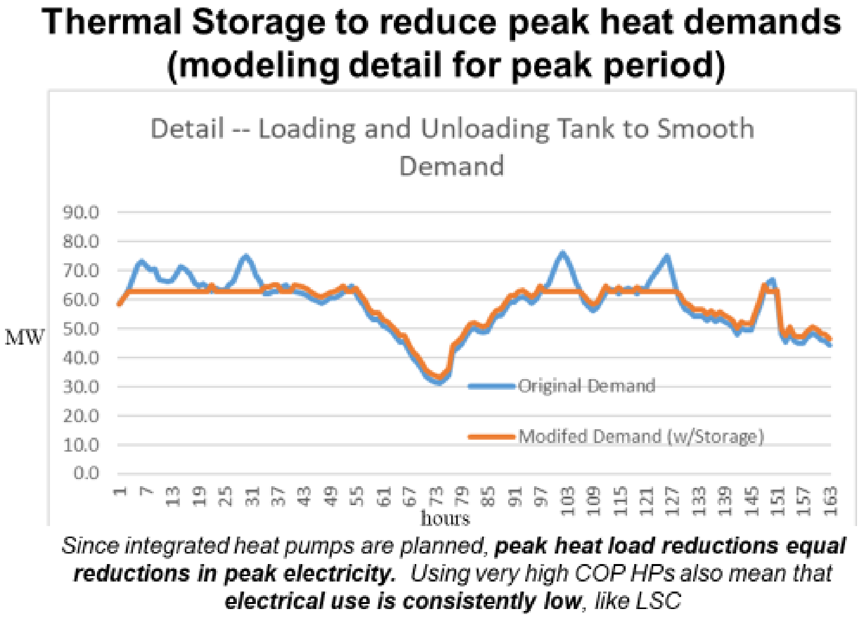
[xxi] This calculation assumes entering (chilled) water at 39°F and 62°F return water (the tank is filled with 62°F return water after use until the next "charge"). Thermal storage capacity is proportional to this temperature difference.

[xxii] This value is simply the thermal capacity divided by the COP of the system that charges it. This value assumes the chiller system or heat pump used to charge the tank operates with a COP of 4.5. A less efficient cooling system results in the displacement of more electric power; a more efficient system means less electricity is displaced.

materials (PCMs) could also be similarly analyzed (using appropriate cost information) if larger, more compact storage was desired.


Thermal Storage to reduce peak heat demands (modeling detail for peak period)

Since integrated heat pumps are planned, ***peak heat load reductions equal reductions in peak electricity.*** *Using very high COP HPs also mean that* ***electrical use is consistently low****, like LSC*

Figure 25: Hot Water Storage Load Shifting. The modeling associated with our future Earth Source Heat demonstration project included modeling the impact of a hot water storage tank in the design. The modeling run shown above assumed 12M liters of storage – about 3M gallons.

Using the same tanks size (as our chilled water tank), we calculate the following storage values:

- Storage capacity: **4.4 M** million gallons (assumed)
- Up to **656 MW_t - h** thermal capacity (based on temperature difference of 60°F)
- If operated within a renewable grid using ASHPs with COP of 3, this system provides grid benefits equivalent to a **219 MW_t - h**[xxiii] electric grid battery system costing ` **$77 M**.

2.5 *Seasonal Storage Research*

Cornell's research effort into ESH includes an active investigation into the potential for *seasonal* heat storage using a modified (and more efficient) version of Aquifer Thermal Storage (ATS). The arrangement we are studying involves using direct geothermal heat (with or without a high-

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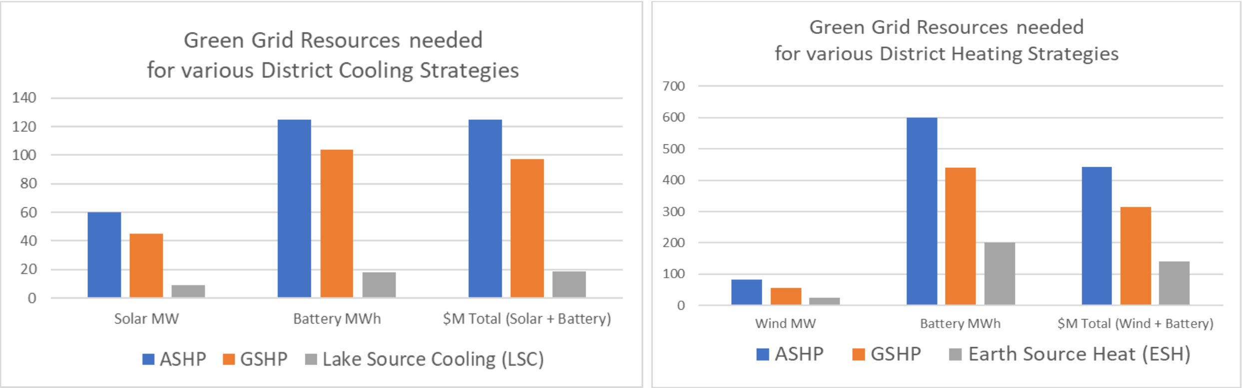
[xxiii] As before, this value is simply the thermal capacity divided by the COP of the system that charges it. A COP of 3 is generous for a heat pump system extracting heat from cold winter air to deliver water ~180°F, which is Cornell's requirement; lower COPs mean even higher electrical usage and thus higher storage equivalents. For a very efficient system like Earth Source Heat with an effective overall COP of 8, the grid "benefit" is lower, about 82 MWh in equivalent battery storage, worth about $40M.

efficiency SuperCOP heat pumps) in the winter and also providing downhole heat reinjection in the summer when excess heat is plentiful in our region. Such a system, if proven feasible, could significantly improve the potential for success of deep geothermal in this region while slashing grid storage needs for heat electrification[xxiv].

3. Conclusions

Using the challenge of greening the NYS grid and electrify Cornell heating as a quantifiable test case, this paper shows how innovative renewable heat and cooling technologies provide significant financial and environmental benefits by effectively avoiding the need to increase renewable electricity generation capacity, batteries, and associated transmission infrastructure. This paper also suggests how thermal storage systems (chilled water and/or hot water storage tanks) can be operated so that these systems are no longer considered not just as conveniences or cost-saving options, but critical strategies that can be employed and developed to help green the grid. We highly recommend that policy makers and researchers continue to explore the potential for highly efficient heating strategies as a major focus in continuing efforts to decarbonize and green the grid.



Figures 25a and 25b: Grid Resources for various district thermal strategies. Innovative renewable cooling (left) and heating (right) systems dramatically reduce the size of solar and wind farms, respectively, and battery storage systems needed to create a 100% renewable electrical grid compared to conventional Air Source Heat Pump (ASHP) and Ground Source Heat Pump (GSHP) technologies. Cost data is based on National Renewable Energy Laboratory (NREL) reports.

Some results of this analysis are shown in Figures 25a and 25b and include the following:

- The operation of Cornell's innovative renewable cooling solution, Lake Source Cooling, effectively reduces grid renewable energy (solar PV) needs by **~50 MW_e** and battery storage needs by **~100 MWh** compared to Air Source Heat Pump (ASHP) systems while requiring less raw materials, lower land use, higher reliability, and reduced dependence on

[xxiv] This system essentially creates a thermal battery to provide an entire winter season of storage. Cornell and NREL are preparing technical papers on this topic as this research is more fully developed.

refrigerants. LSC benefits compared to Ground Source Heat Pumps (GSHP) systems are smaller but still significant.

  - Compared to ASHPs, Cornell's decision to use Lake Source Cooling to meet campus needs saved an equivalent of over **$68M** in estimated PV capital costs and over **$39M** in estimated battery storage costs (over **$100M** in total) that would have otherwise been needed to decarbonize the grid. The total modeled savings of the LSC system in comparison to GSHPs is about **$80M**.
  - Cornell's chilled water storage tank, if operation is coordinated with the grid, could provide an additional equivalent of up to **$20M** (equivalent battery value) in support of the goal of electrification and grid decarbonization. This "storage equivalent" is for a shorter durations (hours to days depending on usage).

- The renewable geothermal heat "Earth Source Heat" would potentially reduce 100% renewable grid wind energy needs by **about 58 MW_e** and electrical storage needs by ~ **about 400 MWh** compared to ASHP systems (and ~32 MW_e and ~240 MWh_e energy and storage needs, respectively, compared to GSHP systems) while providing additional benefits like lower raw material needs, lower land use, higher reliability, and reduced dependence on refrigerants.
  - Earth Source Heat, if successful, would not only meet Cornell's base load heating needs but it also reduce renewable electricity and battery storage capital costs to green the grid by about **$300M** compared to ASHPs (or **$170M** in savings compared to GSHPs).
  - The addition of hot water storage to the Cornell district heating system will provide additional benefits, estimated through modeling at an additional equivalent of ~**$77M** in support of the goal of electrification and complete grid decarbonization.

- Significant savings in capital investments result by avoiding having to increase renewable generation and storage capacity. Further savings result avoiding the need to add additional electrical transmission and distribution infrastructure. Highly efficient thermal systems operating with lower temperature hot water (< 100^{o}C) can significantly reduce the needed investment and impacts of grid improvements at all levels[xxv].

- Before decarbonization is realized, while natural gas is still the balancing fuel for power generation in the State, these highly efficient thermal technologies are especially important in reducing natural gas combustion emissions resulting from grid power generation. Using conventional (less efficient) technologies will result in reduced GHG impacts.

[xxv] NYISO is investing almost $2B to upgrade lines for the near term: https://www.nyiso.com/-/the-road-to-2040-our-role-expanding-transmission-to-meet-the-needs-of-a-clean-energy-grid. Sophisticated long-term studies are underway to understand the range of full investment needed (which depends on technology choices).

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- NYISO provides extensive data and links to studies that illuminate the current and projected future cases for NYS power grid and its supply sources. Their website provides unparalleled transparency and public access to data and sources to help citizens understand the details of electrical generation and use in the NYS power grid.
- The New York State Energy Research and Development Authority (NYSERDA) provides support in communicating, coordinating, and presenting data made available from NYISO on behalf of NYS and also supports forums like Geothermal Rising to allow discussion of these complex topics.

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