How can we decarbonize a school's energy consumption cost-effectively, considering both heating and electricity use?

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Abstract

Fossil fuels, namely coal, oil, and gas, significantly impact global climate change, responsible for over 75 percent of greenhouse gas emissions worldwide and contributing to nearly 90 percent of total carbon dioxide emissions. As renewable energy options gain popularity, there is growing interest in their application, including within school systems. In this study, we investigated how to decarbonize both electricity and heating/cooling, examining the feasibility and costs of implementing solar + storage systems for meeting different percentages of electricity demand, as well as assessing various heating/cooling technologies, including heat pumps, electric furnaces, natural gas boilers, geothermal, and solar thermal. Our analysis recognized the optimal size of a solar and storage system and highlighted that as we increase unmet demand, the cost of solar generation technology plays a bigger part compared to storage costs. We also identified the most cost-effective heating/cooling technology to meet demand and eliminate carbon emissions to be air-based heat pumps. These findings are valuable for medium-scale buildings like schools and can serve as a reference for broader decarbonization efforts.

Introduction and thesis

In today's world, we face unprecedented environmental challenges, and the urgent need to reduce greenhouse gas emissions to combat climate change has become a global priority. This concern extends to various sectors of society, including educational institutions. Busy buildings like schools can implement energy-efficient measures, especially in electricity generation and heating. By doing so, we can not only cut down on pollution and create a more eco-friendly way of getting energy but also set the stage for a cleaner and healthier future with the potential to drive sustainable change within their communities.

In the United States, K-12 school districts collectively spend over $6 billion on energy each year, greater than the amount spent on computers and textbooks combined (Energy Star). Surprisingly, up to 30 percent of this energy is used inefficiently or unnecessarily (Energy Star). By becoming more energy-efficient, schools can not only reduce their carbon footprint but also create a better learning environment for students. Many school districts have been able to use the money saved from improved energy efficiency to fund building upgrades that enhance the overall learning experience. (Energy Star). According to research by the regional education laboratory program, maintaining classroom temperatures between 68 to 75 degrees Fahrenheit during the winter and 73 to 79 degrees Fahrenheit during the summer is crucial for optimal student learning (Institute of Education Sciences). This highlights the significance of energy consumption for heating, especially in regions with varying climates. Typically, K-12 schools in the U.S. consume about 10 kilowatt-hours of electricity and 50 cubic feet of natural gas per square foot annually, with an average spending of $0.67 per square foot on electricity and $0.19 per square foot on natural gas (P3 Cost Analysts). For instance, a typical 1,000-student high school may spend about $149,500 on energy annually, depending on location and usage (P3 Cost Analysts). Moreover, space heating, lighting, and water heating comprise around 74%–86% of their total energy usage, depending on a school's location (P3 Cost Analysts). While there is a strong incentive to find cost-saving solutions that do not compromise student well-being and education, meeting these demands with clean technologies remains challenging, given the current state of renewable energy adoption and technology development.

Overview of Clean Energy Technologies

Solar Energy:

- What It Is: Active solar energy is harnessed from the sun's radiation using photovoltaic (PV) cells or solar panels, which convert sunlight into electricity.
- How It Works: Solar panels contain semiconductor (usually silicon) that emits low-voltage electrical current when exposed to the sun. The generated electricity can be used immediately or stored in batteries.
- Typical Costs: The cost of solar systems varies based on size and location. Residential installations can range from a few thousand dollars to tens of thousands, while larger commercial or utility-scale projects cost millions.
- Pros: Renewable, nondepletable, reduce mining/transport of fossil fuels, no greenhouse gas or pollutants emitted
- Cons: Intermittent (daylight-dependent), no cost-effective way to store surplus electricity generated, disrupted desert habitats by solar farms.

Wind Energy:

- What It Is: Wind energy is generated by the kinetic energy of moving air masses through wind turbines.
- How It Works: Wind turbines, usually mounted on tall towers, have rotor blades that spin with the wind, turning a generator to produce electricity.
- Typical Costs: Wind turbine costs vary by size and location. Onshore wind turbines can range from a few hundred thousand to several million dollars, while offshore wind farms are more expensive.
- Pros: Renewable, non-depletable, no greenhouse gas emissions or air pollutants generated, can share land use (won't cause habitat destruction or soil/water contamination)
- Cons: Intermittent (wind-dependent), can't replace base-load power (sources that are always available), can kill birds and bats, can be considered an eyesore or source of noise pollution.

Geothermal Energy:

- What It Is: Geothermal energy derives from the Earth's internal heat, accessed through wells, converted into electricity, or used directly for heating.
- How It Works: Geothermal power plants tap into underground reservoirs of hot water or steam and use the heat to drive turbines, generating electricity.
- Typical Costs: Geothermal plants require substantial upfront investment, typically tens to hundreds of millions of dollars, but have low ongoing operating costs.
- Pros: Renewable, consistent, baseload power, low greenhouse gas emissions, highly efficient, minimal land use.
- Cons: Limited to specific geological areas, resource depletion over time, drilling risks.

Nuclear Energy:

- What It Is: Nuclear energy is produced through the controlled fission of uranium or plutonium nuclei in nuclear reactors.
- How It Works: Nuclear reactors use the heat from nuclear fission to produce steam, which drives turbines to generate electricity.
- Typical Costs: Nuclear power plants are capital-intensive, ranging from billions to tens of billions of dollars. Operating costs are relatively low.
- Pros: Low greenhouse gas emissions, continuous power supply, high energy density, and security.
- Cons: Nuclear waste disposal challenges, the potential for accidents (e.g., Chernobyl, Fukushima), long permitting and construction timelines, high decommissioning costs, and public safety concerns.

In this study, we want to focus on solar energy due to its low costs, accessibility in the current world technological progress, and the unique demand profile of schools (demand is maximized during the day, matching with the generation of solar energy). However, the challenge is that solar energy is unreliable and needs large amounts of energy storage.

Overview of Energy Storage Technologies

Lithium-Ion Batteries:

- What They Are: Lithium-ion batteries are widely used rechargeable battery that stores electrical energy by moving lithium ions between positive and negative electrodes.
- How They Work: During charging, lithium ions move from the positive electrode to the negative electrode, and during discharge, they move back, creating an electrical current.
- Typical Applications: Portable electronics, electric vehicles, grid energy storage.
- Typical Costs: The cost of lithium-ion batteries has been decreasing steadily, ranging from \$150 to \$200 per kilowatt-hour (kWh) for utility-scale installations, and prices were expected to continue to decline.
- Pros: High energy density, lightweight, long cycle life, fast charging, low self-discharge.
- Cons: limited lifespan, potentially flammable, environmental concerns in production and disposal, costly for large-scale grid applications

Thermal Energy Storage:

- What It Is: Thermal energy storage systems store heat or cold for heating, cooling, or electricity generation.
- How It Works: Energy is stored by heating or cooling a material (e.g., molten salt, water, or phase-change materials) and then releasing it when needed. Heat can be converted back to electricity if required by using a heat engine.
- Typical Applications: Solar power plants, district heating and cooling, industrial processes.
- Typical Costs: Costs depend on the system size and technology used, with typical costs ranging from $20 to $200 per kWh of stored energy.
- Pros: Efficient for long-term storage, can provide both heating and cooling or electricity.
- Cons: Limited by the type of material used, energy losses during the storage and retrieval, large infrastructure requirements.

Hydrogen Storage:

- What It Is: Hydrogen can be stored as a chemical energy carrier for various applications.
- How It Works: Hydrogen is typically stored as a gas under pressure or as a liquid at low temperatures.
- Typical Applications: Fuel cells, industrial processes, transportation.
- Typical Costs: Hydrogen storage costs vary widely based on the method, but they are generally higher than battery storage, with costs ranging from $2 to $10 per kg of stored hydrogen.
- Pros: High energy density, versatile applications, produces no greenhouse gas emissions when used in fuel cells.
- Cons: Energy-intensive hydrogen production, storage and transportation challenges, costly infrastructure development, low energy efficiency.

Redox Flow Batteries:

- What They Are: Redox flow batteries store energy in chemical solutions in external tanks.
- How They Work: Electrolytes flow through cells, where chemical reactions generate electricity.
- Typical Applications: Grid energy storage, renewable integration.
- Typical Costs: Costs can range from $150 to $400 per kWh for utility-scale systems, depending on the specific chemistry and design.
- Pros: Scalable, long cycle life, can separately size power and energy capacity.
- Cons: Geographically limited, lower energy density compared to other battery technologies, complex system design and maintenance

Pumped Hydro Storage:

- What It Is: Pumped hydro involves moving water between two reservoirs at different elevations to store and release energy.
- How It Works: During periods of excess energy, water is pumped uphill, and during peak demand, it flows downhill, driving turbines to generate electricity.

- Typical Applications: Grid balancing, large-scale energy storage.
- Typical Costs: Pumped hydro is relatively cost-effective, costing around $100 to $200 per kWh.
- Pros: High efficiency, long lifespan, well-established technology.
- Cons: Requires specific geographical features (two reservoirs at different elevations), limited locations for implementation, environmental impact on local ecosystems.

Compressed Air Energy Storage (CAES):

- What It Is: CAES stores energy by compressing air and storing it in underground caverns.
- How It Works: During discharge, the compressed air is expanded to generate electricity.
- Typical Applications: Grid energy storage, backup power.
- Typical Costs: CAES can cost $100 to $200 per kWh, depending on geological conditions.
- Pros: High cycling capacity, relatively low cost, long service life.
- Cons: Energy losses during compression and expansion, limited geological suitability for underground storage, environmental considerations for air quality.

Flywheel Energy Storage:

- What It Is: Flywheels store energy as kinetic energy in a rotating mass.
- How They Work: Energy is stored as the flywheel spins at a constant speed and is released by converting the kinetic energy into electricity.
- Typical Applications: Grid frequency regulation, uninterruptible power supplies.
- Typical Costs: Flywheel systems typically cost between $500 and $1,000 per kWh, but they offer advantages like high cycle life and rapid response times.
- Pros: Rapid response time, high efficiency, long service life.
- Cons: Limited energy storage duration, mechanical maintenance requirements, noise and vibration issues.

Overview of heating technologies

Heat Pumps:

- What They Are: Heat pumps are heating and cooling systems that can both heat and cool spaces by transferring heat between indoor and outdoor environments.
- How They Work: Heat pumps use refrigerants to absorb and release heat. In heating mode, they extract heat from outdoor air, the ground, or water and distribute it indoors.
- Typical Costs: The cost of heat pump installation varies, with air-source heat pumps being more affordable than ground-source (geothermal) heat pumps.
- Pros: Highly energy-efficient, provide heating and cooling, low operating costs, environmentally friendly.
- Cons: Reduced efficiency in very cold climates, Upfront installation costs can be high, May require a backup heating source in extreme cold.

Furnaces:

- What They Are: Furnaces are heating systems that burn fuel (e.g., natural gas, oil, propane) to produce and distribute heat throughout a building.
- How They Work: Furnaces ignite fuel and use a heat exchanger to warm the air, which is blown through ducts into rooms.
- Typical Costs: Costs vary by fuel type and efficiency, but they are generally more affordable upfront than other systems.
- Pros: Fast and effective heating, suitable for cold climates, cost-effective for short-term heating.
- Cons: Higher operating costs compared to other options, Reduced energy efficiency, Combustion-based, which can produce emissions.

Geothermal Heating:

- What It Is: Geothermal heating uses the stable temperature of the Earth's subsurface to provide both heating and cooling.
- How It Works: A geothermal heat pump system circulates fluid through underground loops to transfer heat between the ground and the building.
- Typical Costs: Installation costs can be higher than traditional systems, but lower operating costs can offset this over time.
- Pros: Highly energy-efficient and environmentally friendly, stable performance in extreme weather conditions, lower operating costs and long-term savings.
- Cons: High upfront installation costs, requires access to suitable geological conditions, longer payback period.

Solar Heating:

- What It Is: Solar heating systems use solar collectors to capture sunlight and convert it into heat for space heating or water heating.
- How They Work: Solar collectors absorb solar energy, which is transferred to a heat transfer fluid (e.g., water or antifreeze) and then distributed for heating.
- Typical Costs: Costs vary based on system size and complexity but can have a moderate upfront investment.
- Pros: Uses renewable energy sources, low operating costs, reduces reliance on conventional fuels.
- Cons: Weather-dependent and reduced efficiency on cloudy days, may require a backup heating system, upfront installation costs can be moderate.

Literature Review

An Evaluation of Energy Storage Cost and Performance Characteristics (Mongird et al.)

This paper assessed the cost and performance of various Battery Energy Storage Systems (BESS) technologies, including lithium-ion batteries, lead-acid batteries, redox flow batteries, sodium-sulfur batteries, sodium-metal halide batteries, and zinc-hybrid cathode batteries while also considering non-BESS storage technologies, such as Pumped Storage Hydropower (PSH), flywheels, Compressed Air Energy Storage (CAES), and ultracapacitors, along with Concentrated Thermal systems (CTs). Their findings indicate that for a 4-hour BESS, lithium-ion batteries currently offer the most favorable choice in terms of cost, performance, calendar and cycle life, and technological maturity. Redox flow batteries, which have seen several installations, rank second in terms of overall cost, performance, life, Technology Readiness Level (TRL), and Manufacturing Readiness Level (MRL). While their Round-Trip Efficiency (RTE) is relatively low, there is potential for enhancement through stack optimization and improved flow battery management algorithms. For longer-term energy storage, Pumped Storage Hydropower (PSH) and Compressed Air Energy Storage (CAES) emerge as the most cost-effective options, with costs per kilowatt-hour ($/kWh) being the lowest when using an Energy to Power (E/P) ratio of 16 at $165/kWh and $104/kWh, respectively, inclusive of Balance of Plant (BOP) and Capital and Construction (C&C) expenses.

A Study and Assessment of the Status of Energy Efficiency and Conservation at School Buildings (Ragab et al.)

This paper presents a comprehensive study on energy efficiency and conservation measures in a school building. The study includes an energy audit with thermography and power analyzer measurements, as well as an awareness survey among the school population. The energy audit aimed to assess energy consumption levels and formulate strategies for reduction. It compared the school's annual electrical consumption to similar U.S. schools. The lighting survey revealed excessive lighting compared to international standards, and adjusting the light intensity could save AED 68,606 annually. Installing motion sensors in classrooms and labs could save AED 93,691 annually with a 2.6-month payback period. Using Networked Optimization Software for the HVAC system could save approximately 469,000 kWh, equivalent to AED 202,000 annually, with a 5.4-month payback period. Thermography indicated good insulation in the building envelope, but some doors needed sealing. An awareness survey showed room for improvement in energy conservation practices. Recommendations included an energy awareness campaign, an energy education program, and the appointment of energy conservation leaders among students. Implementing these measures could result in anticipated savings of approximately AED 364,000, or about 16% of the annual electricity bill.

Evaluation of Energy Transition Pathways to Phase out Coal for District Heating in Berlin (Gonzalez-Salazar et al.)

This paper introduces a methodology for analyzing and evaluating energy transition pathways in complex district heating systems. The methodology combines models for heat demand and supply, the power market, and alternative energy sources. It's designed to be adaptable for different systems and countries. The study applied this methodology to the district heating network in Berlin, focusing on SA1. The results indicate the feasibility of phasing out coal by 2030 without disruptions in heat provision where low-carbon sources can partially replace coal-based heat, but a gas-based combined heat and power (CHP) plant is needed to bridge the gap. This transition could reduce CO2 emissions by 2.15 million tons in 2030, equivalent to 13% of Berlin's emissions. District heating remains cost-effective, even with gradual coal substitution, making it a viable option for large cities aiming for low-carbon heating networks.

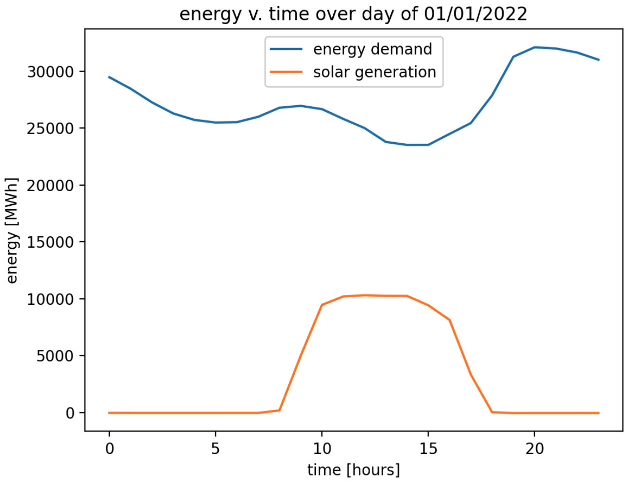
A Review of Recent Advances in Emerging Alternative Heating and Cooling Technologies (Ismail et al.)

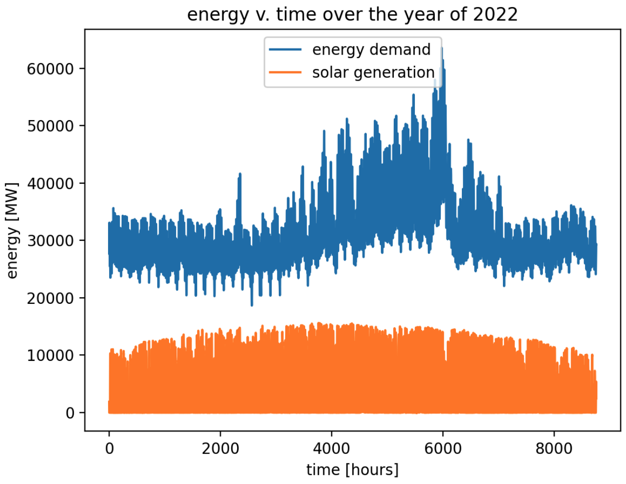
This paper explores emerging alternative technologies for eco-friendly heating and cooling systems. While none of the seven technologies examined have reached commercialization, the analysis reveals various challenges. Magnetocaloric technology faces material availability and aging issues. Electrocaloric technology relies on toxic lead-based materials, necessitating research into lead-free alternatives. Thermoelectric and thermoacoustic technologies have yet to achieve satisfactory efficiencies and are primarily used for research. Barocaloric is limited by the short fatigue life of its core material, natural rubber. In contrast, Elastocaloric stands out as the most promising alternative, thanks to the abundance of its core material and scalability, making it capable of covering a broad range of heating and cooling needs.

Methods

Solar + Storage for Electricity Decarbonization

The daily MW of energy demanded and daily solar generation in California over 2022 was obtained from CASIO. The energy demand profile in California typically peaks in the evening, while solar energy generation is highest in the afternoons, where the sun is the highest and is intermittent depending on weather conditions, time of day, and season. There may be periods of low or no solar generation, especially during the night and on cloudy or rainy days. There is a clear difference in the plot that solar energy cannot alone meet the demand profile and is far from being able to meet the energy demand.





Since the current solar generation cannot fulfill the demands of California, the sum of energy demand over the year is divided by the sum of solar generation over the year to find the number of times we need to expand our current size of solar generation to fulfill the full energy demand of California. This number, found to be 6.66, is multiplied by the daily solar generation to find the 6.66x solar generation at each hour of the day.

First, we determine the energy storage requirements to meet 100% of demand (at all timesteps). To find the amount of stored electricity that needs to be discharged at each timestep, the hourly 6.66x solar generation is subtracted from the hourly demand. To make sure the storage never goes negative, a storage value is initialized, and for each hourly timestep, the difference between demand and generation (i.e. the amount of electricity needed from storage) is subtracted from the storage value, and the new storage value is checked to make sure it's not negative. If the storage state is always positive, the storage is overbuilt, and the initial storage value is decreased until a storage value becomes negative. If there is a negative value, the storage is underbuilt, and the initial storage value is increased until all outputs are positive.

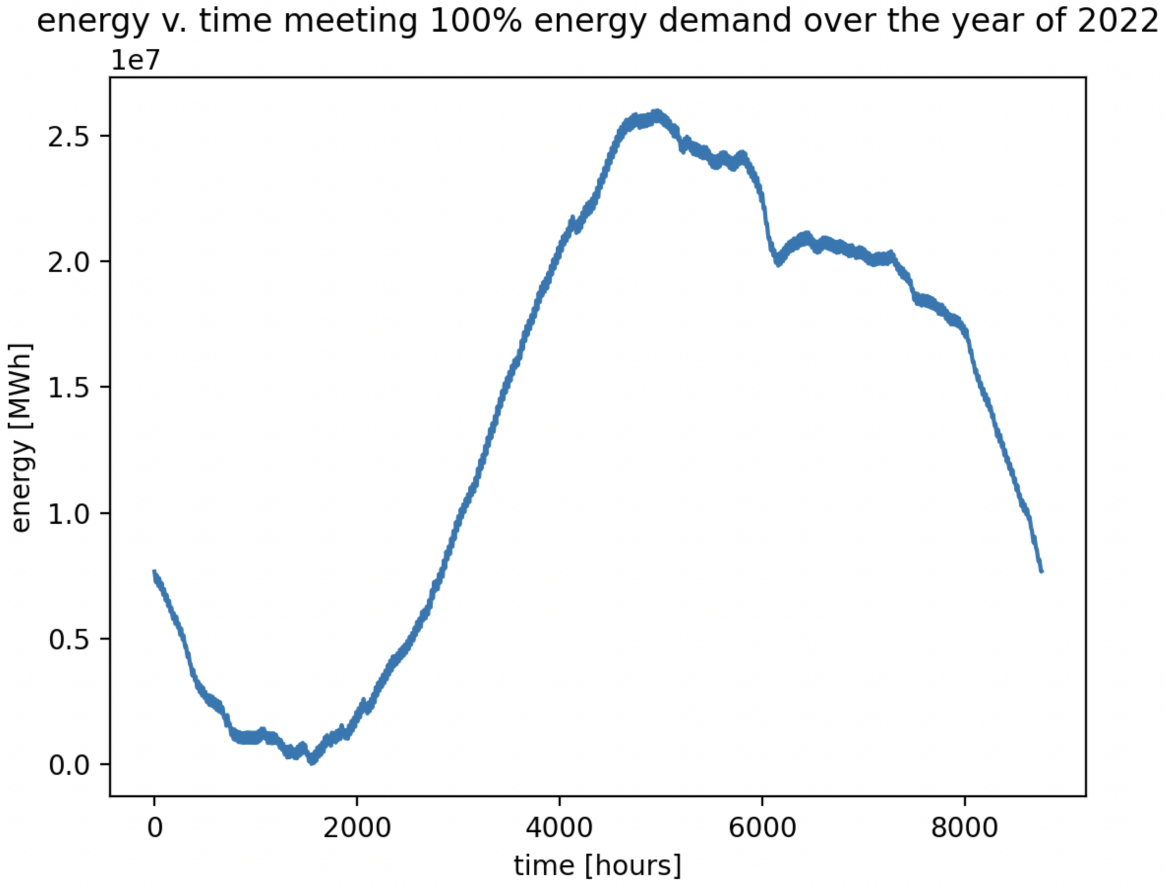
To determine how energy storage requirements change for meeting less than 100% of demand, we update the algorithm to consider storage capacity and unmet demand.

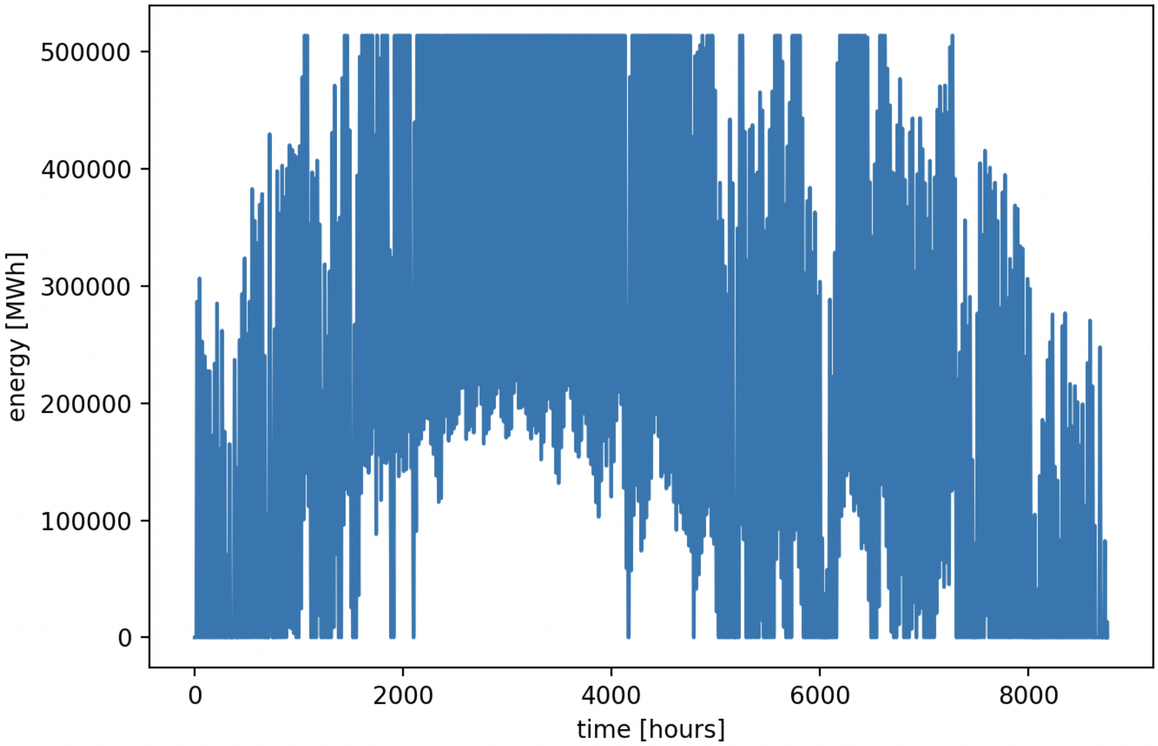
1. Set a storage capacity
2. Set a desired unmet demand
3. Simulate its operation over the year (unmet demand when storage goes below 0 and curtailed when storage reaches capacity)
    a. Constraint #1: energy at beginning = end
4. Calculate the unmet demand
5. Iterate until calculated unmet demand = desired

The concluded number is the amount of storage needed to supply the energy demand in California completely by solar energy in 2022 is 27,321,311 MWh. To meet 90% of energy demand in California, a storage capacity of around 514,000 MWh is needed. To meet 80% of the energy demand in California, a storage capacity of around 280,600 MWh is needed, which is a drastic decrease compared to the storage capacity required for meeting 100% of the demand. Around half of the storage needed for every decrease in 10% of demand is met.

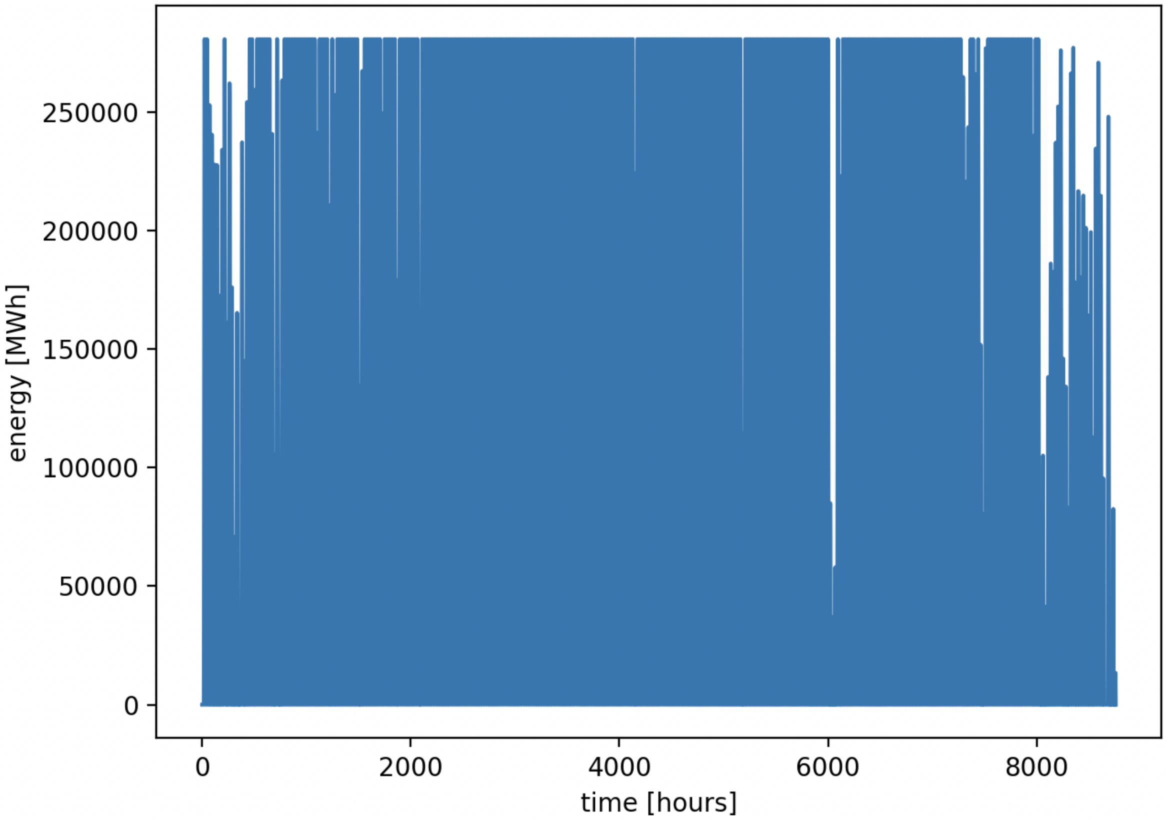
Using cost inputs of $1/W for solar energy generation, which can be rewritten as $1.00e6/MW, and $20/kWh for the cost of solar energy storage, which can be rewritten as $2.00e4/MWh, the cost of solar generation technology can be found by multiplying the cost with the highest generation in each case scenario, and cost of storage can be found by multiplying the price with the storage capacity needed for each scenario. The total cost can be found by adding the cost of solar generation technology with the cost of storage.

% demand met	Amount of solar installed [MW]	starting storage [MW]	Ending storage [MW]	Storage capacity needed [MWh]	Cost of solar generation technology ($1.00e6/ MW)	Cost of storage ($2.00e4 /MWh)	Total cost
100%	1.04e5	7.68e6	7.68e6	2.73e7	1.04e11	5.46e11	6.5e11
90%	1.04e5	0	0	5.14e5	1.04e11	1.03e10	1.14e11
80%	1.04e5	0	0	2.81e5	1.04e11	5.61e9	1.10e11





energy v. time meeting 90% energy demand over the year of 2022



energy v. time meeting 80% energy demand over the year of 2022

Results

For a system meeting 100% of the energy demand, the total cost is notably high, amounting to \$6.5e11, with a storage cost of 5.46e11 and a technology cost of 1.04e11. This indicates that achieving complete energy self-sufficiency with current storage costs can be a substantial financial burden.

As we consider lower energy self-sufficiency percentages, such as meeting 90% and 80% of the energy demand, we observe a considerable reduction in total costs. For a 90% self-sufficiency scenario, the total cost decreases to \$1.14e11, with a storage cost of 1.03e10 and a technology cost of 1.04e11, while for 80% self-sufficiency, it drops further to \$1.10e11, with a storage cost of 5.61e9 and a technology cost of 1.04e11. It is important to note that as we increase the unmet percentage of energy demand, solar generation technology costs become more dominant in the total cost compared to the cost of storage.

Heating

LCOH (Levelized cost of heating) numbers were obtained using the equation LCOH = CAPEX / 8760 hours + OPEX. CAPEX is the capital cost of the heating method in dollars per kW, OPEX is the operation and management costs in dollars per kWh, and 8760 hours represent a year in hours to unify the units of the equation.

OPEX is calculated based on fuel costs but could increase based on maintenance costs. For a natural gas boiler, the fuel cost is 0.75 dollars per m^3 (EIA), which converts to about 0.066 dollars per kWh, based on the LHV of natural gas of 57.1 MJ/kg and an efficiency of 90%. For fuel oil and propane gas furnaces, the fuel cost is 2.50 dollars per gallon and 4.00 dollars per gallon (EIA), respectively, which converts to about 0.089 dollars per kWh, using an LHV of 96.548 MJ per gallon and efficiency of 95% for fuel oil, and 146.326 MJ per gallon with efficiency of 90% for propane gas furnaces.

For electricity-based technologies, the electricity cost is 0.1564 \$/kWh-e (EIA), which converts to a heating cost of 0.045 \$/kWh-t for an air heat pump based on a COP of 3, 0.165 \$/kWh-t for an electric resistance heating based on an efficiency of 95%, and 0.039 \$/kWh for a geothermal heat pump based on a COP of 4. Solar thermal has nearly zero fuel costs due to its reliance on the sun.

CAPEX was obtained based on literature searches and evaluation of available technologies on the market. The CAPEX value of a fuel oil furnace ranges from 10 to 30 dollars per MBtu, which converts to about 2930 dollars per kW (waterprofessionals). The CAPEX value of a geothermal heat pump is about 1666 dollars per kW (IRENA). The CAPEX cost of a natural gas boiler is about 300 dollars per kW (Statista Research Department). The CAPEX cost of solar thermal totals about 3000 dollars per kW with 3 solar panels of 1500 dollars per kW each, with the addition of 0.5 dollars per W of the installation fee (EIA) (Fernández).

It is also important to account for the carbon cost, which is estimated at 0.05 dollars per kg of carbon emissions (Wygonik). For each heating technology, we calculate the carbon emissions (kg per kWh) and then multiply by the carbon cost to get an additional OPEX.

With the above numbers, we can calculate an LCOH, which is presented in the results section.

We can also calculate the actual cost of a system, assuming a 50,000 ft^2 school with a heating load of 500 kW/ft^2, giving a heat requirement of 1.8x10^8 kWh per month. We calculate the overall system cost over 15 years to determine the cost savings for different technologies. The values are presented in the results section.

Finally, we calculate the carbon emissions savings for a natural gas boiler vs. an electric air heat pump, which were found to be the cheapest technologies. Carbon emissions for different sources of electricity (NG vs. solar plant)

The calculated LCOH for a natural gas boiler is about 0.101 dollars per kWh, 0.431 dollars per kWh for fuel oil furnace, 0.229 dollars per kWh for geothermal heating, 0.372 dollars per kWh for solar thermal, 0.061 dollars per kWh for an electric heat pump, 0.256 dollars per kWh for an electric furnace, and 0.168 dollars per kWh for a propane gas furnace.

The results for LCOH after including the carbon costs are similar. The calculated LCOH for a natural gas boiler is about 0.11 dollars per kWh, 0.44 dollars per kWh for a fuel oil furnace, 0.24 dollars per kWh for geothermal heating, 0.37 dollars per kWh for solar thermal, 0.07 dollars per kWh for an air heat pump, 0.28 dollars per kWh for an electric resistance heating, and 0.18 dollars per kWh for a propane gas furnace.

The results for fuel costs of each heating method are presented below.

	$	LHV	efficiency/COP	fuel cost
natural gas	$0.75/m^3	47.1MJ/kg	0.9	0.06639338951
propane gas furnace	$2.50/gallon	96.537611 MJ/gallon	0.95	0.0885664465
fuel oil furnace	$4.00/gallon	146.325696 MJ/gallon	0.9	0.08856947198

air heat pump	$0.1564/kWh	N/A	3	0.04468571429
electric resistance heating	$0.1564/kWh	N/A	0.95	0.1646315789
geothermal heat pump	$0.1564/kWh	N/A	4	0.0391

The results for overall system costs are presented below.

	CAPEX [$/kW]	Fuel Cost / OPEX [$/kWh]	LCOH [$]
Natural Gas Boiler	300	0.06639338951	0.1006399649
Fuel Oil Furnace	2930	0.08856947198	0.4310352254
Geothermal	1666	0.0391	0.2292826484
Solar Thermal	3000	0	0.3724657534
Air Heat Pump	140	0.04468571429	0.06066744945
Electric resistance heating	800	0.1646315789	0.2559557799
Propane gas Furnace	700	0.0885664465	0.1684751223

The results for carbon emissions are presented below.

	carbon emission [kg/kWh]	carbon cost using $0.05/kg [$/kWh]	LCOH + carbon cost [$]	cost of technology (500 kW system + 1.8e5kWh per month) over 15 years [$]
Natural Gas Boiler	0.21	$0.01	$0.11	460229.164

Fuel Oil Furnace	0.245	$0.01	$0.44	234936.3406
Geothermal	0.109125	$0.01	$0.23	52110.87671
Solar Thermal	0.041	$0.00	$0.37	77423.83562
Air Heat Pump	0.1247142857	$0.01	$0.07	51540.1409
Electric resistance heating	0.4365	$0.02	$0.28	581472.0404
Propane gas Furnace	0.22	$0.01	$0.18	169625.522

Conclusions

From our calculations over using complete solar energy for electricity, we determined that the total cost of implementing a solar system with storage that meets demand 100% is extremely high, and as we increase the unmet demand, solar generation technology costs become more dominant in the total cost compared to the cost of storage. These results underscore the significant impact of energy self-sufficiency targets on the economic feasibility of solar and storage systems. While striving for complete self-sufficiency comes with substantial costs, aiming for lower percentages of demand coverage can lead to significantly more cost-effective solutions. It is essential to strike a balance between energy independence and financial feasibility when designing and implementing solar and storage projects, considering the specific needs and budget constraints of the system in question.

Our analysis of heating technologies demonstrates that electric air heat pumps are both cheaper and reduce CO2 emissions because of their small CAPEX cost and reliance on electricity for fuel. It is important to note that although there are no fuel costs for solar thermal systems considered, they still have a higher Levelized Cost of Heating (LCOH) when compared to air heat pumps, which highlights the importance of considering operational costs. There is still much additional research that can be done in addition to the result of this paper. It is important to acknowledge that different heating technologies may vary depending on specific circumstances, such as the tradeoff between upfront capital expenditure (CAPEX) and ongoing operating costs (OPEX) and the cost calculations of new installations as opposed to replacements, as well as school policies for implementing different heating technologies.

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