

City-scale decarbonization experiments with integrated energy systems

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SUPPLEMENTAL INFORMATION

Supplementary Note 1. We detail the calculation for the emissions reduction obtained from changing the energy system design. The 2012 gas consumption of the Cardinal co-generation plant was 4.4E6 mmbtu. Stanford consumed 83% of the resulting energy, resulting in annual operating emissions of 196E3 tons. In 2016, we estimate from the model that is detailed in the Methods that the aggregate Stanford system used 264E6 kWh of electricity and 71E3 mmbtu of gas, resulting in annual operating emissions of 73e3 tons. The corresponding reduction from the energy system redesign is 65%. For electricity-related carbon emissions, we use the carbon intensities in table S1 and 2016 generation data for the CAISO balancing area. For gas-related carbon emissions, we use 5.302 kgCO₂/mmbtu¹.

Fuel	Carbon intensity (kgCO ₂ -eq/MWhe)
Biogas	230
Biomass	230
Geothermal	42
Hydro	4
Nuclear	16
Small Hydro	4
Solar PV	46
Solar thermal	22
Thermal (assumed to be gas)	469
Wind	12
Imports	428

Table S1 | 50th percentile for life-cycle carbon intensity of electricity generated from different sources, according to Table A.II.4 in the IPCC 2011 Special Report on Renewable Energy Sources and Climate Change Mitigation³. The carbon intensity of CAISO imports is reported in the CAISO 2016 Greenhouse Gas Emission Tracking Methodology⁴.

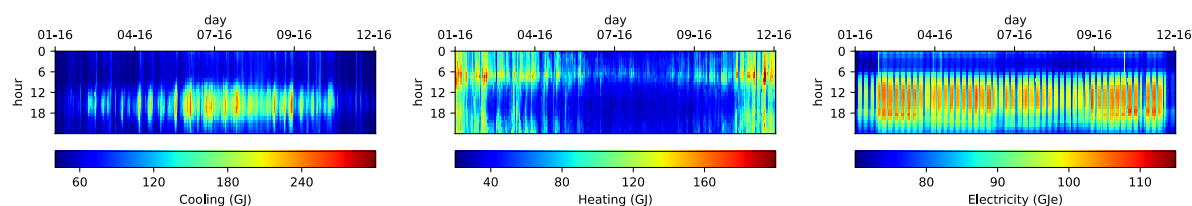


Figure S1 | Heat maps for base case schedule and loads. According to the IEA, the 2009 energy consumption of a CA household is 62mmbtu (or 65GJ)².

	Scenario 1X	Scenario 2X	Scenario 3X	Scenario 5X
Max overgen (GW)	0	0	1.48	16.4
Solar overgen (%)	0	0	8.4	25.3
Solar (%)	9.1	18.3	27.4	45.6
Thermal (%)	27.1	19.9	17.1	12.11
Imports (%)	30.2	28.3	22.0	8.7
Max solar (GW)	7.86	15.7	23.6	39.3
Solar gen (TWh)	19.4	38.9	58.3	97.2
Annual CO2 (mtons)	56.6	48.5	40.8	25.6
CO2 reduction (%)	0	14.2	27.8	54.8

Table S2 | Summary for carbon scenarios. In the absence of data on CAISO exports at the location the generation data was scraped⁵, here we make the assumption that 2 GW of thermal generation is exported at every hour during the year. This assumption is justified by comparing recalculated carbon intensities to CAISO-provided carbon intensities in figure S2.

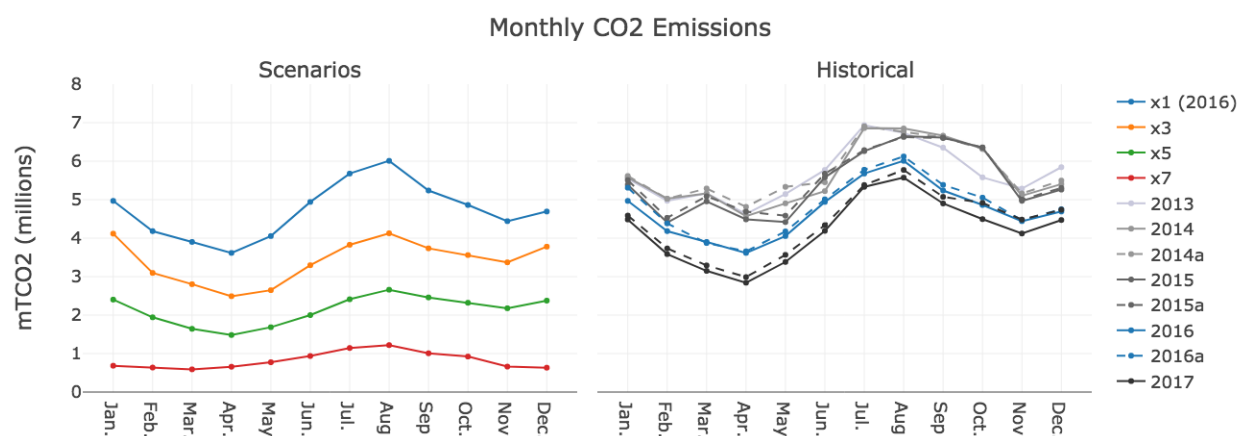


Figure S2 | Monthly CO2 emissions: (a) scenarios for different increased penetrations of solar relative to 2016; (b) comparison from historical data calculated from generation data from CAISO's daily renewables watch⁵ and IPCC numbers to the numbers on the CAISO Today's Outlook dashboard⁶.

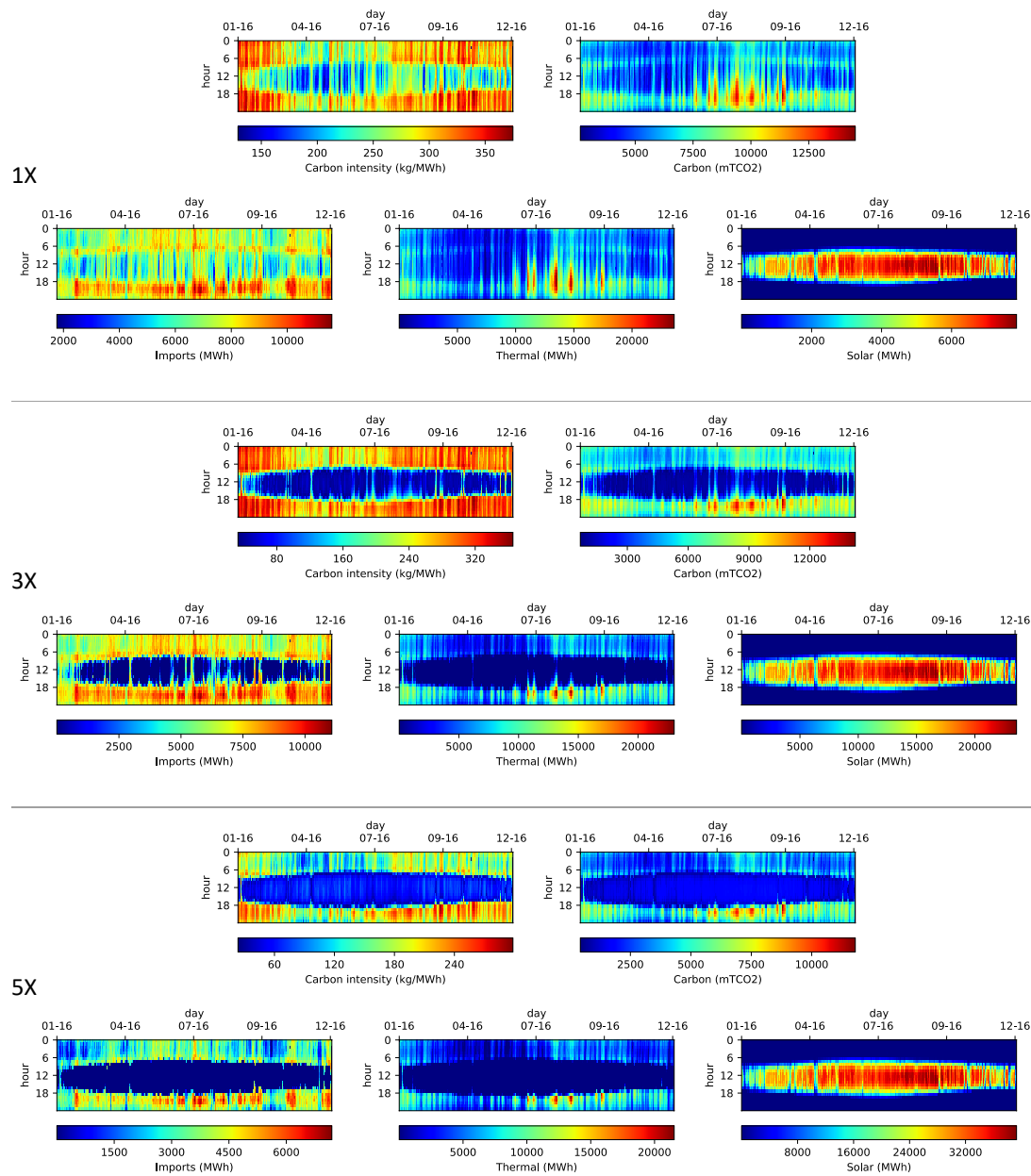


Figure S3 | Heatmaps for carbon intensity, carbon emissions, and generation from imports, thermal or solar power for the 1X, 3X and 5X carbon scenarios. In the 5X scenario, it is assumed that the overgeneration is homogeneously redistributed throughout the day (through some form of storage), lowering the carbon intensity of all hours (see figure S3). As the daily variability of carbon intensity reduces, so does the need for loads that shift consumption in time.

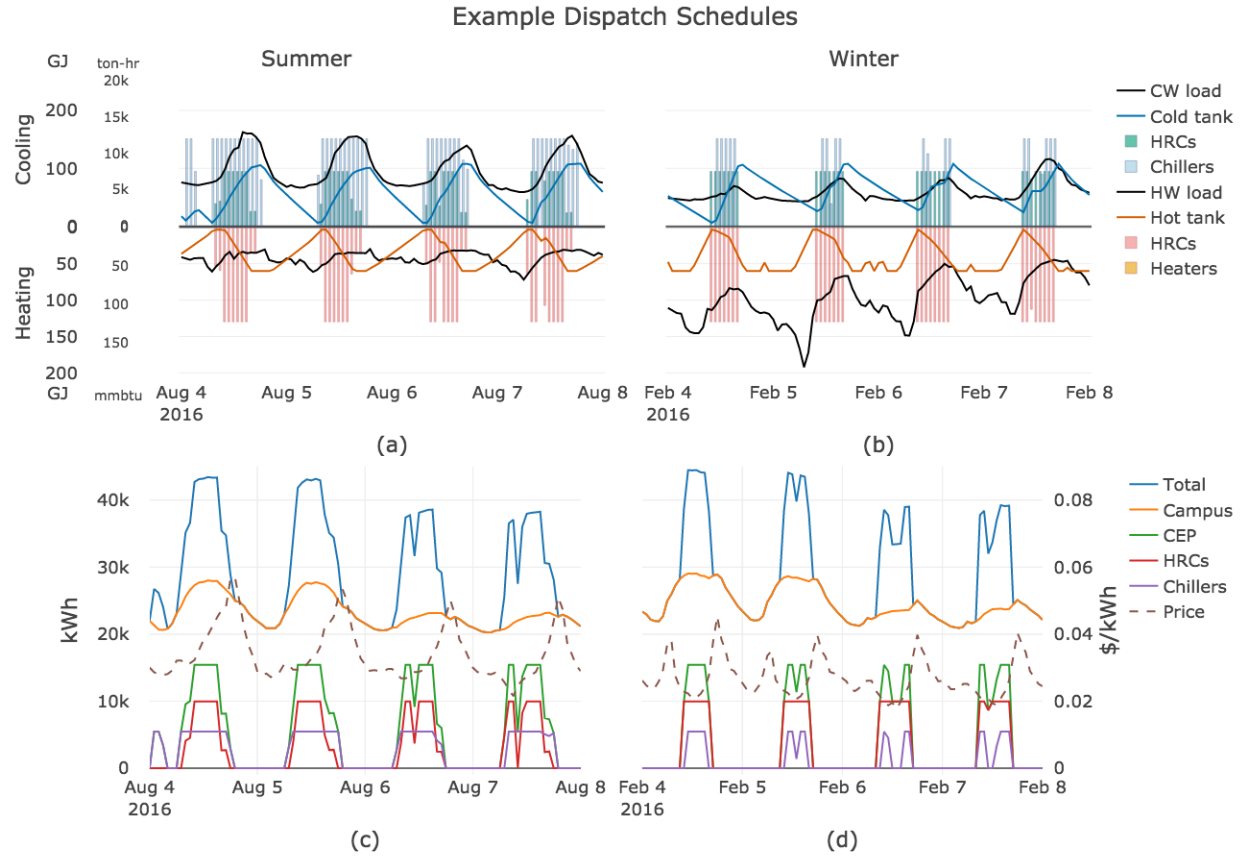


Figure S4 | Carbon-optimal version of Figure 3 for scenario 3X. Optimal thermal dispatch schedule for a Thursday to Sunday period in the summer (a) and winter (b), and corresponding electrical energy flows and electric price (c-d). Heating is provided by a stream of hot water at 160°F and cooling is provided by a stream of chilled water at 40°F. To convert from engineering to SI units in figures S4a and b, we use 1.055 GJ/mmbtu for heating and 0.0126 GJ/ton-hour for cooling.

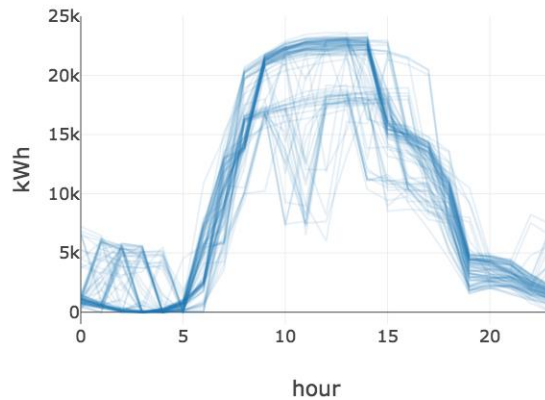


Figure S5 | Estimation of the solar generation capacity that can be accommodated by the campus in the carbon-optimal case for scenario 3X. Plot of daily consumption profiles for the months of June, July and August 2016 (we subtract the minimum daily load). 50% of these 92 lines are above 20 MW in the middle of the day, 67% are above 15 MW.

Supplementary Note 2. We detail the calculation of energy storage equivalence. The tanks store 600 mmbtu of heat and 90E3 tons of cooling. We use the calculation methodology outlined in the Methods, with $r = 2$, $\eta_{HRC,c} = 1.32$ kWh/ton-hr, $\eta_{HRC,h} = 0.0164$ kWh/mmbtu, $\eta_{Ch,c} = 0.45$ kWh/ton-hr to find that the tanks could be replaced by 93 MWh of electrochemical storage. For perspective, we also use a second method for calculating the equivalent electrochemical storage size where no hot water is wasted: assuming that HRCs are used to fill the tanks and complemented by chillers, this requires 48 MWh of electrical energy for the HRCs and 25 MWh for the chillers. Assuming a round trip efficiency of 85%, this translates to ~85 MWh. The ten million gallons of cold storage and two million gallons of hot storage at Stanford cost \$7.4 million, so [85-93] MWh of electrochemical storage would have to cost \$[79-87] kWh⁻¹ to be on par if two types of storage had the same lifetime. Assuming an annual discount rate of 5% and that thermal storage lasts approximately three times longer than electrochemical storage, electrochemical storage would have to cost \$[40-44] kWh⁻¹. We note that thermal storage and electrochemical storage are not equivalent because electrochemical storage can target a wider range of value streams that are not required here.

Parameter	Industry Units	SI Units
Electric Chiller efficiency	0.47 kWh/ton-hr	37 kWh/GJ
HRC cooling efficiency	1.15 kWh/ton-hr	119 kWh/GJ
HRC heating-to-cooling	0.016 mmbtu/ton-hr	1.53 GJ/GJ
Gas boiler efficiency	85% (mmbtu/mmbtu)	NA

Table S3 | Typical values for efficiency of the machines at the Stanford Central Energy Plant⁷.

References

1. US Environmental Protection Agency. Greenhouse Gases Equivalencies Calculator. Available at: <https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references>. (Accessed: 27th April 2018)
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3. Moomaw, W. *et al.* Annex II: Methodology. *IPCC Spec. Rep. Renew. Energy Sources Clim. Chang. Mitig.* **16**, NP (2014).
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