Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Addressing Energy Storage Needs at Lower Cost via On-Site Thermal Energy Storage in Buildings

Supplemental Information

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Supplementary Note 1: Calculating Energy Storage Technical Potential (Methodology and Additional Data)

Methodology

The process for determining thermal energy storage (TES) potential can be repeated for any region in the world if sufficient building load profiles and renewable generation profiles are available. For the assessment of the thermal energy storage potential for buildings within the contiguous United States, we used building load profiles within Scout (https://scout.energy.gov/). Scout is an open-source software tool developed by the U.S. Department of Energy's (DOE's) Building Technologies Office for estimating the national energy use, carbon emissions, and costs associated with building energy efficiency measures.[1,2] Scout incorporates baseline energy projections for residential and commercial buildings within the United States through 2050 based on the U.S. Department of Energy's Energy Information Administration (EIA) Annual Energy Outlook.[3] Additionally, Scout incorporates baseline data for the installed stock of various technologies and for equipment performance.

Renewable generation profiles were obtained from the National Renewable Energy Laboratory's System Advisor Model (SAM).[4] SAM is a free techno-economic software tool that aids decision-making for renewable energy projects. It allows for the modeling of a variety of renewable energy systems, including wind and solar installations. Solar and wind profiles were obtained for representative cities in each EIA Electric Market Module region. To obtain average wind and solar profiles for the contiguous United States, we weighted sample profiles across the contiguous United States by the total building electrical energy consumption for each grid region as determined by Scout, and then averaged the values together.

To predict the increase in electrical load attributed to future space heating electrification, we applied scaling factors to baseline 2050 electrical load predictions for air-source heat pumps. These scaling factors were based on the respective annual thermal delivery of fuel-based space heating divided by the annual thermal delivery of air-source heat pumps. Thermal delivery for both fuel and electrical heating were determined via Scout's default coefficient of performance (COP) characteristics for the year 2050.

To generate projections for average daily thermal energy storage requirements by season, 8,760 profiles for all thermal and non-thermal end uses in residential and commercial buildings were calculated with Scout. We ran Scout with the "--sect_shapes" modifier to generate JSON files, as shown in the Scout documentation.[a] Depending on whether the user wants energy usage resolution down to EIA Electricity Market Module regions or AIA climate zones, the user can also include the "--alt_regions" modifier. Next, the programming environment of the user's choice can be used to extract end-use profile from the JSON file using the following nesting: (index of end-use measure) → ("Sector_shapes") → ("Technical potential") → (index of target region) → (target year) → ("baseline"). We extracted performance characteristics used for the electrification scenarios from the microsegment files found in (.../supporting_data/stock_energy_tech_data/) from the Scout default directory. Once the 8760 end-use profiles were developed, they were averaged over 24-hour periods for the desired season (Jun-Aug for summer, Dec-Feb for winter). This allowed for the determination of average needs for short duration energy storage. A flowchart of the procedure is shown in Figure S1.

[a] Scout Tutorials: Sector-level hourly energy loads, available from: https://scout-bto.readthedocs.io/en/latest/tutorials.html?highlight=8760#sector-level-hourly-energy-loads

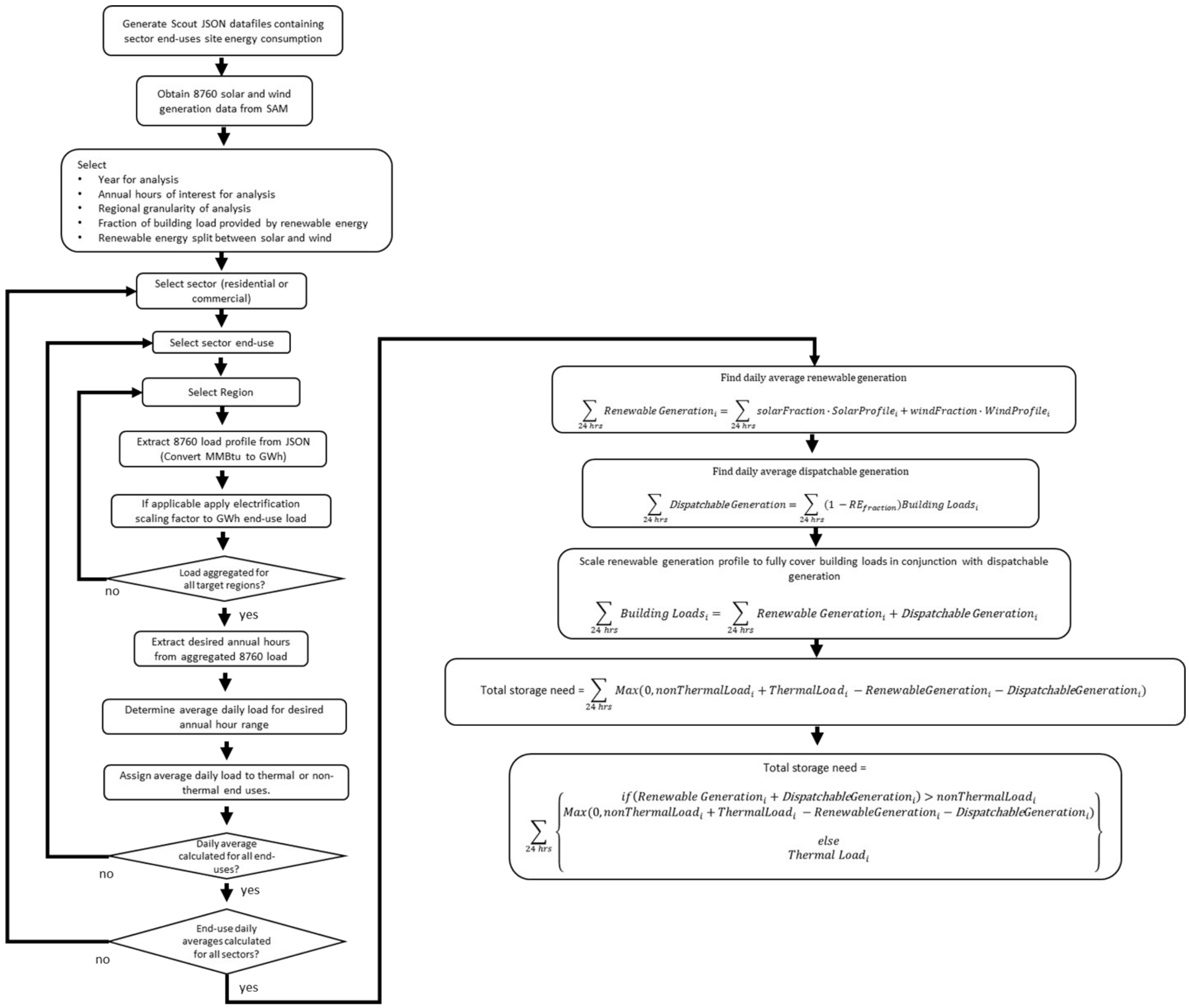

Figure S1: Procedure for determining thermal storage potential in residential and commercial buildings

Additional Data

Figure S2 shows modeling results for various scenarios in which heat pumps are used for both cooling and heating. Results are shown for various supply energy mixes of renewables (solar and wind) and dispatchable generation (DG) from other sources (e.g., fossil fuels, nuclear), as this has a significant impact on the storage requirements for supporting building loads. Figure S2 assumes 75% renewable electricity (RE) supply. Similar graphs for a 100% RE supply scenario are shown in Figure 2 in the main article.

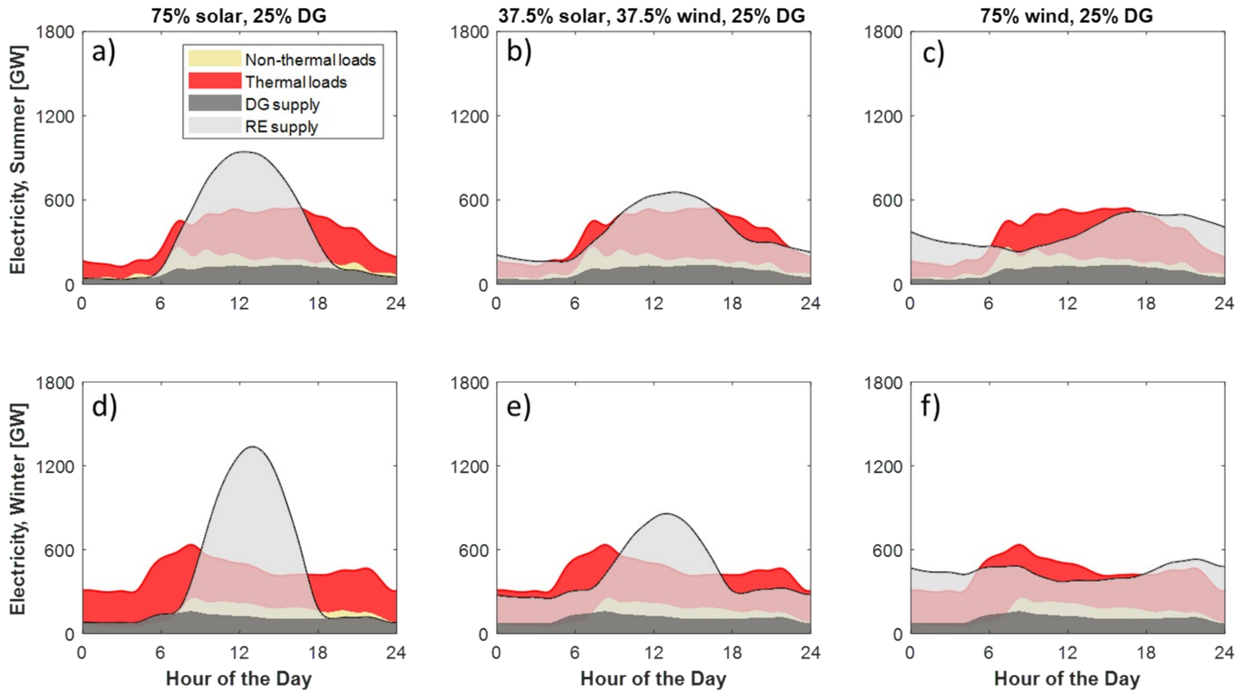

Figure S2: Average summer (a–c) and winter (d–f) U.S. commercial and residential building electricity demand, overlaid with 75% RE supply profiles. The balance of electricity supply is assumed to come from DG sources. The results assume air-source heat pumps are used for heating. Similar graphs for a 100% RE supply scenario are shown in the main article.

Like in the 100% RE scenario, in most cases, the entirety of non-thermal loads can be covered at all times by the RE + DG supply, meaning that non-thermal loads can be met directly from this supply without needing storage. DG supply (shown in Figure S2 as dark grey shaded regions) comes from non-intermittent sources (i.e., not solar or wind), and therefore does not need to be shifted using storage. This results in overall storage requirements being less than the 100% RE scenario in the main article.

Figure S3 shows the total storage requirement in electrical equivalent for balancing the 75% RE + 25% DG supply and demand profiles from Figure S2, for both thermal and non-thermal loads and for various fractions of solar and wind. A similar graph for 100% RE supply is shown in Figure 2 in the main article. Compared to the 100% RE scenario, any non-thermal storage needs are almost eliminated (except for the scenario where all RE is solar), and thermal storage needs are reduced by anywhere from 6% to 25%, depending on the solar-to-wind split of the RE supply.

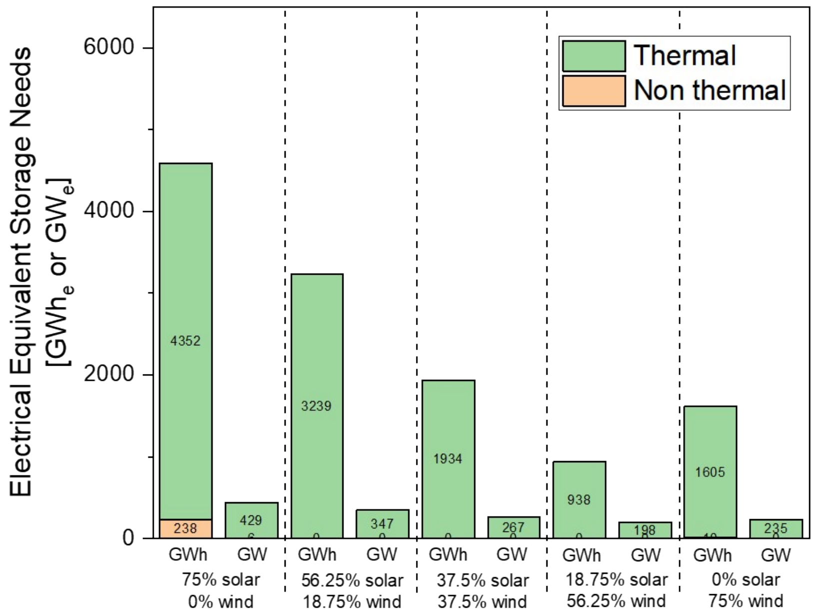

Figure S3: Energy storage potential to support commercial and residential buildings in the United States for a 2050 grid with 75% RE, broken out into thermal and non-thermal contributions. Heating electrification using air-source heat pumps is assumed. A similar graph for a 2050 grid with 100% RE is shown in the main article.

Supplementary Note 2: Justification of Assumed Values for Parameters in Levelized Cost of Storage Equation

The rationale behind the values assumed for the levelized cost of storage (LCOS) parametric studies, shown in Figure 4 and Figure 5 in the main article, are explained in the following table and notes. While we assumed certain values for each parameter for the reasons outlined below, different assumptions can be used to evaluate LCOS under different scenarios.

Table S1: Justification of assumed values for parameters in LCOS equation

Parameter	Value(s)	Justification/Reference
C_T	15–75 \$/kWh	• See Note 1 below
$D_T \cdot u_T$	State-of-the-art: 50–120 cycles/yr; next-generation: 275–365 cycles/yr	• See Note 2 below
η_S	0.7–0.95	• Reference 5 gives a range of 0.7–0.85[5] • Reference 5 gives values >1 with large diurnal temperature swings[5] • Reference 6 gives a range of 0.7–1.8[6]
L_T	20 years	• Reference 7 gives a range of 15–30 years[7]
$COPav$	3	• Reference 8 gives a range of 2–4[8]
COP_C/COP_{av}	1–1.4	• See Note 3 below
p	\$0.13/kWh	• The U.S. average residential price of electricity was \$0.13/kWh as of March 2021[9]
r	7.5%	• Reference 10 gives a range of 3–10%[10] (See also Note 4 below)

C_E	100–350 \$/kWh	• Reference 11 gives a range of \$400/kWh$_e$ (year 2020) to \$150/kWh$_e$ (year 2050) in mid cost scenario[11]
$D_E \cdot u_E$	State-of-the-art: 275–365 cycles/yr; next-generation: 275-365 cycles/yr	• Electrical energy storage can be used year-round at high utilization (275–365 cycles/yr) due to the year-round presence of electrical loads in buildings
$\eta_{RT,E}$	0.95	• Reference 12 gives a range of 0.9–0.97[12]
L_E	10 years	• References 12 and 13 give a range of 5–15 years[12,13]

Table 1 Notes:

1. Currently, the U.S. DOE target is \$15/kWh$_{th}$[14] for hot storage; however, data from existing concentrating solar power plants shows current costs in the range of ~\$38/kWh$_{th}$ (~\$90/kWh$_e$ assuming the standard Rankine steam cycle efficiency of 42%)[15]. For cold storage, data on ice and chilled water storage shows costs in the range of ~\$30/kWh$_{th}$–\$50/kWh$_{th}$.[16,17] The U.S. DOE has also set a materials cost target of \$15/kWh$_{th}$ for buildings TES.[18] Considering the variability and uncertainty in costs for state-of-the-art TES, we have assumed a conservative estimate of \$25/kWh$_{th}$–\$75/kWh$_{th}$, with a more optimistic range of \$15/kWh$_{th}$–\$25/kWh$_{th}$ for next generation TES.

2. HVAC-integrated TES must be designed for heating or cooling, and envelope-integrated TES utilizing PCMs is most effective at certain times of the year,[19] leading to low utilization. For this reason, we have assumed a conservative utilization for state-of-the-art TES of 90–180 cycles per year (i.e., one complete cycle per day for 3–6 months). A location with balanced seasons, such as Charlotte, North Carolina or the Midwestern United States, might have utilization closer to 90 cycles per year, whereas a cooling dominated or heating dominated location such as Pheonix, Arizona or Duluth, Minnesota might have utilization closer to 180 cycles per year for cooling TES and heating TES, respectively.

3. For COP_C/COP_{av}, models of a standalone vapor compression air-conditioning system and a system hybridized with TES (created in Engineering Equation Solver) were used to calculate air-conditioning COP for various outdoor air temperatures, assuming a 24°C indoor air temperature setpoint. This data was then used to develop an empirical equation for COP as a function of ambient temperature, as shown in Figure S4. Next, the day with the largest difference between high temperature and low temperature for each month for an example location (Los Angeles) was taken, as shown in Table S2, and COP_C and COP_{av} were calculated using the empirical equation for COP and the high/low daily temperature

for each month. The average COP_C/COP_{av} was then determined by considering only those months that would likely require cooling (e.g., March–November for Los Angeles). This resulted in COP_C/COP_{av} of 1.48 for Los Angeles. These numbers are in line with our assumed values of 1.4 and 1 in the main article.

4. The fairly high discount rate of 7.5% was chosen, as is typical, to reflect higher risk/uncertainty of TES in buildings due to it being a relatively new technology with limited deployment.[10]

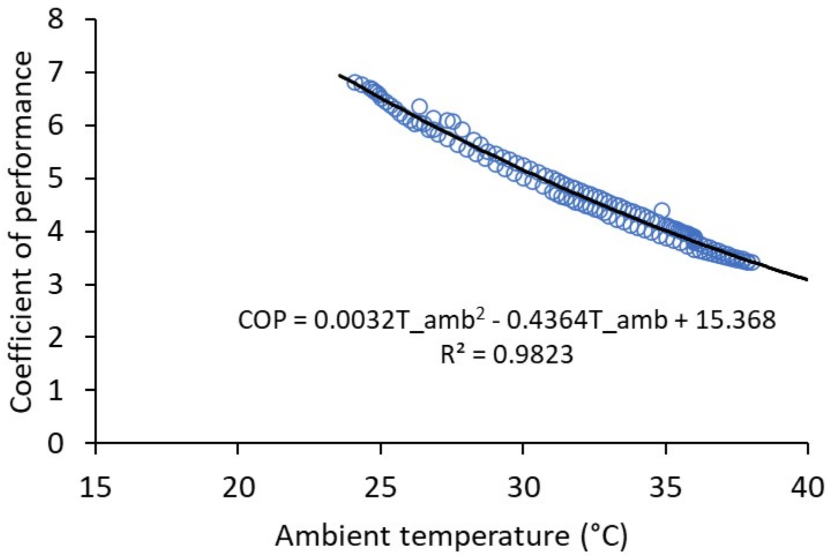

Figure S4: Empirical data on COP as a function of ambient temperature.

Table S2: Example calculation for COP_C/COP_{av} for Los Angeles

			LA				
	low T (°F)	high T (°F)	low T (°C)	high T (°C)	COP_C	COP_{av}	COP_C/COP_{av}
J	49	68	9	20	11.53	7.92	n/a
F	50	68	10	20	11.33	7.92	n/a
M	52	70	11	21	10.92	7.58	1.44
A	55	72	13	22	10.32	7.25	1.42
M	58	74	14	23	9.73	6.93	1.40
J	62	78	17	26	8.99	6.31	1.42
J	65	83	18	28	8.44	5.57	1.51
A	66	85	19	29	8.27	5.29	1.56
S	64	83	18	28	8.62	5.57	1.55
O	60	79	16	26	9.36	6.16	1.52

N	53	72	12	22	10.71	7.25	1.48
D	49	68	9	20	11.53	7.92	n/a

Avg. COP_C/COP_{av}	**1.48**

Supplementary Note 3: Definitions of Levelized Cost of Storage and Levelized Cost of Energy

The LCOS is similar to the levelized cost of energy (LCOE), which is often used for the costs of power plants.[20] The LCOE is the average revenue, per kWh of energy generated, that will recover *all* costs for building and operating a storage system. The LCOS is defined similarly, but it subtracts the cost of charging the storage system (i.e., the price paid for electricity to charge the storage system). Thus, the LCOS is the required incremental cost above the off-peak electricity period of discharging the storage during the peak period to recover the storage investment. If LCOS > ($p_{peak} - p_{offpeak}$), where p is the retail price of electricity, then it makes more sense to pay for the electricity during the peak period. If LCOS < ($p_{peak} - p_{offpeak}$), then the storage is cost-effective, and it is a better option than paying for the peak price electricity.

The way that LCOS and LCOE are defined for the purposes of this perspective is shown in Figure S5. Contributions to LCOS include the capital cost, charging inefficacy cost (due to inefficiency of storage), and operations and maintenance costs. However, operations and maintenance costs are neglected in this study because they are typically a marginal contribution to levelized cost. The costs to acquire the electricity used to charge the storage are not included in the LCOS. However, the LCOE (sometimes referred to as LCOS in other studies) does include costs to acquire electricity, as shown in Figure S5.

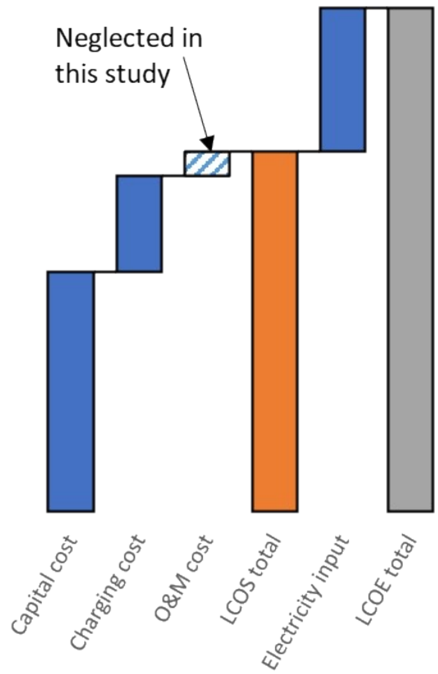

Figure S5: Definitions of LCOE and LCOS used in this study and their respective contributions. Note that these definitions are consistent with Albertus et al.[21] and the U.S. Department of Energy's Energy Storage Grand Challenge.[22]

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